Columbia | Engineering

The Fu Foundation School of Engineering and Applied Science

BULLETIN 2015–2016

UNDERGRADUATE ADMISSIONS

Office of Undergraduate Admissions
212 Hamilton Hall, Mail Code 2807
1130 Amsterdam Avenue
New York, NY 10027
Phone: 212-854-2522
Fax: 212-854-3393
E-mail: ugrad-ask@columbia.edu
undergrad.admissions.columbia.edu

GRADUATE ADMISSIONS

Graduate Admissions, Financial Aid, and Student Affairs
530 S. W. Mudd, Mail Code 4708
500 West 120th Street
New York, NY 10027
Phone: 212-854-6438
Fax: 212-854-5900
E-mail: seasgradmit@columbia.edu
gradengineering.columbia.edu

FINANCIAL AID

Office of Financial Aid and Educational Financing
Office: 618 Lerner Hall
Mailing: 100 Hamilton Hall, Mail Code 2802
1130 Amsterdam Avenue
New York, NY 10027
Phone: 212-854-3711
Fax: 212-854-5353
Undergraduate Inquiry E-mail: ugrad-finaid@columbia.edu
Graduate Inquiry E-mail: engradfinaid@columbia.edu
cc-seas.financialaid.columbia.edu

Need more information?

You can find the contact information for the people who know in the Columbia University Resource List on pages 256-259 or visit the Columbia Engineering website, engineering.columbia.edu.

For the most current information, visit our online bulletin at bulletin.engineering.columbia.edu.

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The Fu Foundation School of Engineering and Applied Science

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Mission

The mission of The Fu Foundation School of Engineering and Applied Science is to expand knowledge and advance technology through research, while educating students to become leaders informed by an engineering foundation. Enriched with the intellectual resources of a global university in the City of New York, we push disciplinary frontiers, confront complex issues, and engineer innovative solutions to address the grand challenges of our time. We create a collaborative environment that embraces interdisciplinary thought, integrated entrepreneurship, cultural awareness, and social responsibility and advances the translation of ideas into practical innovations.

A MESSAGE FROM THE DEAN

Welcome to Columbia University's Fu Foundation School of Engineering and Applied Science (SEAS). As students here, you are among the very best and brightest of your generation, and you will be educated at a school that will empower you to become the next leaders in the fields of engineering and applied science.

You are becoming part of a vibrant, intellectually challenging school with a distinguished history of transformational breakthroughs that have impacted the world. From the School's beginning in 1864 through today, the work of faculty, alumni, and students of Columbia's Engineering School has pushed the frontiers of disciplinary knowledge to create, invent, and innovate devices, procedures, and processes to make life better.

Our first dean, Charles Frederick Chandler, set the benchmark. A pioneering crusader, he was also the president of New York City's Metropolitan Board of Health, overseeing purity of food and drugs, ensuring the safety of milk, conveying clean water into the city, and establishing building codes. Bringing engineering solutions to society's greatest challenges continues to be a hallmark of Columbia Engineering.

Today, the pace of translating technological innovations into real-world impact has never been faster, and our faculty and students remain at the forefront, providing solutions for some of the world's most intractable problems.

I believe that Engineering is in a Renaissance, and nowhere is that more apparent than at Columbia Engineering. This Renaissance is characterized by great research, great creativity and invention, great innovation, and incredible translation of these innovations to entrepreneurial solutions that impact nearly every aspect of life. It has sparked a new way of thinking, one that crosses disciplinary lines, so that today, engineering is not only informed by other fields, but now is informing other fields.

Our School has become the nexus that connects the academic disciplines of our world-class sister schools at Columbia, helping to shape the future of medicine, journalism, business, policy, science, the social sciences, even the arts and humanities. Beginning at the undergraduate level with an emphasis on the liberal arts of the Core Curriculum, we now have pan disciplinary collaborations at the graduate level, leading to many enriched academic opportunities at the vanguard of research and scholarship.

Columbia Engineering is an exciting and stimulating community and I encourage you to take full advantage of the exceptional opportunities for learning and advancement that await you here.

With best wishes for the academic year,

Mary C. Boyce

Mary C. Boyce
Dean of Engineering
Morris A. and Alma Schapiro Professor

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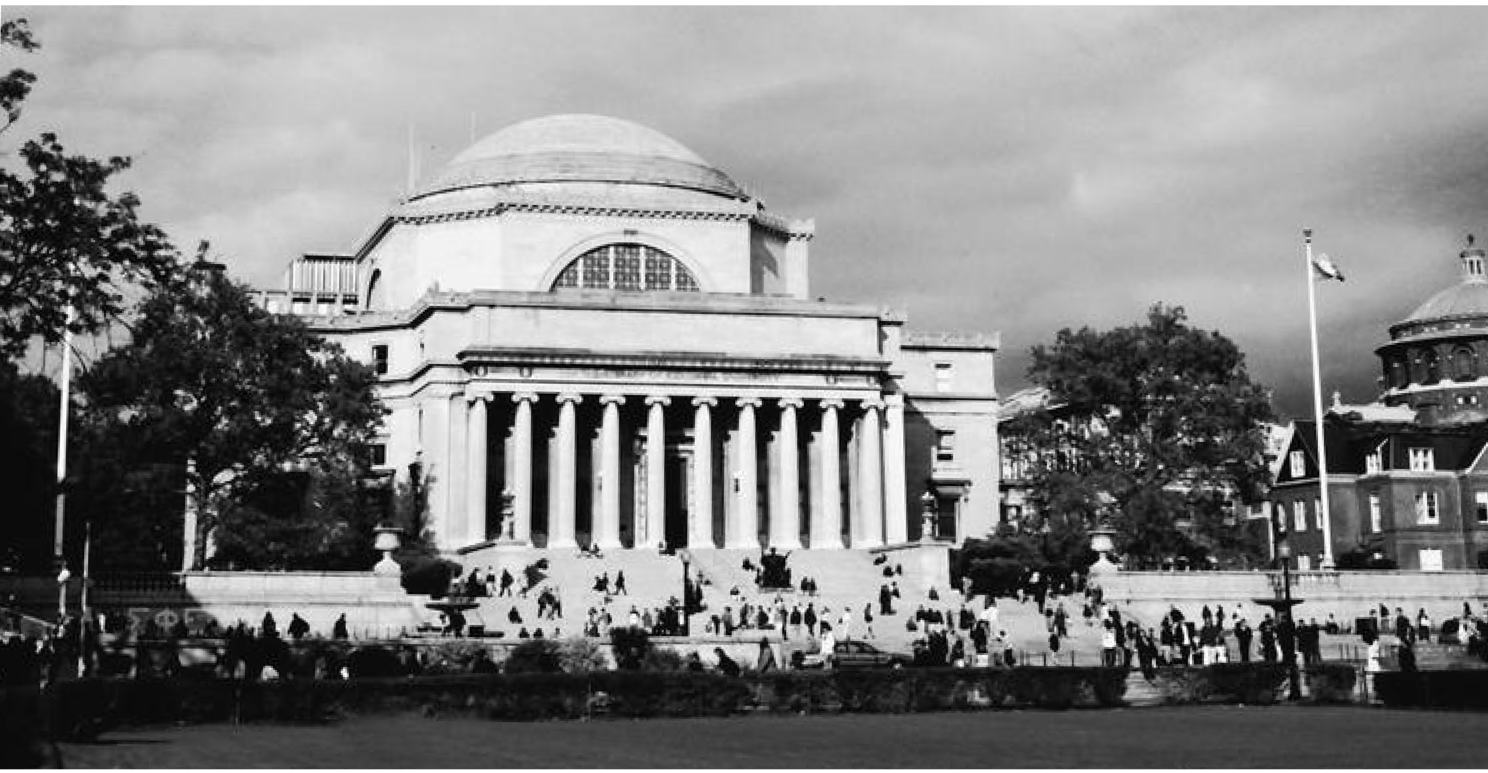


HISTORY OF THE SCHOOL

A COLONIAL CHARTER

Since its founding in 1754, as King's College, Columbia University has always been an institution both of and for the City of New York. And with an original charter directing it to teach, among other things, "the arts of Number and Measuring, of Surveying and Navigation, . . . the knowledge of . . . Meteors, Stones, Mines and Minerals, Plants and Animals, and everything useful for the Comfort, the Convenience and Elegance of Life," it has also always been an institution of and for engineers.

EARLY ENGINEERS

An early and influential graduate from the School was John Stevens, Class of 1768. Instrumental in the establishment of U.S. patent law, Stevens procured many patents in early steamboat technology, operated the first steam ferry between New York and New Jersey, received the first railroad charter in the U.S., built a pioneer locomotive, and amassed a fortune, which allowed his sons to found the Stevens Institute of Technology.

THE GILDED AGE

As the city grew, so did the School. King's College was rechartered as Columbia College in 1784, and relocated from the Wall Street area to what is now Midtown in 1857. Students began entering the new School of Mines in 1864. Trained in mining, mineralogy, and engineering, Columbia graduates continued to make their mark both at home and abroad.

Working around the globe, William Barclay Parsons, Class of 1882, was an engineer on the Chinese railway and the Cape Cod and Panama Canals, and most importantly, for New York as chief engineer of the city's first subway. Opened in 1904, the subway's electric cars took passengers from City Hall to Brooklyn, the Bronx, and the newly renamed and relocated Columbia University in Morningside Heights.

A MODERN SCHOOL FOR MODERN TIMES

The School of Mines became the School of Mines, Engineering, and Chemistry in 1896, and its professors—now called the Faculty of Engineering and Applied Science—included Michael Idvorsky Pupin, a graduate of the Columbia College Class of 1883. As a professor at Columbia, Pupin did pioneering work in carrier-wave detection and current analysis, with important applications in radio broadcasting; invented the "Pupin coil," which extended the range of long-distance telephones; and taught classes in electromechanics.

An early student of Pupin's was Irving Langmuir. Langmuir, Class of 1903, enjoyed a long career at the General Electric research laboratory, where he invented a gas-filled tungsten lamp; contributed to the development of the radio vacuum tube; extended Gilbert Lewis's work on electron bonding and atomic structure; and researched monolayering and surface chemistry, which led to a Nobel Prize in chemistry in 1932.

But early work on radio vacuum tubes was not restricted to private industry. Working with Pupin, an engineering student named Edwin Howard Armstrong was conducting experiments with the Audion tube in the basement of Philosophy Hall when he discovered how to amplify radio signals through regenerative circuits. Armstrong, Class of 1913, was stationed in France during the First World War, where he invented the superheterodyne circuit to tune in and detect the frequencies of enemy aircraft ignition systems. After the war, Armstrong improved his method of frequency modulation (FM), and by 1931, had both eliminated the static and improved the fidelity of radio broadcasting forever. The historic significance of Armstrong's contributions was recognized by the U.S. government when the Philosophy Hall laboratory was designated a National Historic Landmark in 2003.

As the United States evolved into a major twentieth-century political power, the University continued to build onto its undergraduate curriculum the broad range of influential graduate and professional schools that define it today. Renamed once again in 1926, the School of Engineering prepared students for careers not only as engineers of nuclear-age technology, but as engineers of the far-reaching political implications of that technology as well.

After receiving a master's degree from the School in 1929, Admiral Hyman George Rickover served during the Second World War as head of the electrical section of the Navy's Bureau of Ships. A proponent of nuclear sea power, Rickover directed the planning

and construction of the world's first nuclear submarine, the 300-foot-long Nautilus, launched in 1954.

TECHNOLOGY AND BEYOND

Today, The Fu Foundation School of Engineering and Applied Science, as it was named in 1997, continues to provide leadership for scientific and educational advances. Even Joseph Engelberger, Class of 1946, the father of modern robotics, could not have anticipated the revolutionary speed with which cumbersome and expensive "big science" computers would shrink to the size of a wallet.

No one could have imagined the explosive growth of technology and its interdisciplinary impact. The Engineering School is in a unique position to take advantage of the research facilities and talents housed at Columbia to form relationships among and between other schools and departments within the University. The School's newest department, Biomedical Engineering, with close ties to the Medical School, is but one example. Interdisciplinary centers are the norm, with cross-disciplinary research going on in biomedical imaging, environmental chemistry, materials science, medical digital libraries, nanotechnology, digital government, and new media technologies. The School and its departments have links to the Departments of Physics, Chemistry, Earth Science, and Mathematics, as well as the College of Physicians and Surgeons, the Graduate School of Journalism, Lamont-Doherty Earth Observatory, Teachers College, Columbia Business School, and the Graduate School of Architecture, Planning and Preservation. The transforming gift of The Fu Foundation has catapulted the School into the forefront of collaborative research and teaching and has given students the opportunity to work with prize-winning academicians, including Nobel laureates, from many disciplines.

NEW RESEARCH FRONTIERS

Columbia is one of the top universities in the world whose technology transfer operations earn the largest patent income from inventions created by its faculty.

Columbia Engineering faculty have been instrumental in developing and establishing many of the widely accepted global standards for storage and transmission of high-quality audio and video data. Perhaps the most famous of these is the MPEG-2 data compression standard, which is embedded in millions of DVDs and DVD players. With Columbia Engineering faculty continuing to play a key role in current and evolving information technology, Columbia is the only university actively participating in a broad range of standards-based patent pools, including AVC (Advanced Video Coding), the world standard for audio/video compression that is now one of the most commonly used HD formats and most commonly used in streaming media; ATSC, a standard developed by the Advanced Television Systems Committee for digital television transmission that is now the U.S. standard; MVC (Multi-View Coding), the standard for emerging 3D video; and

Blu-ray Disc, the standard for recording and retrieval of data and HD audio-visual media.

Columbia Engineering also holds a host of exciting new patents in many other emerging research areas. Among these is a laser-based method that makes possible the sharper display screens found in high-end smart phones. Sequential lateral solidification (SLS) is based on breakthrough research in understanding how a substance is rapidly melted and solidified. The result is an optimal crystalline material that enables a new generation of smart phones, thin computers, and next-generation video displays. And, thanks to the innovations taking place in Columbia Engineering labs, it may soon be possible to put an entire computer on a sheet of glass or plastic.

Other breakthrough technologies and innovation coming out of Columbia Engineering labs include a dongle that connects easily to a smartphone and can perform a lab-quality test of three infectious disease markers in just 15 minutes; a video camera that runs without a battery; a new 3D microscope that can image freely moving living things in real time, up to 100 times faster than conventional methods; technology for air carbon capture; medical robotics; Smart Grid technology for managing distribution and maintenance of power grids and urban infrastructure; and state-of-the-art DNA sequencing by synthesis technology that enables rapid and low-cost sequencing for future personalized medicine.

ENTREPRENEURSHIP

Another exciting area at Columbia Engineering is entrepreneurship. In 2014, the School's faculty and students generated 150 inventions, almost 40 licenses and options, and 7 startups in all kinds of fields, from medical to cleantech to high-tech.

Throughout the academic year, the School hosts many activities and networking events to support its active startup community, including the Columbia Engineering Fast Pitch Competition, Columbia Venture Competition, and Ignition Grants program, which funds ventures started by current students.

Entrepreneurship has also emerged as an important central educational theme at Columbia Engineering. The School promotes engineering innovation and engaged entrepreneurship through a range of programs and offers a 15-credit, interdisciplinary minor in entrepreneurship made up of both Engineering and Business School courses. The School also provides a four-year entrepreneurship experience for all interested Columbia Engineering students, regardless of major.

A FORWARD-LOOKING TRADITION

But, for all its change, there is still a continuous educational thread that remains the same. Columbia Engineering still remains an institution of manageable size within a great university. Committed to the educational philosophy that a broad, rigorous exposure to the liberal arts provides the surest chart with which an engineer can navigate the future, all undergraduates must complete a modified but equally rigorous version of Columbia College's celebrated Core Curriculum. It is these selected courses in contemporary civilization in the West and other global cultures that best prepare a student for advanced course work; a wide range of eventual professions; and a continuing, life-long pursuit of knowledge, understanding, and social perspective. It is also these Core courses that most closely tie today's student to the alumni of centuries past. Through a shared exposure to the nontechnical areas, all Columbia Engineering students—past, present, and future—gain the humanistic tools needed to build lives not solely as technical innovators, but also as social and political ones as well.

A COLLEGE WITHIN THE UNIVERSITY

A unique educational opportunity, The Fu Foundation School of Engineering and Applied Science at Columbia University offers programs to both undergraduate and graduate students who undertake a course of study leading to the bachelor's, master's, or doctoral degree in engineering and applied science. Combining the advantages of a small college with the extensive resources of a major research university, students at Columbia Engineering pursue their academic interests under the guidance of outstanding senior faculty members who teach both undergraduate and graduate level courses. Encouraged by the faculty to undertake research at all levels, students at the School receive the kind of personal attention that only Columbia's exceptionally high faculty-student ratio affords.

THE NEW YORK ADVANTAGE

Besides the faculty, the single greatest facility at a Columbia student's disposal is without doubt the City of New York. Within easy reach by walking, bus, subway, or taxi, New York's broad range of social, cultural, and business communities offer an unparalleled opportunity for students to expand their horizons or deepen their understanding of almost any human endeavor imaginable. With art from small SoHo galleries to major Uptown museums; music from Harlem jazz clubs to the Metropolitan Opera; theater from performance art in the East Village to musicals on Broadway; food from French on the Upper East Side to Asian in Chinatown; and sports teams from the Jets to the Yankees, New York is the crossroads of the world.

New York is fast becoming a major player in high-tech research and development, where Fortune 500 companies traded on Wall Street seek partnerships with high-tech startups in Tribeca. As part of the research community themselves, Columbia students have exceptional opportunities for contact with industry both on and off campus. Senior representatives of these companies often visit Columbia to lecture as adjunct faculty members or as special speakers, and undergraduate and graduate students frequently undertake research or internships with these and other companies, oftentimes leading to offers of full-time employment after graduation.

In addition to its ties to private industry, Columbia also has a historically close relationship with the public sector of New York, stretching back to the eighteenth century. No other city in the world offers as many impressive examples of the built environment—the world's most famous collection of skyscrapers, long-span bridges, road and railroad tunnels, and one of the world's largest subway and water supply systems. Involved in all aspects of the city's growth and capital improvements over the years, Columbia engineers have been responsible for the design, analysis, and maintenance of New York's enormous infrastructure of municipal services and communications links, as well as its great buildings, bridges, tunnels, and monuments.

THE UNIVERSITY AT LARGE

Columbia University occupies two major campuses, as well as additional special-purpose facilities throughout the area. Besides the main campus located on the Upper West Side in Morningside Heights, further uptown in Washington Heights is the Columbia University Medical Center (CUMC), which includes Columbia's College of Physicians and Surgeons, the Mailman School of Public Health, the New York State Psychiatric Institute, College of Dental Medicine, and School of Nursing. Columbia Medical Center is the world's first academic medical center, and opened in 1928 when Columbia's health-related schools and Presbyterian Hospital (which has since merged with New York Hospital to become NewYork-Presbyterian Hospital) moved to the Washington Heights location. Columbia Engineering's Biomedical Engineering Department has offices on both the Morningside campus and CUMC.

Beyond its schools and programs, the measure of Columbia's true breadth and depth must take into account its seventy-odd internationally recognized centers and institutions for specialized research, which study everything from human rights to molecular recognition, as well as the close affiliations it holds with Teachers College, Barnard College, the Juilliard School, and both the Jewish and Union Theological Seminaries. Columbia also maintains major off-campus facilities such as the Lamont-Doherty Earth Observatory in Palisades, NY, and the Nevis Laboratories in Irvington, NY. Involved in many cooperative ventures, Columbia also conducts ongoing research at such facilities as Brookhaven National Laboratory in Upton, NY, and the NASA Goddard Institute for Space Studies located just off the Morningside campus.

THE MORNINGSIDE HEIGHTS CAMPUS

The Fu Foundation School of Engineering and Applied Science is located on Columbia's Morningside campus. One of the handsomest urban institutions in the country, the 13.1 million gross square feet (gsf) of the Morningside campus comprise more than 200 buildings of housing; off-campus apartments and commercial buildings; recreation and research facilities; centers for the humanities and social and pure sciences; and professional schools in architecture, business, the fine arts, journalism, law, and many other fields.

THE FU FOUNDATION SCHOOL OF ENGINEERING AND APPLIED SCIENCE

The Fu Foundation School of Engineering and Applied Science occupies four laboratory and classroom buildings at the north end of the campus, including the Northwest Corner Science and Engineering Building, an interdisciplinary teaching and research building on the Morningside campus. It was designed by the world-renowned architect Jose Rafael Moneo to serve as a physical and intellectual bridge, linking laboratories and maximizing the ready sharing and exchange of ideas, resources, and information. With its beehive-like setting, the new building is already enhancing existing collaborations and stimulating new ones, enabling researchers across the University to work together to create new areas of knowledge, in fields where the biological, physical, and digital worlds fuse. This pandisciplinary frontier is the nexus at which engineering and applied scientific advances will provide innovative solutions to some of modern society's most challenging problems in a wide range of sectors, from health to cybersecurity and smart infrastructure to the environment.

Offering multiple programs of study, with facilities specifically designed and equipped to meet the laboratory and research needs of both undergraduate and graduate students, the School is the site of an almost overwhelming array of basic and advanced research installations, from the Columbia Genome Center and the Columbia Nano Initiative, newly established to serve as the hub for multidisciplinary and collaborative research programs in nanoscale science and engineering. Shared facilities and equipment to support nano research at the Engineering School include a state-of-the-art clean room in CEPSR and a recently constructed Transmission Electron Microscope (TEM) Laboratory on the first floor of Havemeyer.

In addition to this group of advanced research opportunities and one that stems from an interdisciplinary framework is the Columbia Data Science Institute, hosted by Columbia Engineering. Founded in 2012 with a grant from New York City, the Data Science Institute spans nine schools at Columbia, including Journalism, the Graduate School of Arts and Sciences, and Columbia University Medical Center. The mission of the Data Science Institute is to train data science innovators and develop ideas for the social good.

Details about specific programs' laboratories and equipment can be found in the sections describing those programs.

Columbia Engineering Computing Facilities

The Botwinick Multimedia Learning Laboratory at Columbia University has redefined the way engineers are educated here.

Designed with both education and interaction in mind, the lab provides students and instructors with 40 Apple Mac Pro workstations connected to central servers and a network-based RAID storage array, a full set of professional-grade engineering software tools, and a collaborative classroom learning environment to help them engage in real-world interactions with community clients, Engineering faculty, and professional practitioners. It is utilized in some of the School's introductory first-year engineering projects, as well as advanced classes in 3-D modeling and animation, technology and society, and entrepreneurship.

The Makerspace

Columbia Engineering's Makerspace provides students a dedicated place at the School to collaborate, learn, explore, experiment, and create prototypes. Students can utilize the space to work on a variety of innovative projects, including independent or group design projects, product development, and new venture plans. Located on the 12th floor of the Mudd Building, this facility fosters student creativity by bringing together the workspace and tools for computer-aided design, physical prototyping, fabric arts, woodworking, electronics, and software.

Carleton Commons

Located on the fourth floor (campus level) of the Mudd Building, the newly renovated Carleton Commons and Blue Java Café comprise 2,800 square feet with seating for 160 and areas for casual meetings, individual and group work, and quiet study. Carleton Commons gives students a dedicated and comfortable space to gather, relax between classes, or meet and work with one another on problem sets or projects. The new design also enables flexible and reconfigurable use of the space for larger gatherings and special events.

CENTRAL COMPUTING RESOURCES

Columbia University Information Technology (CUIT)

Help Desk Support Center
202 Philosophy Hall
Monday–Friday: 10:00 a.m.–6:00 p.m.

Phone: 212-854-1919
Monday–Thursday: 8:00 a.m.–11:00 p.m.
Friday: 8:00 a.m.–7:00 p.m.
Saturday: 10:00 a.m.–6:00 p.m.
Sunday: 3:00 p.m.–11:00 p.m.
E-mail: askcuit@columbia.edu
cuit.columbia.edu/support

CUIT provides Columbia University students, faculty, and staff with myriad central computing and communications services, including Columbia's wireless and high-speed campus Ethernet network, available to all students in residence hall rooms. CUIT also manages an array of computer labs, terminal clusters, ColumbiaNet kiosk stations, electronic classrooms, and provides a variety of technical support services via the CUIT Helpdesk.

CUIT services include the following:

- *E-mail accounts:* CUIT provides a web-based program for accessing Columbia e-mail. It provides a secure and convenient way to send and receive mail from anywhere, using any web browser.
- *Computer account IDs* provide access to Columbia's secure online information resources, campus computer labs, and printing on CUIT printers. All Columbia students, faculty, and staff are assigned an ID account (called University Network ID or UNI).
- *Columbia's website* provides access to hundreds of online services and resources, including extensive academic, scholarly, and administrative resources, myriad library catalogs and references, the Directory of Classes, registration information, campus publications, and events listings.
- *Technical support* is available through the CUIT Help Desk, which provides technical assistance to students on the Morningside campus online, by phone, or in person. (See beginning of this section for hours and contact information.)
- *CourseWorks* is the University course management system. It allows instructors to easily develop and maintain course websites, distribute class materials, link to online reserves, administer quizzes and tests, communicate with students, and promote online discussions.
- *Electronic classrooms* are equipped with multimedia capabilities such as computer and projection systems, DVD and CD-ROM players, VCRs, and audio systems.
- *Public computer kiosks* are available in various locations around the Morningside campus for accessing Columbia's web resources and e-mail.
- *Computer labs and clusters* provide students, faculty, and researchers with access to a range of software. Some locations have consultants to provide lab help.
- *Printing facilities* are available throughout the Morningside campus and Barnard College. These high-speed, high-volume printers are located in CUIT computer labs, libraries, residence halls, and other computer clusters and electronic classrooms.
- *Computer security* is extremely important at Columbia and CUIT provides several resources online, including links to download antivirus and anti-spyware software. The site also provides information on how to protect your system, data, and privacy when working online.
- *Electronic Data Service,* run jointly by CUIT and the Libraries, provides computing support for researchers with data-intensive applications, including statistical software, and finding and selecting appropriate data.
- *Telephone and cable TV service* is available to students living in University residence halls.

COLUMBIA UNIVERSITY LIBRARIES

Phone: 212-851-2950
E-mail: ref-sci@columbia.edu
library.columbia.edu

Columbia University Libraries/Information Services (CUL/IS) is one of the top five academic research library systems in North America. The collections include 11.9 million volumes, 168,000 current serial subscriptions, as well as extensive electronic resources, manuscripts, rare books, microforms, maps, graphic and audio-visual materials. The services and collections are organized into 20 libraries and various academic technology centers. The Libraries employ more than 550 professional and support staff. The website of the Libraries is the gateway to its services and resources.

The Science and Engineering Library, located in 401 Northwest Corner Building, focuses on research support for the fields of astronomy, biology, chemistry, engineering, physics, and psychology, as well as providing a collaborative environment supporting rapidly expanding interdisciplinary science and engineering research. The Science and Engineering Library is home to the Digital Science Center, where high-end computers are especially equipped with software and hardware to support teaching, learning, research, and innovation in the science and engineering disciplines. Group study, individual carrels, and staff consultation spaces along with printing and scanning facilities are included in this library, which offers spectacular views of the Columbia campus and Morningside Heights.

Online, CUL provides access to extensive collections of electronic journals, ebooks (including handbooks), standards, patents, and society publications. Databases such as Compendex, INSPEC, Scopus, and Web of Science help patrons to pinpoint relevant engineering and science research.

CENTER FOR CAREER EDUCATION

East Campus, Lower Level
Mailing: 2960 Broadway, MC 5727
Delivery: 70–74 Morningside Drive
New York, NY 10027
Phone: 212-854-5609
Fax: 212-854-5640
E-mail: careereducation@columbia.edu
careereducation.columbia.edu

The Columbia University Center for Career Education (CCE) helps students and alumni develop the key competencies to make informed decisions and take the necessary steps to achieve their career goals. CCE establishes connections and facilitates interaction among undergraduate students, graduate students, alumni, and employers to generate opportunities that help students pursue their personal and professional career objectives.

We encourage students and alumni to (1) visit us at the Career Center; (2) register for Columbia's job and internship database, LionSHARE; and (3) review our website to access a wide range of services and resources. CCE develops relationships with employers to connect students with internships, full-time, part-time, and temporary on- and off-campus employment opportunities throughout the year. In addition, CCE provides career development opportunities for students beginning in their first year at Columbia, offering externships, internships, résumé and interviewing preparation, site visits to employers, professionals in residence, career fairs, alumni-student networking events, and individual counseling.

Highlights among career fairs include the Engineering Career Fair in the fall and the Startup Career Fair in the spring. Additionally, CCE partners with Columbia Engineering on specialized networking events, employer information sessions, and workshops tailored to department and student club needs.

CCE has developed formal externship and internship and professional development programs in partnership with alumni and employers, including the Science Technology Engineering Program, the Virtual Internship Program, the Startup Internship Program, Columbia Arts Experience, and the Kenneth Cole Community Action Program. Also through our Columbia Experience Overseas program, we offer summer internships in London, Hong Kong, Beijing, Shanghai, Singapore, Mumbai, and Amman. Alumni mentors are assigned to all students participating in these formal internship programs. CCE also administers the Work Exemption Program and the Columbia Engineering Internship Fund to help students undertake unpaid internships. Some of these programs are open to all students while others are open only to undergraduate students. We invite you to connect with CCE to learn about eligibility requirements.

CCE also maintains a dossier service, managed by Interfolio, for graduate students and alumni. A dossier consists of letters of reference and other credentials that speak to a candidate's scholarship, research interests, and teaching experience. It is typically used in applying for teaching positions at either the secondary school or the college level and for graduate/professional school and fellowship applications. Undergraduate students or alumni with undergraduate degrees from Columbia Engineering work with the James H. and Christine Turk Berick Center for Student Advising for dossier management.

We welcome your visit to the Center for Career Education in person at East Campus or via our website at careereducation.columbia.edu to learn more about our programs and resources.

THE INTERNATIONAL STUDENTS AND SCHOLARS OFFICE

International House North
524 Riverside Drive, Suite 200
Mailing: 2960 Broadway, MC 5724
New York, NY 10027

Phone: 212-854-3587
Fax: 212-851-1235
E-mail: isso@columbia.edu
columbia.edu/cu/isso

The International Students and Scholars Office (ISSO) offers many services for international students. Services for international students include document and other immigration-related services, and orientation programs.

International students are urged to make use of the services at the ISSO during their stay at the University and are also invited to visit the ISSO website at columbia.edu/cu/isso, to find comprehensive information for both prospective and current students.

The International Students and Scholars Office is an essential source of information regarding immigration and Department of State regulations that affect students studying in the United States. The staff can also assist or make appropriate referrals with many other nonacademic matters, including adjustment to the University and the City of New York.

The office's street address is 524 Riverside Drive in International House North, just north of 122nd Street. The orientation program for new international students arriving for the September term takes place during orientation week, usually the last week in August or the first week in September. For further information, consult the International Students and Scholars Office using the contact information above.

Undergraduate Studies

The undergraduate programs at Columbia Engineering not only are academically exciting and technically innovative but also lead into a wide range of career paths for the educated citizen of the twenty-first century. Whether you want to become a professional engineer, work in industry or government, or plan to pursue a career in the physical and social sciences, medicine, law, business, or education, Columbia Engineering will provide you with an unparalleled education.

The School firmly believes that students gain the most when engineering is brought up front, early in the four-year curriculum. Therefore, each first-year student takes the Art of Engineering, which addresses the fundamental concepts of math and science in an engineering context, as well as nontechnical issues in professional engineering practice such as ethics and project management. Students in the Art of Engineering choose a half-semester, hands-on project in one of the School's nine undergraduate engineering disciplines, followed by a half-semester general project that changes each year. Depending on the project chosen, students will solder, 3D print, laser cut, simulate, design websites, and much more. These skills are further developed as students progress toward their senior year projects. Beginning in the fall of 2014, Columbia Engineering students are also able to utilize the School's brand new Makerspace, a collaborative environment where students can learn, explore, experiment, and create prototypes.

While pursuing their own interests, undergraduate students are encouraged to participate in a broad range of ongoing faculty research projects encompassed by the Student Research Involvement Program (SRIP). An annual publication describes faculty projects in which students may participate, lists necessary qualifications, and details whether the student's participation will be voluntary, for academic credit, or for monetary compensation. Students can apply for available research positions in Columbia Labs through the SRIP website at portal.seas.columbia.edu/research/student.php/position.

In addition to in-depth exploration of engineering and applied science, Columbia Engineering undergraduates explore the humanities and social sciences with Columbia College students through intellectually challenging Core Curriculum courses taught by the Faculty of Arts and Sciences. These courses in art, literature, music, major cultures, and economics, among others, provide students with a broad, intellectually disciplined, cultural perspective on the times they live in and the work they do.

POLICY ON DEGREE REQUIREMENTS

The Committee on Instruction and faculty of The Fu Foundation School of Engineering and Applied Science review degree requirements and curricula matters each year, and the bulletin reflects these faculty recommendations and curricular changes in its yearly reprinting. School policy requires students to fulfill all general degree requirements as stated in the bulletin of the first year of their matriculation into the School. Students declare their major during the first semester of their sophomore year. Requirements for the major or minor are in accordance with the bulletin during the year in which the student declares the major or minor.

THE FIRST-YEAR/SOPHOMORE PROGRAM

Students entering Columbia Engineering are encouraged to consider the wide range of possibilities open to them, both academically and professionally. To this end, the first and second years of the four-year undergraduate program comprise approximately 66 semester points of credit that expose students to a cross-fertilization of ideas from different disciplines within the University. The sequence of study proceeds from an engagement with engineering and scientific fundamentals, along with humanities and social sciences, toward an increasingly focused training in the third and fourth years designed to give students mastery of certain principles and arts central to engineering and applied science.

Liberal Arts Core for Columbia Engineering Students: 27-Point Nontechnical Requirement

This requirement provides a broad liberal arts component that enhances the Engineering professional curriculum to help students meet the challenges of the twenty-first century. Our students are destined to be leaders in their professions and will require sophisticated communication, planning, and management skills. The Committee on Instruction established the School's nontechnical requirement so that students would learn perspectives and principles of the humanities and social sciences as part of a well-rounded and multiperspective education. Through discussion, debate, and writing, students improve their abilities to engage in ethical, analytic, discursive, and imaginative thinking that will prove indispensable later in life.

- Engineering students must take 16 to 18 points of credit of required courses in list A and 9 to 11 elective points chosen from the approved courses in list B. The total combined number of nontechnical points (from lists A and B, below) must add up to at least 27. Neither list can be modified by advising deans or faculty advisers.
- Advanced Placement (AP) credit in appropriate subject areas can be applied toward the 9-point elective nontechnical requirement.

If electing Global Core, students must take two courses from the List of Approved Courses (college.columbia .edu/sites/default/files/global_core.pdf) for a letter grade.

A. Required Nontechnical Courses (16–18 points of credit)

These courses must be taken at Columbia.

1. ENGL C1010: University writing (3 points)
2. One of the following two-semester sequences: HUMA C1001-C1002: Masterpieces of Western literature and philosophy (All students registering for this course should be prepared to discuss books 1–12 of the Iliad on the first day of class) or
   COCI C1101-C1102: Introduction to contemporary civilization in the West or
   Global Core: Any 2 courses from approved list (6–8 points)
3. One of the following two courses: HUMA W1121: Masterpieces of Western art, or HUMA W1123: Masterpieces of Western music (3 points)
4. ECON W1105: Principles of economics. (This course can be satisfied through Advanced Placement; see the Advanced Placement chart on page 14.) Note: Engineering students may not take BC1003: Introduction to economic reasoning as a substitute for ECON W1105. (4 points)

B. Elective Nontechnical Courses (9–11 points of credit)

The following course listing by department specifies the Columbia College, Barnard, or Columbia Engineering courses that either fulfill or do not fulfill the nontechnical requirement.

(Professional, workshop, lab, project, scientific, studio, music instruction, and master's-level professional courses do not satisfy the 27-point nontechnical requirement.)

AFRICAN-AMERICAN STUDIES: All courses

AMERICAN STUDIES: All courses

ANCIENT STUDIES: All courses

ANTHROPOLOGY: All courses in sociocultural anthropology
All courses in archaeology except field work
No courses in biological/physical anthropology [V1010, V1011, W3204, V3940, G4147-G4148, W4200, G4700]

ARCHITECTURE: No courses

ART HISTORY AND ARCHEOLOGY: All courses

ASIAN AMERICAN STUDIES: All courses

ASTRONOMY: No courses

BIOLOGICAL SCIENCES: No courses

BUSINESS: No courses

CHEMISTRY: No courses

CLASSICS: All courses

COLLOQUIA: All courses

COMPARATIVE ETHNIC STUDIES: All courses

COMPARATIVE LITERATURE AND SOCIETY: All courses

COMPUTER SCIENCE: No courses

CREATIVE WRITING: All courses
(This is an exception to the workshop rule.)

DANCE: All courses except performance classes

DRAMA AND THEATRE ARTS: All courses except workshops, rehearsal, or performance classes, THTR BC2120 Technical production, THTR BC3135 Set design, and THTR BC3134 Lighting design

EARTH AND ENVIRONMENTAL SCIENCES: No courses

EAST ASIAN LANGUAGES AND CULTURE: All courses

ECOLOGY, EVOLUTION, AND ENVIRONMENTAL BIOLOGY: No courses except EEEB W4321 or W4700

ECONOMICS: All courses except
W3025 Financial economics
W3211 Intermediate microeconomics
W3213 Intermediate macroeconomics
W3412 Introduction to econometrics
W4020 Economics of uncertainty and information
W4211 Advanced microeconomics
W4213 Advanced macroeconomics
W4251 Industrial organization
W4280 Corporate finance
W4412 Advanced econometrics
W4415 Game theory
W4911 Seminar in microeconomics
W4913 Seminar in macroeconomics
W4918 Seminar in econometrics
BC1003 Introduction to economic reasoning (equivalent to ECON W1105)
BC1007 Mathematical methods for economics
BC2411 Statistics for economics
BC3014 Entrepreneurship
BC3018 Econometrics
BC3033 Intermediate macroeconomic theory
BC3035 Intermediate microeconomic theory
BC3038 International money and finance

EDUCATION: All courses

ENGINEERING: Only
BMEN E4010 Ethics for biomedical engineers
EEHS E3900 History of telecommunications

ENGLISH AND COMPARATIVE LITERATURE: All courses

FILM STUDIES: All courses except lab courses, and
W3850 Senior seminar in screenwriting
W4005 The film medium: script analysis

FRENCH AND ROMANCE PHILOLOGY: All courses

GERMANIC LANGUAGES: All courses

GREEK: All courses

HISTORY: A ll courses

HISTORY AND PHILOSOPHY OF SCIENCE: All courses

HUMAN RIGHTS: All courses

ITALIAN: All courses

JAZZ STUDIES: All courses

LATIN: All courses

LATINO STUDIES: All courses

LINGUISTICS: All courses except CLLN W4202

MATHEMATICS: No courses

MEDIEVAL AND RENAISSANCE STUDIES: All courses

MIDDLE EASTERN AND ASIAN LANGUAGE AND CULTURES: All courses

MUSIC: All courses except performance courses, instrument instruction courses, and workshops

PHILOSOPHY: All courses except
F1401 Introduction to logic
V3411 Symbolic logic
W4137 Nonclassical logics
G4431 Introduction to set theory
G4424 Modal logic
CSPH W4801 Mathematical logic I
CSPH G4802 Incompleteness results in logic
Courses in logic

PHYSICAL EDUCATION: No courses

PHYSICS: No courses

POLITICAL SCIENCE: All courses except
W3220 Logic of collective choice
W3704 Data analysis and statisitcs for political science research
W3720 Scope and methods
W4209 Game theory and political theory
W4210 Research topics in game theory
W4291 Advanced topics in quantitative research
W4292 Advanced topics in quantitative research
W4360 Math methods for political science
W4365 Design and analysis of sample surveys
W4368 Experimental research: design, analysis and interpretation
W4910 Principles of quantitative political research
W4911 Analysis of political data
W4912 Multivariate political analysis

PSYCHOLOGY: Only
W1001 The science of psychology
W2235 Thinking and decision making
W2240 Human communication
W2280 Introduction to developmental psychology
W2610 Introduction to personality
W2620 Abnormal behavior
W2630 Social psychology
W2640 Introduction to social cognition
W2680 Social and personality development
W3615 Children at risk
W3630 Seminar in social cognition

RELIGION: All courses

SLAVIC LANGUAGES: All courses

SOCIOLOGY: All courses except SOCI W3020 Social Statistics

SPANISH AND PORTUGUESE: All courses

SPEECH: No courses

STATISTICS: No courses

SUSTAINABLE DEVELOPMENT: No courses

URBAN STUDIES: All courses

VISUAL ARTS: No more than one course, which must be at the 3000-level or higher (This is an exception to the workshop rule.)

WOMEN AND GENDER STUDIES: All courses

Music Instruction Courses

Music instruction and performance courses do not count toward the 128 points of credit required for a B.S. degree. Please note that this includes courses taken at Teachers College, Columbia College, and the School of the Arts.

Visual Arts Courses

Students are allowed to take courses in the Visual Arts Department for general credit to be applied toward the B.S. degree. However, no more than one visual arts course, which must be taken at the 3000 level or higher, may count toward the nontechnical elective requirement. This 3000 course is an exception to the rule that no workshop classes can fulfill the nontech elective requirement.

Technical Course Requirements

The prescribed First Year–Sophomore Program curriculum requires students to complete a program of technical course work introducing them to five major areas of technical inquiry: engineering, mathematics, physics, chemistry, and computer science.

All first-year Engineering undergraduate students take ENGI E1102: The art of engineering (4 points). In this course, students see how their high school science and math knowledge can be applied in an engineering context to solve real-world problems through classroom presentations and participation in an in-depth, hands-on project. Along the way, guest lecturers discuss social implications of technology, entrepreneurship, project management, and other important nontechnical issues affecting the practicing engineer.

While students need not officially commit to a particular branch of engineering until the third semester, most programs recommend, and in some cases may require, that particular courses be taken earlier for maximum efficiency in program planning. For information concerning these requirements, students should turn to the individual program sections in this bulletin.

Professional-Level Courses

First- and second-year students may take one professional-level course chosen from the list below.

Each course is designed to acquaint Engineering students with rigorous intellectual effort in engineering and applied science early in their academic careers.

The courses stipulate minimal prerequisites. Each course serves as an introduction to the area of study in addition to teaching the subject matter. Each course is taught by regular department faculty and thus provides a double introduction to both subject area and faculty.

The courses are:

APAM E1601y Introduction to computational mathematics and physics
Mathematics and physics problems solved by using computers. Topics include elementary interpolation of functions, solution of nonlinear algebraic equations, curve-fitting and hypothesis testing, wave propagation, fluid motion, gravitational and celestial mechanics, and chaotic dynamics.

BMEN E1001x Engineering in medicine
The present and historical role of engineering in medicine and health care delivery. Engineering approaches to understanding organismic and cellular function in living systems. Engineering in the diagnosis and treatment of disease. Medical imaging, medical devices: diagnostic and surgical instruments, drug delivery systems, prostheses, artificial organs. Medical informatics and organization of the health care system. Current trends in biomedical engineering research.

CHEN E2100x Introduction to chemical engineering
This course serves as an introduction to the chemical engineering profession. Students are exposed to concepts used in the analysis of chemical engineering problems. Rigorous analysis of material and energy balances on open and closed systems is emphasized. An introduction to important processes in the chemical and biochemical industries is provided.

CIEN E1201y The art of structural design
Basic scientific and engineering principles used for the design of buildings, bridges, and other parts of the built infrastructure. Application of these principles to the analysis and design of a number of actual large-scale structures. History of major structural design innovations and the engineers who introduced them. Critical examination of the unique aesthetic/artistic perspectives inherent in structural design. Management, socioeconomic, and ethical issues involved in the design and construction of large-scale structures. Recent developments in sustainable engineering, including green building design and adaptable structural systems.

EAEE E2100x A better planet by design
Introduction to design for a sustainable planet. Scientific understanding of the challenges. Innovative technologies for water, energy, food, materials provision. Multiscale modeling and conceptual framework for understanding environmental, resource, human ecological, and economic impacts and design performance, evaluation. Focus on linkages between planetary, regional, and urban waste, energy, mineral, food, climate, economic, and ecological cycles. Solution strategies for developed and developing country settings.

ELEN E1201x and y Introduction to electrical engineering
Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course.

GRAP E1115x and y Engineering graphics
Focus on 3D software design for applications in engineering design, manufacturing, and graphics presentations. Introduction to 3D design using advanced 3D modeling and visualization technologies using Maya and SolidWorks. The design process includes idea conception and 3D model development, as well as 3D printing and CNC milling manufacturing specifications derived directly from 3D models produced in class. Introduction to the process of creating 3D models that are suitable for 3D printing, CNC milling, injection molding, and laser cutting for buildings. DIfferent models and drawing specifications taught that are required by different manufacturing technologies .

MECE E1001x Mechanical engineering: micro-machines to jumbo jets
The role of mechanical engineering in developing many of the fundamental technological advances on which today's society depends. Topics include airplanes, automobiles, robots, and modern manufacturing methods, as well as the emerging fields of micro-electro-mechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the art innovations in each case study.

MSAE E1001y Atomic-scale engineering of new materials
An introduction to the nanoscale science and engineering of new materials. The control and manipulation of atomic structure can create new solids with unprecedented properties. Computer hard drives, compact disc players, and liquid crystal displays (LCDs) are explored to understand the role of new materials in enabling technologies. Group problem-solving sessions are used to develop understanding.

Physical Education

Two terms of physical education *(C1001-C1002)* are a degree requirement for Columbia Engineering students. No more than 4 points of physical education courses may be counted toward the degree. One point of the physical education requirement can be fulfilled with a Barnard physical education course or a Barnard dance technique course. A student who intends to participate in an intercollegiate sport should register for the appropriate section of *C1005: Intercollegiate athletics.* Intercollegiate athletes who attend regularly receive 1 point of credit up to the maximum of 4. Those who are advised to follow a restricted or adapted activity program should contact Abbey Lade in the Department of Intercollegiate Athletics and Physical Education. The physical education program offers a variety of activities in the areas of aquatics, fitness, martial arts, individual and dual lifetime sports, team sports, and outdoor education. Most activities are designed for the beginner/intermediate levels. Advanced courses are indicated on the schedule. The majority of the activities are offered in ten time preferences. However, there are early-morning conditioning activities, Friday-only classes at Baker Athletics Complex, and special courses that utilize off-campus facilities during weekends and vacation periods. The courses offered by the department for each term are included in the online Directory of Classes, and a description of the scheduled activities for each time preference is posted on the www.dodgefitnesscenter.com website. Students may register for only one section of physical education each term.

Advanced Placement

Prior to entering Columbia, students may have taken Advanced Placement examinations through the College Entrance Examination Board (CEEB) in a number of technical and nontechnical areas. A maximum of 16 points may be applied. Students may be assigned to an advanced level course in mathematics or physics based on their AP scores.

In the required pure science areas, the number of advanced placement academic credits awarded to students of engineering and applied science varies from the levels awarded for liberal arts programs, notably in mathematics, physics, chemistry, and computer science. The benefit of advanced placement is acceleration through certain First Year–Sophomore Program requirements and thus the opportunity of taking specialized courses earlier.

Each year the school reviews the CEEB advanced placement curriculum and makes determinations as to appropriate placements, credit, and/or exemption. Please see the Advanced Placement Credit Chart.

International Baccalaureate (IB)

Entering students may be granted 6 points of credit for each score of 6 or 7 on IB Higher Level Examinations if taken in disciplines offered as undergraduate programs at Columbia. Students should consult their adviser at the James H. and Christine Turk Berick Center for Student Advising for further clarification.

British Advanced Level Examinations

Pending review by the appropriate

Advanced Placement Credit Chart

In order to receive AP credit, students must be in possession of appropriate transcripts or scores.

Subject	AP Score	AP Credit	Requirements or Status
Art history	5	3	No exemption from HUMA W1121
Biology	5	3	No exemption
Chemistry	4 or 5	3	Requires completion of CHEM C1604 with grade of C or better
	4 or 5	6	Requires completion of CHEM C3045-C3046 with grade of C or better
Computer science A or AB	4 or 5	3	Exemption from COMS W1004
English			
Language and composition	5	3	No exemption
Literature and composition	5	3	No exemption
Economics			
Micro & macro	5 and 4	4*	Exemption from ECON W1105 (Test must be in both with a score of 5 in one and at least 4 in the other)
French			
Language	4 or 5	3	
Literature	4 or 5	3	
German			
Language	4 or 5	3*	
Government and politics			
United States	4 or 5	3*	Requires completion of 3000 level or higher course in the American politics subfield with a C or higher
Comparative	4 or 5	3*	Requires completion of 3000 level or higher course in the Comparative politics subfield with a C or higher. Students may be given an exemption, based on AP scores, from only one undergraduate introduction political science class, either POLS W1201 or POLS V1501
History			
European	5	3	
United States	5	3	
Italian language	4 or 5	3	
Latin literature	5	3	
Mathematics			
Calculus AB	4 or 5	3	
Calculus BC	4	3	
Calculus BC	5	6	
Physics			
C-E&M	4 or 5	3	Requires beginning with PHYS C2801 and earning grade of C or better
C-MECH	4 or 5	3	Requires beginning with PHYS C2801 and earning grade of C or better
Physics B	4 or 5	3	No exemption
Spanish			
Language	4 or 5	3	
Literature	4 or 5	3	

*AP credits may be applied toward minor requirements.

department at Columbia, students with grades of A or B on British Advanced Level examinations may be granted 6 points of credit if the examinations were taken in disciplines offered as undergraduate programs at Columbia University. The appropriate transcript should be submitted to the James H. and Christine Turk Berick Center for Student Advising, 403 Lerner.

Other National Systems

Pending review by the appropriate department at Columbia, students whose secondary school work was in other national systems, such as the French Baccalauréat, may be granted credit in certain disciplines for sufficiently high scores. The appropriate transcript should be submitted to the Center for Student Advising, 403 Lerner.

STUDY ABROAD

Engineering today is a global profession. Engineers are increasingly being called upon to work with other engineers from across the world, or they may even find themselves living abroad on an overseas assignment. Learning problem-solving skills in a foreign context will help engineering students to expand their horizons, and their adaptability to cross-cultural communication will make them a valuable addition to a team of engineers.

Study abroad allows engineering students to discover the field through the perspective of engineers working in a different language and culture, enabling them to learn the relationship of culture to science and develop the range of transferable skills that employers are seeking today. Study abroad will help students develop intellectually, emotionally, culturally, and socially.

Columbia Engineering undergraduate students can study abroad for either a semester (fall, spring, or summer) or, exceptionally, for a full academic year. Students from every engineering major have studied abroad without adding any time to their course of study at Columbia. Most do so in the spring semester of their sophomore year or in their junior year.

The Office for Undergraduate Student Affairs will help students identify the appropriate choice for their country of interest and their major. The Associate Dean for Undergraduate Student Affairs and Global Programs and departmental advisers will help students with their course equivalencies for approved programs so they can graduate on time. Students can take nontechnical electives overseas, or with departmental permission, they may choose technical electives or courses in their major.

It is essential that students begin planning as early as possible—ideally this would be during their first year. Students are encouraged to meet with the Office of Global Programs to review possible overseas destinations and to decide on an appropriate abroad experience. The SEAS Office of Undergraduate Student Affairs will explain all Columbia Engineering study abroad formalities and requirements. Students must obtain approval from their departmental advisers to ensure that their work abroad meets the requirements of their majors, as well as clearance from their Advising Dean in the James H. and Christine Turk Berick Center for Student Advising.

Eligibility Requirements

In order to participate in a semester-long or yearlong study-abroad program, students must:

- Have at least a 3.0 GPA
- Be making good progress toward finishing the first and second year requirements
- Although knowledge of the language of the study abroad country is not a requirement, students are encouraged to have some foreign language skills in order to enhance their cultural competency and their overall study abroad experience. NOTE: For programs in countries where the language of instruction is not English, students must take all course work in the local language and will have to show proficiency in that language prior to departure.

Students' study-abroad plans must be approved by the Office of Global Programs by October 15 for spring programs and March 15 for summer, fall and academic-year programs. A review of each student's academic and disciplinary records is conducted as part of this process. Students on academic or disciplinary probation are not permitted to study abroad during the term of their probation. Students must then register for their study abroad with the Office of Global Programs by November 15 for spring programs and March 15 for summer, fall, and academic year programs.

Study-abroad students remain enrolled at Columbia, and tuition is paid to Columbia. Students participating in Columbia-approved programs pay housing costs directly to their host or sponsoring institution. Students receiving financial aid at Columbia will remain eligible for financial aid when they study abroad with Columbia's approval. Students who wish to be considered for financial aid while studying abroad should consult the Office of Financial Aid and Educational Financing, 618 Lerner.

Program Information

Choosing the right university abroad is an important step in planning to study abroad. Study-abroad options vary widely in size, geographical location, academic philosophy, language requirements, living arrangements, and opportunities for research and internships. Students must establish a set of goals for the study-abroad experience, taking into account their foreign-language skills and adaptability to new environments, as well as their research objectives and professional aspirations.

Students must visit the Office of Global Programs' website to review the various lists of program options and then consult with the SEAS Associate Dean for Undergraduate Student Affairs and Global Programs for specific information or help in choosing an institution that offers the best courses in their engineering major. Early planning is crucial so that study abroad plans can be integrated into the student's curriculum plan.

Summer study-abroad programs allow students to earn credits for language instruction and nontechnical electives. Students can either participate in Columbia-approved summer programs for transfer credit or on Columbia-sponsored programs for direct credit. The Columbia-sponsored summer programs include the Chinese Language Program in Beijing, the Business Chinese and Internship Program in Shanghai, the Italian Cultural Studies Program in Venice, the Columbia University Summer Arabic Language Program in Amman, Jordan, and the Columbia University Programs in Paris at Reid Hall.

Students who wish to have an international experience but are unable to study abroad are encouraged to consider the following options as viable alternatives to gaining such global experience and exposure.

Non-credit-bearing internships, including the CEO program in London, Hong Kong, Singapore, Shanghai, Beijing, and Amman, are coordinated by the Center for Career Education. Please visit the Center's website for more information.

In addition, the Summer Ecosystems Experience for Undergraduate Education through the Center for Environmental Research and Conservation (CERC) provides opportunities for engineering students in Brazil, Puerto Rico, the Dominican Republic, and Jordan. Other internship options may be possible through Columbia Engineering international partner institutions.

Academic Credit

Students in Columbia-sponsored programs receive direct Columbia credit, and the courses and grades appear on students' academic transcripts. These include Reid Hall, Paris; the Berlin

Consortium for German Studies; the Kyoto Center for Japanese Studies; the Columbia University Summer Arabic Language Program in Amman, Jordan, and the Tsinghua University program in Beijing.

Credit from approved programs that are not Columbia sponsored is certified as transfer credit toward the Columbia degree upon successful completion of the program verifiable by academic transcript. Students must earn a grade of C or better in order for credits to transfer. Course titles and grades for approved programs do not appear on the Columbia transcript, and the grades are not factored into students' GPAs.

Faculty from the Columbia Engineering academic departments have the responsibility to assess all work completed abroad and make decisions about how these courses fit into major requirements. It is imperative that students gain course-by-course approval from their department prior to departure on a study-abroad program.

COMBINED PLAN PROGRAMS

Office of Undergraduate Admissions
212 Hamilton Hall, MC 2807
1130 Amsterdam Avenue
New York, NY 10027
Phone: 212-854-2522
Fax: 212-854-1209
E-mail: combinedplan@columbia.edu
undergrad.admissions.columbia.edu/apply/combined-plan

Columbia Engineering maintains cooperative program relationships with institutions nationwide and with other Columbia University undergraduate divisions. The Combined Plan programs (3-2 and 4-2) allow students to receive a degree both in the liberal arts and in engineering. Combined Plan students complete the requirements for the liberal arts degree along with required prerequisite course work for their studies in engineering during the three or four years at their liberal arts college before entering the School of Engineering and Applied Science. They then must complete all the requirements for the B.S. degree within four consecutive semesters.

The Combined Plan Program within Columbia University

Under this plan, the pre-engineering student studies in Columbia College, Barnard College, or the School of General Studies for three or four years, then attends The Fu Foundation School of Engineering and Applied Science for two years, and is awarded the Bachelor of Arts degree and the Bachelor of Science degree in engineering upon completion of the fifth or sixth year. This program is optional at Columbia, but the School recommends it to all students who wish greater enrichment in the liberal arts and pure sciences.

The Combined Plan with Other Affiliated Colleges

There are more than one hundred affiliated liberal arts colleges, including those at Columbia, in which a student can enroll in a Combined Plan program leading to two degrees. Each college requires the completion of a specified curriculum, including major and degree requirements, to qualify for the baccalaureate from that institution. Every affiliated school has a liaison officer who coordinates the program at his or her home institution. Students interested in this program should inform the liaison officer as early as possible, preferably in the first year, in order to receive guidance about completing program requirements. Applicants from nonaffiliated schools are welcome to apply through our competitive review process.

Visit the Office of Undergraduate Admissions website for a complete list of affiliated schools, admission application instructions, information on financial aid, and curriculum requirements for Combined Plan program admission. Please note that no change of major is allowed after an admission decision has been rendered.

See page 25 for information on the 4-2 Master of Science Program, which is administered through the Office of Graduate Student Affairs.

THE JUNIOR-SENIOR PROGRAMS

Students may review degree progress via DARS (Degree Audit Reporting System) as presented on Student Services Online. Required courses that are not completed are detailed as deficiencies and must be completed during summer session or carried as overload courses in later semesters.

Having chosen their program major in the second semester of their sophomore year, students are assigned to a faculty adviser in the department in which the program is offered. In addition to the courses required by their program, students must continue to satisfy certain distributive requirements, choosing elective courses that provide sufficient content in engineering sciences and engineering design. The order and distribution of the prescribed course work may be changed with the adviser's approval. Specific questions concerning course requirements should be addressed to the appropriate department or division. The Vice Dean's concurrent approval is required for all waivers and substitutions.

Tau Beta Pi

Tau Beta Pi is the nation's second-oldest honor society, founded at Lehigh University in 1885. With the creed "Integrity and excellence in engineering," it is the only engineering honor society representing the entire engineering profession. Columbia's chapter, New York Alpha, is the ninth oldest and was founded in 1902. Many Columbia buildings have been named for some of the more prominent chapter alumni: Charles Fredrick Chandler, Michael Idvorsky Pupin, Augustus Schermerhorn, and, of course, Harvey Seeley Mudd.

Undergraduate students whose scholarship places them in the top eighth of their class in their next-to-last year or in the top fifth of their class in their last college year are eligible for membership consideration. These scholastically eligible students are further considered on the basis of personal integrity, breadth of interest both inside and outside engineering, adaptability, and unselfish activity. Benefits of membership include exclusive scholarships and fellowships. Many networking opportunities for jobs and internships are also available, with 230 collegiate chapters and more than 500,000 members in Tau Beta Pi.

Taking Graduate Courses as an Undergraduate

With the faculty adviser's approval, a student may take graduate courses while still an undergraduate in the School.

Such work may be credited toward one of the graduate degrees offered by the Engineering Faculty, subject to the following conditions: (1) the course must be accepted as part of an approved graduate program of study; (2) the course must not have been used to fulfill a requirement for the B.S. degree and must be so certified by the Dean; and (3) the amount of graduate credit earned by an undergraduate cannot exceed 15 points. Undergraduates may not take CVN courses.

The Bachelor of Science Degree

Students who complete a four-year sequence of prescribed study are awarded the Bachelor of Science degree. The general requirement for the Bachelor of Science degree is the completion of a minimum of 128 academic credits with a minimum cumulative grade-point average (GPA) of 2.0 (C) at the time of graduation. The program requirements, specified elsewhere in this bulletin, include the first-year–sophomore course requirements, the major departmental requirements, and technical and nontechnical elective requirements. Students who wish to transfer points of credit may count no more than 68 transfer points toward the degree, and must satisfy the University's residence requirements by taking at least 60 points of credit at Columbia. Courses may not be repeated for credit unless it is stated otherwise in the course description.

The bachelor's degree in engineering and applied science earned at Columbia University prepares students to enter a wide range of professions. Students are, however, encouraged to consider graduate work, at least to the master's degree level, which is increasingly considered necessary for many professional careers.

The Engineering Accreditation Commission (EAC) of ABET, an organization formed by the major engineering professional societies, accredits university engineering programs on a nationwide basis. Completion of an accredited program of study is usually the first step toward a professional engineering license. Advanced study in engineering at a graduate school sometimes presupposes the completion of an accredited program of undergraduate study.

The following undergraduate programs are accredited by the EAC of ABET: biomedical engineering, chemical engineering, civil engineering, Earth and environmental engineering, electrical engineering, and mechanical engineering.

The 4-1 Program at Columbia College

Students who are admitted as first-year students to the School of Engineering and Applied Science and subsequently complete the four-year program for the Bachelor of Science degree, have the opportunity to apply for admission to either Columbia College or Barnard College and, after one additional year of study, receive the Bachelor of Arts degree.

The program will be selective, and admission will be based on the following factors: granting of the B.S. at Columbia Engineering at the end of the fourth year; fulfillment of the College Core requirements by the end of the fourth year at the School; a minimum GPA of 3.0 in the College Core and other courses; and the successful completion of any prerequisites for the College major or concentration. To be admitted to the program, a plan needs to be in place for the student to complete the major or concentration by the end of their fifth year.

Interested students should contact their advising dean for further information.

Minors

Columbia Engineering undergraduates may choose to add minors to their programs. This choice should be made in the fall of their sophomore year, when they also decide on a major.

In considering a minor, students must understand that all minors are not, and cannot, be available to all students. In addition, the School cannot guarantee that a selected minor can be completed within the usual residence period needed for a major. Indeed, students choosing minors should expect to encounter scheduling difficulties. The potential for the successful completion of a minor depends on the student's major and the minor chosen, as well as the course schedules and availability, which may change from year to year. The list of minors, as well as their requirements, appear on pages 200–204.

PROGRAMS IN PREPARATION FOR OTHER PROFESSIONS

The Fu Foundation School of Engineering and Applied Science prepares its students to enter any number of graduate programs and professions outside of what is generally thought of as the engineering field. In an increasingly technological society, where the line between humanities and technology is becoming blurred, individuals with a thorough grounding in applied mathematics and the physical and engineering sciences find themselves highly sought after as professionals in practically all fields of endeavor.

Engineering students interested in pursuing graduate work in such areas as architecture, business, education, journalism, or law will find themselves well prepared to meet the generally flexible admissions requirements of most professional schools. Undergraduate students should, however, make careful inquiry into the kinds of specific preparatory work that may be required for admission into highly specialized programs such as medicine.

Premed

Engineering students seeking admission to dental, medical, optometric, osteopathic, or veterinary schools directly after college must complete all entrance requirements by the end of the junior year and should plan their program accordingly. Students should consult with their adviser in the James H. and Christine Turk Berick Center for Student Advising to plan an appropriate program. Students should also connect with Preprofessional Advising to learn more about extracurricular and research opportunities related to premed studies.

It is necessary to apply for admission to health professions schools a little over one year in advance of the entry date. If candidates are interested in going directly on to health professions school following graduation, they should complete all requirements and the Medical College Admissions Test (MCAT) by the summer following the junior year. It is, however, entirely acceptable to delay application and entrance to these schools several years beyond graduation.

Candidates planning for an application to medical or dental school will also need to be evaluated by the

Premedical Advisory Committee prior to application. A Premedical Advisory Committee application is made available each year in December. Please consult with Preprofessional Advising for more information regarding this process.

Engineering's curriculum covers many of the premedical courses required by medical schools. However, in addition to completing the mathematics, chemistry, and physics courses required by the First Year–Sophomore Program, most medical schools ask for a full year of organic chemistry, a full year of biology, and a full year of English.

The following courses are required by medical schools:

- One year of calculus for some schools
- One year of physics, with lab
- One year of general chemistry, with lab
- One year of biology, with lab (BME labs will qualify)
- One year of organic chemistry, with lab
- One year of English
- Biochemistry or additional biology (required by some schools)

For further information, please consult Preprofessional Advising at preprofessional@columbia.edu.

Prelaw

Students fulfilling the School of Engineering and Applied Science's curriculum are well prepared to apply to and enter professional schools of law, which generally do not require any specific prelaw course work. Schools of law encourage undergraduate students to complete a curriculum characterized by rigorous intellectual training involving relational, syntactical, and abstract thinking. A sound education is best for most prelaw students. While selecting courses, keep in mind the need to hone your writing skills, your communication skills, and your capacity for logical analysis.

Courses in history, political science, economics, statistics, and anthropology help students understand the structure of society and the problems of social ordering with which the law is concerned. The study of philosophy, literature, fine arts, foreign languages, and other cultures imparts familiarity with traditions of universal thought and trends that influence legal developments nationally and internationally. The examination of human behavior through sociology and psychology will aid a prospective law student in understanding the types and effects of behavior to which the law relates.

The systematic ordering of abstractions and ideas in logic and the sciences contributes much to a prelaw student's ability to analyze, understand, and rationally organize his or her thoughts. Finally, it is useful in some fields of law for a student to have a fundamental knowledge of technology, engineering, computers, and accounting.

Urban Teaching: New York State Initial Certification in Adolescence Education Grades 7–12 for Teachers of Mathematics and the Sciences or in Elementary Education Grades 1–6

Barnard College Education Program
335-336 Milbank Hall
3009 Broadway
New York, NY 10027

Phone: 212-854-7072
education.barnard.edu

The Barnard Education Program provides courses leading to certification to teach in New York State (with reciprocal agreements with 41 other states) at either the elementary or secondary level. Students gain experience and develop skills in urban school classrooms. Required course work includes psychology and education, a practicum, and student teaching, totaling 23–26 points of credit depending on the level of certification sought.

Certification to teach mathematics requires 36 points in mathematics. Pure science courses required are: 36 points in the sciences, of which 18 must be in the area of the certification sought: chemistry, biology, physics, or Earth science.

Deadline for application, which includes an essay and letters of recommendation, is the first Monday in March of the student's sophomore year. This allows program faculty to support students through program planning to ensure that students can meet the requirements for certification. However, when space allows, applications will be considered through the fall of the junior year. Applications from juniors are due no later than the first Monday in October. Students who plan to study abroad during the spring of their junior year should apply during the fall semester of their sophomore year. Students should decide on their interest in teacher certification by the end of the first year in order to start course work in the sophomore year.

JOINT PROGRAMS

School of International and Public Affairs

The Fu Foundation School of Engineering and Applied Science and the School of International and Public Affairs offer a joint program enabling a small number of students to complete the requirements for the degrees of Bachelor of Science and Master of International Affairs in five years instead of six. Not only an excellent academic record but also maturity, fluency in an appropriate foreign language, and pertinent experience will determine admission to this program. For more information, please contact your advising dean.

UNDERGRADUATE ADMISSIONS

Office of Undergraduate Admissions
212 Hamilton Hall, MC 2807
1130 Amsterdam Avenue
New York, NY 10027

Phone: 212-854-2522
Fax: 212-854-3393
E-mail: ugrad-ask@columbia.edu
undergrad.admissions.columbia.edu

For information about undergraduate admissions, please visit the Office of Undergraduate Admissions website or contact the office by phone or e-mail.

The 2015–2016 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

University charges such as tuition, fees, and residence hall and meal plans are billed in the first Student Account Statement of the term, which is sent out in July and December of each year for the upcoming term. This account is payable and due in full on or before the payment due date announced in the Statement, typically at the end of August or early January before the beginning of the billed term. Any student who does not receive the first Student Account Statement is expected to pay at registration.

If the University does not receive the full amount due for the term on or before the payment due date of the first Statement, a late payment charge of $150 will be assessed. An additional charge of 1 percent per billing cycle may be imposed on any amount past due thereafter.

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due. If a student's account is referred for collection, the student may be charged an additional amount equal to the cost of collection, including reasonable attorney's fees and expenses incurred by the University.

TUITION

Undergraduate students enrolled in The Fu Foundation School of Engineering and Applied Science pay a flat tuition charge of $25,263 per term, regardless of the number of course credits taken.

MANDATORY FEES

Orientation fee: $418 (one-time charge in the first term of registration)
Student Life fee: $762 per term
Health Service fee: $429 per term
International Services charge: $50 per term (international students only)
Transcript fee: $105 (one-time charge)

OTHER FEES

Application and late fees:

- Application for undergraduate admission: $85
- Application for undergraduate transfer admission: $85
- Late registration fee during late registration: $50;
  after late registration: $100

Books and course materials: Depends upon course

Laboratory fees: See course listings

Room and board (estimated): $12,000

HEALTH INSURANCE

Columbia University offers the Student Medical Insurance Plan, which provides both Basic and Comprehensive levels of coverage. Full-time students are automatically enrolled in the Basic level of the Plan and billed for the insurance premium in addition to the Health Service fee. Visit the Columbia Health website at health.columbia.edu for detailed information about medical insurance coverage options and directions for making confirmation, enrollment, or waiver requests.

PERSONAL EXPENSES

Students should expect to incur miscellaneous personal expenses for such items as clothing, linen, laundry, dry cleaning, and so forth. Students should also add to the above expenses the cost of two round trips between home and the University to cover travel during the summer and the month-long, midyear break.

The University advises students to open a local bank account upon arrival in New York City. Since it often takes as long as three weeks for the first deposit to clear, students should plan to cover immediate expenses using either a credit card, traveler's checks, or cash draft drawn on a local bank. Students are urged not to arrive in New York without sufficient start-up funds.

LABORATORY CHARGES

Students may need to add another $100 to $300 for drafting materials or laboratory fees in certain courses. Each student taking laboratory courses must furnish, at his or her own expense, the necessary notebooks, blank forms, and similar supplies. In some laboratory courses, a fee is charged to cover expendable materials and equipment maintenance. Students engaged in special tests, investigations, theses, or research work are required to meet the costs of expendable materials as may be necessary for this work and in accordance with such arrangements as may be made between the student and the department immediately concerned.

DAMAGES

All students will be charged for damage to instruments or apparatus caused by their carelessness. The amount of the charge will be the actual cost of repair, and, if the damage results in total loss of the apparatus, adjustment will be made in the charge for age or condition. To ensure that there may be no question as to the liability for damage, students should note whether the apparatus is in good condition before use and, in case of difficulty, request instruction in its proper operation. Where there is danger of costly damage, an instructor should be requested to inspect the apparatus. Liability for breakage will be decided by the instructor in charge of the course.

When the laboratory work is done by a group, charges for breakage will be divided among the members of the group. The students responsible for any damage will be notified that a charge is being made against them.

The amount of the charge will be stated at that time or as soon as it can be determined.

TUITION AND FEE REFUNDS

Students who make a complete withdrawal from a term are assessed a withdrawal fee of $75. Late fees, application fees, withdrawal fees, tuition deposits, special fees, computer fees, special examination fees, and transcript fees are not refundable.

The Health Service Fee, Health Insurance Premium, University facilities fees, and student activity fees are not refundable after the change of program period.

Students who withdraw within the first 60 percent of the academic period are subject to a refund calculation, which refunds a portion of tuition based on the percentage of the term remaining after the time of withdrawal. This calculation is made from the date the student's written notice of withdrawal is received by the Dean's Office.

Percentage Refund for Withdrawal during First Nine Weeks of Term

Prorated for calendars of a different duration:

1st week	100%
2nd week	100%
3rd week	90%
4th week	80%
5th week	70%
6th week	60%
7th week	50%
8th week	40%
9th week and after	0%

For students receiving federal student aid, refunds will be made to the federal aid programs in accordance with Department of Education regulations. Refunds will be credited in the following order:

Federal Unsubsidized Stafford Loans
Federal Stafford Loans
Federal Perkins Loans
Federal PLUS Loans (when disbursed through the University)
Federal Pell Grants
Federal Supplemental Educational Opportunity Grants
Other Title IV funds

Withdrawing students should be aware that they will not be entitled to any portion of a refund until all Title IV programs are credited and all outstanding charges have been paid.

Office of Financial Aid and Educational Financing
618 Lerner Hall
2920 Broadway
Mailing: 100 Hamilton
1130 Amsterdam Avenue, MC 2802
New York, NY 10027
Monday–Friday: 9:00 a.m.–5:00 p.m.

Phone: 212-854-3711
Fax: 212-854-5353
E-mail: ugrad-finaid@columbia.edu
cc-seas.financialaid.columbia.edu

Columbia is committed to meeting the full demonstrated financial need for all applicants admitted as first-year students. Financial aid is available for all four undergraduate years, provided that students continue to demonstrate financial need. International students who did not apply for financial aid in their first year are not eligible to apply for financial aid in any subsequent years.

All transfer applicants who are citizens or permanent residents of the United States or students granted refugee visas by the United States are considered for admission in a need-blind manner. Foreign transfer candidates applying for aid must understand that such aid is awarded on an extremely limited basis. Columbia meets 100% of demonstrated financial need for admitted transfer students and does not give any scholarships for academic, athletic, or artistic merit.

Please visit the Financial Aid website at cc-seas.financialaid.columbia.edu/ for more information on financial aid, including requirements and application instructions.

Satisfactory Academic Progress

Columbia University complies with federal SAP regulations. To be eligible for Federal Student Aid (Federal Pell Grant, Federal SEOG, Federal Work-Study, Federal Perkins Loan, Federal Direct/PLUS loan), an otherwise eligible student must meet or exceed the SAP standards set by his or her school or program at the time SAP is assessed. The SAP policy may be found online at sfs.columbia.edu/central-sap-policy.

Graduate Studies

Graduate programs of study in The Fu Foundation School of Engineering and Applied Science are not formally prescribed, but are planned to meet the particular needs and interests of each individual student. Departmental requirements for each degree, which supplement the general requirements given below, appear in the sections on individual graduate programs.

Applicants for a graduate program are required to have completed an undergraduate degree and to furnish an official transcript as part of the admissions application. Ordinarily the candidate for a graduate degree will have completed an undergraduate course in the same field of engineering in which he or she seeks a graduate degree. However, if the student's interests have changed, it may be necessary to make up such basic undergraduate courses as are essential to graduate study in his or her new field of interest.

No more than one term of graduate-level course work or, in the case of part-time students, no more than 15 points of credit of graduate-level course work, completed before the program is approved, may be counted toward the degree. Students registered in the School have a minimum requirement for each Columbia degree of 30 points of credit of course work completed at Columbia University. The student must enroll for at least 15 of these points while registered as a matriculating student in a degree program in the Engineering School. (See also the section Special Nondegree Students and the chapter Columbia Video Network.) Students wishing to change from the Ph.D. degree to the Eng.Sc.D. degree must therefore enroll for at least 15 points while registered in the School. For residence requirements for students registered in the Graduate School of Arts and Sciences or those wishing to change from the Eng.Sc.D. degree to the Ph.D. degree, see the bulletin of the Graduate School of Arts and Sciences.

Students admitted to graduate study are expected to enter upon and continue their studies in each succeeding regular term of the academic year. Any such student who fails to register for the following term will be assumed to have withdrawn unless a leave of absence has been granted by the Office of Graduate Student Affairs.

While many candidates study on a full-time basis, it is usually possible to obtain all or a substantial part of the credit requirement for the master's or Eng.Sc.D. degrees through part-time study.

Under special conditions, and with the prior approval of the department of his or her major interest and of the Assistant Dean or Director, a student may be permitted to ‘ a required subject at another school. However, credit for such courses will not reduce the 30-point minimum that must be taken.

For graduation, a candidate for any degree except a doctoral degree must file an Application for Degree or Certificate on the date specified in the Academic Calendar. Candidates for a doctoral degree must apply for the final examination. If the degree is not earned by the next regular time for the issuance of diplomas subsequent to the date of filing, the application must be renewed. Degrees are awarded three times a year—in October, February, and May.

THE MASTER OF SCIENCE DEGREE

The Master of Science degree is offered in many fields of engineering and applied science upon the satisfactory completion of a minimum of 30 points of credit of approved graduate study extending over at least one academic year.

While a suitable Master of Science program will necessarily emphasize some specialization, the program should be well balanced, including basic subjects of broad importance as well as theory and applications. The history of modern economic, social, and political institutions is important in engineering, and this is recognized in the prescribed undergraduate program of the School. If the candidate's undergraduate education has been largely confined to pure science and technology, a program of general studies, totaling from 6 to 8 points, may be required. Supplementary statements covering these special requirements are issued by the School's separate departments. An applicant who lacks essential training will be required to strengthen or supplement the undergraduate work by taking or repeating certain undergraduate courses before proceeding to graduate study. No graduate credit (that is, credit toward the minimum 30-point requirement for the Master of Science degree) will be allowed for such subjects. Accordingly, Master of Science programs may include from 35 to 45 points and may require three terms for completion. Doctoral research credits cannot be used toward M.S. degree requirements.

All degree requirements must be

completed within five years of the beginning of graduate study. Under extraordinary circumstances, a written request for an extension of this time limit may be submitted to the student's department for approval by the department chairman and the Assistant Dean or Director. A minimum grade-point average of 2.5 is required for the M.S. degree. A student who, at the end of any term, has not attained the grade-point average required for the degree may be asked to withdraw.

After the first semester of enrollment, an M.S. student may submit an application to apply and transfer to another academic program. If the student is not successful with the application process, then he or she must make sure requirements for the original academic program are completed.

The 4-2 Master of Science Program

The 4-2 Master of Science Program provides the opportunity for students holding bachelor's degrees from affiliated liberal arts colleges (see the listing under the heading The Combined Plan Program with Other Affiliate Colleges) with majors in mathematics, physics, chemistry, or certain other physical sciences to receive the M.S. degree after two years of study at Columbia in the following fields of engineering and applied science: biomedical, chemical, civil, computer science, Earth and environmental, electrical, industrial, and mechanical engineering; applied physics; applied mathematics; engineering mechanics; operations research; and materials science.

Each applicant must produce evidence of an outstanding undergraduate record, including superior performance in physics and mathematics through differential equations. The program of study will be individually designed in consultation with a faculty adviser and will integrate undergraduate work with the field of engineering or applied science the student chooses to follow. During the first year, the program will consist primarily of basic undergraduate courses; during the second year, of graduate courses in the selected field. The student must complete at least 30 credits of graduate study to qualify for the degree.

A student whose background may require supplementary preparation in some specific area, or who has been out of school for a considerable period, will have to carry a heavier than normal course load or extend the program beyond two years.

Graduates of the 4-2 Master of Science program may not be eligible to take the Fundamentals of Engineering (FE) exam if their undergraduate degree is not in engineering or a related field. Students should also check with individual state boards to determine eligibility requirements for employment.

Please contact the Office of Graduate Student Affairs, The Fu Foundation School of Engineering and Applied Science, 530 S.W. Mudd, MC 4718, 500 West 120th Street, New York, NY 10027; you should also contact your home institution's Combined Plan liaison for program information. You may, in addition, e-mail questions to seasgradmit@columbia.edu.

Dual Degree Program with the School of Journalism in Computer Science

The Graduate School of Journalism and the Engineering School offer a dual degree program leading to the degrees of Master of Science in Journalism and the Master of Science in Computer Science. (See Computer Science.)

Joint Program with the School of Business in Industrial Engineering

The Graduate School of Business and the Engineering School offer a joint program leading to the degrees of Master of Business Administration and Master of Science in Industrial Engineering. (See Industrial Engineering and Operations Research.)

Master of Science Program in Management Science and Engineering

In collaboration with the Graduate School of Business, the Industrial Engineering and Operations Research department offers a unique master's degree program in which students take business and engineering courses. (See Industrial Engineering and Operations Research.)

Master of Science Program in Data Science

The Data Science Institute is housed in the Engineering School and encompasses the interdisciplinary expertise of nine schools within Columbia University, including the Engineering School, the Graduate School of Arts and Sciences, the Journalism School, the Graduate School of Business, the Graduate School of Architecture, Planning and Preservation, the School of International and Public Affairs, the Medical Center, the Mailman School of Public Health, and the Law School. The Institute offers a master's degree program allowing students to select an elective concentration of study incorporating one of the six centers: Cybersecurity, Financial and Business Analytics, Foundations of Data Science, Health Analytics, New Media, and Smart Cities. Students can also pursue an Entrepreneurship track.

DOCTORAL DEGREES: ENG.SC.D. AND PH.D.

Two doctoral degrees in engineering are offered by the University: the Doctor of Engineering Science, administered by The Fu Foundation School of Engineering and Applied Science and the Doctor of Philosophy, administered by the Graduate School of Arts and Sciences. Both doctoral programs are subject to review by the Committee on Instruction of the School. Doctoral students may submit a petition to the Office of Graduate Student Affairs to change from the Eng.Sc.D. degree to the Ph.D. degree or from the P.D. degree to the Eng.Sc.D. degree. The petition must be submitted within the first year of enrollment or by the completion of 30 points. Any petitions submitted after this period will not be considered. Doctoral degree status can be changed only once; students, therefore, must determine which doctoral degree program is most appropriate for their academic and professional endeavours.

Departmental requirements may include comprehensive written and oral qualifying examinations. A student must have a satisfactory grade-point average to be admitted to the doctoral qualifying examination. Thereafter, the student must write a dissertation embodying original research under the sponsorship of a member of his or her department and submit it to the department. If the department recommends the dissertation for defense, the student applies for final examination, which is held before an examining committee approved by the appropriate Dean's Office. This application must be made at least three weeks before the date of the final examination.

The defense of the dissertation constitutes the final test of the candidate's qualifications. It must be demonstrated that the candidate has made a contribution to knowledge in a chosen area. In content the dissertation should, therefore, be a distinctly original contribution in the selected field of study. In form it must show the mastery of written English, which is expected of a university graduate.

For the Ph.D. Degree

A student must obtain the master's degree (M.S.) before enrolling as a candidate for the Ph.D. degree. Application for admission as a doctoral candidate may be made while a student is enrolled as a master's degree candidate. Candidates for the Ph.D. degree must register full time and complete six Residence Units. The minimum requirement in course work for the doctoral degree is 60 points of credit beyond the bachelor's degree. A master's degree from an accredited institution may be accepted in the form of advanced standing as the equivalent of one year of residence (30 points of credit and two Residence Units). An application for advanced standing must be completed during the first semester of study. Ph.D. candidates will be required to complete not less than 30 additional points of credit in residence for a letter grade beyond the M.S..

Ph.D. candidates should obtain a copy of the bulletin of the Graduate School of Arts and Sciences, in which are printed the requirements of the department of major interest.

For the Eng.Sc.D. Degree

A student must obtain the master's degree (M.S.) before enrolling as a candidate for the Eng.Sc.D. degree. The minimum requirement in course work for the doctoral degree is 60 points of credit beyond the bachelor's degree. Eng.Sc.D. candidates will be required to complete not less than 30 additional points of credit in residence beyond the M.S. for a letter grade. A master's degree from an accredited institution may be accepted in the form of advanced standing as the equivalent of 30 points of credit. Candidates for the Eng.Sc.D. degree must, in addition to the 60-point requirement, accumulate 12 points of credit in the departmental course *E9800: Doctoral research instruction* (see below). The candidate for the degree of Doctor of Engineering Science must submit evidence that his or her dissertation has been filed in compliance with requirements set by the faculty of Engineering and Applied Science.

Doctoral Research Instruction

An Eng.Sc.D. candidate is required to complete 12 credits in the departmental course *E9800: Doctoral research instruction* in accordance with the following guidelines:

1. After obtaining a master's degree or advanced standing, at which time the student begins doctoral research, the student is eligible to register for *E9800* (3, 6, 9, or 12 points of credit).
2. Registration for *E9800* at a time other than that prescribed above is not permitted, except by written permission of the Dean.
3. The 12 points of *E9800* required for the Eng.Sc.D. degree do not count toward the minimum residence requirements, e.g. 30 points beyond the master's degree or 60 points beyond the bachelor's degree.
4. If a student is required to take course work beyond the minimum residence requirements, the 12 points of doctoral research instruction must still be taken in addition to the required course work.
5. A student must register continuously through the fall and the spring terms. This requirement does not include the summer session.

Completion of Requirements

The requirements for the Eng.Sc.D. degree must be completed in no more than seven years. The seven-year time period begins at the time the student becomes a candidate for the Eng.Sc.D. degree and extends to the date on which the dissertation defense is held.

Extension of the time allowed for completion of the degree may be granted on recommendation of the student's sponsor and the department chairman to the Dean when special circumstances warrant. Such extensions are initiated by submitting a statement of work in progress and a schedule for completion together with the sponsor's recommendation to the department chairman.

Please contact the Office of Graduate Student Affairs for more information.

SPECIAL NONDEGREE STUDENTS

Qualified persons who are not interested in a degree program but who wish only to take certain courses may be permitted to register as special students, provided facilities are available.

Many graduate courses in The Fu Foundation School of Engineering and Applied Science are offered in the late afternoon and evening in order to make them available to working individuals who wish to further their knowledge in the areas of engineering and applied science. Individuals who find it difficult or impossible to attend classes on the Columbia campus may be able to receive instruction from the School through the Columbia Video Network without leaving their work sites. Individuals interested in this program should read the section describing the distance learning Columbia Video Network (CVN), which follows in this bulletin.

Special students receive grades and must maintain satisfactory attendance and performance in classes or laboratories and will be subject to the same rules as degree candidates. Should a special student decide to pursue a degree program, work completed as a special student may be considered for advanced standing, but no more than 15 points of course work completed as a special student may be counted toward a graduate degree.

For additional information and regulations pertaining to special students, see Graduate Admissions.

Columbia Video Network
540 S. W. Mudd, MC 4719
500 West 120th Street
New York, NY 10027

Phone: 212-854-6447
E-mail: info@cvn.columbia.edu
cvn.columbia.edu

BACKGROUND

Continuing a long-standing tradition of academic excellence and innovation, Columbia University's Fu Foundation School of Engineering and Applied Science established the Columbia Video Network (CVN) in 1986 to meet a growing need within the engineering community for a graduate distance education program. Classes and degrees offered through CVN are fully accredited; the degrees are granted by Columbia University.

Classes available through CVN are taught on campus by Columbia University faculty in electronic classrooms. Faculty and students meet in classrooms equipped with cameras, electronic writing tablets, and SMART™ boards. The recorded lectures are fully downloadable for study at home, office, or on the road.

CVN students take the same classes, have the same homework assignments, take the same exams, and earn the same degrees as on-campus students in Master of Science (M.S.) programs.

COURSE OFFERINGS AND DEGREE PROGRAMS

CVN makes select SEAS graduate courses available to off-campus students in autumn (September–December) and spring (January–May) terms. CVN administrators work closely with faculty representatives from each department to select the classes that best fit the needs of new and continuing students around the world. During the summer semester (and on request in the autumn and spring terms), CVN makes prerecorded courses available. SEAS currently offers M.S. degrees in the following disciplines through CVN:

- Applied physics
- Applied physics—applied math
- Biomedical engineering
- Chemical engineering
- Civil engineering
- Computer science
- Earth and environmental engineering
- Electrical engineering
- Industrial engineering—systems engineering
- Materials science and engineering
- Mechanical engineering
- Operations research
- Operations research—methods in finance

In addition, students admitted to the Doctor of Engineering Science can complete the course work component of the program via CVN.

STUDENT REGISTRATION

Students who have earned an undergraduate degree in engineering, mathematics, or related field can apply to take classes for credit or audit without first enrolling in a degree program at the University or taking the GRE or TOEFL exams by registering as nondegree students. CVN also offers Certification of Professional Achievement programs in various fields, which may lead to study in a related M.S. program.

Although you need not be admitted to a degree program to begin taking classes through CVN, you should apply as soon as possible if you would like to earn a degree from Columbia University; up to 6 credits taken as a CVN nondegree student may be counted toward a degree when applying through CVN, subject to the approval of the student's departmental adviser. Earning credit as a nondegree student does not guarantee acceptance into a degree program.

Only CVN students may transfer up to 6 credits from another university toward an M.S., subject to the approval of the student's adviser and the department.

Columbia University students admitted to an on-campus program are not eligible to take CVN courses.

PROGRAM BENEFITS

The CVN program allows working professionals to enroll in courses and earn graduate engineering degrees without leaving their communities, their families, or their jobs. The key component of CVN is flexibility without compromise to the high-caliber teaching, resources, and standards inherent in The Fu Foundation School of Engineering and Applied Science. CVN students are a part of the Columbia community and may take classes on campus. To further enhance the sense of community, CVN uses the Canvas Learning Management System to provide a place where CVN students and faculty can communicate. Homework and exams are submitted and graded there, and course notes and other reference materials are available for downloading.

Professors and teaching assistants are available via e-mail, phone, or online office hours to address academic questions. CVN's administrative staff is available to assist with registration procedures, technical queries, and academic advising, so working professionals can devote their energies to their studies, their families, and their careers.

Office of Graduate Student Affairs
530 S. W. Mudd, MC 4708
500 West 120th Street
New York, NY 10027

Phone: 212-854-6438
Fax: 212-854-5900
E-mail: seasgradmit@columbia.edu
gradengineering.columbia.edu

The basic requirement for admission as a graduate student is a bachelor's degree received from an institution of acceptable standing. Ordinarily, the applicant will have majored in the field in which graduate study is intended, but in certain programs, preparation in a related field of engineering or science is acceptable. The applicant will be admitted only if the undergraduate record shows promise of productive and effective graduate work.

Students who hold an appropriate degree in engineering may apply for admission to study for the Ph.D. degree. However, students are required to obtain the master's degree first. Applications for admission as a doctoral candidate may be made after completion of 15 points of work as a candidate for the master's degree.

Students may be admitted in one of the following five classifications: candidate for the M.S. degree, candidate for the M.S. degree leading to the Ph.D. degree, candidate for the Doctor of Engineering Science degree, candidate for the Doctor of Philosophy degree (see also the bulletin of the Graduate School of Arts and Sciences), or special student (not a degree candidate). Note: Not more than 15 points of credit completed as a special nondegree student may be counted toward a degree.

APPLICATION REQUIREMENTS

Applicants must submit an online application and required supplemental materials, as described below. The applicant must obtain one official transcript from each postsecondary institution attended and upload it to the online application. Consideration for admission will be based not only on the completion of an earlier course of study, but also upon the quality of the record presented and upon such evidence as can be obtained concerning the candidate's personal fitness to pursue professional work.

Additionally, candidates must provide three letters of recommendation and the results of required standardized exams. The Graduate Record Examination (general) is required for all candidates. GRE scores are valid for five years from the test date. The Test of English as a Foreign Language (TOEFL), the International English Language Testing System (IELTS), or the Pearson Test of English (PTE) is required of all candidates who received their bachelor's degree in a country in which English is not the official and spoken language. TOEFL, IELTS, and PTE scores are valid for two years from the test date. Applicants can only apply to one degree program per admission term.

ENGLISH PROFICIENCY

The Office of Graduate Student Affairs no longer requires students to demonstrate English proficiency as a graduation requirement at The Fu Foundation School of Engineering and Applied Science. Regardless of TOEFL, IELTS, or PTE scores submitted for admission, students should continue to work on maintaining adequate verbal and/or written abilities for successful integration within their classes and future professional endeavors. Students are highly encouraged to be proactive about addressing their English proficiency by utilizing the many resources available within Columbia University and throughout New York City.

Students have the option of enrolling in courses offered through the American Language Program (ALP) at Columbia University. However, course credits earned through ALP do not count toward the minimum engineering academic course work requirements. Enrollment in ALP courses is solely the financial responsibility of the student. As a rule, ISSO will not permit students to drop courses or fall below full-time registration for language proficiency deficiencies.

APPLICATION FEE

The nonrefundable application fee for all graduate degree and nondegree programs is $85.

GRADUATE ADMISSION CALENDAR

Applicants are admitted twice yearly, for the fall and spring semesters.

- Fall admission application deadlines: *December 15* for Ph.D., Eng.Sc.D.,

and M.S. leading to Ph.D. programs and *February 15* for most M.S. only and nondegree applicants. Please visit the Office of Graduate Student Affairs website for specific M.S. only program deadlines.
- Spring admission application deadline: *October 1* for all departments and degree levels.

Applicants who wish to be considered for scholarships, fellowships, and assistantships should file complete applications for fall admission.

EXPRESS APPLICATION

Columbia Engineering seniors already enrolled in a B.S. program with a minimum GPA of 3.5 are eligible to submit an express application.

This online application, which waives the submission of GRE scores, letters of recommendation, and official transcripts, streamlines and simplifies the application process for graduate study. Contact your academic department or the Office of Graduate Student Affairs for further details.

ONE-TERM SPECIAL STUDENT STATUS

Individuals who meet the eligibility requirements, who are U.S. citizens or U.S. permanent residents, and who wish to take courses for enrichment, may secure faculty approval to take up to two graduate-level courses for one term only as a one-term special student. This option is also appropriate for individuals who missed application deadlines. Applications for special student status are available at the Office of Graduate Student Affairs and must be submitted during the first week of the fall or spring semester.

If a one-term special student subsequently wishes either to continue taking classes the following term or to become a degree candidate, a formal application must be made through the Office of Graduate Student Affairs.

TRANSFER APPLICANTS

Master degree students are not eligible for transfer credits.

Students possessing a conferred M.S. degree may be awarded two residence units toward their Ph.D., as well as 30 points of advanced standing toward their Ph.D. or Eng. Sc.D. with approval from the academic department and the Office of Graduate Student Affairs.

GRADUATE TUITION, FEES, AND PAYMENTS

The 2015–2016 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

University charges such as tuition, fees, and residence hall and meal plans are billed in the first Student Account Statement of the term, which is sent out in July and December of each year for the upcoming term. This account is payable and due in full on or before the payment due date announced in the Statement, typically at the end of August or early January before the beginning of the billed term. Any student who does not receive the first Student Account Statement is expected to pay at registration.

If the University does not receive the full amount due for the term on or before the payment due date of the first Statement, a late payment charge of $150 will be assessed. An additional charge of 1 percent per billing cycle may be imposed on any amount past due thereafter.

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due. If a student's account is referred for collection, the student may be charged an additional amount equal to the cost of collection, including reasonable attorney's fees and expenses incurred by the University.

TUITION

Graduate students enrolled in M.S. and Eng.Sc.D. programs pay $1,782 per credit, except when a special fee is fixed. Graduate tuition for Ph.D. students is $21,138 per Residence Unit. The Residence Unit, full-time registration for one semester rather than for individual courses (whether or not the student is taking courses), provides the basis for tuition charges. Ph.D. students should consult the bulletin for the Graduate School of Arts and Sciences.

COMPREHENSIVE FEE/ MATRICULATION AND FACILITIES

Eng.Sc.D. candidates engaged only in research, and who have completed their twelve (12) credits of Doctoral Research Instruction (see "The Graduate Programs" in this bulletin), are assessed a Comprehensive Fee of $1,948 per term by The Fu Foundation School of Engineering and Applied Science.

Ph.D. candidates engaged only in research are assessed $1,948 per term for Matriculation and Facilities by the Graduate School of Arts and Sciences.

MANDATORY FEES

University facilities fee:

- Full-time master's programs: $469 per term
- All other full-time programs: $434 per term

Health Service fee: $429 per term

International Services charge:
$50 per term (international students only)

Transcript fee: $105 (one-time charge)

OTHER FEES

Activities fees:
- Full-time master's program: $125
- Part-time master's program: $75

Application and late fees:
- Application for graduate admission: $85
- Late registration fee:
  - during late registration: $50
  - after late registration: $100

Books and course materials:
Depends upon course

Laboratory fees: See course listings

IEOR master's program fee:
- Full-time master's program: $1,000
- Part-time master's program: $500

HEALTH INSURANCE

Columbia University offers the Student Medical Insurance Plan, which provides both Basic and Comprehensive levels of coverage. Full-time students are automatically enrolled in the Basic level of the Plan and billed for the insurance premium in addition to the Health Service fee. Visit the Columbia Health website at health.columbia.edu for detailed information about medical insurance coverage options and directions for making confirmation, enrollment, or waiver requests.

PERSONAL EXPENSES

Students should expect to incur miscellaneous personal expenses for such items as food, clothing, linen, laundry, dry cleaning, and so forth.

The University advises students to open a local bank account upon arrival in New York City. Since it often takes as long as three weeks for the first deposit to clear, students should plan to cover immediate expenses using either a credit card, traveler's checks, or cash draft drawn on a local bank. Students are urged not to arrive in New York without sufficient start-up funds.

LABORATORY CHARGES

Students may need to add another $100 to $300 for drafting materials or laboratory fees in certain courses. Each student taking laboratory courses must furnish, at his or her own expense, the necessary notebooks, blank forms, and similar supplies. In some laboratory courses, a fee is charged to cover expendable materials and equipment maintenance; the amount of the fee is shown with the descriptions in the course listings. Students engaged in special tests, investigations, theses, or research work are required to meet the costs of expendable materials as may be necessary for this work and in accordance with such arrangements as may be made between the student and the department immediately concerned.

DAMAGES

All students will be charged for damage to instruments or apparatus caused by their carelessness. The amount of the charge will be the actual cost of repair, and, if the damage results in total loss of the apparatus, adjustment will be made in the charge for age or condition. To ensure that there may be no question as to the liability for damage, students should note whether the apparatus is in good condition before use and, in case of difficulty, request instruction in its proper operation. Where there is danger of costly damage, an instructor should be requested to inspect the apparatus. Liability for breakage will be decided by the instructor in charge of the course. When the laboratory work is done by a group, charges for breakage will be divided among the members of the group. The students responsible for any damage will be notified that a charge is being made against them. The amount of the charge will be stated at that time or as soon as it can be determined.

TUITION AND FEE REFUNDS

Students who make a complete withdrawal from a term are assessed a withdrawal fee of $75. Late fees, application fees, withdrawal fees, tuition deposits, special fees, computer fees, special examination fees, and transcript fees are not refundable.

The Health Service Fee, Health Insurance Premium, University facilities fees, and student activity fees are not refundable after the change of program period.

Students who withdraw within the first 60 percent of the academic period are subject to a *pro rata* refund calculation, which refunds a portion of tuition based on the percentage of the term remaining after the time of withdrawal. This calculation is made from the date the student's written notice of withdrawal is received by the Office of Graduate Student Affairs.

Percentage Refund for Withdrawal during First Nine Weeks of Term

Prorated for calendars of a different duration, if the entire program is dropped:

1st week	100%
2nd week	100%
3rd week	90%
4th week	80%
5th week	70%
6th week	60%
7th week	50%
8th week	40%
9th week and after	0%

Refund Policy When Dropping Individual Courses

Tuition for courses dropped by the last day of the Change-of-Program period is refunded in full. There is no refund of tuition for individual courses dropped after the last day of the Change-of-Program period. The Change-of-Program period is usually the first two weeks of the fall or spring semesters (please note that the first week of the semester usually begins on a Tuesday).

Please note: The prorated schedule above does not pertain to individual classes dropped (unless your entire schedule consists of only one class). The prorated schedule pertains to withdrawals. Withdrawal is defined as dropping one's entire program.

For students receiving federal student aid, refunds will be made to the federal aid programs in accordance with Department of Education regulations. Refunds will be credited in the following order:

Federal Unsubsidized Stafford Loans
Federal Stafford Loans
Federal Perkins Loans
Federal PLUS Loans (when disbursed through the University)
Federal Pell Grants
Federal Supplemental Educational Opportunity Grants
Other Title IV funds

Withdrawing students should be aware that they will not be entitled to any portion of a refund until all Title IV programs are credited and all outstanding charges have been paid.

FINANCING GRADUATE EDUCATION

The academic departments of Columbia Engineering and the Office of Financial Aid and Educational Financing seek to ensure that all academically qualified students have enough financial support to enable them to work toward their degree. Possible forms of support for tuition, fees, books, and living expenses are: institutional grants, fellowships, teaching and research assistantships, on- or off-campus employment, and student loans. The Office of Financial Aid and Educational Financing assists students with developing financing plans for completing a degree.

Columbia University graduate funds are administered by two separate branches of the University, and the application materials required by the two branches differ. Institutional grants, fellowships, and teaching and research assistantships are all departmentally-administered funds. Questions regarding these awards should be directed to your academic department. Federal Student Loans (Unsubsidized, Graduate PLUS, and Perkins) and private student loans are administered by the Office of Financial Aid and Educational Financing. Questions about loans should be directed to the financial aid office.

INSTRUCTIONS FOR FINANCIAL AID APPLICANTS

Deadlines

Apply for financial aid at the same time that you apply for admission. Your admissions application must be received by the December 15 deadline to be eligible for The Fu Foundation School of Engineering and Applied Science departmental funding (institutional grants, fellowships, and teaching and research assistantships. Spring admissions applicants will not be considered for departmental funding.

Incoming applicants and continuing students should complete the FAFSA by May 5 for fall enrollment.

Guidelines for continuing students are available from departmental advisers in advance of the established deadline. All continuing supported students must preregister for classes during the preregistration period.

GRADUATE SCHOOL DEPARTMENTAL FUNDING

The graduate departments of Columbia Engineering offer an extensive array of funding. Funding decisions, based solely on merit, and contingent upon making satisfactory academic progress, are made by the departments. All applicants for admission and continuing students maintaining satisfactory academic standing will be considered for departmental funds. Applicants should contact their department directly for information. Columbia Engineering prospective and continuing graduate students must complete their FAFSA in order to be considered for all forms of graduate financing (both departmentally-administered and financial aid–administered funds). The application for admission to Columbia Engineering graduate programs is also used to apply for departmental funding. Outside scholarships for which you qualify must be reported to your department and the Office of Financial Aid and Educational Financing. The School reserves the right to adjust your institutional award if you hold an outside scholarship, fellowship, or other outside funding.

Institutional Grants

Institutional grants are awarded to graduate students on the basis of academic merit. Recipients must maintain satisfactory academic standing.

Fellowships

Fellowships are financial and intellectual awards for academic merit that provide stipends to be used by fellows to further their research. If you are awarded a fellowship, you are expected to devote time to your own work, and you are not required to render any service to the University or donor. You may publish research produced by your fellowship work. As a fellow, you may not engage in remunerative employment without consent of the Dean. Applicants should contact the department directly for information. See the complete listing of fellowships on pages 222–226.

Assistantships

Teaching and research assistantships, available to doctoral students in all departments, provide tuition exemption and a living stipend. Duties may include teaching, laboratory supervision, participation in faculty research, and other related activities. Teaching and research assistantships require up to twenty hours of work per week. If you are participating in faculty research that fulfills degree requirements, you may apply for a research assistantship. Assistantships are awarded on the basis of academic merit.

ALTERNATIVE FUNDING SOURCES

External Awards

Because it is not possible to offer full grant and fellowship support to all graduate students and because of the prestige inherent in holding an award through open competition, applicants are encouraged to consider major national and international fellowship opportunities. It is important that prospective graduate students explore every available source of funding for graduate study.

In researching outside funding you may look to faculty advisers, career services offices, deans of students, and offices of financial aid where frequently you may find resource materials, books, and grant applications for a wide variety of funding sources. You must notify both your Columbia Engineering academic department and the Office of Financial Aid and Educational Financing of any outside awards that you will be receiving.

Funding for International Students

To secure a visa, international students must demonstrate that they have sufficient funding to complete the degree. Many international students obtain support for their educational expenses from their government, a foundation, or a private agency.

International students who apply to doctoral programs of study by the December 15 deadline and are admitted to a Columbia Engineering doctoral program are automatically considered for departmental funding (institutional grants, fellowships, and teaching and research assistantships, upon completion of the required financial aid forms referred to above. Spring admissions applicants will not be considered for departmental funding. Continuing international students must preregister for classes during the preregistration period and complete an enrollment status form to be considered for departmental funding.

Most private student loan programs are restricted to U.S. citizens and permanent residents. However, international students may be eligible to apply for these domestic loan programs with a creditworthy cosigner who is a citizen or permanent resident in the United States. Depending on the loan program, you may need a valid U.S. Social Security number.

Students who study at Columbia Engineering on temporary visas should fully understand the regulations concerning possible employment under those visas. Before making plans for employment in the United States, international students should consult with the International Students and Scholars Office (ISSO), located at 524 Riverside Drive, Suite 200; 212-854-3587. Its website is columbia.edu/cu/isso.

OTHER FINANCIAL AID—FEDERAL AND PRIVATE PROGRAMS

U.S. citizens and permanent residents enrolled at least half-time in a degree-granting program are eligible to apply for federal student loans. To apply for federal student loans, students should complete the Free Application for Federal Student Aid (FAFSA) using Columbia University's school code 002707 by May 5 for fall enrollment

Several private student loan programs are available to both U.S. citizens and international students. These loans require that you have a good credit standing. International students may be eligible for a private loan with a creditworthy U.S. citizen or permanent resident cosigner.

Detailed information and application instructions for student loans may be found at the Office of Financial Aid and Educational Financing website at cc-seas.financialaid.columbia.edu/content/graduate-engineering-aid.

Determination of your eligibility for financial aid is based in part on the number of courses for which you register. If you enroll in fewer courses than you initially reported on the loan request form, your loan eligibility may be reduced.

The FAFSA and the online loan request form must be completed each academic year, and you must maintain satisfactory academic progress as defined in "The Graduate Programs" section in order to remain eligible for federal student loans.

VETERAN'S BENEFITS

Various Department of Veterans Affairs programs provide educational benefits for sons, daughters, and spouses of deceased or permanently disabled veterans as well as for veterans and in-service personnel who served on active duty in the U.S. Armed Forces after January 1, 1955. In these programs the amount of benefits varies. Under most programs the student pays tuition and fees at the time of registration but receives a monthly allowance from Veterans Affairs.

Since interpretation of regulations governing veterans' benefits is subject to change, veterans and their dependents should keep in touch with the Department of Veterans Affairs. For additional information and assistance in completing the necessary forms, contact 1-800-827-1000, or consult their website (www.va.gov).

Detailed information regarding the veteran population at Columbia and policies including the Veteran's Readmission Provision may be found on the Veterans Affairs website (veteranaffairs.columbia.edu).

EMPLOYMENT

Students on fellowship support must obtain the permission of the Dean before accepting remunerative employment.

Students who study at Columbia Engineering on temporary visas should fully understand the regulations concerning possible employment under those visas. Before making plans for employment in the United States, international students should consult with the International Students and Scholars Office (ISSO) located at 524 Riverside Drive, Suite 200; 212-854-3587. Its website is columbia.edu/cu/isso.

On-Campus Employment

The Center for Career Education maintains an extensive listing of student employment opportunities. The Center for Career Education (CCE) is located at East Campus, Lower Level, 212-854-5609, careereducation.columbia.edu.

Off-Campus Employment in New York City

One of the nation's largest urban areas, the city offers a wide variety of opportunities for part-time work. Many students gain significant experience in fields related to their research and study while they meet a portion of their educational expenses.

CONTACT INFORMATION

For questions about institutional grants, fellowships, and teaching and research assistantships, contact your academic department.

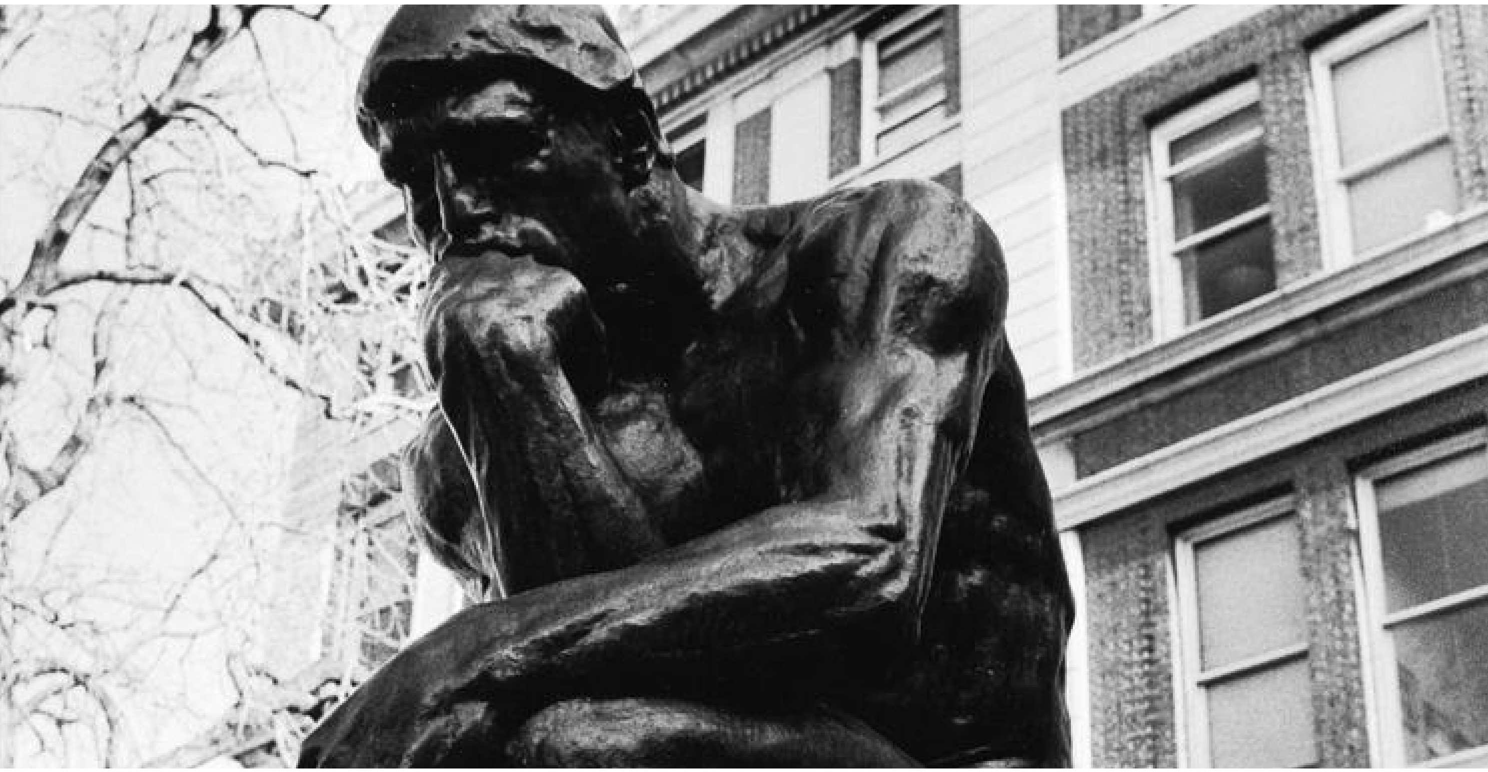
For questions about on- or off-campus non-need-based employment, contact the Center for Career Education, located at East Campus, Lower Level, 212-854-5609, careereducation.columbia.edu.

For questions about student loans, contact:

Office of Financial Aid and Educational Financing
618 Lerner Hall
Mailing: 100 Hamilton Hall
1130 Amsterdam Avenue, MC 2802
New York, NY 10027

Phone: 212-854-3711
Fax: 212-854-5353
E-mail: gradseas-finaid@columbia.edu
cc-seas.financialaid.columbia.edu/content/graduate-engineering-aid.

Faculty and Administration



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Kathleen McKeown
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Jocelyn Morales
Associate Director, Graduate Student Services

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Media Producer, Columbia Video Network

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Jane Nisselson
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Quy O
Associate Director of Technology Services

Clarissa Peña
Student Services Manager, Graduate Student Affairs

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DeShanda Porter
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Marina Zamalin
Instructional Technologist, Columbia Video Network

Departments and Academic Programs

KEY TO COURSE LISTINGS

This section contains a description of the curriculum of each department in the School, along with information regarding undergraduate and graduate degree requirements, elective courses, and suggestions about courses and programs in related fields. All courses are listed, whether or not they are being offered during the current year; if a course is not being given, that is indicated. Included as well are courses cross-listed with other departments and undergraduate divisions within the University.

DESIGNATORS

Each course is preceded by a *four-letter designator,* which indicates the department or departments presenting the course.

Course Designator	Department Subject
AHIS	Art History
AMCS	Applied Math and Computer Science
AMST	American Studies
APAM	Applied Physics and Applied Math
APBM	Applied Physics and Biomedical Engineering
APMA	Applied Mathematics
APPH	Applied Physics
ARCH	Architecture
ASCE	Asian Civilization: East Asian
ASCM	Asian Civilization: Middle East
ASTR	Astronomy
BIOC	Biology and Chemistry
BIOL	Biology
BIST	Biostatistics
BMCH	Biomedical and Chemical Engineering
BMEB	Biomedical Engineering, Electrical Engineering, and Biology
BMEE	Biomedical Engineering and Electrical Engineering
BMEN	Biomedical Engineering
BMME	Biomedical Engineering and Mechanical Engineering
BUSI	Business
CBMF	Computer Science, Biomedical Engineering and Medical Informatics
CHAP	Chemical Engineering and Applied Physics and Applied Math
CHBM	Chemical Engineering and Biomedical Engineering
CHCB	Chemistry, Biology and Computer Science
CHEE	Chemical Engineering and Earth and Environmental Engineering
CHEM	Chemistry
CHEN	Chemical Engineering
CIEE	Civil Engineering and Earth and Environmental Engineering
CIEN	Civil Engineering
COCI	Contemporary Civilization
COMS	Computer Science
CMBS	Cellular, Molecular, and Biophysical Studies
CSEE	Computer Science and Electrical Engineering
CSEN	Computer Science and English
CSOR	Computer Science and Operations Research
DNCE	Dance
DRAN	Decision, Risk, and Operations
EACE	Earth and Environmental Engineering and Chemical Engineering
EAEE	Earth and Environmental Engineering
EAIA	Earth and Environmental Engineering and International and Public Affairs
ECBM	Electrical Engineering, Computer Science and Biomedical Engineering
ECIA	Earth and Environmental and Civil Engineering and International and Public Affairs
ECIE	Economics and Industrial Engineering
ECON	Economics
EEBM	Electrical Engineering and Biomedical Engineering
EECS	Electrical Engineering and Computer Science
EEHS	Electrical Engineering and History
EEME	Electrical Engineering and Mechanical Engineering
EEOR	Electrical Engineering and Operations Research
EESC	Earth and Environmental Sciences
EHSC	Environmental Health Sciences
ELEN	Electrical Engineering
ENGI	Engineering
ENGL	English
EMME	Engineering Mechanics and Mechanical Engineering
ENME	Engineering Mechanics
FINC	Finance
FREN	French
GERM	German

GRAP	Graphics
HIST	History
HUMA	Humanities
IEME	Industrial Engineering and Mechanical Engineering
IEOR	Industrial Engineering and Operations Research
INAF	International Affairs
INTA	Earth and Environmental Engineering, Civil Engineering, and International and Public Affairs
MATH	Mathematics
MEBM	Mechanical Engineering and Biomedical Engineering
MECE	Mechanical Engineering
MECH	Mechanical Engineering and Chemical Engineering
MECS	Mechanical Engineering and Computer Science
MEEM	Mechanical Engineering and Engineering Mechanics
MEIE	Mechanical Engineering and Industrial Engineering
MSAE	Materials Science and Engineering
MSIE	Management Science and Industrial Engineering and Operations Research
MUSI	Music
PHED	Physical Education
PHIL	Philosophy
PHYS	Physics
PLAN	Planning
POLS	Political Science
PSLG	Physiology
PSYC	Psychology
RELI	Religion
SCNC	Science
SIEO	Statistics and Industrial Engineering and Operations Research
SOCI	Sociology
SPAN	Spanish
STAT	Statistics
STCS	Statistics and Computer Science
URBS	Urban Studies
VIAR	Visual Arts

HOW COURSES ARE NUMBERED

The course number that follows each designator consists of a *capital letter* followed by four digits. The capital letter indicates the University division or affiliate offering the course:

B	Business
C	Columbia College
E	Engineering and Applied Science
G	Graduate School of Arts and Sciences
P	Mailman School of Public Health
S	Summer Session
U	International and Public Affairs
V	Interschool course with Barnard
W	Interfaculty course
Z	American Language Program

The *first digit* indicates the level of the course, as follows:

0	Course that cannot be credited toward any degree
1	Undergraduate course
2	Undergraduate course, intermediate
3	Undergraduate course, advanced
4	Graduate course that is open to qualified undergraduates
6	Graduate course
8	Graduate course, advanced
9	Graduate research course or seminar

An *x* following the course number means that the course meets in the fall semester; *y* indicates the spring semester.

DIRECTORY OF CLASSES

Room assignments, days and hours, and course changes for all courses are available online at columbia.edu/cu/bulletin/uwb.

The School reserves the right to withdraw or modify the courses of instruction or to change the instructors at any time.

APPLIED PHYSICS AND APPLIED MATHEMATICS

200 S. W. Mudd, MC 4701
Phone: 212-854-4457
Applied Physics and Applied Mathematics: apam.columbia.edu/
Materials Science and Engineering: seas.columbia.edu/matsci

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208 S. W. Mudd

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Michal Lipson, Electrical Engineering
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Lorenzo M. Polvani
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Christopher H. Scholz, Earth and Environmental Sciences
Amiya K. Sen, Electrical Engineering
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C. Julian Chen
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Supratik Guha
Timothy M. Hall
David E. Keyes
Jerome Meli
Ron L. Miller
Thomas Morgan
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Shalom J. Wind

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Yigal Komem
John Marshall
Patricia Mooney

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Jacek Chowdhary
Jerry I. Dadap
Igor Geogdzhayev
Yoshitomo Okawachi

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Robert Field
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Seung Yub Lee
Jeffrey Levesque
Li Liu
Catherine Naud
Young Seouk Park
Carlos Perez Garcia-Pando
Jan Perlwitz
Denis Potapenko
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Francesca Turco
Shuguang Wang
Jingbo Wu

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Colton Conroy
Alessandro Farsi
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Edouard Grave
Chris Hansen
Michael Inkpen
Jae Kyung Jang
Kristen Jensen
Dalal Kanan
Alexander Klenner
Tae Kyung Lee
Giacomo Lovat
Mengqian Lu
William G. K. Martin
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Zhi Zhou

ASSOCIATE
John C. Arbo

SPECIAL LECTURERS
Daniel N. Beshers
C. K. Chu

SPECIAL RESEARCH SCIENTISTS
Leonard Druyan
Qiancheng Ma
Thomas C. Marshall

The Department of Applied Physics and Applied Mathematics includes undergraduate and graduate studies in the fields of applied physics, applied mathematics, and materials science and engineering. The graduate program in applied physics includes plasma physics and controlled fusion; solid-state physics; optical and laser physics; medical physics; atmospheric, oceanic, and earth physics; and applied mathematics. The graduate programs in materials science and engineering are described on pages 176–178.

Current Research Activities in Applied Physics and Applied Mathematics

Plasma physics and fusion energy. In experimental plasma physics, research is being conducted on (1) equilibrium, stability, and transport in fusion plasmas: high-beta tokamaks, spherical tokamaks, and levitated dipoles; (2) magnetospheric physics: trapped particle instabilities and stochastic particle motion; (3) confinement of toroidal nonneutral plasmas; (4) plasma source operation and heating techniques; and (5) the development of new plasma measurement techniques. The results from our fusion science experiments are used as a basis for collaboration with large national and international experiments. For example, methods of active feedback control of plasma instability developed at Columbia University are guiding research on NSTX at the Princeton Plasma Physics Laboratory, on the DIII-D tokamak at General Atomics, and for the design of the next generation burning plasma experiment, ITER. In theoretical plasma physics, research is conducted in the theory of plasma equilibrium and stability, active control of MHD instabilities, the kinetic theory of turbulence and transport, and the development of techniques based on the theory of general coordinates and dynamical systems. The work is applied to magnetic fusion, nonneutral and space plasmas.

Optical and laser physics. Active areas of research include inelastic light scattering in nanomaterials, optical diagnostics of film processing, new laser systems, nonlinear optics, ultrafast optoelectronics, photonic switching, optical physics of surfaces, laser-induced crystallization, and photon integrated circuits.

Solid-state physics. Research in solid-state physics covers nanoscience and nanoparticles, electronic transport and inelastic light scattering in low-dimensional correlated electron systems, fractional quantum Hall effect, heterostructure physics and applications, molecular beam epitaxy, grain boundaries and interfaces, nucleation in thin films, molecular electronics, nanostructure analysis, and electronic structure calculations. Research opportunities also exist within the NSF Nanoscale Science and Engineering Center, which focuses on electron transport in molecular nanostructures; and the DOE Energy Frontier Research Center, which focuses on conversion of sunlight into electricity in nanometer-sized thin films.

Applied mathematics. Current research encompasses analytical and numerical analysis of deterministic and stochastic partial differential equations, large-scale scientific computation, fluid dynamics, dynamical systems and chaos, as well as applications to various fields of physics and biology. The applications to physics include quantum and condensed-matter physics, materials science, electromagnets and optics, plasma physics, medical imaging, and the earth sciences, notably atmospheric, oceanic, and climate science, and solid earth geophysics (see below). The applications to biology include machine learning and biophysical modeling, including collaborations with Columbia's Institute for Data Sciences and Engineering (IDSE), the Department of Systems Biology, and the Department of Statistics. Extensive collaborations exist with national climate research centers (the Geophysical Fluid Dynamics Laboratory and the National Center for Atmospheric Research) and with national laboratories of the U.S. Department of Energy, custodians of the nation's most powerful supercomputers.

Atmospheric, oceanic, and earth physics. Current research focuses on the dynamics of the atmosphere and the ocean, climate modeling, cloud physics, radiation transfer, remote sensing, geophysical/geological fluid dynamics, geochemistry. The department engages in ongoing research and instruction with the NASA Goddard Institute for Space Studies and the Lamont-Doherty Earth Observatory. Six faculty members share appointments with the Department of Earth and Environmental Sciences.

In addition to the faculty and graduate students, many others participate in these projects, including full-time research faculty, faculty and students from other departments, and visiting scientists.

Laboratory and Computation Facilities in Applied Physics and Applied Mathematics

The Plasma Physics Laboratory, founded in 1961, is one of the leading university laboratories for the study of plasma physics in the United States. There are four experimental facilities. The Columbia High-Beta Tokamak (HBT-EP) supports the national program to develop controlled fusion energy. It utilizes high voltage, pulsed power systems, and laser and magnetic diagnostics to study the properties of high-beta plasmas and the use of feedback stabilization to increase the achievable beta. A collaborative program with the Princeton Plasma Physics Laboratory and the DIII-D tokamak group at General Atomics is studying the properties of high-beta plasmas in order to maximize fusion power production in these large, neutral beam-heated tokamaks and spherical tori. The plasma physics group and MIT conduct joint experiments with laboratory magnetospheres and advanced models for space weather and radiation belt dynamics. The stellarator known as Columbia Nonneutral Torus (CNT) conducts research on the magnetohydrodynamic stability, microwave heating, and microwave diagnostics of neutral stellarator plasmas. Two smaller devices investigate respectively an innovative tokamak-stellarator hybrid plasma confinement concept and the use of toroidal electron-heated plasmas as sources of ions for accelerators. The Columbia Linear Machine (CLM) is a continuously operating, linear mirror device for the study of collisionless plasma instabilities, plasma, transport, and feedback stabilization. Columbia's Collisionless Terrella Experiment investigates plasma transport in magnetospheric geometry and the generation of strong plasma flow from nonlinear electrostatic potentials.

Experimental research in solid-state physics and laser physics is conducted within the department and also in association with the Columbia Center for Integrated Science and Engineering and the School of Mines. Facilities include laser processing and spectroscopic apparatus, ultrahigh vacuum chambers for surface analysis, picosecond and femtosecond lasers, a molecular beam epitaxy machine, and a clean room that includes photo-lithography and thin film fabrication systems. Within this field, the Laser Diagnostics and Solid-State Physics Laboratory conducts studies in laser spectroscopy of nanomaterials and semiconductor thin films, and laser diagnostics of thin film processing. The Laser Lab focuses on the study of materials under high pressure, laser surface chemical processing, and new semiconductor structures. Research is also conducted in the shared characterization laboratories and clean room operated by the NSF Nanoscale Science and Engineering Center.

The department maintains an extensive network of computing clusters and desktop computers. The research of the Plasma Lab is supported by a dedicated data acquisition/data analysis system, and the applied math group has access to a Beowulf cluster. Materials Science and

APPLIED PHYSICS PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS[1]	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** ODE (3)[2]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5) Lab W3081 (2)	C1494 (3) Lab C2699 (3)
CHEMISTRY/ BIOLOGY (choose one course)	CHEM C1403 (3), **or** higher **or** BIOL W2001 (4) **or** BIOL C2005 (4), or higher			
ENGLISH COMPOSITION (three tracks, chooose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice, see list of first- and second-year technical electives			
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] With the permission of the faculty adviser, students with advanced standing may start the calculus sequence at a higher level.
[2] Applied physics majors should satisfy their ODE requirement with the Mathematics Department (ordinarily MATH V2030). Students who take APMA E2101 prior to declaring their major in applied physics may use this course to satisfy their ODE requirement with the permission of the faculty adviser.

Applied Physics built an intel-based 600 core computing cluster that is dedicated to performing first-principles computations of materials. Researchers in the department are additionally using supercomputing facilities at the National Center for Atmospheric Research; the San Diego Supercomputing Center; the National Energy Research Supercomputer Center in Berkeley, California; the National Leadership Class Facility at Oak Ridge, Tennessee; various allocations via XSEDE; and others. The Amazon Elastic Compute Cloud (EC2) is also utilized to supplement computing resources in times of high demand.

Current Research Activities and Laboratory Facilities in Materials Science and Engineering

See page 173.

UNDERGRADUATE PROGRAMS

The Department of Applied Physics and Applied Mathematics offers three undergraduate programs: applied physics, applied mathematics, and materials science. The materials science program is described on pages 173–176.

The applied physics and applied mathematics programs provide an excellent preparation for graduate study or for careers in which mathematical and technical sophistication are important. Using the large number of electives in these programs, students can tailor their programs to fit their personal and career interests. By focusing their technical electives, students can obtain a strong base of knowledge in a specialized area. In addition to formal minors, some areas of specialization that are available are described on pages 55–56. All technical electives are normally at the 3000 level or above.

UNDERGRADUATE PROGRAMS IN APPLIED PHYSICS

The applied physics program stresses the basic physics that underlies most developments in engineering and the mathematical tools that are important

APPLIED PHYSICS: THIRD AND FOURTH YEARS		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		APPH E3200 (3) Mechanics MSAE E3111 (3) Thermodynamics APMA E3101 (3) Linear algebra APPH E4901 (1) Seminar	APPH E3100 (3) Intro. to quantum mechanics APPH E3300 (3) Applied electromagnetism APMA E3102 (3) Partial differential equations	APPH E4300 (3) Applied electrodynamics APPH E4100 (3) Quantum physics Course in first AP area (3) APPH E4903 (2) Seminar	Course in second AP area (3) APPH E4018 (2) Laboratory
ELECTIVES	TECH[1]	3 points	3 points	2 points	9 points
	NONTECH OR TECH	3 points	3 points	3 points	3 points
TOTAL POINTS		16	15	16	17

[1] They must include at least 2 points of laboratory courses. If PHYS W3081 is taken as part of the first two years of the program, these technical electives need not include laboratory courses. Technical electives must be at the 3000 level or above unless prior approval is obtained.

to both physicists and engineers. Since the advances in most branches of technology lead to rapid changes in state-of-the-art techniques, the applied physics program provides the student with a broad base of fundamental science and mathematics while retaining the opportunity for specialization through technical electives.

The applied physics curriculum offers students the skills, experience, and preparation necessary for several career options, including opportunities to minor in economics and to take business-related courses. In recent years, applied physics graduates have entered graduate programs in many areas of applied physics or physics, enrolled in medical school, or been employed in various technical or financial areas immediately after receiving the B.S. degree.

Opportunities for undergraduate research exist in the many research programs in applied physics. These include fusion and space plasma physics, optical and laser physics, and condensed matter physics. Undergraduate students can receive course credit for research or an independent project with a faculty member. Opportunities also exist for undergraduate students in the applied physics program to participate in this research through part-time employment during the academic year and full-time employment during the summer, either at Columbia or as part of the NSF REU program nationwide. Practical research experience is a valuable supplement to the formal course of instruction. Applied physics students participate in an informal undergraduate seminar to study current and practical problems in applied physics, and obtain hands-on experience in at least two advanced laboratory courses.

Majors are introduced to two areas of application of applied physics (AP) by a course in each of two areas. Approved areas and courses are

DYNAMICAL SYSTEMS:
APMA E4101 or PHYS G4003

OPTICAL OR LASER PHYSICS:
APPH E4110 or E4112

NUCLEAR SCIENCE: APPH E4010

PLASMA PHYSICS: APPH E4301

PHYSICS OF FLUIDS: APPH E4200

SOLID STATE/CONDENSED MATTER PHYSICS: PHYS G4018

BIOPHYSICAL MODELING: APMA E4400

In addition to these courses, courses listed in the Specialty Areas in Applied Physics can be used to satisfy this requirement with preapproval of the applied physics adviser.

All students must take 30 points of electives in the third and fourth years, of which 17 points must be technical courses approved by the adviser. The 17 points include 2 points of an advanced laboratory in addition to *APPH E4018.* Technical electives must be at the 3000 level or above unless prior approval is obtained from the department. A number of approved technical electives are listed in the section on specialty areas. The remaining points of electives are intended primarily as an opportunity to complete the absolutely mandatory four-year, 27-point nontechnical requirement for the B.S. degree, but if this 27-point nontechnical requirement has been met already, then any type of course work can satisfy these elective points.

UNDERGRADUATE PROGRAMS IN APPLIED MATHEMATICS

The applied mathematics program is flexible and intensive. A student must take the required courses listed below,

APPLIED MATHEMATICS PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS[1]	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202(3) **and** ODE (3)[2]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5) Lab W3081 (2)	C1494 (3) Lab C2699 (3)
CHEMISTRY/ BIOLOGY (choose one course)	CHEM C1403 (3), or higher **or** BIOL W2001 (4) **or** BIOL C2005 (4), or higher			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice, see list of first- and second-year technical electives			
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	E1102 (4) either semester			

[1] With the permission of the faculty adviser, students with advanced standing may start the calculus sequence at a higher level.

[2] Applied mathematics majors should satisfy their ODE requirement with the Mathematics Department (ordinarily MATH V2030). Students who take APMA E2101 prior to declaring their major in applied mathematics may use this course to satisfy their ODE requirement with the permission of the faculty adviser.

or prove equivalent standing, and then may elect the other courses from mathematics, computer science, physics, Earth and environmental sciences, biophysics, economics, business and finance, or other application fields. Each student tailors his or her own program in close collaboration with an adviser. He or she must also register for the applied mathematics seminar during both the junior and senior years. During the junior year, the student attends the seminar lectures for 0 points; during the senior year, he or she attends the seminar lectures as well as tutorial problem sessions for 3 or 4 points.

While it is common for students in the program to go on to graduate school, many graduating seniors will find employment directly in industry, government, education, or other fields.

Of the 27 points of elective content in the third and fourth years, at least 15 points of technical courses approved by the adviser must be taken. The remaining points of electives are intended primarily as an opportunity to complete the absolutely mandatory four-year, 27-point nontechnical requirement for the B.S. degree, but if this 27-point nontechnical requirement has been met already, then any type of course work can satisfy these elective points.

Transfers into the applied mathematics program from other majors require a GPA of 3.0 or above, and the approval of the applied mathematics program chair.

UNDERGRADUATE DOUBLE MAJOR IN APPLIED PHYSICS AND APPLIED MATHEMATICS

Students satisfy all requirements for both majors, except for the seminar requirements. They are required to take both senior seminars, *APMA E4903* and *APPH E4903* (taking one in the junior year and one in the senior year, due to timing conflicts), but not the junior seminars, *APMA E4901* and *APPH E4901.* A single course may be used to fulfill a requirement in both majors. Students must maintain a GPA at or above 3.75, and must graduate with at least 143 points, 15 above the regular 128-point requirement. These extra 15 points should be technical electives appropriate for one or both majors.

APPLIED MATHEMATICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		APMA E3101 (3)[1] Linear algebra (Applied math, I) APMA E4901 (0) Seminar Course from Group A or Group B[2] APMA E4204 (3)[1] Complex variables	APMA E3102 (3)[1] Partial differential equations (Applied math, II) Course from Group A or Group B[2] APMA E4300 (3) Introduction to numerical methods (Computational math, I)	MATH W4061 (3) Modern analysis APMA E4101 (3) Introduction to dynamical systems (Applied math, III) APMA E4903 (4) Seminar	APMA E3900 (3)[3] Research Courses designated MATH, APMA, or STAT (3)
ELECTIVES	TECH[4]	3 points	3 points	3 points	6 points
	NONTECH	3 points	3 points	3 points	3 points
TOTAL POINTS		15	15	16	15

[1] MATH V2010 may be substituted for APMA E3101; MATH V3028 may be substituted for APMA E3102; MATH V3007 may be substituted for APMA E4204.
[2] One course from Group A and one course from Group B required for graduation. Group A: IEOR E3658: Probability; STAT W4105: Probability; SIEO W3600: Introduction to probability and statistics; SIEO W4150: Introduction to probability and statistics; STAT W3105: Introduction to probability; MATH W4155: Probability theory. Group B: STAT W3107: Statistical inference; STAT W4107: Statistical inference; STAT W4109: Probability and statistical inference; SIEO W 4606: Elementary stochastic processes; IEOR E3106: Introduction to stochastic models; IEOR E4106: Introduction to operations research: stochastic models; IEOR E4703: Monte Carlo simulation; COMS W4771: Machine learning.
[3] With an adviser's permission, an approved technical elective may be substituted.
[4] Any course in science or engineering at the 3000 level or above qualifies as a technical elective.

To apply, a student first obtains the approval of both the general undergraduate AP adviser and the general undergraduate AM adviser, and then the approval of the Dean.

SPECIALTY AREAS IN APAM

Both applied physics and applied mathematics students can focus their technical electives and develop a strong base of knowledge in a specialty area. There is no requirement to focus electives, so students may take as many or as few of the recommended courses in a specialty area as is appropriate to their schedules and interests. Some specialties are given below, but this is not an exclusive list and others can be worked out in coordination with the student's adviser. The courses that are often taken, or in some cases need to be taken, in the junior year are denoted with a "J."

Technical Electives

- Applications of Physics
  Courses that will give a student a broad background in applications of physics:

  ELEN E3000x: Circuits, systems, and electronics (J)
  MSAE E3103x: Elements of materials science (J)
  APPH E4010x: Intro to nuclear science
  PHYS G4018y: Solid-state physics
  APMA E4101y: Intro to dynamical systems
  APPH E4110x: Modern optics
  APPH E4112y: Laser physics
  APPH E4200x: Physics of fluids
  APPH E4301y: Intro to plasma physics

- Earth and Atmospheric Sciences
  The Earth sciences provide a wide range of problems of interest to physicists and mathematicians ranging from the dynamics of the Earth's climate to earthquake physics to dynamics of Earth's deep interior. The Lamont-Doherty Earth Observatory, which is part of Columbia University, provides enormous resources for students interested in this area.

ATMOSPHERE, OCEANS, AND CLIMATE

APPH E4008y: Intro to atmospheric science
APPH E4200x: Physics of fluids
APPH E4210y: Geophysical fluid dynamics
EESC W4925x: Principles of physical oceanography
EESC W4930y: Earth's oceans and atmosphere

SOLID EARTH GEOPHYSICS

EESC W4001x: Advanced general geology
EESC W4113x: Intro to mineralogy
APPH E4200x: Physics of fluids
EESC W4701y: Intro to igneous petrology
EESC W4941y: Principles of geophysics
EESC W4950x: Mathematical methods in the Earth sciences

(See also courses listed under Scientific Computation and Computer Science on page 56.)

- Basic Physics and Astrophysics
  Fundamental physics and astrophysics can be emphasized. Not only is astrophysics providing a deeper understanding of the universe, but it is also testing the fundamental principles of physics.

PHYS W3002y: From quarks to the cosmos: applications of modern physics
ASTR C3601x: General relativity, black holes, and cosmology (J)
ASTR C3602y: Physical cosmology (J)
ASTR G4001y: Astrophysics, I
APMA E4101x: Intro to dynamical systems

- Business and Finance

The knowledge of physics and mathematics that is gained in the applied physics and applied mathematics programs is a strong base for a career in business or finance.

ECONOMICS

ECON W3211x,y: Intermed microeconomics (J)
ECON W3213x,y: Intermed macroeconomics(J)

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

IEOR E4003x: Industrial economics
IEOR E4201x: The eng of management, I
IEOR E4202y: The eng of management, II

FINANCE

MATH W4071x: Mathematics of finance
IEOR E4106y: Intro to operations research: stochastic models (J)
SIEO W4150x,y: Probability and statistics (J)
ECIE W4280: Corporate finance
IEOR E4700x: Intro to financial engineering

- Mathematics Applicable to Physics

Applied physics students can specialize in the mathematics that is applicable to physics. This specialization is particularly useful for students interested in theoretical physics.

MATH V3386x: Differential geometry
APMA E4001y: Principles of applied mathematics
APMA E4101x: Intro to dynamical systems
APMA E4301x: Numerical methods for partial differential equations
APMA E4302x: Parallel scientific computing
PHYS G4019y: Mathematical methods of physics

- Fundamental Mathematics in Applied Mathematics

This specialization is intended for students who desire a more solid foundation in the mathematical methods and underlying theory. For example, this specialization could be followed by students with an interest in graduate work in applied mathematics.

MATH V3386x: Differential geometry
APMA E4101x: Intro to dynamical systems
APMA W4150x: Applied functional analysis
MATH W4032x: Fourier analysis
MATH W4062y: Modern analysis, II
SIEO W4150x,y: Intro to probability and statistics (J)
PHYS W4386x-W4387y: Geometrical concepts in physics

- Quantitative Biology

Traditionally biology was considered a descriptive science in contrast to the quantitative sciences that are based on mathematics, such as physics. This view no longer coincides with reality. Researchers from biology as well as from the physical sciences, applied mathematics, and computer science are rapidly building a quantitative base of biological knowledge. Students can acquire a strong base of knowledge in quantitative biology, both biophysics and computational biology, while completing the applied physics or applied mathematics programs.

PROFESSIONAL-LEVEL COURSE:
APPH E3400y: Physics of the human body

RECOMMENDED:
BIOL C2005x-C2006y: Intro biology, I and II
APMA E4400y: Intro to biophysical modeling

OTHER TECHNICAL ELECTIVES (A COURSE IN AT LEAST TWO AREAS RECOMMENDED):

BIOLOGICAL MATERIALS

BIOL W4070x: The biology and physics of single molecules
CHEN E4650x: Biopolymers

BIOMECHANICS

BMEN E3320y: Fluid biomechanics (J)
BMEN E4300y: Solid biomechanics (J)

GENOMICS AND BIOINFORMATICS

BIOL W3037y: Whole genome bioinformatics (J)
ECBM E3060x: Intro to genomic information science and technology (J)
CBMF W4761y: Computational genomics

NEUROBIOLOGY

BIOL W3004x: Neurobiology, I (J)
BIOL W3005y: Neurobiology, II (J)
ELEN G4011x: Computational neuroscience

The second term of biology will be considered a technical elective if a student has credits from at least two other of the recommended courses in quantitative biology at the 3000 level or above.

- Scientific Computation and Computer Science

Advanced computation has become a core tool in science, engineering, and mathematics and provides challenges for both physicists and mathematicians. Courses that build on both practical and theoretical aspects of computing and computation include:

MATH V3020x: Number theory and cryptography (J)
COMS W3137x,y: Data structures and algorithms (or COMS W3139y: Honors data structures and algorithms) (J)
COMS W3157x,y: Advanced programming (J)
COMS W3203x,y: Discrete mathematics: intro to combinatorics and graph theory (J)
COMS W4203y: Graph theory
APMA E4300y: Intro to numerical methods
APMA E4301x: Numerical methods for partial differential equations
AMCS E4302x: Parallel scientific computing
COMS W4701x,y: Artificial intelligence
COMS W4771y: Machine learning

- Solid-State Physics

Much of modern technology is based on solid-state physics, the study of solids and liquids. Courses that will build a strong base for a career in this area are

PHYS W3083y: Electronics laboratory (J)
MSAE E3103x: Elements of material science (J)
ELEN E3106x: Solid-state devices and materials (J)
MSAE E4100x: Crystallography
PHYS G4018y: Solid-state physics
MSAE E4206x: Electronic and magnetic properties of solids
MSAE E4207y: Lattice vibrations and crystal defects

UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE

See page 173.

GRADUATE PROGRAMS

Financial aid is available for students pursuing a doctorate. Fellowships, scholarships, teaching assistantships, and graduate research assistantships are awarded on a competitive basis. The Aptitude Test of the Graduate Record Examination is required of candidates for admission to the department and for financial aid; the Advanced Tests are recommended.

M.S. Program in Applied Physics

The program of study leading to the degree of Master of Science, while emphasizing continued work in basic physics, permits many options in several applied physics specialties. The program may be considered simply as additional education in areas beyond the bachelor's level, or as preparatory to doctoral studies in the applied physics fields of plasma physics, laser physics, or solid-state physics. Specific course requirements for the master's degree are determined in consultation with the program adviser, but must include four of the six core courses listed below.

The core courses provide a student with a solid foundation in the fundamentals of applied physics, but with the approval of the faculty adviser, other graduate-level courses with APPH designators not listed below may also count as core courses.

APPH E4100x: Quantum physics of matter
APPH E4110x: Modern optics
APPH E4112y: Laser physics
APPH E4200x: Physics of fluids
APPH E4300x: Applied electrodynamics
APPH E4301y: Introduction to plasma physics

M.S. Program in Applied Physics/ Concentration in Applied Mathematics

This 30-point program leads to an M.S. degree. Students must complete five core courses and five electives. The core courses provide a student with a foundation in the fundamentals of applied mathematics and contribute 15 points of graduate credit toward the degree. Students must complete five of the following seven courses:

APMA E4001: Principles of applied mathematics
APMA E4101: Intro to dynamical systems
APMA E4150: Applied functional analysis
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Intro to numerical methods
APMA E4301: Numerical methods for partial differential equations
APMA E6301: Analytic methods for partial differential equations
APMA E6302: Numerical analysis for partial differential equations

A student must select five elective courses from those listed below (or any of those not used to satisfy the core requirements from the list above) for a total of 15 points of graduate credit. Additional courses not listed below can be applied toward the elective requirements, subject to the approval of the faculty adviser. Computer science elective courses include:

CSOR W4231: Analysis of algorithms, I
COMS W4236: Intro to computational complexity
COMS W4241: Numerical algorithms and complexity
COMS W4252: Computational learning theory

Industrial engineering/operations research elective courses include:

IEOR E4003: Industrial economics
IEOR E4004: Intro to operations research: deterministic models
IEOR E4007: Optimization: models and methods
IEOR E4106: Intro to operations research: stochastic models
SIEO W4150: Intro to probability and statistics
IEOR E4403: Advanced engineering and corporate economics
IEOR E4407: Game theoretic models of operations
STAT W4606: Elementary stochastic processes
IEOR E4700: Intro to financial engineering

Other elective courses include:

MECE E4100: Mechanics of fluids
MSAE E4215: Mechanical behavior of structural materials
EEME E6601: Intro to control theory

M.S. Program in Materials Science and Engineering

See page 176.

M.S. Program in Medical Physics

This CAMPEP-approved 36-point program in medical physics leads to the M.S. degree. It is administered by faculty from the School of Engineering and Applied Science in collaboration with faculty from the College of Physicians and Surgeons and the Mailman School of Public Health. It provides preparation toward certification by the American Board of Radiology. The program consists of a core curriculum of medical and nuclear physics courses, anatomy, lab, seminar, a tutorial, one elective, and two practicums. Specific course requirements are *APPH E4010, E4330, E4710, E4500, E4501, E4550, E4600, E6319, E6330, E6335,* and *APBM E4650.* Approved electives include *APPH E4711, APPH E6336, APAM E6650*, and a third practicum. Up to 6 points of this 36-point program may be waived based on prior equivalent academic work. A student who enters the 36-point M.S. Program in Medical Physics having satisfactorily completed, prior to beginning the Program, a course determined by the faculty to be equivalent in content to a required course within the Program may be considered to have satisfied that content requirement, may be allowed to have that requirement waived, and may be permitted to graduate from the M.S. Program in Medical Physics with fewer than 36 points, but not fewer than the 30-point minimum required by the School of Engineering and Applied Science. Evaluation of prior course work may include review of syllabi, comparison of textbooks, consultation with instructors, and/or written or oral examination administered by Program faculty. A passing grade on a comprehensive examination is required for graduation. This examination, on subjects covered in the curriculum, is taken after two terms of study.

Certification of Professional Achievement in Medical Physics

This graduate program of instruction leads to the Certification of Professional Achievement and requires satisfactory completion of six of the following courses:

APPH E4330: Radiobiology
APPH E4500: Health physics
APPH E4600: Dosimetry
APBM E4650: Anatomy for physicists and engineers
APPH E6319: Clinical nuclear medicine physics
or APPH E6330: Diagnostic radiology physics
APPH E6335: Radiation therapy physics
or APPH E6336: Advanced topics in radiation therapy

This is a part-time nondegree program. Students are admitted to the department as certificate-track students.

PH.D. AND ENG.SC.D. PROGRAMS

After completing the M.S. program in applied physics, doctoral students specialize in one applied physics field. Some specializations have specific course requirements for the doctorate; elective courses are determined in consultation with the program adviser. Successful completion of an approved 30-point program of study is required in addition to successful completion of a written qualifying examination taken after two semesters of graduate study. An oral examination, taken within one year after the written qualifying examination, and a thesis proposal examination, taken within two years after the written qualifying examination, are required of all doctoral candidates.

Applied Mathematics

This graduate specialty, for students registered in the Department of Applied Physics and Applied Mathematics, emphasizes applied mathematics research in nonlinear dynamics, fluid mechanics, and scientific computation, with a current emphasis on geophysical, biophysical, and plasma physics applications.

Applied mathematics deals with the use of mathematical concepts and techniques in various fields of science and engineering. Historically, mathematics was first applied with great success in astronomy and mechanics. Then it developed into a main tool of physics, other physical sciences, and engineering. It is now important in the biological, geological, and social sciences. With the coming of age of the computer, applied mathematics has transcended its traditional style and now assumes an even greater importance and a new vitality.

Compared with the pure mathematician, the applied mathematician is more interested in problems coming from other fields. Compared with the engineer and the physical scientist, he or she is more concerned with the formulation of problems and the nature of solutions. Compared with the computer scientist, he or she is more concerned with the accuracy of approximations and the interpretation of results. Needless to say, even in this age of specialization, the work of mathematicians, scientists, and engineers frequently overlaps. Applied mathematics, by its very nature, has occupied a central position in this interplay and has remained a field of fascination and excitement for active minds.

Materials Science and Engineering Program

See page 177.

Plasma Physics

This graduate specialty is designed to emphasize preparation for professional careers in plasma research, controlled fusion, and space research. This includes basic training in relevant areas of applied physics, with emphasis on plasma physics and related areas leading to extensive experimental and theoretical research in the Columbia University Plasma Physics Laboratory. Specific course requirements for the plasma physics doctoral program are *APPH E4018, E4200, E4300, E6101, E6102,* and *E9142* or *E9143,* or equivalents taken at another university.

Optical and Laser Physics

This graduate specialty involves a basic training in relevant areas of applied physics with emphasis in quantum mechanics, quantum electronics, and related areas of specialization. Some active areas of research in which the student may concentrate are laser modification of surfaces, optical diagnostics of film processing, inelastic light scattering in nanomaterials, nonlinear optics, ultrafast optoelectronics photonic switching, optical physics of surfaces, and photon integrated circuits. Specific course requirements for the optical and laser physics doctoral specialization are set with the academic adviser.

Solid-State Physics

This graduate specialty encompasses the study of the electrical, optical, magnetic, thermal, high-pressure, and ultrafast dynamical properties of solids, with an aim to understanding them in terms of the atomic and electronic structure. The field emphasizes the formation, processing, and properties of thin films, low-dimensional structures—such as one- and two-dimensional electron gases, nanocrystals, surfaces of electronic and optoelectronic interest, and molecules. Facilities include a microelectronics laboratory, high-pressure diamond anvil cells, a molecular beam epitaxy machine, ultrahigh vacuum systems, lasers, equipment for the study of optical properties and transport on the nanoscale, and the instruments in the shared facilities overseen by the Center for Integrated Science and Engineering (CISE). There are also significant resources for electrical and optical experimentation at low temperatures and high magnetic fields. Specific course requirements for the solid-state physics doctoral specialization are set with the academic adviser, in consultation with the Committee on Materials Science and Engineering/Solid-State Science and Engineering.

COURSES IN APPLIED PHYSICS

APAM E1601y Introduction to computational mathematics and physics
3 pts. Lect: 3. Not offered in 2015–2016.
Introduction to computational methods in applied mathematics and physics. Students develop solutions in a small number of subject areas to acquire experience in the practical use of computers to solve mathematics and physics problems. Topics change from year to year. Examples include elementary interpolation of functions, solution of nonlinear algebraic equations, curve-fitting and hypothesis testing, wave propagation, fluid motion, gravitational and celestial mechanics, and chaotic dynamics. Basic requirement for this course is one year of college-level calculus and physics; programming experience is not required.

APPH E3100y Introduction to quantum mechanics
3 pts. Lect: 3. Professor Herman.
Prerequisites: PHYS C1403 or equivalent, and differential and integral calculus. Corequisites: APMA E3101 or equivalent. Basic concepts and assumptions of quantum mechanics, Schrodinger's equation, solutions for one-dimensional problems, including square wells, barriers, and the harmonic oscillator, introduction to the hydrogen atom, atomic physics and X-rays, electron spin.

APPH E3200x Mechanics: fundamentals and applications
3 pts. Lect: 3. Professor Cole.
Prerequisites: PHYS C1402, C1402; MATH E1210, or equivalent. Basic non-Euclidean coordinate systems, Newtonian mechanics, oscillations, Green's functions, Newtonian gravitation, Lagrangian mechanics, central force motion, two-body collisions, noninertial reference frames, rigid body dynamics. Applications, including GPS and feedback control systems, are emphasized throughout.

APPH E3300y Applied electromagnetism
3 pts. Lect: 3. Professor Venkataraman.
Corequisite: APMA E3102. Vector analysis, electrostatic fields, Laplace's equation, multipole expansions, electric fields in matter: dielectrics, magnetostatic fields, magnetic materials, and superconductors. Applications of electromagnetism to devices and research areas in applied physics.

APPH E3400y Physics of the human body
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: PHYS C1201 or C1401, and Calculus I; corequisites: PHYS C1202 or C1402, and Calculus II. This introductory course analyzes the human body from the basic principles of physics. Topics covered include the energy balance in the body, the mechanics of motion, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics, gas exchange and transport in the lungs, vision, structural properties and limits, electrical properties and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body organ, property, or function will be derived and then applied.

APPH E3900x and y Undergraduate research in applied physics
0–4 pts. Members of the faculty.
Prerequisite: Written permission from instructor and approval from adviser. This course may be repeated for credit, but no more than 6 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in applied physics or carry out a special project under the supervision of the staff. Credit for course is contingent upon the submission of an acceptable thesis or final report.

APPH 84008x Introduction to atmospheric science
3 pts. Lect: 3. Professor Polvani.
Prerequisites: Advanced calculus and general physics, or instructor's permission. Basic physical processes controlling atmospheric structure: thermodynamics; radiation physics and radiative transfer; principles of atmospheric dynamics; cloud processes; applications to Earth's atmospheric general circulation, climatic variations, and the atmospheres of the other planets.

APPH E4010x Introduction to nuclear science
3 pts. Lect: 3. Professor Ostrow.
Prerequisites: MATH V1202 and E1210 and PHYS C1403 or equivalents. Introductory course for individuals with an interest in medical physics and other branches of radiation science. Topics include basic concepts, nuclear models, semiempirical mass formula, interaction of radiation with matter, nuclear detectors, nuclear structure and instability, radioactive decay process and radiation, particle accelerators, and fission and fusion processes and technologies.

APPH E4018y Applied physics laboratory
2 pts. Lab: 4. Professor Volpe.
Prerequisite: ELEN E3401 or equivalent. Typical experiments are in the areas of plasma physics, microwaves, laser applications, optical spectroscopy physics, and superconductivity.

APPH E4090y Nanotechnology
3 pts. Lect: 3. Professor Wind.
Prerequisites: APPH E3100 and MSAE E3103 or their equivalents with instructor's permission. The science and engineering of creating materials, functional structures and devices on the nanometer scale. Carbon nanotubes, nanocrystals, quantum dots, size dependent properties, self-assembly, nanostructured materials. Devices and applications, nanofabrication. Molecular engineering, bionanotechnology. Imaging and manipulating at the atomic scale. Nanotechnology in society and industry.

APPH E4100x Quantum physics of matter
3 pts. Lect: 3. Professor Venkataraman.
Prerequisite: APPH E3100. Corequisite: APMA E3102 or equivalent. Basic theory of quantum mechanics, well and barrier problems, the harmonic oscillator, angular momentum identical particles, quantum statistics, perturbation theory and applications to the quantum physics of atoms, molecules, and solids.

APPH E4110y Modern optics
3 pts. Lect: 3. Professor Yu.
Prerequisite: APPH E3300. Ray optics, matrix formulation, wave effects, interference, Gaussian beams, Fourier optics, diffraction, image formation, electromagnetic theory of light, polarization and crystal optics, coherence, guided wave and fiber optics, optical elements, photons, selected topics in nonlinear optics.

APPH E4112y Laser physics
3 pts. Lect: 3. Professor Yu.
Recommended but not required: APPH E3100 and E3300 or their equivalents. Optical resonators, interaction of radiation and atomic systems, theory of laser oscillation, specific laser systems, rate processes, modulation, detection, harmonic generation, and applications.

CHAP E4120y Statistical mechanics
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisite: CHEN E3210 or equivalent thermodynamics course, or instructor's permission. Fundamental principles and underlying assumptions of statistical mechanics. Boltzmann's entropy hypothesis and its restatement in terms of Helmholtz and Gibbs free energies and for open systems. Correlation times and lengths. Exploration of phase space and observation time scale. Correlation functions. Fermi-Dirac and Bose-Einstein statistics. Fluctuation-response theory. Applications to ideal gases, interfaces, liquid crystals, microemulsions and other complex fluids, polymers, Coulomb gas, interactions between charged polymers and charged interfaces, ordering transitions.

APPH E4130x Physics of solar energy
3 pts. Lect: 3. Not offered in 2015–2016
Prerequisites: General physics (PHYS C1403 or C1602) and mathematics, including ordinary differential equations and complex numbers (such as MATH V1202 or E1210) or instructor's permission. The physics of solar energy including solar radiation, the analemma, atmospheric efforts, thermodynamics of solar energy, physics of solar cells, energy storage and transmission, and physics and economics in the solar era.

APPH E4200x Physics of fluids
3 pts. Lect: 3. Professor Volpe.
Prerequisites: APMA E3102 or equivalent; PHYS C1401 or C1601 or equivalent. An introduction to the physical behavior of fluids for science and engineering students. Derivation of basic equations of fluid dynamics: conservation of mass, momentum, and energy. Dimensional analysis. Vorticity. Laminar boundary layers. Potential flow. Effects of compressibility, stratification, and rotation. Waves on a free surface; shallow water equations. Turbulence.

APPH E4210y Geophysical fluid dynamics
3 pts. Lect: 3. Professor Sobel.
Prerequisites: APMA E3101, E3102 (or equivalents) and APPH E4200 (or equivalent), or permission from instructor. Fundamental concepts in the dynamics of rotating, stratified flows. Geostrophic and hydrostatic balances, potential vorticity, f and beta plane approximations, gravity and Rossby waves, geostrophic adjustment and quasigeostrophy, baroclinic and barotropic instabilities, Sverdrup balance, boundary currents, Ekman layers.

APPH E4300x Applied electrodynamics
3 pts. Lect: 3. Professor Navratil.
Prerequisite: APPH E3300. Overview of properties and interactions of static electric and magnetic fields. Study of phenomena of time dependent electric and magnetic fields including induction, waves, and radiation as well as special relativity. Applications are emphasized.

APPH E4301y Introduction to plasma physics
3 pts. Lect: 3. Professor Navratil.
Prerequisite: PHYS W3008 or APPH E3300. Definition of a plasma. Plasmas in laboratories and nature, plasma production. Motion of charged particles in electric and magnetic fields, adiabatic invariants. Heuristic treatment of collisions, diffusion, transport, and resistivity. Plasma as a conducting fluid. Electrostatic and magnetostatic equilibria of plasmas. Waves in cold plasmas. Demonstration of laboratory plasma behavior, measurement of plasma properties. Illustrative problems in fusion, space, and nonneutral or beam plasmas.

APPH E4330y Radiobiology for medical physicists
3 pts. Lect: 3. Professor Zaider.
Prerequisite: APPH E4010 or equivalent or Corequisite: APPH E4010. Interface between clinical practice and quantitative radiation biology. Microdosimetry, dose-rate effects and biological effectiveness thereof; radiation biology data, radiation action at the cellular and tissue level; radiation effects on human populations, carcinogenesis, genetic effects; radiation protection; tumor control, normal-tissue complication probabilities; treatment plan optimization.

APPH E4500x Health physics
3 pts. Lect: 3. Professor Morgan.
Prerequisite: APPH E4600 or Corequisite: APPH E4600. Fundamental principles and objectives of health physics (radiation protection), quantities of radiation dosimetry (the absorbed dose, equivalent dose, and effective dose) used to evaluate human radiation risks, elementary shielding calculations and protection measures for clinical environments, characterization and proper use of health physics instrumentation, and regulatory and administrative requirements of health physics programs in general and as applied to clinical activities.

APPH E4501y Medical health physics tutorial
0 pts. Professor Morgan.
Prerequisite: Permission of the course coordinator. Required for, and limited to, M.S. degree candidates in the Medical Physics Program. Course addresses procedures for personnel and area monitoring, radiation and contamination surveys, instrument calibration, radioactive waste disposal, radiation safety compliance, licensure requirements, and other matters contributing to professional competence in the field of medical health physics. Course includes lectures, seminars, tours, and hands-on experience. This two-week tutorial is offered immediately following spring semester final examinations and is taken for Pass/Fail only.

APPH E4550y Medical physics seminar
0 pts. Lect: 1. Professor Arbo.
Required for all graduate students in the Medical Physics Program. Practicing professionals and faculty in the field present selected topics in medical physics.

APPH E4600x Fundamentals of radiological physics and radiation dosimetry
3 pts. Lect: 3. Professor Meli.
Prerequisite: APPH E4010 or equivalent or Corequisite: APPH E4010. Basic radiation physics: radioactive decay, radiation producing devices, characteristics of the different types of radiation (photons, charged and uncharged particles) and mechanisms of their interactions with materials. Essentials of the determination, by measurement and calculation, of absorbed doses from ionizing radiation sources used in medical physics (clinical) situations and for health physics purposes.

APBM E4650x Anatomy for physicists and engineers
3 pts. Lect: 3. Professor Rozenshtein.
Prerequisite: Engineering or physics background. Systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women's issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, U/S, etc.).

APPH E4710x Radiation instrumentation and measurement laboratory, I
3 pts. Lect: 1. Lab: 4. Professor Arbo.
Prerequisite or corequisite: APPH E4010. Lab fee: $50. Theory and use of alpha, beta, gamma, and X-ray detectors and associated electronics for counting, energy spectroscopy, and dosimetry; radiation safety; counting statistics and error propagation; mechanisms of radiation emission and interaction. (Topic coverage may be revised.)

APPH E4711x or y Radiation instrumentation and measurement laboratory, II
3 pts. Lect: 1. Lab: 4. Professor Arbo.
Prerequisite: APPH E4710. Lab fee: $50. Additional detector types; applications and systems including coincidence, low-level, and liquid scintillation counting; neutron activation; TLD dosimetry, gamma camera imaging. (Topic coverage may be revised.)

APPH E4901x Seminar: problems in applied physics
1 pt. Lect: 1. Professor Mauel.
This course is required for, and can be taken only by, all applied physics majors and minors in the junior year. Discussion of specific and self-contained problems in areas such as applied electrodynamics, physics of solids, and plasma physics. Topics change yearly.

APPH E4903x Seminar: problems in applied physics
2 pts. Lect: 1. Tutorial: 1. Professor Mauel.
This course is required for, and can be taken only by, all applied physics majors in the senior year. Discussion of specific and self-contained problems in areas such as applied electrodynamics, physics of solids, and plasma physics. Formal presentation of a term paper required. Topics change yearly.

APPH E4990x and y Special topics in applied physics
1–3 pts. Not offered in 2015–2016.
Prerequisite: Instructor's permission. This course may be repeated for credit. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

APAM E4999x and y–S4999 Supervised internship
1–3 pts. Members of the faculty.
Prerequisite: Obtained internship and approval from adviser. Only for master's students in the Department of Applied Physics and Applied Mathematics who may need relevant work experience as part of their program of study. Final report required. This course may not be taken for pass/fail or audited.

APPH 86081x Solid state physics, I
3 pts. Lect: 3. Professor Pinczuk.
Prerequisites: APPH E3100 or the equivalent. Knowledge of statistical physics on the level of MSAE E3111 or PHYS G4023 strongly recommended. Crystal structure, reciprocal lattices, classification of solids, lattice dynamics, anharmonic effects in crystals, classical electron models of metals, electron band structure, and low-dimensional electron structures.

APPH E6082y Solid state physics, II
3 pts. Lect: 3. Professor Altshuler.
Prerequisite: APPH E6081 or instructor's permission. Semiclassical and quantum mechanical electron dynamics and conduction, dielectric properties of insulators, semiconductors, defects, magnetism, superconductivity, low-dimensional structures, and soft matter.

APPH E6085x Computing the electronic structure of complex materials
3 pts. Lect: 3. Professor Marianetti.
Prerequisite: APPH E3100 or equivalent. Basics of density functional theory (DFT) and its application to complex materials. Computation of electronics and mechanical properties of materials. Group theory, numerical methods, basis sets, computing, and running open source DFT codes. Problem sets and a small project.

APPH E6091y Magnetism and magnetic materials
3 pts. Lect. 3. Not offered in 2015–2016.
Prerequisites: MSAE E4206, APPH E6081, or equivalent. Types of magnetism. Band theory of ferromagnetism. Magnetic metals, insulators, and semiconductors. Magnetic nanostructures: ultrathin films, superlattices, and particles. Surface magnetism and spectroscopies. High speed magnetization dynamics. Spin electronics.

APPH E6101x Plasma physics, I
3 pts. Lect: 3. Professor Mauel.
Prerequisite: APPH E4300. Debye screening. Motion of charged particles in space- and time-varying electromagnetic fields. Two-fluid description of plasmas. Linear electrostatic and electromagnetic waves in unmagnetized and magnetized plasmas. The magnetohydrodynamic (MHD) model, including MHD equilibrium, stability, and MHD waves in simple geometries.

APPH E6102y Plasma physics, II
3 pts. Lect: 3. Professor Cole.
Prerequisite: APPH E6101. Magnetic coordinates. Equilibrium, stability, and transport of torodial plasmas. Ballooning and tearing instabilities. Kinetic theory, including Vlasov equation, Fokker-Planck equation, Landau damping, kinetic transport theory. Drift instabilities.

APPH E6110x Laser interactions with matter
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: APPH E4112 or equivalent, and quantum mechanics. Principles and applications of laser-matter coupling, nonlinear optics, three- and four-wave mixing, harmonic generation, laser processing of surfaces, laser probing of materials, spontaneous and stimulated light scattering, saturation spectroscopy, multiphoton excitation, laser isotope separation, transient optical effects.

APPH E6319y Clinical nuclear medicine physics
3 pts. Lect: 3. Professor Esser.
Prerequisite: APPH E4010 or equivalent recommended. Introduction to the instrumentation and physics used in clinical nuclear medicine and PET with an emphasis on detector systems, tomography and quality control. Problem sets, papers, and term project.

APPH E6330y Diagnostic radiology physics
3 pts. Lect: 3. Professor Jambalwalikar.
Prerequisite: APPH E4600. Physics of medical imaging. Imaging techniques: radiography, fluoroscopy, computed tomography, mammography, ultrasound, magnetic resonance. Includes conceptual, mathematical/theoretical, and practical clinical physics aspects.

APPH E6333x or y Radiation therapy physics practicum
3 pts. Lab: 6. Professor Wuu.
Prerequisites: Grade of B+ or better in APPH E6335 and instructor's permission. Students spend two to four days per week studying the clinical aspects of radiation therapy physics. Projects on the application of medical physics in cancer therapy within a hospital environment are assigned; each entails one or two weeks of work and requires a laboratory report. Two areas are emphasized: 1. computer-assisted treatment planning (design of typical treatment plans for various treatment sites including prostate, breast, head and neck, lung, brain, esophagus, and cervix) and 2. clinical dosimetry and calibrations (radiation measurements for both photon and electron beams, as well as daily, monthly, and part of annual QA).

APPH E6335y Radiation therapy physics
3 pts. Lect: 3. Professor Wuu.
Prerequisites: APPH E4600; APPH E4330 recommended. Review of X-ray production and fundamentals of nuclear physics and radioactivity. Detailed analysis of radiation absorption and interactions in biological materials as specifically

related to radiation therapy and radiation therapy dosimetry. Surveys of use of teletherapy isotopes and X-ray generators in radiation therapy plus the clinical use of interstitial and intracavitary isotopes. Principles of radiation therapy treatment planning and isodose calculations. Problem sets taken from actual clinical examples are assigned.

APPH E6336x Advanced topics in radiation therapy
3 pts. Lect: 3. Professors Amols and Wuu.
Prerequisite: APPH E6335. Advanced technology applications in radiation therapy physics, including intensity modulated, image guided, stereotactic, and hypofractionated radiation therapy. Emphasis on advanced technological, engineering, clinical and quality assurance issues associated with high-technology radiation therapy and the special role of the medical physicist in the safe clinical application of these tools.

APPH E6340x or y Diagnostic radiology practicum
3 pts. Lab: 6. Members of the faculty.
Prerequisites: Grade of B+ or better in APPH E6330 and instructor's permission. Practical applications of diagnostic radiology for various measurements and equipment assessments. Instruction and supervised practice in radiation safety procedures, image quality assessments, regulatory compliance, radiation dose evaluations and calibration of equipment. Students participate in clinical QC of the following imaging equipment: radiologic units (mobile and fixed), fluoroscopy units (mobile and fixed), angiography units, mammography units, CT scanners, MRI units and ultrasound units. The objective is familiarization in routine operation of test instrumentation and QC measurements utilized in diagnostic medical physics. Students are required to submit QC forms with data on three different types of radiology imaging equipment.

APPH E6365x or y Nuclear medicine practicum
3 pts. Lab: 6. Members of the faculty.
Prerequisites: Grade of B+ or better in APPH E6319 and instructor's permission. Practical applications of nuclear medicine theory and application for processing and analysis of clinical images and radiation safety and quality assurance programs. Topics may include tomography, instrumentation, and functional imaging. Reports.

APPH E6380x or y Health physics practicum
3 pts. Lab: 6. Members of the faculty.
Prerequisites: Grade of B+ or better in APPH E4500 and instructor's permission or Corequisite: APPH E4500 and permission of the instructor. Radiation protection practices and procedures for clinical and biomedical research environments. Includes design, radiation safety surveys of diagnostic and therapeutic machine source facilities, the design and radiation protection protocols for facilities using unsealed sources of radioactivity—nuclear medicine suites and sealed sources—brachytherapy suites. Also includes radiation protection procedures for biomedical research facilities and the administration of programs for compliance to professional health physics standards and federal and state regulatory requirements for the possession and use of radioactive materials and machine sources of ionizing and nonionizing radiations in clinical situations. Individual topics are decided by the student and the collaborating Clinical Radiation Safety Officer.

APAM E6650x and y–S6650 Research project
1–6 pts. Members of the faculty.
Prerequisite: Written permission from instructor and approval from adviser. This course may be repeated for credit. A special investigation of a problem in nuclear engineering, medical physics, applied mathematics, applied physics, and/or plasma physics consisting of independent work on the part of the student and embodied in a formal report.

APPH E9142x-E9143y Applied physics seminar
3 pts. Sem: 3. Instructor to be announced.
These courses may be repeated for credit. Selected topics in applied physics. Topics and instructors change from year to year.

APAM E9301x and y–S9301 Doctoral research
0–15 pts. Members of the faculty.
Prerequisite: Qualifying examination for the doctorate. Required of doctoral candidates.

APAM E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree must register for 12 points of doctoral research instruction. Registration for APAM E9800 may not be used to satisfy the minimum residence requirement for the degree.

APAM E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the course work has been completed, and until the dissertation has been accepted.

COURSES IN APPLIED MATHEMATICS

APMA E2101y Introduction to applied mathematics
3 pts. Lect: 3. Professor Tippett.
Prerequisite: Calculus III. A unified, single-semester introduction to differential equations and linear algebra with emphases on (1) elementary analytical and numerical technique and (2) discovering the analogs on the continuous and discrete sides of the mathematics of linear operators: superposition, diagonalization, fundamental solutions. Concepts are illustrated with applications using the language of engineering, the natural sciences, and the social sciences. Students execute scripts in Mathematica and MATLAB (or the like) to illustrate and visualize course concepts (programming not required).

APMA E3101x Linear algebra
3 pts. Lect: 3. Professor Tippett.
Matrix algebra, elementary matrices, inverses, rank, determinants. Computational aspects of solving systems of linear equations: existence-uniqueness of solutions, Gaussian elimination, scaling, ill-conditioned systems, iterative techniques. Vector spaces, bases, dimension. Eigenvalue problems, diagonalization, inner products, unitary matrices.

APMA E3102y Partial differential equations
3 pts. Lect: 3. Professor Mandli.
Prerequisite: MATH E1210 or equivalent. Introduction to partial differential equations; integral theorems of vector calculus. Partial differential equations of engineering in rectangular, cylindrical, and spherical coordinates. Separation of the variables. Characteristic-value problems. Bessel functions, Legendre polynomials, other orthogonal functions; their use in boundary value problems. Illustrative examples from the fields of electromagnetic theory, vibrations, heat flow, and fluid mechanics.

APAM E3105x Programming methods for scientists and engineers
3 pts. Lect: 2.5. Lab: 1. Not offered in 2015–2016.
Introduction to modern techniques of computer programming for the numerical solutions to familiarity with basic and advanced concepts of modern numerical programming and acquire practical experience solving representative problems in math and physics.

APMA E3900x and y Undergraduate research in applied mathematics
0–4 pts. Members of the faculty.
Prerequisite: Written permission from instructor and approval from adviser. This course may be repeated for credit, but no more than 6 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in applied mathematics or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report.

APMA E4001y Principles of applied mathematics
3 pts. Lect: 3. Professor Du.
Prerequisites: Introductory Linear Algebra required. Ordinary Differential Equations recommended. Review of finite-dimensional vector spaces and elementary matrix theory. Linear transformations, change of basis, eigenspaces. Matrix representation of linear operators and diagonalization. Applications to difference equations, Markov processes, ordinary differential equations, and stability of nonlinear dynamical systems. Inner product spaces, projection operators, orthogonal bases, Gram-Schmidt orthogonalization. Least squares method, pseudo-inverses, singular value decomposition. Adjoint operators, Hermitian and unitary operators, Fredholm Alternative Theorem. Fourier series and eigenfunction expansions. Introduction to the theory of distributions and the Fourier Integral Transform. Green's functions. Application to Partial Differential Equations.

APMA E4101x Introduction to dynamical systems
3 pts. Lect: 3. Professor Weinstein.
Prerequisites: APMA E2101 (or MATH V1210) and APMA E3101 or their equivalents, or instructor's permission. An introduction to the analytic and geometric theory of dynamical systems; basic existence, uniqueness and parameter dependence of solutions to ordinary differential equations; constant coefficient and parametrically forced systems; Fundamental solutions; resonance; limit points, limit cycles and classification of flows in the plane (Poincare-Bendixson Theorem); conservative and dissipative systems; linear and nonlinear stability analysis of equilibria and periodic solutions; stable and unstable manifolds; bifurcations, e.g., Andronov-Hopf; sensitive dependence and chaotic dynamics; selected applications.

APMA E4150x Applied functional analysis
3 pts. Lect: 3. Professor Bal.
Prerequisites: Advanced calculus and course in basic analysis, or instructor's permission. Introduction to modern tools in functional analysis that are used in the analysis of deterministic and stochastic partial differential equations and in the analysis of numerical methods: metric and normed spaces, Banach space of continuous functions, measurable spaces, the contraction mapping theorem, Banach and Hilbert spaces bounded linear operators on Hilbert spaces and their spectral decomposition, and time permitting distributions and Fourier transforms.

APMA E4200x Partial differential equations
3 pts. Lect: 3. Professor Quenneville-Bélair.
Prerequisite: Course in ordinary differential equations. Techniques of solution of partial differential equations. Separation of the variables. Orthogonality and characteristic functions, nonhomogeneous boundary value problems. Solutions in orthogonal curvilinear coordinate systems. Applications of Fourier integrals, Fourier and Laplace transforms. Problems from the fields of vibrations, heat conduction, electricity, fluid dynamics, and wave propagation are considered.

APMA E4204x Functions of a complex variable
3 pts. Lect. 3. Professor Bal.
Prerequisite: MATH V1202 or equivalent. Complex numbers, functions of a complex variable, differentiation and integration in the complex plane. Analytic functions, Cauchy integral theorem and formula, Taylor and Laurent series, poles and residues, branch points, evaluation of contour integrals. Conformal mapping. Schwarz-Christoffel transformation. Applications to physical problems.

APMA E4300x Introduction to numerical methods
3 pts. Lect: 3. Professor Mandli.
Prerequisites: MATH V1201, E1210, and APMA E3101 and ENGI E1006 or their equivalents. Programming experience in Python extremely useful. Introduction to fundamental algorithms and analysis of numerical methods commonly used by scientists, mathematicians, and engineers. Designed to give a fundamental understanding of the building blocks of scientific computing that will be used in more advanced courses in scientific computing and numerical methods for PDEs (e.g., APMA4301, APMA4302). Topics include numerical solutions of algebraic systems, linear least-squares, eigenvalue problems, solution of nonlinear systems, optimization, interpolation, numerical integration and differentiation, initial value problems, and boundary value problems for systems of ODE's. All programming exercises will be in Python.

APMA E4301y Numerical methods for partial differential equations
3 pts. Lect: 3. Professor Mandli.
Prerequisites: APMA E4300 and APMA E3102 or APMA A4200 or equivalents. Numerical solution of differential equations, in particular partial differential equations arising in various fields of application. Presentation emphasizes finite difference approaches to present theory on stability, accuracy, and convergence with minimal coverage of alternate approaches (left for other courses). Method coverage includes explicit and implicit time-stepping methods, direct and iterative solvers for boundary-value problems.

APMA E4302x Methods in computational science
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: APMA E4300, application and knowledge in C, Fortran or similar compiled language. Introduction to the key concepts and issues in computational science aimed at getting students to a basic level of understanding where they can run simulations on machines aimed at a range of applications and sizes from a single workstation to modern super-computer hardware. Topics include but are not limited to basic knowledge of unix shells, version control systems, reproducibility, OpenMP, MPI, and many-core technologies. Applications will be used throughout to demonstrate the various use cases and pitfalls of using the latest computing hardware.

APMA E4400y Introduction to biophysical modeling
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: PHYS W1401 or equivalent, and APMA E2101 or MATH E1210 or equivalent. Introduction to physical and mathematical models of cellular and molecular biology. Physics at the cellular scale (viscosity, heat, diffusion, statistical mechanics). RNA transcription and regulation of genetic expression. Genetic and biochemical networks. Bioinformatics as applied to reverse-engineering of naturally-occurring networks and to forward-engineering of synthetic biological networks. Mathematical and physical aspects of functional genomics.

APMA E4901x Seminar: problems in applied mathematics
0 pts. Lect: 1. Professor Wiggins.
This course is required for, and can be taken only by, all applied mathematics majors in the junior year. Prerequisites or corequisites: APMA E4200 and E4204 or their equivalents. Introductory seminars on problems and techniques in applied mathematics. Typical topics are nonlinear dynamics, scientific computation, economics, operations research, etc.

APMA E4903x Seminar: problems in applied mathematics
3–4 pts. Lect: 1. Tutorial: 2. Professor Wiggins.
This course is required for all applied mathematics majors in the senior year. Prerequisites or corequisites: APMA E4200 and E4204 or their equivalents. For 4 pts. credit, term paper required. Examples of problem areas are nonlinear dynamics, asymptotics, approximation theory, numerical methods, etc. Approximately three problem areas are studied per term.

APMA E4990x and y Special topics in applied mathematics
1–3 pts. Lect: 3. Instructor to be announced.
Prerequisites: Advanced calculus and junior year applied mathematics, or their equivalents. This course may be repeated for credit. Topics and instructors from the Applied Mathematics Committee and the staff change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, biological sciences, and other fields.

APMA E6209x Approximation theory
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisite: MATH W4061 or some knowledge of modern analysis. Theory and application of approximate methods of analysis from the viewpoint of functional analysis. Approximate numerical and analytical treatment of linear and nonlinear algebraic, differential, and integral equations. Topics include function spaces, operators in normed and metric spaces, fixed point theorems and their applications.

APMA E6301y Analytic methods for partial differential equations
3 pts. Lect: 2. Professor Weinstein.
Prerequisites: Advanced calculus, basic concepts in analysis, APMA E3101, and E4200 or their equivalents, or instructor's permission. Introduction to analytic theory of PDEs of fundamental and applied science; wave (hyperbolic), Laplace and Poisson equations (elliptic), heat (parabolic) and Schroedinger (dispersive) equations; fundamental solutions, Green's functions, weak/distribution solutions, maximum principle, energy estimates, variational methods, method of characteristics; elementary functional analysis and applications to PDEs; introduction to nonlinear PDEs, shocks; selected applications.

APMA E6302x Numerical analysis of partial differential equations
3 pts. Lect: 2. Professor Du.
Prerequisite: APMA E3102 or E4200. Numerical analysis of initial and boundary value problems for partial differential equations. Convergence and stability of the finite difference method, the spectral method, the finite element method and applications to elliptic, parabolic, and hyperbolic equations.

APMA E6304y Integral transforms
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisites: APMA E4204 and MATH E1210, or their equivalents. Laplace, Fourier, Hankel, and Mellin transforms. Selection of suitable transform for a given partial differential equation boundary value problem. Operational properties of transforms. Inversion theorems. Approximate evaluation of inversion integrals for small and large values of parameter. Application to the solution of integral equations.

APMA E6901x and y–E6901y Special topics in applied mathematics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Advanced calculus and junior year applied mathematics, or their equivalents. This course may be repeated for credit. Topics and instructors from the Applied Mathematics Committee and the staff change from year to year. For students in engineering, physical sciences, biological sciences, and other fields.

APMA E8308y Asymptotic methods in applied mathematics
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisite: APMA E4204 or equivalent. Asymptotic treatment of ordinary and partial differential equations in problems arising in applied mathematics. Asymptotic series. Asymptotic evaluation of integrals. Expansion of solutions of ordinary differential equations: connection problem and turning points. Stoke's phenomenon. Differential equations with a parameter: “boundary layer” phenomenon. Application to partial differential equations: problems from fluid dynamics, wave propagation theory, electromagnetic theory.

APMA E9101x-E9102y Research
1–4 pts. Members of the faculty.
Prerequisite: Permission of the supervising faculty member. This course may be repeated. Advanced study in a special area.

APMA E9810x or y SEAS colloquium in climate science
0 pts. Lect: 1. Professors Polvani and Sobel.
Prerequisite: Instructor's permission. Current research in problems at the interface between applied mathematics and earth and environmental sciences.

APMA E9815x or y Geophysical fluid dynamics seminar
1–3 pts. May be repeated for up to 10 points of credit. Not offered in 2015–2016.
Prerequisite: Instructor's permission. Problems in the dynamics of geophysical fluid flows.

COURSES IN MATERIALS SCIENCE AND ENGINEERING

See page 178.

BIOMEDICAL ENGINEERING

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Helen H. Lu
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Van C. Mow, Stanley Dicker Professor
Paul Sajda
Gordana Vunjak-Novakovic, The Mikati Foundation Professor of Biomedical Engineering

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LECTURER
Katherine Reuther

JOINT FACULTY
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Elizabeth S. Olson, Associate Professor of Otolaryngology/Head and Neck Surgery
Michael P. Sheetz, William R. Kenan Jr. Professor of Cell Biology
Kenneth L. Shepard, Lau Family Professor of Electrical Engineering
Milan N. Stojanovic, Associate Professor of Medical Science

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Kung-Ming Jan, Associate Professor of Clinical Medicine
Lawrence Schwartz, James Picker Professor of Radiology
Scott A. Small, Bob and Rose Katz Professor of Neurology (in the Taub Institute, Sergievsky Center and in Radiology)
Henry M. Spotnitz, Professor of Surgery
Binsheng Zhao, Associate Professor of Clinical Radiology (Physics)

Biomedical engineering is an evolving discipline in engineering that draws on collaboration among engineers, physicians, and scientists to provide interdisciplinary insight into medical and biological problems. The field has developed its own knowledge base and principles that are the foundation for the academic programs designed by the Department of Biomedical Engineering at Columbia.

The programs in biomedical engineering at Columbia (B.S., M.S., Ph.D., Eng.Sc.D., and M.D./Ph.D.) prepare students to apply engineering and applied science to problems in biology, medicine, and the understanding of living systems and their behavior, and to develop biomedical systems and devices. Modern engineering encompasses sophisticated approaches to measurement, data acquisition and analysis, simulation, and systems identification. These approaches are useful in the study of individual cells, organs, entire organisms, and populations of organisms. The increasing value of mathematical models in the analysis of living systems is an important sign of the success of contemporary activity. The programs offered in the Department of Biomedical Engineering seek to emphasize the confluence of basic engineering science and applied engineering with the physical and biological sciences, particularly in the areas of biomechanics, cell and tissue engineering, and biosignals and biomedical imaging.

Programs in biomedical engineering are taught by its own faculty, members of other Engineering departments, and faculty from other University divisions who have strong interests and involvement in biomedical engineering. Several of the faculty hold joint appointments in Biomedical Engineering and other University departments.

Courses offered by the Department of Biomedical Engineering are complemented by courses offered by other departments in The Fu Foundation School of Engineering and Applied Science and by many departments in the Faculty of Medicine, the College of Dental Medicine, and the Mailman School of Public Health, as well as the science departments within the Graduate School of Arts and Sciences. The availability of these courses in a university that contains a large medical center and enjoys a basic commitment to interdisciplinary research is important to the quality and strength of the program.

Educational programs at all levels are based on engineering and biological fundamentals. From this basis, the program branches into concentrations along three tracks: biomechanics, cell and tissue engineering, and biosignals and biomedical imaging. The intrinsic breadth of these tracks, and a substantial elective content, prepare bachelor's and master's students to commence professional activity in any area of biomedical engineering or to go on to graduate school for further studies in related fields. The program also provides excellent preparation for the health sciences and the study of medicine. Graduates of the doctoral program are prepared for research activities at the highest level.

Areas of particular interest to Columbia faculty include biomechanics (Professors Ateshian, Guo, Hess, Jacobs, Morrison, and Mow), cellular and tissue engineering and artificial organs (Professors Danino, Hung, Kam, Leonard, Leong, Lu, Morrison, Sia, and Vunjak-Novakovic), auditory biophysics (Professor Olson), and biosignals and biomedical imaging (Professors Guo, Hielscher, Hillman, Jacobs, Konofagou, Laine, Sajda, and Wang).

Facilities

The Department of Biomedical Engineering has been supported by grants obtained from NIH, NSF, DoT, DoD, New York State, numerous research foundations, and University funding. The extensive new facilities that have recently been added both at the Medical Center and Morningside campus include new teaching and research laboratories that provide students with unusual access to contemporary research equipment specially selected for its relevance to biomedical engineering. An undergraduate wet laboratory devoted to biomechanics and cell and tissue engineering has been added, together with a biosignals and biomedical imaging and data processing laboratory. Each laboratory incorporates equipment normally reserved for advanced research and provides exceptional access to current practices in biomedical engineering and related sciences.

Research facilities of the Biomedical Engineering faculty include the Liu Ping Laboratory for Functional Tissue Engineering (Professor Mow), the Heffner Biomedical Imaging Laboratory (Professor Laine), the Laboratory for Intelligent Imaging and Neural Computing (Professor Sajda), the Biophotonics and Optical Radiology Laboratory (Professor Hielscher), the Bone Bioengineering Laboratory (Professor Guo), the Cellular Engineering Laboratory (Professor Hung), the Biomaterial and Interface Tissue Engineering Laboratory (Professor Lu), the Neurotrauma and Repair Laboratory (Professor Morrison), the Laboratory for Stem Cells and Tissue Engineering (Professor Vunjak-Novakovic), the Ultrasound and Elasticity Imaging Laboratory (Professor Konofagou), the Microscale Biocomplexity Laboratory (Professor Kam), the Molecular and Microscale Bioengineering Laboratory (Professor Sia), the Laboratory for Functional Optical Imaging (Professor Hillman), the Cell and Molecular Biomechanics Laboratory (Professor C. Jacobs), the Cognitive Electrophysiology Laboratory (Professor J. Jacobs), the Nanobiotechnology and Synthetic Biology Laboratory (Professor Hess), the Neural Engineering and Control Laboratory (Professor Wang), and the Laboratory for Nanomedicine and Regenerative Medicine (Professor Leong). These laboratories are supplemented with core facilities, including a tissue culture facility, a histology facility, a confocal microscope, an atomic force microscope, a 2-photon microscope, epifluorescence microscopes, a freezer room, biomechanics facilities, a machine shop, and a specimen preparation room.

UNDERGRADUATE PROGRAM

The objectives of the undergraduate program in biomedical engineering are as follows:

1. Professional employment in areas such as the medical device industry, engineering consulting, and biotechnology;
2. Graduate studies in biomedical engineering or related fields;
3. Attendance at medical, dental, or other professional schools.

The undergraduate program in biomedical engineering will prepare graduates who will have:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice
(l) an understanding of biology and physiology
(m) the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering, to solve the problems at the interface of engineering and biology
(n) the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and nonliving materials and systems.

The undergraduate curriculum is designed to provide broad knowledge of the physical and engineering sciences and their application to the solution of biological and medical problems. Students are strongly encouraged to take courses in the order specified in the course tables; implications of deviations must be discussed with a departmental adviser before registration. The first two years provides a strong grounding in the physical and chemical sciences, engineering fundamentals, mathematics, and modern biology. This background is used to provide a unique physical approach to the study of biological systems. The last two years of the undergraduate program provide substantial exposure to fundamentals in biomedical engineering with emphasis on the integration of principles of biomedical engineering, quantitative analysis of physiology, and experimental quantification and measurements of biomedical systems. The common core biomedical engineering curriculum provides a broad yet solid foundation in biomedical engineering. The flexible choice of technical electives in the Department of Biomedical Engineering, other departments in the Engineering School, as well as in other departments in the arts and sciences allows students to broaden their biomedical engineering education to their individualized interests for a personalized curriculum. These qualities allow the faculty to prepare students for activity in all contemporary areas of biomedical engineering. Graduates of the program are equipped for employment in the large industrial sector devoted to health care, which includes pharmaceuticals, medical devices, artificial organs, prosthetics and sensory aids, diagnostics, medical instrumentation, and medical imaging. Graduates also accept employment in oversight organizations (FDA, NIH, OSHA, and others), medical centers, and research institutes. They are prepared for graduate study in biomedical engineering and several related areas of engineering and the health sciences. Students can meet entrance requirements for graduate training in the various allied health professions. No more than three additional courses are required to satisfy entrance requirements for most U.S. medical schools.

All biomedical engineering students are expected to register for nontechnical electives, both those specifically required by the School of Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

First and Second Years

As outlined in this bulletin, in the first two years, all engineering students are expected to complete a sequence of courses in mathematics, physics, chemistry, computer science, engineering, modern biology, English composition, and physical education, as well as nontechnical electives including the humanities. For most of these sequences, the students may choose from two or more tracks. If there is a question regarding the acceptability of a course as a nontechnical elective, please consult the approved listing of courses beginning on page 11 or contact your advising dean for clarification.

Please see the charts in this section for a specific description of course requirements.

For students who are interested in the biomedical engineering major, they must take *E1201: Introduction to electrical engineering*. For the computer science requirement, students must take *ENGI W1006*. They must take the two-semester *BIOL C2005* and *C2006: Introduction to Biology I & II* in the second year, which gives students a comprehensive overview of modern biology from molecular to organ system levels. In addition, all students must take *APMA E2101: Introduction to applied mathematics* in their second year.

Third and Fourth Years

The biomedical engineering programs at Columbia at all levels are based on engineering and biological fundamentals. This is emphasized in our core requirements. All students must take the two-semester introduction to biomedical engineering course, *BMEN E3010* and *E3020: Biomedical engineering I & II*, which provide a broad yet solid foundation in the biomedical engineering discipline. In parallel, all students take the two-semester *Quantitative physiology, I* and *II* sequence (*BMEN E4001-E4002*), which is taught by biomedical engineering faculty and emphasizes quantitative applications of engineering principles in understanding biological systems and phenomena from molecular to organ system levels. In the fields of biomedical engineering, experimental techniques and principles are fundamental skills that good biomedical engineers must master. Beginning in junior year, all students take the two-semester sequence *Biomedical engineering laboratory, I & II (BMEN E3810, E3820)*. In this two-semester series, students learn through hands-on experience the principles and methods of biomedical engineering experimentation, measurement techniques, quantitative theories of biomedical engineering, data analysis, and independent design of biomedical engineering experiments, in parallel to the *Biomedical engineering I & II* and *Quantitative physiology I & II* courses. In addition, all students must take *BMEN E4110: Biostatistics for engineers*. In the senior year, students are required to take a two-semester capstone design course, *Biomedical engineering design (BMEN E3910 and E3920)*, in which students work within a team to tackle an open-ended design project in biomedical engineering. The underlying philosophy of these core requirements is to provide our biomedical engineering students with a broad knowledge and understanding of topics in the field of biomedical engineering. Parallel to these studies in core courses, students are required to take flexible technical elective courses (21 points) to obtain an in-depth understanding of their chosen interests. A technical elective is defined as a 3000-level or above course taught in SEAS or 3000-level or above courses in biology, chemistry, or biochemistry. At least 15 points (five courses) of these technical electives must have engineering content, while at least two of the five courses have to be from the Department of Biomedical Engineering. The curriculum prepares students who wish to pursue careers in medicine by satisfying most requirements in the premedical programs with no more than three additional courses. Some of these additional courses may also be counted as nonengineering technical electives. Please see the course tables for schedules leading to a bachelor's degree in biomedical engineering.

It is strongly advised that students take required courses during the specific term that they are designated in the course tables, as scheduling conflicts may arise if courses are taken out of sequence.

Technical Elective Requirements

Students are required to take at least 48 points of engineering content course work toward their degree. The 48-point requirement is a criterion established by ABET. Taking into consideration the number of engineering content points conferred by the required courses of the BME curriculum, a portion of technical electives must be clearly engineering in nature (Engineering Content Technical Electives), specifically as defined below:

1. Technical elective courses with sufficient engineering content that can count toward the 48 units of engineering courses required for ABET accreditation:

   a. All 3000-level or higher courses in the Department of Biomedical Engineering, except *BMEN E4010, E4103, E4104, E4105, E4106, E4107,* and *E4108*. (Note that only 3 points of *BMEN E3998* may be counted toward technical elective degree requirements.)
   b. All 3000-level or higher courses in the Department of Mechanical Engineering, except *MECE E4007: Creative engineering and entrepreneurship*
   c. All 3000-level or higher courses in the Department of Chemical Engineering, except *CHEN E4020: Safeguarding intellectual and business property*
   d. All 3000-level or higher courses in the Department of Electrical Engineering, except *EEHS E3900: History of telecommunications: from the telegraph to the Internet*
   e. All 3000-level or higher courses in the Civil Engineering and Engineering Mechanics program, except *CIEN E4128, E4129, E4130, E4131, E4132, E4133, E4134, E4135, E4136, and E4140*
   f. All 3000-level or higher courses in the Earth and Environmental Engineering program
2. Courses from the following departments are not allowed to count toward the required 48 units of engineering courses:

   a. Department of Applied Physics and Applied Mathematics
   b. Department of Computer Science
   c. Department of Industrial Engineering and Operations Research
   d. Program of Materials Science and Engineering

Once 48 points of engineering content are satisfied, students may choose any course above the 3000 level in Columbia Engineering as well as biology, chemistry, and biochemistry as technical electives.

The accompanying charts describe the eight-semester degree program schedule of courses leading to the bachelor's degree in biomedical engineering.

The undergraduate Biomedical Engineering program is designed to provide a solid biomedical engineering curriculum through its core requirements while providing flexibility to meet the individualized interests of the students. The following are suggested sample courses for various topic areas that students may consider. Note that students are not limited to these choices. All students are encouraged to design their own educational paths through flexible technical electives while meeting the following requirements: (1) courses must be at the 3000-level or above; (2) five of the seven electives must meet the above criteria to be considered engineering content; and (3) two of the seven electives must be biomedical engineering courses. To help students choose their electives, the following *suggested* sample curricula in various interest fields in biomedical engineering are provided. *Students do not need to follow them rigidly* and may substitute other courses, provided they meet the requirements above.

CELL AND TISSUE ENGINEERING

CHEM C3443:	Organic chemistry I	(3.5)
CHEM C3444:	Organics chemistry II	(3.5)
BMCH E4500:	Biological transport and rate process	(3)
BMEN E4510:	Tissue engineering	(3)
BMEN E4590:	BioMems: cellular and molecular applications	(3)
BMEN E4210:	Thermodynamics of biological systems	(3)
BMEN E4550:	Micro- and nanostructures in cellular engineering	(3)

BIOMECHANICS

BMEN E3100:	Mechanics of fluids	(3)
EMEN E3105:	Mechanics	(4)
MECE E3113:	Mechanics of solids	(3)
MECE E3301:	Thermodynamics	(3)
BMEN E4310:	Solid biomechanics	(3)
BMEN E4320:	Fluid biomechanics	(3)
BMEN E4340:	Biomechanics of cells	(3)

BIOSIGNALS AND BIOMEDICAL IMAGING

ELEN E3810:	Signals and systems	(3.5)
BMEN E4410:	Ultrasound imaging	(3)
BMEN E4420:	Biosignal process and modeling	(3)
BMEN E4430:	Principles of MRI	(3)
ELEN E4810:	Digital signal processing	(3)
BMEN E4894:	Biomedical imaging	(3)
BMEN E4898:	Biophotonics	(3)

NEURAL ENGINEERING

ELEN E3810:	Signals and systems	(3.5)
BMEB W4020:	Computational neuroscience: circuits in the brain	(3)
BMEE E4030:	Neural control engineering	(3)
BMEN E4420:	Biosignal process and modeling	(3)
BMEN E4430:	Principles of MRI	(3)
ELEN E4810:	Digital signal processing	(3)
BMEN E4894:	Biomedical imaging	(3)

GENOMICS AND SYSTEMS BIOLOGY

ELEN E3810:	Signals and systems	(3.5)
ECBN E4060:	Introduction to genomic information science and technology	(3)
CHBM E4321:	The genome and the cell	(3)
BMEN E4420:	Biosignal process and modeling	(3)
CHEN E4700:	Principles of genomic technologies	(3)
CHEN E4760:	Genomics sequence laboratory	(3)
CHEN E4800:	Protein engineering	(3)

QUANTITATIVE BIOLOGY

BMEN E3320:	Fluid biomechanics	(3)
BMEB W4020:	Computational neuroscience: circuits in the brain	(3)
ECBN E4060:	Introduction to genomic information science and technology	(3)
BIOL W4070:	The biology and physics of single molecules	(3.5)
BMEN E4310:	Solid biomechanics	(3)
APMA E4400:	Introduction to biological modeling	(3)
CHEN E4650:	Biopolymers	(3)

BIOINDUCTIVE AND BIOMIMETIC MATERIALS

CHEM C3443:	Organic chemistry I	(3.5)
BMCH E3500:	Biological transport process	(3)
BMEN E4510:	Tissue engineering	(3)
BMEN E4590:	BioMems: cellular and molecular applications	(3)

CHEN E4620:	Introduction to polymers and soft materials	(3)
CHEN E4640:	Polymer surface and interface	(3)
CHEN E4800:	Protein engineering	(3)

BIOMATERIALS

CHEM C3443:	Organic chemistry I	(3.5)
BMCH E3500:	Biological transport process	(3)
BMEN E4300:	Solid biomechanics	(3)
BMEN E4301:	Structure, mechanics, and adaptation of bone	(3)
BMEN E4510:	Tissue engineering	(3)
BMEN E4590:	BioMems: cellular and molecular applications	(3)
ELEN E4944:	Principles of device microfabrication	(3)

BIOMEMS AND NANOTECHNOLOGY

MECE E3100:	Mechanics of fluids	(3)
EMEN E3105:	Mechanics	(4)
MECE E3113:	Mechanics of solids	(3)
MSAE E4090:	Nanotechnology	(3)
MECE E4212:	Microelectromechanical systems	(3)
MEBM E4550:	Micro- and nanostructures in cellular engineering	(3)
BMEN E4590:	BioMems: cellular and molecular applications	(3)

ROBOTICS AND CONTROL OF BIOLOGICAL SYSTEMS

MECE E3100:	Mechanics of fluids	(3)
EMEN E3105:	Mechanics	(4)
MECE E3113:	Mechanics of solids	(3)
BMEE E4030:	Neural control engineering	(3)
MECE E4431:	Space vehicle dynamics and controls	(3)
MEBM E4439:	Modeling and identification of dynamic systems	(3)
MECE E4602:	Introduction to robotics	(3)

PREMED AND PRE-HEALTH PROFESSIONAL

MECE E3100:	Mechanics of fluids	(3)
EMEN E3105:	Mechanics	(4)
MECE E3113:	Mechanics of solids	(3)
CHEM C3443:	Organic chemistry I	(3.5)
CHEM C3444:	Organic chemistry II	(3.5)
BMEN E4310:	Solid biomechanics	(3)
BMEN E4320:	Fluid biomechanics	(3)

To meet entrance requirements of most U.S. medical schools, students will need to take CHEM C3543 Organic chemistry laboratory (3), PHYS C1493: Introduction to experimental physics (3), and PSYC W1001: The science of psychology (3) as well.

GRADUATE PROGRAMS

The graduate curriculum in biomedical engineering is track-free at the master's level while at the doctoral level, it consists of three tracks: biomechanics, cell and tissue engineering, and biosignals and biomedical imaging. Initial graduate study in biomedical engineering is designed to expand the student's undergraduate preparation in the direction of the concentration of interest. In addition, sufficient knowledge is acquired in other areas to facilitate broad appreciation of problems and effective collaboration with specialists from other scientific, medical, and engineering disciplines. The Department of Biomedical Engineering offers a graduate program leading to the Master of Science degree (M.S.), the Doctor of Philosophy degree (Ph.D.), and the Doctor of Engineering Science degree (Eng.Sc.D.). Applicants who have a Master of Science degree or equivalent may apply directly to the doctoral degree program. All applicants are expected to have earned the bachelor's degree in engineering or in a cognate scientific program. The Graduate Record Examination (General Test only) is required of all applicants. Students whose bachelor's degree was not earned in a country where English is the dominant spoken language are required to take the TOEFL test. In addition, for the doctoral program, the individual tracks require applicants to have taken the following foundation courses:

- **Biomechanics:** One year of biology and/or physiology, solid mechanics, statics and dynamics, fluid mechanics, ordinary differential equations.
- **Cell and Tissue Engineering:** One year of biology and/or physiology, one year of organic chemistry or biochemistry with laboratory, fluid mechanics, rate processes, ordinary differential equations.
- **Biosignals and Biomedical Imaging:** One year of biology and/or physiology and/or biochemistry. Linear algebra, ordinary differential equations, Fourier analysis, digital signal processing.

Applicants lacking some of these courses may be considered for admission with stipulated deficiencies that must be satisfied in addition to the requirements of the degree program. Columbia Engineering does not admit students holding the bachelor's degree directly to doctoral studies; admission is offered either to the M.S. program or to the M.S. program/doctoral track. The Department of Biomedical Engineering also admits students into the 4-2 program, which provides the opportunity for students holding a bachelor's degree from certain physical sciences to receive the M.S. degree after two years of study at Columbia.

CURRICULUM AND EXAM REQUIREMENTS

Master's Degree

In consultation with an appointed faculty adviser, M.S. students should select a program of 30 points of credit of graduate courses (4000 level or above) appropriate to their career goals. This program must include the course in computational modeling of physiological systems (*BMEN E6003*); two semesters of *BMEN E9700: Biomedical engineering seminar*; at least four other biomedical engineering courses; and at least one graduate-level mathematics course (excluding statistics). Up to 6 credits of *Master's Research BMEN E9100* may be taken to fulfill degree requirements. Students with deficiency in physiology course work are required to take the *BMEN E4001-E4002* sequence before taking *BMEN E6003*. Candidates must achieve a minimum grade-point average of 2.5. A thesis based on experimental, computational, or analytical research is optional and may be counted in lieu of 6 points of course work. Students wishing to pursue the Master's Thesis option should register for *BMEN E9100 Master's Research* and consult with their BME faculty adviser.

Doctoral Degree

Doctoral students must complete a program of 30 points of credit beyond the M.S. degree. The core course requirements (9 credits) for the doctoral program include the course in computational modeling of physiological systems (*BMEN E6003*), plus at least two graduate mathematics courses (one of these can be a graduate-level Biostatistics course). If *BMEN E6003* or a graduate-level mathematics course has already been taken for the master's degree, a technical elective can be used to complete the core course requirements. Students must register for *BMEN E9700: Biomedical engineering seminar* and for research credits during the first two semesters of doctoral study.

BIOMEDICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS (CLASS OF 2016)

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3)
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5)	
CHEMISTRY (three tracks, choose one)	C1403 (3.5) **and** Lab C1500 (3) either semester C1604 (3.5) C3045 (3.5)	C1404 (3.5) C2507 (3) C3046 (3.5), C2507 (3)	C3443 (3.5) C3443 (3.5)	
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
COMPUTER SCIENCE	COMS W1005 (3) MATLAB (in semester I or III)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			
NONTECHNICAL REQUIREMENTS	HUMA W1121 (3) **or** W1123 (3)		HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
TECHNICAL REQUIREMENTS			ELEN E1201 Intro. to EE (3.5)	APMA E2101 Intro. to applied math (3) ENME E3105 Mechanics (4)
			STAT W1211 (3) Intro. to statistics (either semester)	

Remaining courses should be selected in consultation with the student's faculty adviser to prepare for the doctoral qualifying examination and to develop expertise in a clearly identified area of biomedical engineering.

All graduate students admitted to the doctoral degree program must satisfy the equivalent of two semesters' experience in teaching (one semester for M.D./Ph.D. students). This may include supervising and assisting undergraduate students in laboratory experiments, grading, and preparing lecture materials to support the teaching mission of the department. The Department of Biomedical Engineering is the only engineering department that offers Ph.D. training to M.D./Ph.D. students. These candidates are expected to complete their Ph.D. program within 3.5 years, with otherwise the same requirements as those outlined for the Doctoral Degree program.

Doctoral Qualifying Examination

Doctoral candidates are required to pass a qualifying examination. This examination is given once a year, and it should be taken after the student has completed 30 points of graduate study. The qualifying examination consists of an oral exam during which the student presents an analysis of assigned scientific papers, as well as answers to questions in topics covering applied mathematics, quantitative biology and physiology, and track-specific material. A written analysis of the assigned scientific papers must be submitted prior to the oral exam. A minimum cumulative grade-point average of 3.2 is required to register for this examination.

BIOMEDICAL ENGINEERING: THIRD AND FOURTH YEARS (CLASS OF 2016)

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES: ALL TRACKS		BIOL C2005 (4) Introductory biol. I BMEN E3810 (3) BME laboratory, I BMEN E4001 (3) Quantitative physiol., I	BIOL C2006 (4) Introductory biol. II BMEN E3820 (3) BME laboratory, II BMEN E4002 (3) Quantitative physiol., II	BMEN E3910 (4) BME design, I BMEN E3830 (3) BME laboratory, III	BMEN E3920 (4) BME design, II BMEN E4010 (2)[1] Ethics for BMEs
NONTECH ELECTIVES		0–3 points	3 points	0–3 points	3 points
TRACK-SPECIFIC COURSES	**CELL AND TISSUE ENGINEERING**[2]	BMEN E2500 (0) BMCH E3500 (3) Biol. transport. proc. MSAE E3103 (3) Elements of mat. sci.	BMEN E4210 (4) Thermo. biol. sys.	BMEN E4501 (3) Tissue eng., I Technical elective (6)	BMEN E4502 (3) Tissue eng., II Technical elective (3)
TRACK-SPECIFIC COURSES	**BIOMECHANICS**[3]	BMEN E2300 (0) MECE E3100 (3) Mech. of fluids	BMEN E3320 (3) Fluid biomech.	ENME E3113 (3) Mech. of solids MECE E3301 (3) Thermodynamics Technical elective (6)	BMEN 4300 (3) Solid biomech. Technical elective (3)
TRACK-SPECIFIC COURSES	**BIOSIGNALS AND BIOMEDICAL IMAGING**[4]	BMEN E2400 (0) ELEN E3801 (3.5) Signals and systems	BMEN E4420 (3) Biosig. proc. and modeling	ELEN E4810 (3) Dig. sig. processing BMEN E4894 (3) Biomed. imaging BMEN E4430 (3) Principles of MRI Technical elective (3)	BMEN E4410 (3) Princ. Ultrasound **or** BMEN E4898 (3) Biophotonics Technical elective (3)
TOTAL POINTS		16–17	16	19	15

[1] BMEN E4010: Ethics for biomedical engineers is a SEAS nontechnical course.
[2] In the cell and tissue engineering track, of the 9 points of technical electives, at least 4.5 must be from engineering courses.
[3] In the biomechanics track, of the 9 points of technical electives, at least 2.5 points must be from engineering courses.
[4] In the imaging track, core requirements satisfy the 48 points of engineering content.

Doctoral Committee and Thesis

Students who pass the qualifying examination choose a faculty member to serve as their research adviser. Each student is expected to submit a research proposal and present it to a committee that consists of three BME faculty members. The committee considers the scope of the proposed research, its suitability for doctoral research and the appropriateness of the research plan. The committee may approve the proposal without reservation or may recommend modifications. In general, the student is expected to submit his/her research proposal after five semesters of doctoral studies. In accordance with regulations of the Graduate School of Arts and Sciences, each student is expected to submit a thesis and defend it before a committee of five faculty, one of whom holds primary appointment in another department or school or university. Every doctoral candidate is required to have had accepted at least one first-author full-length paper for publication in a peer-reviewed journal prior to recommendation for award of the degree.

BIOMEDICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS (CLASS 2017 AND BEYOND)

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3)	
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5)	
CHEMISTRY (three tracks, choose one)	C1403 (3.5) C1604 (3.5) C3045 (3.5)	C1404 (3.5) C1500 (3) (**or** semester 1) C2507 (3) C3046 (3.5), C2507 (3)		
ENGLISH COMPOSITION	C1010 (3) (**or** any semester)			
COMPUTER SCIENCE	ENGI W1006 (3) (**or** semester II)			
PHYSICAL EDUCATION[1]	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING[1]		ENGI E1102 (4) (**or** in semester I)		
NONTECHNICAL REQUIREMENTS[1]	HUMA W1121 (3) **or** W1123 (3)		HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
TECHNICAL REQUIREMENTS			ELEN E1201 Intro. to EE (3.5) BIOL C2005 Intro. to Biology, I (4)	APMA E2101 (3) Intro. to applied math BIOL C2006 (4) Intro to Biology, II
TOTAL POINTS	19.5[2]	17.5[2]	17.5[2]	15[2]

[1] Students can mix these requirements according to what is available.
[2] Estimations

COURSES IN BIOMEDICAL ENGINEERING

BMEN E1001x Engineering in medicine
3 pts. Lect: 3. Not offered in 2015–2016.
The present and historical role of engineering in medicine and health care delivery. Engineering approaches to understanding organismic and cellular function in living systems. Engineering in the diagnosis and treatment of disease. Medical imaging, medical devices: diagnostic and surgical instruments, drug delivery systems, prostheses, artificial organs. Medical informatics and organization of the health care system. Current trends in biomedical engineering research.

BMEN E3010x Biomedical engineering, I
3 pts. Lect: 3. Professor Guo.
Prerequisites: BIOL C2005 and C2006, or instructor's permission. Corequisites: BMEN E4001, BMEN E3810. Various concepts within the field of biomedical engineering, foundational knowledge of engineering methodology applied to biological and/or medical problems through modules in biomechanics, biomaterials, and cell and tissue engineering.

BMEN E3020y Biomedical engineering, II
3 pts. Lect: 3. Professor Hung
Prerequisites: BIOL C2005 and C2006, or instructor's permission. Corequisites: BMEN E4002, BMEN E3820. Various concepts within the field of biomedical engineering, foundational knowledge of engineering methodology applied to biological and/or medical problems through modules in biomechanics, bioinstrumentation, and biomedical imaging.

BIOMEDICAL ENGINEERING: THIRD AND FOURTH YEARS (CLASS 2017 AND BEYOND)

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	BMEN E3010 (3) Biomedical eng., I BMEN E3810 (3) BME laboratory, I BMEN E4001 (3) Quantitative physiol., I BMEN E4110 (3) Biostat. for engineers	BMEN E3020 (3) Biomedical eng., II BMEN E3820 (3) BME laboratory, II BMEN E4002 (3) Quantitative physiol., II Technical elective (3)[1]	BMEN E3910 (4) BME design, I Technical elective (3)[1] Technical elective (3)[1] Technical elective (3)[1]	BMEN E3920 (4) BME design, II Technical elective (3)[1] Technical elective (3)[1] Technical elective (3)[1]
NONTECH ELECTIVES	3 points	3 points	3 points	
TOTAL POINTS	15	15	16	13

[1] Five of seven technical electives must have engineering content, and two of them must be from the Biomedical Engineering Department.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Varadan.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E4060, but the work requirements differ somewhat.

BMEN E3810x Biomedical engineering laboratory, I
3 pts. Lab: 4. Professor Kyle.
Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.

BMEN E3820y Biomedical engineering laboratory, II
3 pts. Lab: 4. Professor Kyle.
Biomedical experimental design and hypothesis testing. Statistical analysis of experimental measurements. Analysis of variance, post hoc testing. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound, characterization of excitable tissues, microfluidics.

BMEN E3830x Biomedical engineering laboratory, III
3 pts. Lab: 4. Professor Kyle.
Experimental design. Cell adhesion, membrane transport, osmosis, ultrasound, design of cell encapsulation and drug delivery system, respiratory impedance. Selected clinical demonstrations: body compositions, magnetic resonance imaging, echocardiography, blood pressure.

BMEN E3910x-E3920y Biomedical engineering design, I and II
4 pts. Lect: 1. Lab: 3. Professor Kyle.
A two-semester design sequence to be taken in the senior year. Elements of the design process, with specific applications to biomedical engineering: concept formulation, systems synthesis, design analysis, optimization, biocompatibility, impact on patient health and comfort, health care costs, regulatory issues, and medical ethics. Selection and execution of a project involving the design of an actual engineering device or system. Introduction to entrepreneurship, biomedical start-ups, and venture capital. Semester I: statistical analysis of detection/classification systems (receiver operation characteristic analysis, logistic regression), development of design prototype, need, approach, benefits and competition analysis. Semester II: spiral develop process and testing, iteration and refinement of the initial design/ prototype, and business plan development. A lab fee of $100 each is collected.

BMEN E3998x or y Projects in biomedical engineering
1–3 pts. Hours to be arranged. Members of the faculty.
Independent projects involving experimental, theoretical, computational, or engineering design work. May be repeated, but no more than 3 points of this or any other projects or research course may be counted toward the technical elective degree requirements as engineering technical electives.

BMEN E4000x Special topics
3 pts. Lect: 3. Professor Guo.
Additional current topics in biomedical engineering taught by regular or visiting faculty. The same subject matter is not usually considered in different years.

BMEN E4001x Quantitative physiology, I: cells and molecules
3 pts. Lect: 3. Professor Kam.
Prerequisites: BIOL C2005 and C2006.
Corequisites: BMEN E3010 and E3810.
Physiological systems at the cellular and molecular level are examined in a highly quantitative context. Topics include chemical kinetics, molecular binding and enzymatic processes, molecular motors, biological membranes, and muscles.

BMEN E4002y Quantitative physiology, II: organ systems
3 pts. Lect: 3. Professor Morrison.
Prerequisites: BIOL C2005 and C2006.
Corequisites: BMEN E3020, E3820. Students are introduced to a quantitative, engineering approach to cellular biology and mammalian physiology. Beginning with biological issues related to the cell, the course progresses to considerations of the

major physiological systems of the human body (nervous, circulatory, respiratory, renal).

BMEN E4010y Ethics for biomedical engineers
2 pts. Lect: 2. Professor Loike.
Prerequisite: senior status in biomedical engineering or the instructor's permission. Covers a wide range of ethical issues expected to confront graduates as they enter the biotechnology industry, research, or medical careers. Topics vary and incorporate guest speakers from Physicians and Surgeons, Columbia Law School, Columbia College, and local industry.

BMEB W4020x Computational neuroscience: circuits in the brain
3 pts. Lect: 3. Professor Lazar.
Prerequisite: ELEN E3801 or BIOL W3004. The biophysics of computation: modeling biological neurons, the Hodgkin-Huxley neuron, modeling channel conductances and synapses as memristive systems, bursting neurons and central pattern generators, I/O equivalence and spiking neuron models. Information representation and neural encoding: stimulus representation with time encoding machines, the geometry of time encoding, encoding with neural circuits with feedback, population time encoding machines. Dendritic computation: elements of spike processing and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and spike time-dependent plasticity, basic dendritic integration. Projects in MATLAB.

BMEE E4030x Neural control engineering
3 pts. Lect: 3. Professor Wang.
Prerequisites: ELEN E3801. Topics include: basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson's disease treatment, motor neural prostheses, and sensory neural prostheses.

ECBM E4060x Introduction to genomic information
3 pts. Lect: 3. Professor Varadan.
Prerequisites: None. Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequence of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming.

ECBM E4090x or y Brain computer interfaces (BCI) laboratory
3 pts. Lect: 2. Lab: 3. Professor Mesgarani.
Prerequisite: ELEN E3801. Hands-on experience with basic neural interface technologies. Recording EEG (electroencephalogram) signals using data acquisition systems (noninvasive scalp recordings). Real-time analysis and monitoring of brain responses. Analysis of intention and perception of external visual and audio signals.

BMEN E4103x Anatomy of the thorax and abdomen
2 pts. Lect: 2. Professor April.
Prerequisite: Graduate standing in Biomedical Engineering. This course is designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to his/her doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4104).

BMEN E4104x Anatomy laboratory: thorax and abdomen
2 pts. Lect: 2. Professor April.
Prerequisites: Graduate standing in Biomedical Engineering. Corequisites: BMEN E4103.

BMEN E4105x Anatomy of the extremities
2 pts. Lect: 2. Professor April.
Prerequisite: Graduate standing in Biomedical Engineering. This course is designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to his/her doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4106).

BMEN E4106x Anatomy laboratory: extremities
2 pts. Lab: 2. Professor April.
Prerequisites: Graduate standing in Biomedical Engineering. Corequisites: BMEN E4105.

BMEN E4107x Anatomy of the head and neck
2 pts. Lect: 2. Professor April.
Prerequisite: Graduate standing in Biomedical Engineering. This course is designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to his/her doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4108).

BMEN E4108x Anatomy laboratory: head and neck
2 pts. Lab: 2. Professor April.
Prerequisites: Graduate standing in Biomedical Engineering. Corequisites: BMEN E4107.

BMEN E4110x Biostatistics for engineers
3 pts. Lect: 3. Professor Sajda.
Prerequisites: MATH V1202 and APMA E2101. Fundamental concepts of probability and statistics applied to biology and medicine. Probability distributions, hypothesis testing and inference, summarizing data and testing for trends. Signal detection theory and the receiver operator characteristic. Lectures accompanied by data analysis assignments using MATLAB as well as discussion of case studies in biomedicine.

BMEN E4150x The cell as a machine
3 pts. Lect: 3. Professors Sheetz and Kam.
Prerequisite: MATH V1101 or equivalent. Corequisites: One semester of BIOL C2005 or BIOC C3501, and one semester of PHYS C1401 or equivalent. Cells as complex micron-sized machines, basic physical aspects of cell components (diffusion, mechanics, electrostatics, hydrophobicity), energy transduction (motors, transporters, chaperones, synthesis complexes), basic cell functions. Biophysical principles, feedback controls for robust cell function, adaptation to environmental perturbations.

BMEN E4210y Thermodynamics of biological systems
4 pts. Lect: 4. Professor Sia.
Prerequisites: CHEM C1404 and MATH V1202. Corequisite: BIOL C2005 or equivalent. Introduction to the thermodynamics of biological systems, with a focus on connection microscopic molecular properties to macroscopic states. Both classical and statistical thermodynamics are applied to biological systems; phase equilibria, chemical reactions, and colligative properties. Topics in modern biology, macromolecular behavior in solutions and interfaces, protein-ligand binding, and the hydrophobic effect.

BMEN E4301x Structure, mechanics, and adaptation of bone
3 pts. Lect: 3. Not offered in 2015–2016.
Introduction to structure, physiology, and biomechanics of bone. Structure, function, and physiology of skeletal bones; linear elastic properties of cortical and trabecular bone; anisotropy and constitutive models of bone tissue; failure and damage mechanics of bone; bone adaptation and fracture healing; experimental determination of bone properties; and morphological analysis of bone microstructure.

BMEN E4305y Cardiac mechanics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BMEN E3310 and BMEN E3320 or equivalents. Cardiac anatomy, passive myocardial constitutive properties, electrical activation, ventricular pump function, ventricular-vascular coupling, invasive and noninvasive measures of regional and global function, models for predicting ventricular wall stress. Alterations in muscle properties and ventricular function resulting from myocardial infarction, heart failure, and left ventricular assist.

BMEN E4310x or y Solid biomechanics
3 pts. Lect: 3. Professor Jacobs. Offered in Spring 2016 only. For Class of 2016, equivalent to E4300.
Prerequisites: ENME-MECE E3105 and ENME E3113. Applications of continuum mechanics to the understanding of various biological tissues

properties. The structure, function, and mechanical properties of various tissues in biological systems, such as blood vessels, muscle, skin, brain tissue, bone, tendon, cartilage, ligaments, etc., are examined. The establishment of basic governing mechanical principles and constitutive relations for each tissue. Experimental determination of various tissue properties. Medical and clinical implications of tissue mechanical behavior.

BMEN E4320x or y Fluid biomechanics
3 pts. Lect: 3. Professor Elad.
Prerequisites: APMA E2101, ENME E3105, and MECE E4100. The principles of continuum mechanics as applied to biological fluid flows and transport. Continuum formulations of basic conservation laws, Navier-Stokes equations, mechanics of arterial and venous blood flow, blood rheology and non-Newtonian properties, flow and transport in the microcirculation, oxygen diffusion, capillary filtration.

CHBM E4321y The genome and the cell
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BIOL C2005 and MATH E1210. The utility of genomic information lies in its capacity to predict the behavior of living cells in physiological, developmental, and pathological situations. The effect of variations in genome structure between individuals within a species, including those deemed healthy or diseased, and among species, can be inferred statistically by comparisons of sequences with behaviors and mechanistically, by studying the action of molecules whose structure is encoded within the genome. This course examines known mechanisms that elucidate the combined effect of environmental stimulation and genetic makeup on the behavior of cells in homeostasis, disease states, and during development, and includes assessments of the probable effect of these behaviors on the whole organism. Quantitative models of gene translation and intracellular signal transduction will be used to illustrate switching of intracellular processes, transient and permanent gene activation, and cell commitment, development, and death.

BMEN E4340x Biomechanics of cells
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BMEN E3320 and BMEN E4300 or equivalents. Survey of experiments and theoretical analyses of the mechanical behavior of individual living nonmuscle cells. Emphasis on quantitative analytic description using continuum mechanics and molecular level theory from the standpoint of statistical mechanics and mechanical models. Mechanics of erythrocytes, leukocytes, endothelial cells, and fibroblasts; models of aggregation, adhesion, locomotion, amoeba motility, cell division and morphogenesis; molecular level models of actin, myosin, microtubules, and intermediate filaments and relation to mechanical properties of cells and cytoskeleton. Alternative models of cytoskeletal mechanics, foam theory, tensegrity. Analysis of experimental techniques including micropipette studies, optical and magnetic cytometry, and nanoindentation.

BMEE E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation and classification methods for computer aided diagnosis.

BMEN E4410y Ultrasound in diagnostic imaging
3 pts. Lect: 3. Professor Konofagou.
Prerequisites: MATH V1202 or equivalent. Fourier analysis. Physics of diagnostic ultrasound and principles of ultrasound imaging instrumentation. Propagation of plane waves in lossless medium; ultrasound propagation through biological tissues; single-element and array transducer design; pulse-echo and Doppler ultrasound instrumentation, performance evaluation of ultrasound imaging systems using tissue-mimicking phantoms, ultrasound tissue characterization; ultrasound nonlinearity and bubble activity; harmonic imaging; acoustic output of ultrasound systems; biological effects of ultrasound.

BMEN E4420y Biomedical signal processing and signal modeling
3 pts. Lect: 3. Professor Sajda.
Prerequisites: ELEN E3801 and either APMA E2101 or E3101 or instructor's permission. Fundamental concepts of signal processing in linear systems and stochastic processes. Estimation, detection, and filtering methods applied to biomedical signals. Harmonic analysis, auto-regressive model, Wiener and Matched filters, linear discriminants, and independent components. Methods are developed to answer concrete questions on specific data sets in modalities such as ECG, EEG, MEG, ultrasound. Lectures accompanied by data analysis assignments using MATLAB.

BMEN E4430x Principles of magnetic resonance imaging
3 pts. Lect: 3. Professor Kangarlu.
Prerequisites: PHYS C1403 and APMA E2101, or instructor's permission. Fundamental principles of Magnetic Resonance Imaging (MRI), including the underlying spin physics and mathematics of image formation with an emphasis on the application of MRI to neuroimaging, both anatomical and functional. The course examines both theory and experimental design techniques.

MEBM E4439x Modeling and identification of dynamic systems
3 pts. Lect: 3. Professor Chbat.
Prerequisites: APMA E2101, ELEN E3801 or corequisite EEME E3601, or instructor's permission. Generalized dynamic system modeling and simulation. Fluid, thermal, mechanical, diffusive, electrical, and hybrid systems are considered. Nonlinear and high order systems. System identification problem and Linear Least Squares method. State-space and noise representation. Kalman Filter. Parameter estimation via prediction-error and subspace approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

BMEN E4440y Physiological control systems
3 pts. Lect: 3. Professor Chbat.
Prerequisites: MEBM E4439 and APMA E2101, or instructor's permission. Fundamentals of time and frequency domains analyses and stability. Frequency domain controller design. Cardiovascular and respiratory systems simulation. Endogenous control systems: baroreflex, chemoreflex, thermoregulation, pupillary light reflex. Open and closed loop physiological systems. Exogenous control systems: ventilators, infusion pumps. Nonlinear actuators and delayed feedback systems. Acute disease simulation and clinical decision support in the intensive care unit. MATLAB and Simulink environments utilized.

BMEN E4450y Dental and craniofacial tissue engineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MSAE E3103, BMEN E4210, E4501, or equivalent. Principles of dental and craniofacial bioengineering, periodontal tissue engineering: beyond guided tissue regeneration, craniofacial regeneration by stem cells and engineered scaffolds, biomaterials: Engineering approaches in tissue regeneration, bone biology and development: instructive cues for tissue engineers.

BMCH E4500x or y Biological transport and rate processes
3 pts. Lect: 3. Professor Vunjak-Novakovic.
Prerequisites: CHEM C3443, APMA E2101. Corequisites: BIOL C2005. Convective and diffusive movement and reaction of molecules in biological systems. Kinetics of homogeneous and heterogeneous reactions in biological environments. Mechanisms and models of transport across membranes. Convective diffusion with and without chemical reaction. Diffusion in restricted spaces. Irreversible thermodynamic approaches to transport and reaction in biological systems.

BMEN E4501x Tissue engineering, I: biomaterials and scaffold design
3 pts. Lect: 3. Professor Hess.
Prerequisites: BIOL C2005, C2006, BMEN E4001, E4002. An introduction to the strategies and fundamental bioengineering design criteria in the development of biomaterials and tissue engineered grafts. Material structural-functional relationships, biocompatibility in terms of material and host responses. Through discussions, readings, and a group design project, students acquire an understanding of cell-material interactions and identify the parameters critical in the design and selection of biomaterialss for biomedical applications.

BMEN E4502y Tissue engineering, II: biological tissue substitutes
3 pts. Lect: 3. Professor Hung.
Prerequisites: BIOL C2005, C2006, BMEN E4001, E4002. An introduction to the strategies and fundamental bioengineering design criteria behind the development of cell-based tissue substitutes. Topics include biocompatibility, biological grafts, gene therapy-transfer, and bioreactors.

BMEN E4510x or y Tissue engineering
3 pts. Lect: 3. Not offered in 2015–2016. For Class of 2017 and above only.
Prerequisites: BIOL C2005, C2006, BMEN E4001, E4002. An introduction to the strategies and fundamental bioengineering design criteria behind the development of cell-based tissue substitutes. Topics include biocompatibility, biological grafts, gene therapy-transfer, and bioreactors.

BMEN E4540y Bioelectrochemistry
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEM C3079 and C3443 or equivalent. Application of electrochemical kinetics to interfacial processes occurring in biomedical systems. Basics of electrochemistry, electrochemical instrumentation, and relevant cell and electrophysiology reviewed. Applications to interpretation of excitable and nonexcitable membrane phenomena, with emphasis on heterogeneous mechanistic steps. Examples of therapeutic devices created as a result of bioelectrochemical studies.

BMEN E4550y Micro- and nanostructures in cellular engineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BIOL W2005 and W2006 or equivalent. Design, fabrication, and application of micro-/nanostructured systems for cell engineering. Recognition and response of cells to spatial aspects of their extracellular environment. Focus on neural, cardiac, coculture, and stem cell systems. Molecular complexes at the nanoscale.

BMEN E4560y Dynamics of biological membranes
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BIOL C2005, BMEN E4001, or equivalent. The structure and dynamics of biological (cellular) membranes are discussed, with an emphasis on biophysical properties. Topics include membrane composition, fluidity, lipid asymmetry, lipid-protein interactions, membrane turnover, membrane fusion, transport, lipid phase behavior. In the second half of the semester, students will lead discussions of recent journal articles.

BMEN E4570x Science and engineering of body fluids
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: General chemistry, organic chemistry, and basic calculus. Body fluids as a dilute solution of polyelectrolyte molecules in water. Study of physical behavior as affected by the presence of ions in surrounding environments. The physics of covalent, ionic, and hydrogen bonds are reviewed, in relation to the structure/properties of the body fluid. Selected physiological processes are examined in physical-chemical terms for polymers.

BMEN E4590x BioMems: cellular and molecular applications
3 pts. Lect: 3. Professor Sia.
Prerequisites: Chemistry, CHEM C3443, or CHEN C3545 or equivalent, MATH V1201, BIOL W2005 and W2006. Topics include biomicroelectromechanical, microfluidic, and lab-on-a-chip systems in biomedical engineering, with a focus on cellular and molecular applications. Microfabrication techniques, biocompatibility, miniaturization of analytical and diagnostic devices, high-throughput cellular studies, microfabrication for tissue engineering, and in vivo devices.

BMEN E4601y Cellular electricity
3 pts. Lect: 2. Lab: 1. Not offered in 2015–2016.
Bioelectricity of the cell membrane. Basis of cell resting voltage, voltage changes that lead to the action potential and electrical oscillations used in sensing systems. Laboratory includes building electronic circuits to measure capacitance of artificial membranes and ion pumping in frog skin. Lab required.

APBM E4650x Anatomy for physicists and engineers
3 pts. Lect: 3. Professors Lignelli and Rozenshtein.
Prerequisite: Engineering or physics background. A systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women's issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, U/S, etc.).

BMME E4702x Advanced musculoskeletal biomechanics
3 pts. Lect: 2.5. Lab: 0.5. Not offered in 2015–2016.
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joint kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

MEBM E4703y Molecular mechanics in biology
3 pts. Lect: 3. Professor Chbat.
Prerequisites: ENME E3105, APMA E2101, or instructor's permission. Mechanical understanding of biological structures including proteins, DNA and RNA in cells and tissues. Force response of proteins and DNA, mechanics of membranes, biophysics of molecular motors, mechanics of protein-protein interactions. Introduction to modeling and simulation techniques, and modern biophysical techniques such as single molecule FRET, optical traps, AFM, and superresolution imaging,for understanding molecular mechanics and dynamics.

BMEN E4737x Computer control of medical instrumentation
3 pts. Lect: 2. Lab: 1. Not offered in 2015–2016.
Prerequisite: Basic knowledge of the C programming language. Acquisition and presentation of data for medical interpretation. Operating principles of medical devices: technology of medical sensors, algorithms for signal analysis, computer interfacing and programming, interface design. Laboratory assignments cover basic measurement technology, interfacing techniques, use of Labview software instrument interrogation and control, automated ECG analysis, ultrasonic measurements, image processing applied to X-ray images and CAT scans.

BMEN E4738y Transduction and acquisition of biomedical data
3 pts. Lect: 2. Lab: 1. Not offered in 2015–2016.
Data transduction and acquisition systems used in biomedicine. Assembly of biotransducers and the analog/digital circuitry for acquiring electrocardiogram, electromyogram, and blood pressure signals. Each small group will develop and construct a working data acquisition board, which will be interfaced with a signal generator to elucidate the dynamics of timing constraints during retrieval of biodata. Lab required.

BMEE E4740y Bioinstrumentation
3 pts. Lect: 1. Lab: 3. Professor Kyle.
Prerequisites: ELEN E1201, COMS W1005. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data acquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker.

BMEN E4750y Sound and hearing
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: PHYS C1401 and MATH V1105-MATH V1106. Introductory acoustics, basics of waves and discrete mechanical systems. The mechanics of hearing—how sound is transmitted through the external and middle ear to the inner ear, and the mechanical processing of sound within the inner ear.

CBMF W4761y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisites: Working knowledge of at least one programming language, and some background in probability and statistics. Computational techniques

for analyzing and understanding genomic data, including DNA, RNA, protein and gene expression data. Basic concepts in molecular biology relevant to these analyses. Emphasis on techniques from artificial intelligence and machine learning. String-matching algorithms, dynamic programming, hidden Markov models, expectation-maximization, neural networks, clustering algorithms, support vector machines. Students with life sciences backgrounds who satisfy the prerequisites are encouraged to enroll.

BMCH E4810y Artificial organs
3 pts. Lect: 3. Not offered in 2015–2016.
Analysis and design of replacements for the heart, kidneys, and lungs. Specification and realization of structures for artificial organ systems.

BMEN E4840y Functional imaging for the brain
3 pts. Lect: 3. Lab: 1. Professor Razlighi.
Prerequisites: APMA E2101, APMA E4200, ELEN E3801, or instructor's permission. Fundamentals of modern medical functional imaging. In-depth exploration of functional magnetic resonance imaging (fMRI), arterial spin labeling (ASL), and positron emission tomography (PET). Human brain anatomy, physiology, and neurophysiological bases underlying each functional imaging. Statistical and digital signal processing methods specific for functional image analysis. Final cumulative project requiring coding in MATLAB, Python, R, or C.

BMEN E4894x Biomedical imaging
3 pts. Lect: 3. Professor Hielscher.
This course covers image formation, methods of analysis, and representation of digital images. Measures of qualitative performance in the context of clinical imaging. Algorithms fundamental to the construction of medical images via methods of computed tomography, magnetic resonance, and ultrasound. Algorithms and methods for the enhancement and quantification of specific features of clinical importance in each of these modalities.

BMEN E4898y Biophotonics
3 pts. Lect: 3. Professor Hielscher.
Prerequisites: BMEN E4894 Biomedical imaging, PHYS C1403 Classical and quantum waves, or instructor's permission. This course provides a broad-based introduction into the field of Biophotonics. Fundamental concepts of optical, thermal, and chemical aspects of the light-tissue interactions will be presented. The application of these concepts for medical therapy and diagnostics will be discussed. The course includes theoretical modeling of light-tissue interactions as well as optical medical instrument design and methods of clinical data interpretation.

BMEN E6000x and y Graduate special topic
3 pts. Lect: 3. Members of faculty.
Current topics in biomedical engineering. Subject matter will vary by year. Instructors may impose prerequisites depending on the topic.

BMEN E6003x Computational modeling of physiological systems
3 pts. Lect: 3. Professor Morrison.
Prerequisites: BMEN E4001 and E4002 or equivalent, and APMA E4200 or equivalent. Advanced computational modeling and quantitative analysis of selected physiological systems from molecules to organs. Selected systems are analyzed in depth with an emphasis on modeling methods and quantitative analysis. Topics may include cell signaling, molecular transport, excitable membranes, respiratory physiology, nerve transmission, circulatory control, auditory signal processing, muscle physiology, data collection and analysis.

BMEN E6010x or y Biomedical design
3 pts. Lect: 3. Professor Reuther.
Master's students only. Project-based design experience for graduate students. Elements of design process, including need identification, concept generation, concept selection, and implementation. Development of design prototype and introduction to entrepreneurship and implementation strategies. Real-world training in biomedical design and innovation.

EEBM E6020y Methods of computational neuroscience
4.5 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: BMEB W4020. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: ELEN E3801, and either APMA E2101 or E3101, or equivalent, or instructor's permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically-based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course includes a computer simulation laboratory. Lab required.

EEBM E6090-6099x or y Topics in computational neuroscience and neuroengineering
3 pts. Lect: 2. Professor Sajda.
Prerequisite: Instructor's permission. Selected advanced topics in computational neuroscience and neuroengineering. Content varies from year to year, and different topics rotate through the course numbers 6090-6099.

BMEN E6301y Modeling of biological tissues with finite elements
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MECE E6422, or ENME E6315, or equivalent. Structure-function relations and linear/nonlinear constitutive models of biological tissues: anisotropic elasticity, viscoelasticity, porous media theories, mechano-electrochemical models, infinitesimal and large deformations. Emphasis on the application and implementation of constitutive models for biological tissues into existing finite element software packages. Model generation from biomedical images by extraction of tissue geometry, inhomogeneity and anisotropy. Element-by-element finite element solver for large-scale image based models of trabecular bone. Implementation of tissue remodeling simulations in finite element models.

MEBM E6310x-E6311y Mixture theories for biological tissues, I and II
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E6422 and APMA E4200, or equivalent Development of governing equations for mixtures with solid matrix, interstitial fluid, and ion constituents. Formulation of constitutive models for biological tissues. Linear and nonlinear models of fibrillar and viscoelastic porous matrices. Solutions to special problems, such as confined and unconfined compression, permeation, indentation and contact, and swelling experiments.

BMEN E6400x Analysis and quantification of medical images
3 pts. Lect: 3. Professor Laine.
Novel methods of mathematical analysis applied to problems in medical imaging. Design requirements for screening protocols, treatment therapies, and surgical planning. Sensitivity and specificity in screening mammography and chest radiographs, computer aided diagnosis systems, surgical planning in orthopaedics, quantitative analysis of cardiac performance, functional magnetic resonance imaging, positron emission tomography, and echocardiography data.

BMEN E6420y Advanced microscopy: fundamentals and applications
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Physics C1401, C1402, C1403 or C1601, C1602, C2601 or C2801, C2802, or equivalent (general Physics sequence). Fundamentals of techniques including confocal, two-photon, atomic force and electron microscopy. Application of methods to modern biomedical imaging targets. Analysis and interpretation of microscopy data. Enrollment beyond the cap

must be completed using an add/drop form in consultation with class instructor.

BMEN E6500x Tissue and molecular engineering laboratory
4 pts. Lect: 1. Lab: 3. Not offered in 2015–2016.
Prerequisites: Biology BIOL C2005 and BIOL C2006 or permission of instructor. Hands-on experiments in molecular and cellular techniques, including fabrication of living engineered tissues. Covers sterile technique, culture of mammalian cells, microscopy, basic subcloning and gel electrophoresis, creation of cell-seeded scaffolds, and the effects of mechanical loading on the metabolism of living cells or tissues. Theory, background, and practical demonstration for each technique will be presented. Lab required.

BMEN E6505x Advanced scaffold design and engineering complex tissues
3 pts. Lect: 2.5. Lab: 0.5. Professor Lu.
Prerequisites: BMEN E4501 or equivalent. Corequisites: BMEN E4001 or E4002. Advanced biomaterial selection and biomimetic scaffold design for tissue engineering and regenerative medicine. Formulation of bio-inspired design criteria, scaffold characterization and testing, and applications on forming complex tissues or organogenesis. Laboratory component includes basic scaffold fabrication, characterization and *in vitro* evaluation of biocompatibility. Group projects target the design of scaffolds for select tissue engineering applications.

BMEN E8001y Current topics in nanobiotechnology and synthetic biology
3 pts. Lect: 3. Not offered in 2015–2016.
Targeted toward graduate students; undergraduate student may participate with permission of the instructor. Review and critical discussion of recent literature in nanobiotechnology and synthetic biology. Experimental and theoretical techniques, critical advances. Quality judgments of scientific impact and technical accuracy. Styles of written and graphical communication, the peer review process.

EEBM E9070y Massively parallel neural computation
3 pts. Lect: 3. Professor Lazar
Prerequisites: BMEB W4020 or permission of instructor. Drosophila connectomics. Detailed description of the fruit fly's olfactory and vision systems. Parallel processing on GPSs.

BMEN E9100x or y Master's research
1–6 pts. Members of the faculty.
Candidates for the M.S. degree may conduct an investigation of some problem in biomedical engineering culminating in a thesis describing the results of their work. No more than 6 points in this course may be counted for graduate credit, and this credit is contingent upon the submission of an acceptable thesis.

BMEN E9500x or y Doctoral research
1–6 pts. Members of the faculty.
Doctoral candidates are required to make an original investigation of a problem in biomedical engineering, the results of which are presented in the dissertation.

BMEN E9700x or y Biomedical engineering seminar
0 pts. Sem: 1. Professor Wang.
All matriculated graduate students are required to attend the seminar as long as they are in residence. No degree credit is granted. The seminar is the principal medium of communication among those with biomedical engineering interests within the University. Guest speakers from other institutions, Columbia faculty, and students within the department who are advanced in their studies frequently offer sessions.

BMEN E9800x or y Doctoral research instruction
3–12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in biomedical engineering must register for 12 points of doctoral research instruction. Registration may not be used to satisfy the minimum residence requirement for the degree.

BMEN E9900x or y Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate in biomedical engineering or applied biology may be required to register for this course in every term after the student's course work has been completed and until the dissertation has been accepted.

CHEMICAL ENGINEERING

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Chemical engineering is a highly interdisciplinary field concerned with materials and processes at the heart of a broad range of technologies. Practicing chemical engineers are the experts in charge of the development and production of diverse products in traditional chemical industries as well as many emerging new technologies. The chemical engineer guides the passage of the product from the laboratory to the marketplace, from ideas and prototypes to functioning articles and processes, from theory to reality. This requires a remarkable depth and breadth of understanding of physical and chemical aspects of materials and their production.

The expertise of chemical engineers is essential to production, marketing, and application in such areas as pharmaceuticals, high-performance materials in the aerospace and automotive industries, biotechnologies, semiconductors in the electronics industry, paints and plastics, petroleum refining, synthetic fibers, artificial organs, biocompatible implants and prosthetics and numerous others. Increasingly, chemical engineers are involved in new technologies employing highly novel materials whose unusual response at the molecular level endows them with unique properties. Examples include environmental technologies, emerging biotechnologies of major medical importance employing DNA- or protein-based chemical sensors, controlled-release drugs, new agricultural products, and many others.

Driven by this diversity of applications, chemical engineering is perhaps the broadest of all engineering disciplines: chemistry, physics, mathematics, biology, and computing are all deeply involved. The research of the faculty of Columbia's Chemical Engineering Department is correspondingly broad. Some of the areas under active investigation are the fundamental physics, chemistry, and engineering of polymers and other soft materials; the electrochemistry of fuel cells and other interfacial engineering phenomena; the bioengineering of artificial organs and immune cell activation; the engineering and biochemistry of sequencing the human genome; the chemistry and physics of surface-polymer interactions; the biophysics of cellular processes in living organisms; the physics of thin polymer films; the chemistry of smart polymer materials with environment-sensitive surfaces; biosensors with tissue engineering applications; the physics and chemistry of DNA-DNA hybridization and melting; the chemistry and physics of DNA microarrays with applications in gene expression and drug discovery; the physics and chemistry of nanoparticle- polymer composites with novel electronic and photonic properties. Many experimental techniques are employed, from neutron scattering to fluorescence microscopy, and the theoretical work involves both analytical mathematical physics and numerical computational analysis.

Students enrolling in the Ph.D. program will have the opportunity to conduct research in these and other areas. Students with degrees in chemical engineering and other engineering disciplines, in chemistry, in physics, in biochemistry, and in other related disciplines are all natural participants in the Ph.D. program and are encouraged to apply. The Department of Chemical Engineering at Columbia is committed to a leadership role in research and education in frontier areas of research and technology where progress derives from the conjunction of many different traditional research disciplines. Increasingly, new technologies and fundamental research questions demand this type of interdisciplinary approach.

The undergraduate program provides a chemical engineering degree that is a passport to many careers in directly related industries as diverse as biochemical engineering, environmental management, and pharmaceuticals. The degree is also used by many students as a springboard from which to launch careers in medicine, law, management, banking and finance, politics, and so on. For those interested in the fundamentals, a career of research and teaching is a natural continuation of their undergraduate studies. Whichever path the student may choose after graduation, the program offers a deep understanding of the physical and chemical nature of things and provides an insight into an exploding variety of new technologies that are rapidly reshaping the society we live in.

Current Research Activities

Science and Engineering of Polymers and Soft Materials. Theoretical and experimental studies of novel or important macromolecules and their applications, especially surface-active species: ultrasonic sensor, scanning probe microscopy and reflectivity studies of adsorption and self-assembly of highly branched “dendrimers” at the solid-liquid interface, with the aim of creating novel surface coatings; fluorescence tracer studies of molecular level mobility in ultrathin polymer films with the aim of improving resolution in lithography; reflectivity studies and computer simulation of flexible polymer adsorption and the response of adsorbed polymer layers to imposed flows with the aim of improving polymer processing operations; optical microscopy studies and numerical simulation of microporous polymer membrane formation with the aim of improving ultrafiltration membrane technology; synthesis and structural characterization of bioactive polymer surfaces in order to realize new in-vivo devices; contact angle, X-ray photoelectron spectroscopy, and reflectivity analysis, and lattice model simulation, of responsive polymer surfaces based on unique polymeric “surfactants” in order to develop “smart” surface-active materials; preparation and IR/fluorescence characterization of DNA-decorated surfaces for “recognition” of DNA in solution in order to further medical diagnostic technologies; preparation and characterization via TEM, AFM, and reflectivity of nanoparticle-block copolymer composites with the aim of very high density magnetic storage media; self-consistent field theory of nanoparticle-block copolymer composites; computer simulation and theory of unique “living” polymerization processes important to synthetic polymer production and biological systems; theory and simulation of irreversible polymer adsorption.

Genomics Engineering. Research and development of novel bioanalytical reagents, systems, and processes using chemical science, engineering principles, and experimental biological approaches to study problems in genomics are actively pursued in the Department of Chemical Engineering in collaboration with the Columbia Genome Center: high-throughput DNA sequencing; novel gene chip development and fundamental understanding of the processes involved; applying the cutting-edge genomic technologies to study fundamental biology and for disease gene discovery.

Biophysics and Soft Matter Physics. Theoretical and experimental biophysics of biological soft matter: actin filament growth kinetics and its role in living cell motility; DNA hybridization, melting and unzipping; DNA microarrays in biotechnology; model gene circuits; DNA mobility in 2D microfluidics. Physics of synthetic soft matter: nanoparticles in mesostructured polymer phases and phase transitions; universal scaling laws in reacting polymer systems and polymerization phenomena; polymer-interface adsorption phenomena; polymer interfacial reactions; diffusion of particles in thin polymer films; interactions of charged polymer minigels with interfaces.

Bioinductive and Biomimetic Materials. The thrust of this research is to develop new strategies for the molecular design of polymeric and soft materials for biological and biomedical applications. Ongoing research pertains to the development of bioactive hydrogel coatings for applications in glucose sensors. The objective of the coatings is to control the tissue-sensor interactions by incorporating cell-signaling motifs into the hydrogel in such a manner that the hydrogel induces the formation of new vascular tissue within the surface coating. In this fashion, the biosensor can continue to operate in vivo, even if there is an immune response leading to fibrous encapsulation. Complementary research programs are aimed at developing methods for patterning biological surfaces in order to prepare new biocompatible surfaces as well as to fabricate antigen/antibody and protein arrays for diagnostic applications.

Interfacial Engineering and Electrochemistry. Research efforts within the department are focused on mass transfer and reaction mechanisms in electrochemical systems, and the effects that such variables have on process design and materials properties. Applications of the research program include fuel cells, electrodeposition, and corrosion. Both electrochemical and microscopy methods are used extensively for characterization. A significant numerical simulation component of the research programs also exists.

Facilities for Teaching and Research

The Department of Chemical Engineering is continually striving to provide access to state-of-the-art research instrumentation and computational facilities for its undergraduate and graduate students, postdoctoral associates, and faculty. Departmental equipment is considered to be in most cases shared, which means that equipment access is usually open to all qualified individuals with a need to use particular instrumentation.

The most extensive collection of instrumentation in the department is associated with the polymer and soft matter research faculty. Faculty banded together to create a unique shared-facilities laboratory, completed at the end of 2001. The shared facilities include a fully equipped polymer synthesis lab with four fumes hoods, a 10'x16' soft wall clean room, metal evaporator system, a Milligen 9050 peptide synthesizer, and polymer thin film preparation and substrate cleaning stations. Also installed are new, computer-controlled thermal analysis, rheometric, and light-scattering setups. Specialized instrumentation for surface analysis includes an optical/laser system dedicated to characterization of polymer surface dynamics by Fluorescence Recovery after Photobleaching and a PHI 5500 X-ray photoelectron spectrophotometer with monochromator that is capable of angle-dependent depth profiling and XPS imaging. The system can also perform SIMS and ion scattering experiments. A digital image analysis system for the characterization of sessile and pendant drop shapes is also available for the purpose of polymer surface and interfacial tension measurements as well as contact angle analysis. An X-ray reflectometer that can perform X-ray standing wave–induced fluorescence measurements is also housed in the new shared equipment laboratory, along with instrumentation for characterizing the friction and wear properties of polymeric surfaces. The laboratory also houses an infrared spectrometer (Nicolet Magna 560, MCT detector) with a variable angle grazing incidence, temperature-controlled attenuated-total-reflectance, transmission, and liquid cell accessories. These facilities are suitable for mid-IR, spectroscopic investigations of bulk materials as well as thin films. The laboratory also has a UV-Vis spectrometer (a Cary 50), an SLM Aminco 8000 spectrofluorimeter, and a high-purity water system (Millipore Biocel) used for preparation of biological buffers and solutions. Facilities are available for cell tissue culture and for experiments involving biocompatibilization of materials or cellular engineering. In addition, gel electrophoresis apparatus is available for the molecular weight characterization of nucleic acids. A total-internal-reflection-fluorescence (TIRF) instrument with an automated, temperature-controlled flow cell has been built for dedicated investigations of surface processes involving fluorescently tagged biological and synthetic molecules. The instrument can operate at different excitation wavelengths (typically HeNe laser, 633 nm, using Cy5 labeled nucleic acids). Fluorescence is collected by a highly sensitive photomultiplier tube and logged to a personal computer. Because fluorescence is only excited in the evanescent wave region near an interface, signals from surface-bound fluorescent species can be determined with minimal background interference from fluorophores in bulk solution.

Chemistry Department. Access to NMR and mass spectrometry facilities is possible through interactions with faculty members who also hold appointments in the Chemistry Department. The NMR facility consists of a 500 MHz, a 400 MHz, and two 300 MHz instruments that are operated by students and postdocs after training. The mass spectrometry facility is run by students for routine samples and by a professional mass spectrometrist for more difficult samples. The Chemistry Department also provides access to the services of a glass blower and machine shop and to photochemical and spectroscopic facilities. These facilities consist of (1) two nanosecond laser flash photolysis instruments equipped with UV-VIS, infrared, EPR, and NMR detection; (2) three EPR spectrometers; (3) two fluorescence spectrometers; (4) a single photon counter for analysis of the lifetimes and polarization of fluorescence and phosphorescence; and (5) a high-performance liquid chromatographic instrument for analysis of polymer molecular weight and dispersity.

Columbia Genome Center. Because of its affiliation with the Columbia Genome Center (CGC), the Department of Chemical Engineering also has access to more than 3,000 sq. ft. of space equipped with a high-throughput DNA sequencer (Amersham Pharmacia Biotech Mega-Bace 1000), a nucleic acid synthesizer (PE Biosystems 8909 Expedite Nucleic Acid/Peptide Synthesis System), an UV/VIS spectrophotometer (Perkin-Elmer Lambda 40), a fluorescence spectrophotometer (Jobin Yvon, Inc. Fluorolog-3), Waters HPLC, and a sequencing gel electrophoresis apparatus (Life Technologies Model S2), as well as the facilities required for state-of-the-art synthetic chemistry. The division of DNA sequencing and chemical biology at the Columbia Genome Center consists of 6,000 sq. ft. of laboratory space and equipment necessary for carrying out the state-of-the-art DNA analysis. The laboratory has one Amersham Pharmacia Biotech MegaBace 1000 sequencer, three ABI 377 sequencers with complete 96 land upgrades, a Qiagen 9600 Biorobot, a Hydra 96 microdispenser robot, and standard molecular biology equipment.

UNDERGRADUATE PROGRAM

Chemical Engineering

The undergraduate program in chemical engineering at Columbia has five formal educational objectives:

1. Prepare students for careers in industries that require technical expertise in chemical engineering.
2. Prepare students to assume leadership positions in industries that require technical expertise in chemical engineering.
3. Enable students to pursue graduate-level studies in chemical engineering and related technical or scientific fields (e.g., biomedical or environmental engineering, materials science).
4. Provide a strong foundation for students to pursue alternative career paths, especially careers in business, management, finance, law, medicine, or education.
5. Establish in students a commitment to life-long learning and service within their chosen profession and society.

The expertise of chemical engineers is essential to production, marketing, and application in such areas as pharmaceuticals, high performance materials as in the automotive and aerospace industries, semiconductors in the electronics industry, paints and plastics, consumer products such as food and cosmetics, petroleum refining, industrial chemicals, synthetic fibers, and just about every bioengineering and biotechnology area from artificial organs to biosensors. Increasingly, chemical engineers are involved in exciting new technologies employing highly novel materials, whose unusual response at the molecular level endows them with unique properties. Examples include controlled release drugs, materials with designed interaction with in vivo environments, “nanomaterials” for electronic and optical applications, agricultural products, and a host of others. This requires a depth and breadth of understanding of physical and chemical aspects of materials and their production that is without parallel.

The chemical engineering degree also serves as a passport to exciting careers in directly related industries as diverse as biochemical engineering, environmental management, and pharmaceuticals. Because the deep and broad-ranging nature of the degree has earned it a high reputation across society, the chemical engineering degree is also a natural platform from which to launch careers in medicine, law, management, banking and finance, politics, and so on. Many students choose it for this purpose, to have a firm and respected basis for a range of possible future careers. For those interested in the fundamentals, a career of research and teaching is a natural continuation of undergraduate studies.

The first and sophomore years of study introduce general principles of science and engineering and include a broad range of subjects in the humanities and social sciences. Although the program for all engineering students in these first two years is to some extent similar, there are a few important differences for chemical engineering majors. Those wishing to learn about, or major in, chemical engineering should take the professional elective *CHEN E2100 Introduction to chemical engineering* in term III, taught by the Chemical Engineering Department. This course is a requirement for the chemical engineering major. It can also possibly serve as a technical elective for other engineering majors. Those wishing to major in chemical engineering should also take *ENGI E1006 Introduction to computing for engineering and applied scientists* in term II. Chemical engineering majors receive additional instruction in their junior year on the use of computational methods to solve chemical engineering problems.

In the junior-senior sequence one specializes in the chemical engineering major. The table on page 83 spells out the core course requirements, which are split between courses emphasizing engineering science and those emphasizing practical and/or professional aspects of the discipline. Throughout, skills required of practicing engineers are developed (e.g., writing and presentation skills, competency with computers).

The table also shows that a significant fraction of the junior-senior program is reserved for electives, both technical and nontechnical. Nontechnical electives are courses that are not quantitative, such as those taught in the humanities and social sciences. These provide an opportunity to pursue interests in areas other than engineering. A crucial part of the junior-senior program is the 21-point (7 courses) technical elective requirement. Technical electives are science and/or technology based and feature quantitative analysis. Generally, technical electives must be 3000 level or above but there are a few exceptions: *PHYS C1403, PHYS C2601, BIOL C2005, BIOL C2006,* and *BIOL W2501.* The technical electives are subject to the following constraints:

- Two technical electives must be within chemical engineering (e.g., with the designator *BMCH, CHEN, CHEE,* or *CHAP*).
- One technical elective must be within SEAS but taken outside of chemical engineering (that is, a course with a designator other than *BMCH, CHEN, CHEE,* or *CHAP*).
- Two technical electives must be within SEAS (may or may not be within chemical engineering).
- Two technical electives must contain "advanced science" course work, which can include chemistry, physics, biology, and certain engineering courses. Qualifying engineering courses are determined by Chemical Engineering Department advisers. At least one of these classes must be taken outside of SEAS (e.g., in a science department at Columbia; see listing of possible courses above).
- At most, only one computer science (COMS) or industrial engineering and operations research (IEOR) class can be counted toward the technical elective requirement.

The junior-senior technical electives provide the opportunity to explore new, interesting areas beyond the core requirements of the degree. Often, students satisfy the technical electives by taking courses from another SEAS department in order to obtain a minor from that department. Alternately, you may wish to take courses in several new areas, or perhaps to explore familiar subjects in greater depth, or you may wish to gain experience in actual laboratory research. Up to 6 points of *CHEN E3900: Undergraduate research project* may be counted toward the technical elective content. (Note that if more than 3 points of research are pursued, an undergraduate thesis is required.)

The program details discussed above apply to undergraduates who are enrolled at Columbia as first-years and declare the chemical engineering major in the sophomore year. However, the chemical engineering program is designed to be readily accessible to participants in any of Columbia's Combined Plans and to transfer students. In such cases, the guidance of one of the departmental advisers in planning your program is required (contact information for the departmental UG advisers is listed on the department's website: cheme.columbia.edu).

Columbia's program in chemical engineering leading to the B.S. degree is fully accredited by the Engineering Accreditation Commission of ABET.

Requirements for a Minor in Chemical Engineering

See page 201.

GRADUATE PROGRAMS

The graduate program in chemical engineering, with its large proportion of elective courses and independent research, offers experience in any of the fields of departmental activity mentioned in previous sections. For both chemical engineers and those with undergraduate educations in other related fields such as physics, chemistry, and biochemistry, the Ph.D. program provides the opportunity to become expert in research fields central to modern technology and science.

M.S. Degree

The requirements are (1) the core courses: Chemical process analysis (CHEN E4010)/Partial differential equations (APMA E4200), Transport phenomena, III (CHEN E4110), Advanced chemical

CHEMICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** one of the following: MATH V2030 (3) Ord. diff. equations **or** APMA E2101 (3) Intro. to appl. math.
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Lab C1493 (3) Lab W3081 (2)	
CHEMISTRY (three tracks, choose one)	C1403 (3.5) **and** Lab C1500 (3) C1604 (3.5) C3045 (3.5)	C1404 (3.5) C2507 (3) C3046 (3.5) **and** Lab C2507 (3)	C3443 (3.5)	
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			One core humanities elective (3–4 points)[1]	Three core humanities electives (11 points)[1]
CHEM. ENG. REQUIREMENT			CHEN E2100 (3)[2] Intro to chemical engineering	
COMPUTER SCIENCE		ENGI E1006 (3)		
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			
TOTAL POINTS[3]	16.5	17.5	16.5	17

[1] Four core humanities electives should be taken as follows: In Semester III, HUMA C1001, C1101 (4), or any initial course in one of the Global Core sequences offered by the College (3–4); in Semester IV, HUMA C1002, C1102 (4), or the second course in the Global Core sequence elected in Semester III (3–4); also in Semester IV, ECON W1105 (4) with W1105 recitation (0) and either HUMA C1121 or C1123 (3).

[2] Should be taken in Semester III, but may be moved upon adviser's approval to Semester V if CHEM C3543: Organic chemistry lab is taken in Semester III. This course fulfills the SEAS professional engineering elective requirement.

[3] Taking the first track in each row and E1102 in Semester II.

kinetics (CHEN E4130), and Advanced chemical engineering thermodynamics (CHEN E4130)/Statistical mechanics (CHAP E4120); and (2) 18 points of 4000- or 6000-level courses, approved by the graduate coordinator or research adviser, of which up to 6 may be *Master's research (CHEN 9400)*. Students with undergraduate preparation in physics, chemistry, biochemistry, pharmacy, and related fields may take advantage of a special program leading directly to the master's degree in chemical engineering. This program enables such students to avoid having to take all undergraduate courses in the bachelor's degree program.

Doctoral Degrees

The Ph.D. and D.E.S. degrees have essentially the same requirements. All students in a doctoral program must (1) earn satisfactory grades in the three core courses *(CHEN E4010, E4110, E4330, E4130/CHAP E4120);* (2) pass a qualifying exam; (3) defend a proposal of research within 12 months of passing the qualifying exam; (4) defend their thesis; and (5) satisfy course requirements beyond the three core courses. For detailed requirements, please consult the departmental office or graduate coordinator. Students with degrees

CHEMICAL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		CHEN E3110 (3) Transp. phenomena, I CHEE E3010 (3) Principles of chem. eng. thermodynamics CHEN E3020 (3) Analysis of chem. eng. problems, I	CHEN E3120 (3) Transp. phenomena, II CHEN E3210 (3) Chem. eng. thermodynamics CHEN E4230 (3) Reaction kinetics and reactor design	CHEN E4500 (4) Process and product design, I CHEE E4140 (3) Eng. separations processes	
REQUIRED LABS		CHEN C3543 (3)[1] Org. chem. lab		CHEN E4300 (2) Chem. eng. control	CHEN 3810 (3) Chem. eng. lab
REQUIRED ELECTIVES	NONTECH	3 points	3 points	3 points	
	TECH[2]	3 points	3 points	3 points	12 points
TOTAL POINTS (normal track)		18	15	15	15

[1] May be taken in Semester III with adviser's permission if CHEN E2100: Material and energy balances is taken in Semester V.

[2] The total of 21 points (7 courses) of required technical electives must include five engineering courses, two of which must be in chemical engineering and one must be outside chemical engineering, and 6 points (2 courses) of "advanced science" (i.e., courses in chemistry, physics, biology, and certain engineering courses, one of which must be outside engineering).

iin related fields such as physics, chemistry, biochemistry, and others are encouraged to apply to this highly interdisciplinary program.

Areas of Concentration

After satisfying the core requirement of *Chemical process analysis (CHEN E4010), Transport phenomena, III (CHEN E4110), Advanced chemical kinetics (CHEN E4330),* and *Advanced chemical engineering thermodynamics (CHEN E4130)/Statistical mechanics (CHAP E4120),* chemical engineering graduate students are free to choose their remaining required courses as they desire, subject to their research adviser's approval. However, a number of areas of graduate concentration are suggested below, with associated recommended courses. Each concentration provides students with the opportunity to gain in-depth knowledge about a particular research field of central importance to the department. Graduate students outside the department are very welcome to participate in these course concentrations, many of which are highly interdisciplinary. The department strongly encourages interdepartmental dialogue at all levels.

Science and Engineering of Polymers and Soft Materials. Soft materials include diverse organic media with supramolecular structure having scales in the range 1–100 nm. Their small-scale structure imparts unique, useful macroscopic properties. Examples include polymers, liquid crystals, colloids, and emulsions. Their "softness" refers to the fact that they typically flow or distort easily in response to moderate shear and other external forces. They exhibit a great many unique and useful macroscopic properties stemming from the variety of fascinating microscopic structures, from the simple orientational order of a nematic liquid crystal to the full periodic "crystalline" order of block copolymer mesophases. Soft materials provide ideal testing grounds for such fundamental concepts as the interplay between order and dynamics or topological defects. They are of primary importance to the paint, food, petroleum, and other industries as well as a variety of advanced materials and devices. In addition, most biological materials are soft, so that understanding of soft materials is very relevant to improving our understanding of cellular function and therefore human pathologies. At Columbia Chemical Engineering, we focus on several unique aspects of soft matter, such as their special surface and interfacial properties. This concentration is similar in thrust to that of the "Biophysics and Soft Matter" concentration, except here there is greater emphasis on synthetic rather than biological soft matter, with particular emphasis on interfacial properties and materials with important related applications. Synthetic polymers are by far the most important material in this class.

CHEE E4252: Introduction to surface and colloid chemistry
CHEN E4620: Introduction to polymers and soft materials
CHEN E4640: Polymer surfaces and interfaces
CHEN E6620y: Physical chemistry of macromolecules

CHEN E6910: Theoretical methods in polymer physics
CHEN E6920: Physics of soft matter

Biophysics and Soft Matter Physics. Soft matter denotes polymers, gels, self-assembled surfactant structures, colloidal suspensions, and many other complex fluids. These are strongly fluctuating, floppy, fluid-like materials that can nonetheless exhibit diverse phases with remarkable long-range order. In the last few decades, statistical physics has achieved a sound understanding of the scaling and universality characterizing large length scale properties of much synthetic soft condensed matter. More recently, ideas and techniques from soft condensed matter physics have been applied to biological soft matter such as DNA, RNA, proteins, cell membrane surfactant assemblies, actin and tubulin structures, and many others. The aim is to shed light on (1) fundamental cellular processes such as gene expression or the function of cellular motors and (2) physical mechanisms central to the exploding field of biotechnology involving systems such as DNA microarrays and methods such as genetic engineering. The practitioners in this highly interdisciplinary field include physicists, chemical engineers, biologists, biochemists, and chemists.

The “Biophysics and Soft Matter” concentration is closely related to the “Science and Engineering of Polymers and Soft Materials” concentration, but here greater emphasis is placed on biological materials and cellular biophysics. Both theory and experiment are catered to. Students will be introduced to statistical mechanics and its application to soft matter research and to cellular biophysics. In parallel, the student will learn about genomics and cellular biology to develop an understanding of what the central and fascinating biological issues are.

CHAP E4120: Statistical mechanics
CHEN E6920: Physics of soft matter
BIOC G6300: Biochemistry/molecular biology—eukaryotes, I
BIOC G6301: Biochemistry/molecular biology—eukaryotes, II
CHEN E4750: The genome and the cell
CMBS G4350: Cellular molecular biophysics

Genomic Engineering. Genomic engineering may be defined as the development and application of novel technologies for identifying and evaluating the significance of both selected and all nucleotide sequences in the genomes of organisms. An interdisciplinary course concentration in genomic engineering is available to graduate students, and to selected undergraduate students. The National Science Foundation is sponsoring the development of this concentration, which is believed to be the first of its kind. Courses in the concentration equip students in engineering and computer science to help solve technical problems encountered in the discovery, assembly, organization, and application of genomic information. The courses impart an understanding of the fundamental goals and problems of genomic science and gene-related intracellular processes; elucidate the physical, chemical, and instrumental principles available to extract sequence information from the genome; and teach the concepts used to organize, manipulate, and interrogate the genomic database.

The concentration consists of five courses that address the principal areas of genomic technology: sequencing and other means of acquiring genomic information; bioinformatics as a means of assembling and providing structured access to genomic information; and methods of elucidating how genomic information interacts with the developmental state and environment of cells in order to determine their behavior. Professor E. F. Leonard directs the program and teaches *CHEN E4750.* The other instructors are Profs. D. Anastassiou *(ECBM E4060),* Jingyue Ju *(CHEN E4700, E4730),* and C. Leslie *(CBMF W4761).* The Departments of Chemical, Biomedical, and Electrical Engineering and of Computer Science credit these courses toward requirements for their doctorates. Students may take individual courses so long as they satisfy prerequisite requirements or have the instructor’s permission. All lecture courses in the program are available through the Columbia Video Network, which offers a certificate for those students completing a prescribed set of the courses.

The course *Introduction to genomic information science and technology (ECBM E4060)* provides the essential concepts of the information system paradigm of molecular biology and genetics. *Principles of genomic technology (CHEN E4700)* provides students with a solid basis for understanding both the principles that underlie genomic technologies and how these principles are applied. The *Genomics sequencing laboratory (CHEN E4760)* provides hands-on experience in high-throughput DNA sequencing, as conducted in a bioscience research laboratory. *The genome and the cell (CHEN E4750)* conveys a broad but precise, organized, and quantitative overview of the cell and its genome: how the genome, in partnership with extragenomic stimuli, influences the behavior of the cell and how mechanisms within the cell enable genomic regulation. *Computational genomics (CBMF W4761)* introduces students to basic and advanced computational techniques for analyzing genomic data.

Interested parties can obtain further information, including a list of cognate courses that are available and recommended, from Professor Leonard (leonard@columbia.edu).

Interfacial Engineering and Electrochemistry. Electrochemical processes are key to many alternative energy systems (batteries and fuel cells), to electrical and magnetic-device manufacturing (interconnects and magnetic-storage media), and to advanced materials processing. Electrochemical processes are also involved in corrosion and in some waste-treatment systems. Key employers of engineers and scientists with knowledge of electrochemical/interfacial engineering include companies from the computer, automotive, and chemical industries. Knowledge of basic electrochemical principles, environmental sciences, and/or materials science can be useful to a career in this area.

CHEN E4201: Engineering applications of electrochemistry
CHEN E4252: Introduction to surface and colloid science
CHEN E6050: Advanced electrochemistry
CHEN E3900: Undergraduate research project

Bioinductive and Biomimetic Materials. This is a rapidly emerging area of research, and the department's course concentration is under development. At present, students interested in this area are recommended to attend *Polymer surfaces and interfaces (CHEN E4640);* and *Physical chemistry of macromolecules (CHEN E6620).* Other courses in the "Science and Engineering of Polymers and Soft Materials" concentration are also relevant. When complete, the concentration will include courses directly addressing biomaterials and immunological response.

COURSES IN CHEMICAL ENGINEERING

Note: Check the department website for the most current course offerings and descriptions.

CHEN E2100x Introduction to chemical engineering
3 pts. Lect: 3. Professor Chen.
Prerequisites: First year chemistry and physics, or equivalent. This course serves as an introduction to the chemical engineering profession. Students are exposed to concepts used in the analysis of chemical engineering problems. Rigorous analysis of material and energy balances on open and closed systems is emphasized. An introduction to important processes in the chemical and biochemical industries is provided.

CHEE E3010x Principles of chemical engineering thermodynamics
3 pts. Lect: 3. Professor Kumar.
Prerequisite: CHEM C1403. Corequisite: CHEN E3020. Introduction to thermodynamics. Fundamentals are emphasized: the laws of thermodynamics are derived and their meaning explained and elucidated by applications to engineering problems. Pure systems are treated, followed by an introduction to mixtures and phase equilibrium.

CHEN E3020x Analysis of chemical engineering problems
3 pts. Lect: 1.5. Lab: 1.5. Professor Ortiz.
Prerequisites: Vector calculus, ordinary differential equations. Corequisites: CHEE E3010, CHEN E3110. Computational solutions of chemical engineering problems in thermodynamics, transport phenomena, and reaction design.

CHEN E3110x Transport phenomena, I
3 pts. Lect: 3. Professor McNeill.
Prerequisites: mechanics, vector calculus, ordinary differential equations. Corequisite: CHEN E3020. Analysis of momentum and energy transport processes at molecular, continuum, and system scales for systems of simple fluids (gases and low-molecular-weight liquids). Molecular-level origins of fluid viscosity, continuum fluid mechanics analysis of laminar flows, and the resulting dimensionless correlations of kinematic and mechanical characteristics of a system needed for engineering design (e.g., friction factor vs. Reynolds number correlations). Molecular origins of fluid conductivity, continuum heat transfer analysis, and the resulting correlations of a system's thermal characteristics useful in engineering design (e.g., Nusselt number correlations). Examples are reviewed of analyses typical in chemical engineering technologies. Essential mathematical methods are reviewed or introduced in context.

CHEN E3120y Transport phenomena, II
3 pts. Lect: 3. Professor West.
Prerequisite: CHEN E3110. Corequisite: CHEN E3220. Developments in Transport I are extended to handle turbulence. Topics include: Turbulent energy cascade, wall-bounded turbulent shear flow, time-averaging of the equations of change, Prandtl's mixing length hypothesis for the Reynolds stress, the Reynolds analogy, continuum modeling of turbulent flows and heat transfer processes, friction factor, and Nusselt number correlations for turbulent conditions. Then, macroscopic (system-level) mass, momentum, and energy balances for one-component systems are developed and applied to complex flows and heat exchange processes. The final part focuses on mass transport in mixtures of simple fluids: Molecular-level origins of diffusion phenomena, Fick's law and its multi-component generalizations, continuum-level framework for mixtures and its application to diffusion dominated processes, diffusion with chemical reaction, and forced/free convection mass transport.

CHEN E3210y Chemical engineering thermodynamics
3 pts. Lect: 3. Professor Koberstein.
Prerequisites: CHEE E3010 and CHEN E3100. Corequisite: CHEN E3220. This course deals with fundamental and applied thermodynamic principles that form the basis of chemical engineering practice. Topics include phase equilibria, methods to treat ideal and nonideal mixtures, and estimation of properties using computer-based methods.

BMCH E3500y Transport in biological systems
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEM C3443 and MATH E1210. Corequisites: BIOL C2005. Convective and diffusive movement and reaction of molecules in biological systems. Kinetics of homogeneous and heterogeneous reactions in biological environments. Mechanisms arid models of transport across membranes. Convective diffusion with and without chemical reaction. Diffusion in restricted spaces. Irreversible thermodynamic approaches to transport and reaction in biological systems.

CHEN E3810y Chemical engineering laboratory
3 pts. Lab: 3. Professor Ju.
Prerequisites: Completion of core chemical engineering curricula through the fall semester of senior year (includes: CHEN E3110, E3120, E4230, E3100, E3010, E3210, E4140, E4500), or instructor's permission. The course emphasizes active, experiment-based resolution of open-ended problems involving use, design, and optimization of equipment, products, or materials. Under faculty guidance students formulate, carry out, validate, and refine experimental procedures, and present results in oral and written form. The course develops analytical, communications, and cooperative problem-solving skills in the context of problems that span from traditional, large scale separations and processing operations to molecular level design of materials or products. Sample projects include: scale up of apparatus, process control, chemical separations, microfluidics, surface engineering, molecular sensing, and alternative energy sources. Safety awareness is integrated throughout the course.

CHEN E3900x and y Undergraduate research project
1–6 pts. Members of the faculty.
Candidates for the B.S. degree may conduct an investigation of some problem in chemical engineering or applied chemistry or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report. No more than 6 points in this course may be counted toward the satisfaction of the B.S. degree requirements.

CHEN E4001x Essentials of chemical engineering—A
3 pts. Lect: 3. Professor West.
Prerequisites: First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor's permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Reaction Kinetics and Reactor Design, Chemical Engineering Thermodynamics, I and II, and Chemical and Biochemical Separations. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

CHEN E4002x Essentials of chemical engineering—B
3 pts. Lect: 3. Professor West.
Prerequisites: First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor's permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Chemical Engineering Thermodynamics, I and II, Chemical and Biochemical Separations. Reaction Kinetics and Reactor Design. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

CHEN E4010y Mathematical methods in chemical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: CHEN E3120 and E4230, or equivalent, or instructor's permission. Mathematical description of chemical engineering problems and the application of selected methods for their solution. General modeling principles, including model hierarchies. Linear and nonlinear ordinary differential equations and their systems, including those with variable coefficients. Partial differential equations in Cartesian and curvilinear coordinates for the solution of chemical engineering problems.

CHEN E4020y Protection of industrial and intellectual property
3 pts. Lect: 3. Instructor to be announced.
To expose engineers, scientists and technology managers to areas of the law they are most likely to be in contact with during their career. Principals are illustrated with various case studies together with active student participation.

CHEE E4050y Principles of industrial electrochemistry
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEE E3010 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications illustrated by means of laboratory experiments: electroplating, refining, and winning in aqueous solutions and in molten salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

CHEN E4110y Transport phenomena, III
3 pts. Lect: 3. Professor Durning.
Prerequisite: CHEN E3120. Tensor analysis; kinematics of continua; balance of laws for one-component media; constituitive laws for free energy and stress in one-component media; exact and asymptotic solutions to dynamic problems in fluids and solids; balance laws for mixtures; constitutive laws for free energy, stress and diffusion fluxes in mixtures; solutions to dynamic problems in mixtures.

CHEN E4115y Topics in transport phenomena
3 pts. Instructor to be announced.
Prerequisites: Undergraduate fluid mechanics, or transport phenomena, or instructor's permission. Self-contained treatments of selected topics in transport phenomena (e.g., rheology, nonequilibrium thermodynamics, molecular-level aspects of transport turbulence). Topics and instrutor may change from year to year. Intended for junior/senior level undergraduates and graduate students in engineering and the physical sciences.

CHAP E4120y Statistical mechanics
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisites: CHEE E3010 or equivalent thermodynamics course, or instructor's permission. Fundamental principles and underlying assumptions of statistical mechanics. Boltzmann's entropy hypothesis and its restatement in terms of Helmholtz and Gibbs free energies and for open systems. Correlation times and lengths. Exploration of phase space and observation timescale. Correlation functions. Fermi-Dirac and Bose-Einstein statistics. Fluctuation-response theory. Applications to ideal gases, interfaces, liquid crystals, microemulsions and other complex fluids, polymers, Coulomb gas, interactions between charged polymers and charged interfaces, ordering transitions.

CHEN E4130x Advanced chemical engineering thermodynamics
3 pts. Lect: 3. Professor Koberstein.
Prerequisite: Successful completion of an undergraduate thermodynamics course. The course provides a rigorous and advanced foundation in chemical engineering thermodynamics suitable for chemical engineering Ph.D. students expected to undertake diverse research projects. Topics include intermolecular interactions, nonideal systems, mixtures, phase equilibria and phase transitions and interfacial thermodynamics.

CHEN E4140x Engineering separations processes
3 pts. Lect: 3. Professor Durning.
Prerequisites: CHEN E3100, E3120, and E3210 or permission of instructor. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

CHEN E4201x Engineering applications of electrochemistry
3 pts. Lect: 3. Professor West.
Prerequisites: Physical chemistry and a course in transport phenomena. Engineering analysis of electrochemical systems, including electrode kinetics, transport phenomena, mathematical modeling, and thermodynamics. Common experimental methods are discussed. Examples from common applications in energy conversion and metallization are presented.

CHEN E4230y Reaction kinetics and reactor design
3 pts. Lect: 3. Professor Banta.
Prerequisites: CHEE E3010. Reaction kinetics, applications to the design of batch and continuous reactors. Multiple reactions, nonisothermal reactors. Analysis and modeling of reactor behavior. Recitation section required.

CHEN E4231 Solar fuels
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Graduate standing or CHEN E4230. Fundamentals and applications of solar energy conversion, especially technologies for conversion of sunlight into storable chemical energy or solar fuels. Topics include fundamentals of photoelectrochemistry, kinetics of solar fuels production, solar harvesting technologies, solar reactors, and solar thermal production of solar fuels. Applications include solar fuels technology for grid-scale energy storage, chemical industry, manufacturing, environmental remediation.

CHEE E4252x Introduction to surface and colloid chemistry
3 pts. Lect: 3. Professor Somasundaran.
Prerequisites: Elementary physical chemistry. Thermodynamics of surfaces, properties of surfactant solutions and surface films, electrostatic and electrokinetic phenomena at interfaces, adsorption; interfacial mass transfer and modern experimental techniques.

CHEN E4300x Chemical engineering control
2 pts. Lab: 2. Professors Venkatasubramanian and Bedrossian.
Prerequisites: Material and energy balances. Ordinary differential equations including Laplace transforms. Reactor Design. An introduction to process control applied to chemical engineering through lecture and laboratory. Concepts include the dynamic behavior of chemical engineering systems, feedback control, controller tuning, and process stability.

CHEN E4320y Molecular phenomena in chemical engineering
3 pts. Lect: 3. Not offered im 2015–2016.
Prerequisites: CHEN E3120 or instructor's permission. This course introduces a molecular-level understanding of topics in modern chemical engineering. It builds upon and validates the concepts presented in the rest of the chemical engineering curriculum via a molecular perspective.

CHBM E4321x The genome and the cell
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: BIOL C2005, MATH E1210. The utility of genomic information lies in its capacity to predict the behavior of living cells in physiological, developmental, and pathological situations. The effect of variations in genome structure between individuals within a species, including those deemed healthy or diseased, and among species, can be inferred statistically by comparisons of sequences with behaviors, and mechanistically, by studying the action of molecules whose structure is encoded within the genome. This course examines known mechanisms that elucidate the combined effect of environmental stimulation and genetic makeup on the behavior of cells in homeostasis, disease states, and during development, and includes assessments of the probable effect of these behaviors on the whole organism. Quantitative models of gene translation and intracellular signal transduction will be used to illustrate switching of intracellular processes, transient and permanent gene activation, and cell commitment, development, and death.

CHEN E4330x Advanced chemical kinetics
3 pts. Lect: 3. Professor Esposito.
Prerequisite: CHEN E4230 or instructor's permission. Complex reactive systems. Catalysis. Heterogeneous systems, with an emphasis on coupled chemical kinetics and transport phenomena. Reactions at interfaces (surfaces, aerosols, bubbles). Reactions in solution.

CHEN E4400x Chemical process development
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: CHEM C3443 or equivalent or instructor's permission. Process development for new compounds, including fine and specialty chemicals, pharmaceuticals, biologicals, and agrochemicals. Experimental strategy and methods for process scale-up from bench to pilot plant. Evaluation of process economis. Hazard and risk evaluation for environmental and industrial hygiene safety. Capture and use of process know-how for process and plant design, regulatory approvals, and technology transfer to first manufacture.

CHEN E4410x Environmental control technology
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEN E3010x or the equivalent. Causes of pollution and effect on life. Legal aspects, OSHA and EPA rules. Pollution at home and at work; radon, fumes, and dust; ventilation, dust collection, carbon adsorption. Fuel and acid gases, smog and dispersion. Treatment of ground, saline, and wastewater. Primary and secondary (biological) treatment. Tertiary water treatment with membranes, ion excahnge, carbon, and sieves. Solid hazardous waste. Visit New York City wastewater treatment plant.

CHEN E4500x Process and product design, I
4 pts. Lect: 4. Professor Bozic.
Prerequisites: CHEN E2100x, CHEN E4140x. The practical application of chemical engineering principles for the design and economic evaluation of chemical processes and plants. Use of ASPEN Plus for complex material and energy balances of real processes. Students are expected to build on previous course work to identify creative solutions to two design projects of increasing complexity. Each design project culminates in an oral presentation, and in the case of the second project, a written report.

CHEN E4501y Chemical engineering process safety
3 pts. Lect.: 3. Professor Bozic.
Aimed at seniors and graduate students. Provides classroom experience on chemical engineering process safety as well as Safety in Chemical Engineering certification. Process safety and process control emphasized. Application of basic chemical engineering concepts to chemical reactivity hazards, industrial hygiene, risk assessment, inherently safer design, hazard operability analysis, and engineering ethics. Application of safety to full spectrum of chemical engineering operations.

CHEN E4510y Process and product design, II
4 pts. Lect: 4. Professors Koberstein, Joback, and Venkatasubramanian.
Prerequisite: CHEN E4500. Students carry out a semester long process or product design course with significant industrial involvement. The project culminates with a formal written design report and a public presentation. Recitation section required.

CHEE E4530y Corrosion of metals
3 pts. Lect: 3. Professor Duby.
Prerequisite: CHEE E3010 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

CHEN E4540y Energy and process integration
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E4500 or equivalent. Energy optimization of chemical processes through identification of thermodynamically attainable minimum energy targets. Energy cascade diagrams. Composite curves. Identification of energy saving opportunities. Maximum energy recovery networks. Euler's Principle. Capital cost targeting. Introduction to combined heat and power site integration.

CHEN E4600x Atmospheric aerosols
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E3120 or instructor's permission. Atmospheric aerosols and their effects on atmospheric composition and climate. Major topics are aerosol sources and properties, field and laboratory techniques for characterization, gas-aerosol interactions, secondary organic aerosols, aerosol direct and indirect effects on climate.

CHEN E4610y Chemical product design
3 pts. Lect: 3. Professor Joback
Prerequisite: CHEN E3210 and CHEM C3443 or equivalent, or instructor's permission. Application of chemical and engineering knowledge to the design of new chemical products. Relationships between composition and physical properties. Strategies for achieving desired volumetric, rheological, phase equilibrium, thermal, and environmental behavior. Case studies, including separation solvents, blood substitutes, refrigerants, and aircraft deicing fluids.

CHEN E4620y Introduction to polymers and soft materials
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: An elementary course in physical chemistry or thermodynamics. Organic chemistry, statistics, calculus and mechanics are helpful, but not essential. An introduction to the chemistry and physics of soft material systems (polymers, colloids, organized surfactant systems and others), emphasizing the connection between microscopic structure and macroscopic physical properties. To develop an understanding of each system, illustrative experimental studies are discussed along with basic theoretical treatments. High molecular weight organic polymers are discussed first (basic notions, synthesis, properties of single polymer molecules, polymer solution and blend thermodynamics, rubber and gels). Colloidal systems are treated next (dominant forces in colloidal systems, flocculation, preparation and manipulation of colloidal systems) followed by a discussion of self-organizing surfactant systems (architecture of surfactants, micelles and surfactant membranes, phase behavior).

CHEN E4630y Topics in soft materials
3 pts. Instructor to be announced.
Prerequisite: Physical chemistry or instructor's permission. Self-contained treatments of selected topics in soft materials (e.g., polymers, colloids, amphiphiles, liquid crystals, glasses, powders). Topics and instructor may change from year to year. Intended for junior/senior level undergraduates and graduate students in engineering and the physical sciences.

CHEN E4640x Polymer surfaces and interfaces
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E4620 or consent of instructor. A fundamental treatment of the thermodynamics and properties relating to polymer surfaces and interfaces. Topics include the characterization of interfaces, theoretical modeling of interfacial thermodynamics and structure, and practical means for surface modification.

CHEN E4645x Inorganic polymers, hybrid materials and gels
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Organic chemistry. The focus of the first part of the course, taught by Prof. Mark, is on the preparation, characterization, and applications of inorganic ploymers, with a heavy emphasis on those based on main-group elements. Main topics are characterization methods, polysiloxanes, polysilanes, polyphosphazenes, ferrocene-based polymers, other phosphorous-containing polymers, boron-containing polymers, preceramic inorganic polymers, and inorganic-organic hybrid composites. The focus of the second part of the course, taught by Prof. Koberstein, is on gels, both physical and chemical. Topics will include gel chemistry, including epoxies, polyurethanes, polyester, vinyl esters and hydrogels, as well as theoretical methods used to characterize the gel point and gel properties.

CHEN E4650y Polymer physics
3 pts. Lect.: 3. Professor Kumar.
Prerequisites: CHEE E3110, CHEN E3120 and E4620. Senior undergraduate/first-year graduate course on the physics of polymer systems. Topics include scaling behavior of chains under different conditions, mixing thermodynamics, networks and geation, polymer dynamics, including retation and entanglements. Special topics: nanocomposites.

CHEN E4660x Biochemical engineering
3 pts. Lect.: 3. Professor Leonard.
Prerequisite: CHEN E4320 or instructor's permission. Engineering of biochemical and microbiological reaction systems. Kinetics, reactor analysis, and design of batch and continuous fermentation and enzyme processes. Recovery and separations in biochemical engineering systems.

CHEN E4680x Soft materials laboratory
3 pts. Lect/lab: 3. Not offered in 2015–2016.
Prerequisites: Two years of undergraduate science courses and the instructor's permission.

Corequisites: Limited to 15 students. Covers modern characterization methods for soft materials (polymers, complex fluids, biomaterials). Techniques include differential scanning calorimetry, dynamic light scattering, gel permeation chromatography, rheology, and spectroscopic methods. Team-taught by several faculty and open to graduate and advanced undergraduate students. Lab required.

CHEN E4690y Managing systemic risk in complex systems
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E4300 or equivalent, or instructor's permission. Fundamental concepts and tools of process systems engineering for modeling, analyzing, and managing enterprise-wide risk in complex systems. Case studies present important systemic failures in different domains and their lessons. Develop and analyze risk models for real-life-inspired case studies.

CHEN E4700x Principles of genomic technologies
3 pts. Lect: 3. Professor Ju.
Prerequisites: Undergraduate-level biology, organic chemistry, and instructor's permission. Chemical and physical aspects of genome structure and organization, genetic information flow from DNA to RNA to protein. Nucleic acid hybridization and sequence complexity of DNA and RNA. Genome mapping and sequencing methods. The engineering of DNA polymerase for DNA sequencing and polymerase chain reaction. Fluorescent DNA sequencing and high-throughput DNA sequencer development. Construction of gene chip and micro array for gene expression analysis. Technology and biochemical approach for functional genomics analysis. Gene discovery and genetics database search method. The application of genetic database for new therapeutics discovery.

CHEN E4740x Biological transport and rate phenomena, II
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Any two of the following: CHEN E3110; BIOL C2005; CHEN E3210 or BMCH E3500. Analysis of transport and rate phenomena in biological systems and in the design of biomimetic transport-reaction systems for technological and therapeutic applications. Modeling of homogeneous and heterogeneous biochemical reactions. The Bases of biological transport: roles of convection, ordinary diffusion, forced diffusion. Systems where reaction and transport interact strongly. Applications to natural and artificial tissue beds, tumor modeling, controlled release, natural and artificial organ function.

CHEN E4760y Genomics sequencing laboratory
3 pts. Lect: 1. Lab: 2. Not offered in 2015–2016.
Prerequisites: Undergraduate level biology, organic chemistry, and instructor's permission. The chemical, biological and engineering principles involved in the genomics sequencing process will be illustrated throughout the course for engineering students to develop the hands-on skills in conducting genomics research.

CHEN E4780x or y Quantitative methods in cell biology
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisites: Elementary calculus, physics and biology, or instructor's permission. Quantitative statistical analysis and mathematical modeling in cell biology for an audience with diverse backgrounds. The course presents quantitative methods needed to analyze complex cell biological experimental data and to interpret the analysis in terms of the underlying cellular mechanisms. Optical and electrical experimental methods to study cells and basic image analysis techniques are described. Methods of statistical analysis of experimental data and techniques to test and compare mathematical models against measured statistical properties will be introduced. Concepts and techniques of mathematical modeling will be illustrated by applications to mechanosensing in cells, the mechanics of cytokinesis during cell division and synaptic transmission in the nervous system. Image analysis, statistical analysis, and model assessment will be illustrated for these systems.

CHEN E4800x Protein engineering
3 pts. Lect: 3. Professor Banta.
Prerequisite: CHEN E4230, may be taken concurrently, or the instructor's permission. Fundamental tools and techniques currently used to engineer protein molecules. Methods used to analyze the impact of these alterations on different protein functions with specific emphasis on enzymatic catalysis. Case studies reinforce concepts covered, and demonstrate the wide impact of protein engineering research. Application of basic concepts in the chemical engineering curriculum (reaction kinetics, mathematical modeling, thermodynamics) to specific approaches utilized in protein engineering.

BMCH E4810y Artificial organs
3 pts. Lect: 3. Professor Leonard.
Analysis and design of replacements for the heart, kidneys, and lungs. Specification and realization of structures for artificial organ systems.

CHEN E6050x Advanced electrochemistry
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

CHEE E6220y Equilibria and kinetics in hydrometallurgical systems
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

CHEE E6252y Applied surface and colloid chemistry
3 pts. Lect: 2. Lab: 3. Professor Somasundaran.
Prerequisites: CHEN 4252. Applications of surface chemistry principles to wetting, flocculation, flotation, separation techniques, catalysis, mass transfer, emulsions, foams, aerosols, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects. Lab required.

CHEN E6620y Physical chemistry of macromolecules
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E4620 or the instructor's permission. Modern studies of static and dynamic behavior in macromolecular systems. Topics include single-chain behavior adsorption, solution thermodynamics, the glass transition, diffusion, and viscoelastic behavior. The molecular understanding of experimentally observed phenomena is stressed.

CHEN E8001 M.S. chemical engineering colloquium
0 pts. Professor West.
Required for all M.S. students in residence in their first semester. Topics related to professional development and the practice of chemical engineering are discussed. No degree credit is granted. This course is not intended for M.S./Ph.D. students or doctoral students.

CHEN E8100y Topics in biology
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisites: Instructor's permission. This research seminar introduces topics at the forefront of biological research in a format and language accessible to quantitative scientists and engineers lacking biological training. Conceptual and technical frameworks from both biological and physical science disciplines are utilized. The objective is to reveal to graduate students where potential lies to apply techniques from their own disciplines to address pertinent biological questions in their research. Classes entail reading, criticism and group discussion of research papers and textbook materials providing overviews to various biological areas including: evolution, immune system, development and cell specialization, the cytoskeleton and cell motility, DNA transcription in gene circuits, protein

networks, recombinant DNA technology, aging, and gene therapy.

CHEN E9000x and y Chemical engineering colloquium
0 pts. Col: 1. Professor McNeill.
All graduate students are required to attend the department colloquium as long as they are in residence. No degree credit is granted.

CHEN E9001x M.S. Chemical engineering colloquium
0 pts. Lect.: 1. Professor Bozic.
Required for all M.S. students in residence in their first semester. Topics related to professional development and the practice of chemical engineering. No degree credits granted. Intended for M.S./Ph.D. students or doctoral students.

CHEN E9400x and y Master's research
1–6 pts. Members of the faculty.
Prescribed for M.S. and Ch.E. candidates; elective for others with the approval of the Department. Degree candidates are required to conduct an investigation of some problem in chemical engineering or applied chemistry and to submit a thesis describing the results of their work. No more than 6 points in this course may be counted for graduate credit, and this credit is contingent upon the submission of an acceptable thesis. The concentration in pharmaceutical engineering requires a 2-point thesis internship.

CHEN E9500x and y–S9500 Doctoral research
1–15 pts. Members of the faculty.
Prerequisites: The qualifying examinations for the doctorate. Open only to certified candidates for the Ph.D. and Eng.Sc.D. degrees. Doctoral candidates in chemical engineering are required to make an original investigation of a problem in chemical engineering or applied chemistry, the results of which are presented in their dissertations. No more than 15 points of credit toward the degree may be granted when the dissertation is accepted by the department.

CHEN E9600x and y Advanced research problems
2–10 pts. Members of the faculty.
Prerequisites: Recommendation of the professor concerned and approval of the master's research department. For postdoctoral students and other qualified special students who wish to pursue research under the guidance of members of the department. Not open to undergraduates or to candidates for the degrees of Ch.E., M.S., Ph.D., or Eng.Sc.D.

CHEN E9800x and y Doctoral research instruction
3, 6, 9 or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in chemical engineering must register for 12 points of doctoral research instruction. Registration in CHEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

CHEN E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
Open only to certified doctoral candidates. A candidate for the doctorate in chemical engineering may be required to register for this course in every term after the student's course work has been completed, and until the dissertation has been accepted.

CIVIL ENGINEERING AND ENGINEERING MECHANICS

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The Department of Civil Engineering and Engineering Mechanics focuses on two broad areas of instruction and research. The first, the classical field of civil engineering, deals with the planning, design, construction, and maintenance of the built environment. This includes buildings, foundations, bridges, transportation facilities, nuclear and conventional power plants, hydraulic structures, and other facilities essential to society. The second is the science of mechanics and its applications to various engineering disciplines. Frequently referred to as applied mechanics, it includes the study of the mechanical and other properties of materials, stress analysis of stationary and movable structures, the dynamics and vibrations of complex structures, aero- and hydrodynamics, and the mechanics of biological systems.

MISSION

The department aims to provide students with a technical foundation anchored in theory together with the breadth needed to follow diverse career paths, whether in the profession via advanced study or apprenticeship, or as a base for other pursuits.

Current Research Activities

Current research activities in the Department of Civil Engineering and Engineering Mechanics are centered in the areas outlined below. A number of these activities impact directly on problems of societal importance, such as rehabilitation of the infrastructure, mitigation of natural or man-made disasters, and environmental concerns.

Solid mechanics: mechanical properties of new and exotic materials, constitutive equations for geologic materials, failure of materials and components, properties of fiber-reinforced cement composites, damage mechanics.

Multihazard risk assessment and mitigation: integrated risk studies of the civil infrastructure form a multihazard perspective including earthquake, wind, flooding, fire, blast, and terrorism. The engineering, social, financial, and decision-making perspectives of the problem are examined in an integrated manner.

Probabilistic mechanics: random processes and fields to model uncertain loads and material/soil properties, nonlinear random vibrations, reliability and safety of structural systems, computational stochastic mechanics, stochastic finite element and boundary element techniques, Monte Carlo simulation techniques, random micromechanics.

Structural control and health monitoring: topics of research in this highly cross-disciplinary field include the development of “smart” systems for the mitigation and reduction of structural vibrations, assessment of the health of structural systems based on their vibration response signatures, and the modeling of nonlinear systems based on measured dynamic behavior.

Fluid mechanics: numerical simulation of flow and transport processes, turbulence and turbulent mixing, urban canopy flow and transport processes, natural and mixed mode ventilation, wind loading, solid-laden turbulent flows, porous surface turbulence, flow through porous media, flow and transport in fractured rock.

Environmental engineering/water resources: modeling of flow and pollutant transport in surface and subsurface waters, unsaturated zone hydrology, geoenvironmental containment systems, analysis of watershed flows including reservoir simulation.

Structures: dynamics, stability, and design of structures, structural failure and damage detection, fluid and soil structure interaction, ocean structures subjected to wind-induced waves, inelastic dynamic response of reinforced concrete structures, earthquake-resistant design of structures.

Geotechnical engineering: soil behavior, constitutive modeling, reinforced soil structures, geotechnical earthquake engineering, liquefaction and numerical analysis of geotechnical systems.

Structural materials: cement-based materials, micro- and macromodels of fiber-reinforced cement composites, utilization of industrial by-products and waste materials, beneficiation of dredged material.

Earthquake engineering: response of structures to seismic loading, seismic risk analysis, active and passive control of structures subject to earthquake excitation, seismic analysis of long-span cable-supported bridges.

Flight structures: composite materials, smart and multifunctional structures, multiscale and failure analysis, vibration control, computational mechanics and finite element analysis, fluid-structure interaction, aeroelasticity, optimal design, and environmental degradation of structures.

Advanced materials: multifunctional engineering materials, advanced energy materials, durable infrastructure materials, new concretes/composites using nanotubes, nanoparticles, and other additives with alternative binders, sustainable manufacturing technologies, rheological characterization for advanced cement/concrete placement processes.

Computational mechanics: aimed at understanding and solving problems in science and engineering, topics include multiscale methods in space and time (e.g., homogenization and multigrid methods); multiphysics modeling; material and geometric nonlinearities; strong and weak discontinuities (e.g., cracks and inclusions); discretization techniques (e.g., extended finite element methods and mixed formulations); verification and validation (e.g., error analysis); software development and parallel computing.

Multiscale mechanics: solving various engineering problems that have important features at multiple spatial and temporal scales, such as predicting material properties or system behavior based on information from finer scales; focus on information reduction methods that provide balance between computational feasibility and accuracy.

Construction engineering and management: contracting strategies; alternative project delivery systems; minimizing project delays and disputes; advanced technologies to enhance productivity and efficiency; strategic decisions in global engineering and construction markets; industry trends and challenges.

Infrastructure delivery and management: decision support systems for infrastructure asset management; assessing and managing infrastructure assets and systems; capital budgeting processes and decisions; innovative financing methods; procurement strategies and processes; data management practices and systems; indicators of infrastructure performance and service; market analysis.

FACILITIES

The offices and laboratories of the department are in the S. W. Mudd Building and the Engineering Terrace.

Computing

The department manages a substantial computing facility of its own in addition to being networked to all the systems operated by the University. The department facility enables its users to perform symbolic and numeric computation, three-dimensional graphics, and expert systems development. Connections to wide-area networks allow the facility's users to communicate with centers throughout the world. All faculty and student offices and department laboratories are hardwired to the computing facility, which is also accessible remotely to users. Numerous personal computers and graphics terminals exist throughout the department, and a PC lab is available to students in the department in addition to the larger school-wide facility.

Laboratories

Robert A. W. Carleton Strength of Materials Laboratory

The Carleton Laboratory serves as the central laboratory for all experimental work performed in the Department of Civil Engineering and Engineering Mechanics. It is the largest laboratory at Columbia University's Morningside campus and is equipped for teaching and research in all types of engineering materials and structural elements, as well as damage detection, fatigue, vibrations, and sensor networks. The Laboratory has a full-time staff who provide assistance in teaching and research. The Laboratory is equipped with a strong floor that allows for the testing of full-scale structural components such as bridge decks, beams, and columns. Furthermore, it is equipped with universal testing machines ranging in capacity from 150 kN (30,000 lbs.) to 3 MN (600,000 lbs.). The seamless integration of both research and teaching in the same shared space allows civil engineering students of all degree tracks to gain a unique appreciation of modern experimental approaches to material science and engineering mechanics.

The Carleton Laboratory serves as the hub of instruction for classes offered by the Department of Civil Engineering and Engineering Mechanics, most prominently ENME E3114 Experimental Mechanics of Materials, ENME E3106 Dynamics and Vibrations, and CIEN E3141 Soil Mechanics. The Laboratory also hosts and advises the AISC Steel Bridge Team in the design, fabrication, and construction phases of their bridge, which goes to regional and national competition annually.

Additionally, the Carleton Laboratory has a fully outfitted machine shop capable of machining parts, fittings, and testing enclosures in steel, nonferrous metals, acrylic, and wood. The Carleton Machine Shop's machine tool pool is state-of-the-art, either of the latest generation or recently rebuilt and modernized. The machine shop is open for use by undergraduate students performing independent research and is supported by the Lab's senior lab technician.

The Donald M. Burmister Soil Mechanics Laboratory

The Burmister Laboratory contains equipment and workspace to carry out all basic soil mechanics testing for our undergraduate and graduate programs. Several unique apparatuses have been acquired or fabricated for advanced soil testing and research: automated plain strain/triaxial apparatus for stress path testing at both drained and un-drained conditions, direct sheer device for minimum compliance, and a unique sand hopper which prepares foundations and slopes for small scale model testing. The Laboratory has established a link and cooperation for large-scale testing for earthquake and geosynthetic applications with NRIAE, the centrifuge facilities at the Rensselaer Polytechnic Institute and the Tokyo Institute of Technology.

The Heffner Hydrologic Research Laboratory

The Heffner Laboratory is a facility for both undergraduate instruction and research in aspects of fluid mechanics, environmental applications, and water resources. The Heffner Laboratory houses the facilities for teaching the laboratory component of the ENME E3161 Fluid Mechanics course and includes multiple hydraulic benches with a full array of experimental modules.

The Eugene Mindlin Laboratory for Structural Deterioration Research

The Mindlin Laboratory has been developed for teaching and research dedicated to all facets of the assessment of structures, deterioration of structural performance and surface coatings, dynamic testing for earthquakes, and other applications. The commissioning of a state-of-the-art 150 kN Instron universal testing machine, a QUV ultraviolet salt spray corrosion system, a freeze-thaw tester, a Keyence optical microscope and surface analyzer have further expanded the Mindlin Laboratory's capabilities in material testing and characterization. The Mindlin Laboratory also serves as a state-of-the-art medium scale non-destructive structural health monitoring facility, allowing the conduct of research in the assessment of our nation's degrading civil infrastructure.

The Institute of Flight Structures

The Institute of Flight Structures was established within the department through a grant by the Daniel and Florence Guggenheim Foundation. It provides a base for graduate training in aerospace and aeronautical related applications of structural analysis and design.

Center for Infrastructure Studies

The Center was established in the department to provide a professional environment for faculty and students from a variety of disciplines to join with industry and government to develop and apply the technological tools and knowledge bases needed to deal with the massive problems of the city, state, and regional infrastructure. The Center is active in major infrastructure projects through a consortium of universities and agencies.

UNDERGRADUATE PROGRAMS

The Department of Civil Engineering and Engineering Mechanics focuses on two broad areas of instruction and research. The first, the classical field of civil engineering, deals with the planning, design, construction, and maintenance of structures and the infrastructure. These include buildings, foundations, bridges, transportation facilities, nuclear and conventional power plants, hydraulic structures, and other facilities essential to society. The second is the science of mechanics and its applications to various engineering disciplines. Frequently referred to as applied mechanics, it includes the study of the mechanical properties of materials, stress analysis of stationary and movable structures, the dynamics and vibrations of complex structures, aero- and hydrodynamics, micro- and nanomechanics, and the mechanics of biological and energy systems.

Program Objectives

1. Graduates with a broad and fundamental technical base will be able to enter the professional civil engineering workforce either with a B.S. to develop specialized expertise by way of apprenticeship or through the increasingly common path of a specialized M.S.

2. Graduates with a firm foundation in the basic math, science, and engineering science which underlie all technological development will be well equipped to adapt to changing technology in the profession.

3. Graduates equipped with a broad technical background will be able to follow other technical or nontechnical career paths.

4. Graduates will practice their profession with effective writing and communication skills, with professional ethics, as well as with awareness of societal issues.

Engineering Mechanics

The prerequisites for this program are the courses listed in the First Year–Sophomore Program (page 95) or their equivalents, with the provision that *ENME E3105: Mechanics* be taken in the sophomore year and that the student have obtained a grade of B or better.

Civil Engineering

The prerequisites for this program are the courses listed in the First Year–Sophomore Program (page 93) or their equivalents. The civil engineering program offers three areas of concentration: civil engineering and construction management, geotechnical engineering or structural engineering, and water resources/environmental engineering. In the junior and senior years, 15 credits of technical electives are allocated.

Minor in Architecture

Civil engineering program students may want to consider a minor in architecture (see page 200).

CIVIL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	APMA E2101 (3) Intro. to applied math.
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Lab C1493 (3) or chem. lab Lab W3081 (2)	
CHEMISTRY	one-semester lecture (3–4): C1403 **or** C1404 **or** C3045 **or** C1604 Chem lab C1500 (3) either semester **or** physics lab			
GEOLOGY	EESC V1011 (4) or EESC W4001 (4)			
MECHANICS	ENME-MECE E3105 (4) either semester			
CIVIL ENGINEERING	CIEN E1201 (3) (recommended but not required)			CIEN E3004 (3) Urban infra. systems
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
COMPUTER SCIENCE	Computer Language: W1005 (3) (any semester)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

GRADUATE PROGRAMS

The Department of Civil Engineering and Engineering Mechanics offers graduate programs leading to the degree of Master of Science (M.S.) and the degrees of Doctor of Engineering Science (Eng.Sc.D.) and Doctor of Philosophy (Ph.D.). These programs are flexible and may involve concentrations in structures, construction engineering, reliability and random processes, soil mechanics, fluid mechanics, hydrogeology, continuum mechanics, finite element methods, computational mechanics, experimental mechanics, vibrations and dynamics, earthquake engineering, forensic structural engineering, or any combination thereof, such as fluid-structure interaction.

The Graduate Record Examination (GRE) is required for admission to the department.

Civil Engineering

By selecting technical electives, students may focus on one of several areas of concentration or prepare for future endeavors such as architecture. Some typical concentrations are:

- **Structural engineering:** applications to steel and concrete buildings, bridges, and other structures
- **Geotechnical engineering:** soil mechanics, foundation engineering, tunneling, and geodisasters
- **Construction engineering and management:** capital facility planning and financing, strategic management, managing engineering and construction processes, construction industry law, construction techniques, managing civil infrastructure systems, civil engineering and construction entrepreneurship
- **Environmental engineering and water resources:** transport of water-borne substances, hydrology, sediment transport, hydrogeology, and geoenvironmental design of containment systems

CIVIL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES		ENME E3113 (3) Mech. of solids ENME E3161 (4) Fluid mech.	CIEN E3125 (3) Structural design CIEN E3126 (1) Computer-aided struct. design CIEN E3141 (4) Soil mech.	CIEN E3111 (3.5) Uncertainty and risk in civil infrastructure systems CIEN E3129 (3) Proj. mgmt. for construction	CIEN E3128 (4) Design projects
CONCENTRATIONS	GEOTECH ENG. (GE) OR STRUCT. ENG. (SE)	ENME E3106 (3) Dynamics and vibrations	ENME E3114 (4) Exper. mech. of materials CIEN E3121 (3) Struct. anal.	ENME E3332 (3) A first course in finite elements CIEN E3127 (3) Struct. design projects (SE) **or** CIEN E4241 (3) Geotech. eng. fund. (GE)	
	TECH ELECTIVES	3 points		3 points	9 points
	CIVIL ENG. AND CONSTR. MGMT.		ENME E3114 (4) Exper. mech. of materials CIEN E3121 (3) Struct. anal. **or** CIEE E3250 (3) Hydrosystems eng.	CIEN E4133 (3) Capital facility planning and financing CIEN E3127 (3) Struct. design projects **or** CIEN E4241 (3) Geotech. eng. fund.)	CIEN E4131 (3) Princ. of constr. tech.
	TECH ELECTIVES	6 points		3 points	6 points
	WATER RES./ ENVIRON. ENG.		CIEE E3255 (3) Environ. control / pollution CIEE E3250 (3) Hydrosystems eng. CIEN E3303 (1) Independent studies	CIEE E4163 (3) Environ. eng. wastewater CIEE E4257 (3) contam. transport in subsurface sys.	EAEE E4006 (3) Field methods for environ. eng.
	TECH ELECTIVES	6 points		3 points	6 points
NONTECH ELECTIVES		3 points	3 points	3 points	
TOTAL POINTS		16	18	18.5	13

Engineering Mechanics

Programs in engineering mechanics offer comprehensive training in the principles of applied mathematics and continuum mechanics and in the application of these principles to the solution of engineering problems. The emphasis is on basic principles, enabling students to choose from among a wide range of technical areas. Students may work on problems in such disciplines as systems analysis, acoustics, and stress analysis, and in fields as diverse as transportation, environmental, structural, nuclear, and aerospace engineering. Program areas include:

Continuum mechanics: solid and fluid mechanics, theories of elastic

ENGINEERING MECHANICS PROGRAM: FIRST AND SECOND YEARS				
	SEMESTER I	**SEMESTER II**	**SEMESTER III**	**SEMESTER IV**
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** ODE (3)
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Lab C1493 (3) **or** chem. lab Lab C3081 (2)	
CHEMISTRY	one-semester lecture (3–4): C1403 **or** C1404 **or** C3045 **or** C1604 Chem lab C1500 (3) either semester or physics lab			
MECHANICS	ENME-MECE E3105 (4) any semester			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102 **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice, see list of first- and second-year technical electives			
COMPUTER SCIENCE	Computer Language: W1005 (3) (any semester)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

and inelastic behavior, and damage mechanics

- **Vibrations:** nonlinear and random vibrations; dynamics of continuous media, of structures and rigid bodies, and of combined systems, such as fluid-structure interaction; active, passive, and hybrid control systems for structures under seismic loading; dynamic soil-structure interaction effects on the seismic response of structures
- **Random processes and reliability:** problems in design against failure under earthquake, wind, and wave loadings; noise, and turbulent flows; analysis of structures with random properties
- **Fluid mechanics:** turbulent flows, two-phase flows, fluid-structure interaction, fluid-soil interaction, flow in porous media, computational methods for flow and transport processes, and flow and transport in fractured rock under mechanical loading
- **Computational mechanics:** finite element and boundary element techniques, symbolic computation, and bioengineering applications.

A flight structures program is designed to meet the needs of industry in the fields of high-speed and space flight. The emphasis is on mechanics, mathematics, fluid dynamics, flight structures, and control. The program is a part of the Guggenheim Institute of Flight Structures in the department.

Specific information regarding degree requirements is available in the department office.

COURSES IN CIVIL ENGINEERING

See also Courses in Engineering Mechanics at the end of this section.

CIEN E1201y The art of structural design
3 pts. Lect: 3. Professor Deodatis.
An introduction to basic scientific and engineering principles used for the design of buildings, bridges, and other parts of the built infrastructure. Application of these principles to the analysis and design of a number of actual large-scale structures. Experimental verification of these principles through laboratory experiments. Coverage of the history of major structural design innovations and of the engineers who introduced

ENGINEERING MECHANICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES		ENME E3113 (3) Mech. of solids ENME E3161 (4) Fluid mechanics APMA E3101 (3) Applied math., I ENME E3106 (3) Dynamics and vibrations	ENME E3114 (4) Experimental mech. CIEN E3121 (3) Structural analysis APMA E3102 (3) Applied math., II	ENME E3332 (3) A first course in finite elements ENME E4113 (3) Advanced solids ENME E4215 (3) Theory of vibrations	ENME E4202 (3) Advanced mech.
ELECTIVES	TECH	3 points	6 points	6 points	9 points
	NONTECH			3 points	3 points
TOTAL POINTS		16	16	18	15

them. Critical examination of the unique aesthetic/artistic perspectives inherent in structural design. Consideration of management, socioeconomic, and ethical issues involved in the design and construction of large-scale structures. Introduction to some recent developments in sustainable engineering, including green building design and adaptable structural systems.

CIEN E3004y Urban infrastructure systems
3 pts. Lect: 3. Professor Chang.
Introduction to: (a) the infrastructure systems that support urban socioeconomic activities, and (b) fundamental system design and analysis methods. Coverage of water resources, vertical, transportation, communications and energy infrastructure. Emphasis upon the purposes that these systems serve, the factors that influence their performance, the basic mechanisms that govern their design and operation, and the impacts that they have regionally and globally. Student teams complete a semester-long design/analysis project with equal emphasis given to water resources / environmental engineering, geotechnical engineering and construction engineering and management topics.

CIEN E3111x Uncertainty and risk in civil infrastructure systems
3.5 pts. Lect: 3. Professor Deodatis.
Prerequisite: Working knowledge of calculus. Introduction to basic probability; hazard function; reliability function; stochastic models of natural and technological hazards; extreme value distributions; statistical inference methods; Monte Carlo simulation techniques; fundamentals of integrated risk assessment and risk management; topics in risk-based insurance; case studies involving civil infrastructure systems, environmental systems, mechanical and aerospace systems, construction management.

CIEN E3121y Structural analysis
3 pts. Lect: 3. Professor Yin.
Methods of structural analysis. Trusses, arches, cables, frames; influence lines; deflections; force method; displacement method; computer applications.

CIEN E3125y Structural design
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite: ENME E3113. Design criteria for varied structural applications, including buildings and bridges; design of elements using steel, concrete, masonry, wood, and other materials.

CIEN E3126y Computer-aided structural design
1 pt. Lect: 1. Lab: 1. Professor Panayotidi.
Corequisite: CIEN E3125. Introduction to software for structural analysis and design with lab. Applications to the design of structural elements and connections. Lab required.

CIEN E3127x Structural design projects
3 pts. Lect: 3. Professor Panayotidi.
Prerequisites: CIEN E3125 and E3126 or the instructor's permission. Design projects with various structural systems and materials.

CIEN E3128y Design projects
4 pts. Lect: 4. Professor Panayotidi.
Prerequisites: CIEN E3125 and E3126. Capstone design project in civil engineering. This project integrates structural, geotechnical and environmental/water resources design problems with construction management tasks and sustainability, legal and other social issues. Project is completed in teams, and communication skills are stressed. Outside lecturers will address important current issues in engineering practice. Every student in the course will be exposed with equal emphasis to issues related to geotechnical engineering, water resources/environmental engineering, structural engineering, and construction engineering and management.

CIEN E3129x Project management for construction
3 pts. Lect: 3. Professor Chang.
Prerequisite: Senior standing in Civil Engineering or instructor's permission. Introduction to Project Management for design and construction processes. Elements of planning, estimating, scheduling, bidding, and contractual relationships. Computer scheduling and cost control. Critical path method. Design and construction activities. Field supervision.

CIEN E3141y Soil mechanics
4 pts. Lect: 3. Lab 3. Professor W. Sun.
Prerequisite: ENME E3113. Index properties and classification; compaction; permeability and seepage; effective stress and stress distribution; shear strength of soil; consolidation; slope stability.

CIEE E3250y Hydrosystems engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: CHEN E3110 or ENME E3161 or equivalent, SIEO W3600 or equivalent, or the instructor's permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such

as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for nonpoint source pollution. Spatial hydrologic analysis using GIS and watershed models. Note: This course is to be joint listed with CIEN and replaces the previous CIEN 3250.

CIEE E3255y Environmental control and pollution reduction systems
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: EAEE E3200 or ENME E3161 or MECE E3100. Review of engineered systems for prevention and control of pollution. Fundamentals of material and energy balances and reaction kinetics. Analysis of engineered systems to address environmental problems, including solid and hazardous waste, and air, water, soil and noise pollution. Life cycle assessments and emerging technologies.

CIEE E3260y Engineering for developing communities
Lect: 3. 3 pts. Professor Culligan.
Introduction to engineering problems faced by developing communities and exploration of design solutions in the context of a real project with a community client. Emphasis is on the design of sustainable solutions that take account of social, economical, and governance issues, and that can be implemented now or in the near future. The course is open to all undergraduate engineering students. Multidisciplinary teamwork and approaches are stressed. Outside lecturers are used to address issues specific to developing communities and the particular project under consideration.

CIEN E3303x and y Independent studies in civil engineering for juniors
1–3 pts. By conference. Members of the faculty.
A project on civil engineering subjects approved by the chairman of the department. Lab fee: $200.

CIEN E3304x and y Independent studies in civil engineering for seniors
1–3 pts. By conference. Members of the faculty.
A project on civil engineering subjects approved by the chairman of the department. Lab fee: $200.

CIEN E4010y Transportation engineering
3 pts. Lect: 3. Professor Peterson.
An overview of the planning, design, operation, and construction of urban highways and mass transportation systems. Transportation planning and traffic studies; traffic and highway engineering; rapid transit and railroad engineering.

CIEN E4021x Elastic and plastic analysis of structures
3 pts. Lect: 3. Professor Kawashima.
Prerequisite: CIEN E3121 or the equivalent. Overview of classical indeterminate structural analysis methods (force and displacement methods), approximate methods of analysis, plastic analysis methods, collapse analysis, shakedown theorem, structural optimization.

CIEN E4022y Bridge design and management
3 pts. Lect: 3. Professor Yanev.
Prerequisite: CIEN E3125 or the equivalent. Bridge design history, methods of analysis, loads: static, live, dynamic. Design: allowable stress, ultimate strength, load resistance factor, supply/demand. Steel and concrete superstructures: suspension, cable stayed, prestressed, arches. Management of the assets, life-cycle cost, expected useful life, inspection, maintenance, repair, reconstruction. Bridge inventories, condition assessments, data acquisition and analysis, forecasts. Selected case histories and field visits.

CIEN E4100y Earthquake and wind engineering
3 pts. Lect: 3. Professor Ashrafi.
Prerequisite: ENME E3106 or the equivalent. Basic concepts of seismology. Earthquake characteristics, magnitude, response spectrum, dynamic response of structures to ground motion. Base isolation and earthquake-resistant design. Wind loads and aeroelastic instabilities. Extreme winds. Wind effects on structures and gust factors.

CIEN E4111x Uncertainty and risk in infrastructure systems
3 pts. Lect: 3. Professor Deodatis.
Introduction to basic probability, hazard function, reliability function, stochastic models of natural and technological hazards, extreme value distributions, Monte Carlo simulation techniques, fundamentals of integrated risk assessment and risk management, topics in risk-based insurance, case studies involving civil infrastructure systems, environmental systems, mechanical and aerospace systems, construction management. Not open to undergraduate students.

CIEN E4128y Civil engineering management
3 pts. Available only on CVN.
Principles of engineering management with a strong emphasis on planning of infrastructure systems. The course stresses leadership, creativity, and management analysis. Program planning with optimization under financial and environmental constraints; project planning and scheduling using deterministic and stochastic network theories; production rate development and control using statistical, heuristic, simulation, and queuing theory approaches. Students prepare and formally present term projects.

CIEN E4129x and y Managing engineering and construction processes
3 pts. Lect: 3. Professors Odeh and Nagaraja.
Prerequisite: Graduate standing in Civil Engineering, or instructor's permission. Introduction to the principles, methods and tools necessary to manage design and construction processes. Elements of planning, estimating, scheduling, bidding and contractual relationships. Valuation of project cash flows. Critical path method. Survey of construction procedures. Cost control and effectiveness. Field supervision.

CIEN E4130x Design of construction systems
3 pts. Lect: 3. Professor Tirolo.
Prerequisite: CIEN E3125 or the equivalent, or the instructor's permission. Introduction to the design of systems that support construction activities and operations. Determination of design loads during construction. Design of excavation support systems, earth retaining systems, temporary supports and underpinning, concrete formwork and shoring systems. Cranes and erection systems. Tunneling systems. Instrumentation and monitoring. Students prepare and present term projects.

CIEN E4131x and y Principles of construction techniques
3 pts. Lect: 3. Professors Hart and Odeh.
Prerequisite: CIEN E4129 or equivalent. Current methods of construction, cost-effective designs, maintenance, safe work environment. Design functions, constructability, site and environmental issues.

CIEN E4132y Prevention and resolution of construction disputes
3 pts. Lect: 3. Professor Nikain.
Prerequisite: CIEN E4129 or equivalent. Contractual relationships in the engineering and construction industry and the actions that result in disputes. Emphasis on procedures required to prevent disputes and resolve them quickly and cost-effectively. Case studies requiring oral and written presentations.

CIEN E4133x Capital facility planning and financing
3 pts. Lect: 3. Professor Chang.
Prerequisite: CIEN E4129 or equivalent. Planning and financing of capital facilities with a strong emphasis upon civil infrastructure systems. Project feasibility and evaluation. Design of project delivery systems to encourage best value, innovation and private sector participation. Fundamentals of engineering economy and project finance. Elements of life cycle cost estimation and decision analysis. Environmental, institutional, social and political factors. Case studies from transportation, water supply and wastewater treatment.

CIEN E4134y Construction industry law
3 pts. Lect: 3. Professors Quintas and Rubin.
Prerequisite: Graduate standing or the instructor's permission. Practical focus upon legal concepts applicable to the construction industry. Provides sufficient understanding to manage legal aspects, instead of being managed by them. Topics include contractual relationships, contract performance, contract flexibility and change orders, liability and negligence, dispute avoidance/resolution, surety bonds, insurance and site safety.

CIEN E4135y Strategic management global design and construction
3 pts. Lect: 3. Professor LaTuso.
Core concepts of strategic planning, management and analysis within the construction industry. Industry analysis, strategic planning models and industry trends. Strategies for information

technology, emerging markets and globalization. Case studies to demonstrate key concepts in real-world environments.

CIEN E4136y Global entrepreneurship in civil engineering
3 pts. Lect: 3. Professor Anderson.
Capstone practicum where teams develop strategies and business plans for a new enterprise in the engineering and construction industry. Identification of attractive market segments and locations; development of an entry strategy; acquisition of financing, bonding and insurance; organizational design; plans for recruiting and retaining personnel; personnel compensation/incentives. Invited industry speakers.

CIEN E4137y Managing civil infrastructure systems
3 pts. Lect: 3. Professor Chang.
Prerequisites: IEOR E4003, CIEN E4133, or equivalent. Examination of the fundamentals of infrastructure planning and management, with a focus on the application of rational methods that support infrastructure decision-making. Institutional environment and issues. Decision-making under certainty and uncertainty. Capital budgeting and financing. Group decision processes. Elements of decision and finance theory.

CIEN E4138x Real-estate finance for construction management
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: IEOR E2261, CIEN E3129 or permission of instructor. Introduction to financial mechanics of public and private real-estate development and management. Working from perspectives of developers, investors and taxpayers, financing of several types of real-estate and infrastructure projects are covered. Basics of real-estate accounting and finance, followed by in-depth studies of private, public, and public/private-partnership projects and their financial structures. Focused on U.S.-based financing, with some international practices introduced and explored. Financial risks and rewards, and pertinent capital markets and their financing roles. Impacts and incentives of various government programs, such as LEED certification and solar power tax credits. Case studies provide opportunity to compare U.S. practices to several international methods.

CIEN E4139x Theory and practice of virtual design and construction
3 pts. Lect: 3. Professor Reinhardt.
Prerequisites: CIEN E4129 or instructor's permission. History and development of Building Information Modeling (BIM), its uses in design and construction, and introduction to the importance of planning in BIM implementation. Role of visual design and construction concepts and methodologies, including integrated project delivery form in architecture, engineering, and construction industries from project design, cost estimating, scheduling, coordination, fabrication, installation, and financing.

CIEN E4140x Environmental, health, and safety concepts in construction processes
3 pts. Lect: 3. Professor Haining.
Prerequisite: Graduate standing in Civil Engineering and Engineering Mechanics. A definitive review of and comprehensive introduction to construction industry best practices and fundamental concepts of environmental health and safety management systems (EH&S) for the construction management field. How modern EH&S management system techniques and theories not only result in improved safe work environments but ultimately enhance operational processes and performance in construction projects.

CIEE E4163x Environmental engineering: wastewater
3 pts. Lect: 3. Professor Becker.
Prerequisites: Introductory chemistry (with laboratory) and fluid mechanics. Fundamentals of water pollution and wastewater characteristics. Chemistry, microbiology, and reaction kinetics. Design of primary, secondary, and advanced treatment systems. Small community and residential systems.

CIEN E4210x Forensic structural engineering
3 pts. Lect: 3. Professor Ratay.
Prerequisites: Working knowledge of structural analysis and design; graduate student standing or instructor's permission. Review of significant failures, civil/structural engineering design and construction practices, ethical standards and the legal positions as necessary background to forensic engineering. Discussion of standard-of-care. Study of the process of engineering evaluation of structural defects and failures in construction and in service. Examination of the roles, activities, conduct and ethics of the forensic consultant and expert witness. Students are assigned projects of actual cases of nonperformance or failure of steel, concrete, masonry, geotechnical, and temporary structures, in order to perform, discuss, and report their own investigations under the guidance of the instructor.

CIEN E4212y Structural assessment and failure
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: ENME E3113 and CIEN E3121. Laboratory and field test methods in assessment of structures for rehabilitation and to determine causes of failure; ASTM and other applicable standards; case histories of failures and rehabilitation in wood, steel, masonry, and concrete structures.

CIEN E4213x Elastic and inelastic buckling of structures
3 pts. Lect: 3. Professor Laufs.
Stability of framed structures in the elastic and inelastic ranges. Lateral buckling of beams. Torsional buckling of compression members. Buckling of plates of plate-stiffener combinations. Linear stability analysis of cylindrical shells and discussion of its limitations. Discussion of the semiempirical nature of the elastoplastic relations used in the case of plates and shells.

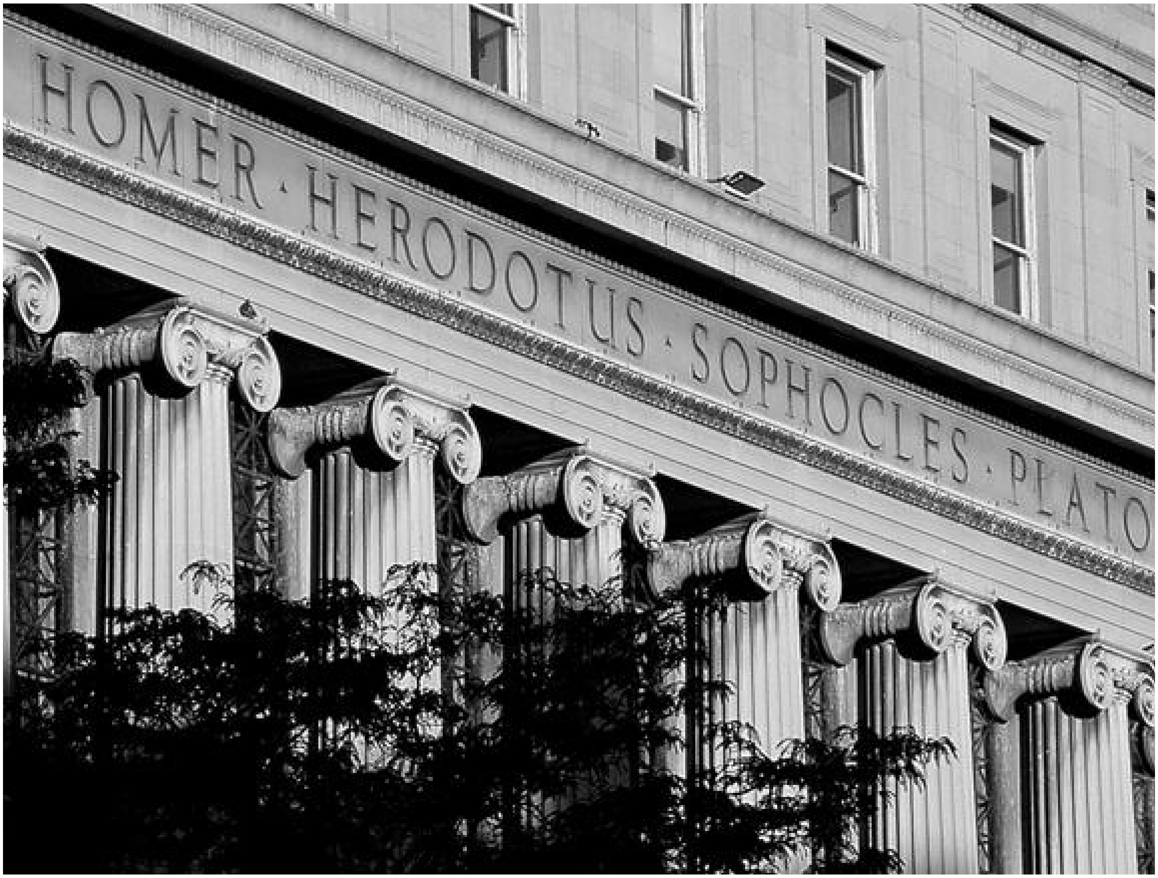
CIEN E4226y Advanced design of steel structures
3 pts. Lect: 3. Professors Aly and Woelke.
Prerequisite: CIEN E3125 or equivalent. Review of loads and structural design approaches. Material considerations in structural steel design. Behavior and design of rolled steel, welded, cold-formed light-gauge, and composite concrete/steel members. Design of multistory buildings and space structures.

CIEN E4232x Advanced design of concrete structures
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite: CIEN E3125 or equivalent. Design of concrete beams for combined torsion, shear and flexure; moment-curvature relation; design of two-way slabs; strut-and-tie method for the design of deep beams and corbels; gravity and shear wall design; retaining wall design. Design project of a multistory reinforced concrete building.

CIEN E4233x Design of large-scale bridges
3 pts. Lect: 3. Professor Zoli.
Prerequisites: CIEN E3121 or equivalent, and CIEN E3127 or equivalent. Design of large-scale and complex bridges with emphasis on cable-supported structures. Static and dynamic loads, component design of towers, superstructures and cables; conceptual design of major bridge types including arches, cable stayed bridges and suspension bridges.

CIEN E4234y Design of large-scale building structures
3 pts. Lect: 3. Professor Tomasetti.
Prerequisites: CIEN E3121 and E3127. Modern challenges in the design of large-scale building structures will be studied. Tall buildings, large convention centers, and major sports stadiums present major opportunities for creative solutions and leadership on the part of engineers. This course is designed to expose the students to this environment by having them undertake the complete design of a large structure from initial design concepts on through all the major design decisions. The students work as members of a design team to overcome the challenges inherent in major projects. Topics include overview of major projects, project criteria and interface with architecture, design of foundations and structural systems, design challenges in the post 9/11 environment, and roles, responsibilities, and legal issues.

CIEN E4235x Multihazard design of structures
3 pts. Lect: 3. Professor Daddazio.
Prerequisite: CIEN E3125 or E4232 or instructor's permission. Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.



CIEN E4236y Design of prestressed concrete structures
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite: CIEN E4232 or instructor's permission. Properties of materials used in prestressed concrete; pre-tensioning versus post-tensioning; loss of prestress due to elastic shortening, friction, anchorage slip, shrinkage, creep and relaxation; full versus partial prestressing; design of beams for flexure, shear and torsion; method of load balancing; anchorage zone design; calculation of deflection by the lump-sum and incremental time-step methods; continuous beams; composite construction; prestressed slabs and columns.

CIEN E4241x Geotechnical engineering fundamentals
3 pts. Lect: 3. Professor Ling.
Prerequisite: CIEN E3141 or instructor's permission. Bearing capacity and settlement of shallow and deep foundations; earth pressure theories; retaining walls and reinforced soil retaining walls; sheet pile walls; braced excavation; slope stability.

CIEN E4242y Geotechnical earthquake engineering
3 pts. Lect: 3. Professor Ling.
Prerequisite: CIEN E3141 or equivalent. Seismicity, earthquake intensity, propagation of seismic waves, design of earthquake motion, seismic site response analysis, in situ and laboratory evaluation of dynamic soil properties, seismic performance of underground structures, seismic performance of port and harbor facilities, evaluation and mitigation of soil liquefaction and its consequences. Seismic earth pressures, slopes stability, safety of dams and embankments, seismic code provisions and practice. To alternate with E4244.

CIEN E4243x Foundation engineering
3 pts. Lect: 3. Professor L. Sun.
Prerequisite: CIEN E3141 or equivalent. Conventional types of foundations and foundation problems: subsurface exploration and testing. Performance of shallow and deep foundations and evaluation by field measurements. Case histories to illustrate typical design and construction problems. To alternate with CIEN E4246.

CIEN E4244x Geosynthetics and waste containment
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CIEN E4241 or the equivalent. Properties of geosynthetics. Geosynthetic design for soil reinforcement. Geosynthetic applications in solid waste containment system. To alternate with CIEN E4242.

CIEN E4245x Tunnel design and construction
3 pts. Lect: 3. Professor Munfakh.
Engineering design and construction of different types of tunnel, including cut and cover tunnel, rock tunnel, soft ground tunnel, immersed tub tunnel, and jacked tunnel. The design for the liner, excavation, and instrumentation are also covered. A field trip will be arranged to visit the tunneling site.

CIEN E4246y Earth retaining structures
3 pts. Lect: 3. Professor Leifer.
Prerequisite: CIEN E3141. Retaining structures, bulkheads, cellular cofferdams, and braced excavations. Construction dewatering and underpinning. Instrumentation to monitor actual performances. Ground improvement techniques, including earth reinforcement, geotextiles, and grouting. To alternate with CIEN E4243.

CIEN E4247x Design of large-scale deep foundation systems
3 pts. Lect.: 3. Professor Leventis.
Prerequisite: CIEN E3141. Focus on deep foundations in difficult conditions and constraints of designing foundations. Design process from the start of field investigations through construction and the application of deep foundations.

CIEN E4250y Waste containment design and practice
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: ENME E3161 and CIEN E3141, or equivalents. Strategies for the containment of buried wastes. Municipal and hazardous waste landfill design; bioreactor landfills; vertical barriers, evapotranspiration barriers and capillary barriers; hydraulic containment; in situ stabilization and solidification techniques; site investigation; monitoring and stewardship of buried wastes; options for land reuse/redevelopment.

CIEE E4252x Environmental engineering
3 pts. Lect: 3. Professor Chandran.
Prerequisites: CHEM C1403 or equivalent; ENME E3161 or the equivalent. Engineering aspects of problems involving human interaction with the natural environment. Review of fundamentals principles that underlie the discipline of environmental engineering, i.e., constituent transport and transformation processes in environmental media such as water, air and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollutant emissions, and hazardous waste remediation. Presented in the context of current issues facing practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management.

CIEN E4253x Finite elements in geotechnical engineering
3 pts. Lect: 3. Professor W. Sun.
Prerequisites: CIEN E3141 and ENME E4332. State-of-the-art computer solutions in geotechnical engineering; 3D consolidation, seepage flows, and soil-structure interaction; element and mesh instabilities.

CIEE E4257x Contaminant transport in subsurface systems
3 pts. Lect: 3. Professor Mutch.
Prerequisites: CIEE E3250 or equivalent. Single and multiple phase transport in porous media; contaminant transport in variably saturated heterogeneous geologic media; physically based numerical models of such processes.

CIEN E4260x Urban ecology studio
4 pts. Lect: 3. Lab: 3. Professor Culligan.
Prerequisites: Senior undergraduate or graduate standing and instructor's permission. Conjoint studio run with the Graduate School of Architecture, Planning and Preservation (GSAPP) that explores solutions to problems of urban density. Engineering and GSAPP students will engage in a joint project that address habitability and sustainability issues in an urban environment, and also provides community service. Emphasis will be on the integration of science, engineering and design within a social context. Interdisciplinary approaches and communication will be stressed.

CIEN E4999x and y Fieldwork
1 pt.
Prerequisite: Instructor's written approval. Written application must be made prior to registration outlining proposed study program. Final reports required. May not be taken for pass/fail credit or audited. International students must consult with the International Students and Scholars Office.

CIEN E6132y Advanced systems and technologies for global project collaboration
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CIEN E4129 or the equivalent. Systems and technologies that support collaborative work in global projects. Information technologies for design, visualization, project management, and collaboration in globally distributed networks of design, fabrication, and construction organizations, including web-based, parametric computer-aided modeling, project organizational simulation, and other emerging applications. Global team project with students at collaborating universities abroad.

CIEN E6133y Advanced construction and infrastructure risk management using real options
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CIEN E6131. Advanced concepts of risk analysis and management applied to civil engineering systems. Identifying and valuing flexibility in construction and operation. Tools to perform risk analysis in flexible civil infrastructure systems. Valuation methods for real options. Risk flexibility analysis; integrating real options analysis with quantitative risk analysis. Applications to case studies on construction management, life-cycle cost analysis for infrastructure assets, public-private partnerships projects, real estate developments, and renewable energy infrastructure projects.

CIEN E6232x Advanced topics in concrete engineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CIEN E3125 or the equivalent. Behavior of concrete under general states of stress, numerical modeling of steel and concrete, finite element analysis of reinforced concrete, design of slabs and their shell concrete structures.

CIEN E6246y Advanced soil mechanics
3 pts. Lect: 2.5. Instructor to be announced.
Prerequisite: CIEN E3141. Stress-dilatancy of sand; failure criteria; critical state soil mechanics; limit analysis; finite element method and case histories of consolidation analysis.

CIEN E6248x Experimental soil mechanics
3 pts. Lect: 2.5. Professor Ling.
Prerequisite: CIEN E3141. Advanced soil testing, including triaxial and plane strain compression tests; small-strain measurement. Model testing; application (of test results) to design.

CIEN E9101x and y–S9101 Civil engineering research
1–4 pts. Members of the faculty.
Advanced study in a specialized field under the supervision of a member of the department staff. Before registering, the student must submit an outline of the proposed work for approval of the supervisor and the department chair.

CIEN E9120x and y–S9120 Independent studies in flight sciences
3 pts. By conference.
Prerequisite: Instructor's permission. This course is geared toward students interested in flight sciences and flight structures. Topics related to aerodynamics, propulsion, noise, structural dynamics, aeroelasticity, and structures may be selected for supervised study. A term paper is required.

CIEN E9130x and y–S9130 Independent studies in construction
3 pts. By conference.
Prerequisites: Permission by department chair and instructor. Independent study of engineering and construction industry problems. Topics related to capital planning and financing, project management, contracting strategies and risk allocation, dispute mitigation and resolution, and infrastructure assessment and management may be selected for supervised study. A term paper is required.

CIEN E9165x and y–S9165 Independent studies in environmental engineering
4 pts. By conference.
Prerequisite: CIEN E4252 or the equivalent. Emphasizes a one-on-one study approach to specific environmental engineering problems. Students develop papers or work on design problems pertaining to the treatment of solid and liquid waste, contaminant migration, and monitoring and sampling programs for remediation design.

CIEN E9201x and y–S9201 Civil engineering reports
1–4 pts. By conference.
A project on some civil engineering subject approved by department chair.

CIEN E9800x and y–S9800 Doctoral research instruction
3–12 pts. May be taken for 3, 6, 9, or 12 points, dependent on instructor's permission.
A candidate for the Eng.Sc.D. degree in civil engineering must register for 12 points of doctoral research instruction. Registration in CIEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

CIEN E9900x and y–S9900 Doctoral dissertation
Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the student's course work has been completed and until the dissertation has been accepted.

COURSES IN ENGINEERING MECHANICS

See also Courses in Civil Engineering at the beginning of this section.

ENME E3105x and y Mechanics
4 pts. Lect: 4. Professors Hone and Kougioumtzoglou.
Prerequisites: PHYS C1401 and MATH V1101, V1102, and V1201. Elements of statics; dynamics of a particle and systems of particles.

ENME E3106x Dynamics and vibrations
3 pts. Lect: 2. Professor Feng.
Prerequisite: Math V1201. Corequisite: ENME E3105. Kinematics of rigid bodies; momentum and energy methods; vibrations of discrete and continuous systems; eigenvalue problems, natural frequencies and modes. Basics of computer simulation of dynamics problems using MATLAB.

ENME E3113x Mechanics of solids
3 pts. Lect: 3. Professor Betti.
Pre- or corequisite: ENME E3105 or equivalent. Stress and strain. Mechanical properties of materials. Axial load, bending, shear, and torsion. Stress transformation. Deflection of beams. Buckling of columns. Combined loadings. Thermal stresses.

ENME E3114y Experimental mechanics of materials
4 pts. Lect: 2. Lab: 3. Professor Kawashima.
Prerequisite: ENME E3113. Material behavior and constitutive relations. Mechanical properties of metals and cement composites. Structural materials. Modern construction materials. Experimental investigation of material properties and behavior of structural elements including fracture, fatigue, bending, torsion, buckling.

ENME E3161x Fluid mechanics
4 pts. Lect: 3. Lab: 3. Professor Gorlé.
Prerequisites: ENME E3105 and ordinary differential equations. Fluid statics. Fundamental principles and concepts of flow analysis. Differential and finite control volume approach to flow analysis. Dimensional analysis. Application of flow analysis: flow in pipes, external flow, flow in open channels.

ENME E3332x A first course in finite elements
3 pts. Lect: 3. Professor Fish.
Prerequisite: Senior standing or instructor's permission. Recommended corequisite: differential equations. Focus on formulation and application of the finite element to engineering problems such as stress analysis, heat transfer, fluid flow, and electromagnetics. Topics include finite element formulation for one-dimensional problems, such as trusses, electrical and hydraulic systems; scalar field problems in two dimensions, such as heat transfer; and vector field problems, such as elasticity and finally usage of the commercial finite element program. Students taking ENME E3332 cannot take ENME E4332.

ENME E4113x Advanced mechanics of solids
3 pts. Lect: 3. Professor Yin. Stress and deformation formulation in two-and three-dimensional solids; viscoelastic and plastic material in one and two dimension energy methods.

ENME E4114y Mechanics of fracture and fatigue
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Undergraduate mechanics of solids course. Elastic stresses at a crack; energy and stress intensity criteria for crack growth; effect of plastic zone at the crack; fracture testing applications. Fatigue characterization by stress-life and strain-life; damage index; crack propagation; fail safe and safe life analysis.

EMME E4115y Micromechanics of composite materials
3 pts. Lect: 3. Professor Yin.
Prerequisite: ENME E4113 or instructor's approval. An introduction to the constitutive modeling of composite materials: Green's functions in heterogenous media, Eshelby's equivalent inclusion methods, eigenstrains, spherical and ellipsoidal inclusions, dislocations, homogenization of elastic fields, elastic, viscoelastic and elastoplastic constitutive modeling, micromechanics-based models.

ENME E4202y Advanced mechanics
3 pts. Lect: 3. Professor Smyth.
Prerequisite: ENME E3105 or equivalent. Differentiation of vector functions. Review of kinematics. Generalized coordinates and constraint equations. Generalized forces. Lagrange's equations. Impulsive forces. Collisions. Hamiltonian. Hamilton's principle.

ENME E4214x Theory of plates and shells
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite: ENME E3113. Static flexural response of thin, elastic, rectangular, and circular plates. Exact (series) and approximate (Ritz) solutions. Circular cylindrical shells. Axisymmetric and nonaxisymmetric membrane theory. Shells of arbitrary shape.

ENME E4215x Theory of vibrations
3 pts. Lect: 3. Professor Betti.
Frequencies and modes of discrete and continuous elastic systems. Forced vibrations-steady-state and transient motion. Effect of damping. Exact and approximate methods. Applications.

ENME E4332x Finite element analysis, I
3 pts. Lect: 3. Professor Waisman.
Prerequisites: Mechanics of solids, structural analysis, elementary computer programming (MATLAB) is recommended, linear algebra and ordinary differential equations. Direct stiffness approach for trusses. Strong and weak forms for one-dimensional problems. Galerkin finite element formulation, shape functions, Gauss quadrature, convergence. Multidimensional scalar field problems (heat conduction), triangular and rectangular elements, Isoparametric formulation. Multidimensional vector field problems (linear elasticity). Practical FE modeling with commercial software (ABAQUS). Computer implementation of the finite element method. Advanced topics. Not open to undergraduate students.

ENME E4363y Multiscale computational science and engineering
3 pts. Lect: 3. Professor Fish.
Prerequisites: ENME E4332, elementary computer programming, linear algebra. Introduction to multiscale analysis. Information-passing bridging techniques: among them, generalized mathematical homogenization theory, the heterogeneous multiscale method, variational multiscale method, the discontinuous Galerkin method and the kinetic Monte Carlo–based methods. Concurrent multiscale techniques: domain bridging, local enrichment, and multigrid-based concurrent multiscale methods. Analysis of multiscale systems.

ENME E6215y Principles and applications of sensors for structural health monitoring
3 pts. Lect: 2.5. Lab: 0.5. Professor Feng.
Prerequisite: ENME E4215. Concepts, principles, and applications of various sensors for sensing structural parameters and nondestructive evaluation techniques for subsurface inspection, data acquisition, and signal processing techniques. Lectures, demonstrations, and hands-on laboratory experiments.

ENME E6216y Structural health monitoring
3 pts. Lect: 3. Professor Betti.
Prerequisites: ENME E4215 and ENME E4332. Principles of traditional and emerging sensors, data acquisition and signal processing techniques, experimental modal analysis (input-output), operational modal analysis (output-only), model-based diagnostics of structural integrity, long-term monitoring and intelligence maintenance. Lectures and demonstrations, hands-on laboaratory experiments.

ENME E6220y Random processes in mechanics
3 pts. Lect: 3. Professor Kougioumtzoglou.
Prerequisites: CIEN E4111 and ENME E4215 (or equivalent). Review of random variables. Random process theory: stationary and ergodic processes, correlation functions, power spectra. Nonstationary and non-Gaussian processes. Linear random vibration theory. Crossing rates, peak distributions, and response analysis of nonlinear structures to random loading. Major emphasis on simulation of various types of random processes. Monte Carlo simulation.

ENME E6315x Theory of elasticity
3 pts. Lect: 2.5. Not offered in 2015–2016.
Foundations of continuum mechanics. General theorems of elasticity. Application to stress analysis and wave propagation.

ENME E6320x Computational poromechanics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: ENME E3332 or instructor's permission. A fluid infiltrating porous solid is a multiphase material whose mechanical behavior is significantly influenced by the pore fluid. Diffusion, advection, capillarity, heating, cooling, and freezing of pore fluid, buildup of pore pressure, and mass exhanges among solid and fluid constituents all influence the stability and integrity of the solid skeleton, causing shrinkage,

swelling, fracture, or liquefaction. These coupling phenomena are important for numerous disciplines, including geophysics, biomechanics, and material sciences. Fundamental principles of poromechanics essential for engineering practice and advanced study on porous media. Topics include balance principles, Biot's poroelasticity, mixture theory, constitutive modeling of path independent and dependent multiphase materials, numerical methods for parabolic and hyperbolic systems, inf-sup conditions, and common stabilization procedures for mixed finite element models, explicit and implicit time integrators, and operator splitting techniques for poromechanics problems.

ENME E6333y Finite element analysis, II
3 pts. Lect: 3. Professor Waisman.
Prerequisite: ENME E4332. FE formulation for beams and plates. Generalized eigenvalue problems (vibrations and buckling). FE formulation for time-dependent parabolic and hyperbolic problems. Nonlinear problems, linearization, and solution algorithms. Geometric and material nonlinearities. Introduction to continuum mechanics. Total and updated Lagrangian formulations. Hyperelasticity and plasticity. Special topics: fracture and damage mechanics, extended finite element method.

ENME E6364x Nonlinear computational mechanics
3 pts. Lect: 3. Professor Fish.
Prerequisites: ENME E4332 or equivalent, elementary computer programming, linear algebra. The formulations and solution strategies for finite element analysis of nonlinear problems are developed. Topics include the sources of nonlinear behavior (geometric, constitutive, boundary condition), derivation of the governing discrete equations for nonlinear systems such as large displacement, nonlinear elasticity, rate independent and dependent plasticity and other nonlinear constitutive laws, solution strategies for nonlinear problems (e.g., incrementation, iteration), and computational procedures for large systems of nonlinear algebraic equations.

ENME E8310x Advance continuum mechanics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E6422 and E6423. This course is open to Ph.D. students and to M.S. students with instructor's permission. Review of continuum mechanics in Cartesian coordinates; tensor calculus and the calculus of variation; large deformations in curvilinear coordinates; electricity problems and applications,

ENME E8320y Viscoelasticity and plasticity
4 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: ENME E6315 or equivalent, or instructor's permission. Constitutive equations of viscoelastic and plastic bodies. Formulation and methods of solution of the boundary value, problems of viscoelasticity and plasticity.

ENME E8323y Nonlinear vibrations
3 pts. Lect: 2.5. Not offered in 2015–2016.
Prerequisite: ENME E4215 or equivalent. Free and forced motion of simple oscillators with nonlinear damping and stiffness. Exact, perturbation, iteration, and graphical methods of solution. Stability of motion. Chaotic vibrations.

COURSES IN GRAPHICS

GRAP E1115x and y Engineering graphics
3 pts. Lect: 1. Lab: 3. Professor Bierd.
Focus on 3D software design for applications in engineering design, manufacturing, and graphics presentations. Introduction to 3D design using advanced 3D modeling and visualization technologies using Maya and SolidWorks. The design process includes idea conception, 3D model development as well as 3D printing and CNC milling manufacturing specifications derived directly from 3D models produced in class. Introduction to the process of creating 3D models that are suitable for 3D printing, CNC milling, Injection Molding and Laser Cutting for buildings. Different models and drawing specifications taught that are required by different manufacturing technologies.

GRAP E2005y Computer-aided engineering graphics
3 pts. Lect: 1.5. Lab: 2.5. Not offered in 2015–2016.
Prerequisite: MATH V1105. Basic concepts needed to prepare and understand engineering drawings and computer-aided representations: preparation of sketches and drawings, preparation and transmission of graphic information. Lectures and demonstrations, hands-on computer-aided graphics laboratory work. Term project.

GRAP E3115x and y Advanced computer modeling and animation
3 pts. Lect: 1. Lab: 3. Professor Bierd.
Focus on the use of 3D modeling, animation, and simulation technologies for 3D design, 3D analysis, design presentations, and manufacturing. Modeling, animation, and simulation for mechanical models, structural models, kinematics models, design visualization, and other applications of 3D software technologies. Introduction to advanced 3D modeling and visualization tools such as SolidWorks, Maya, Revit, Photoshop, Illustrator, and Final Cut Pro. Different uses and applications taught in the context of engineering design, industrial design, process visualization, assembly visualization, and finite element analysis (FEA).

GRAP E4005x Computer graphics in engineering
3 pts. Lect: 3. Professor Dasgupta.
Prerequisites: Any programming language and linear algebra. Numerical and symbolic (algebraic) problem solving with Mathematica. Formulation for graphics application in civil, mechanical, and bioengineering. Example of two-and three-dimensional curve and surface objects in C++ and Mathematica; special projects of interest to electrical and computer science.

COMPUTER ENGINEERING PROGRAM

Administered by both the Electrical Engineering and Computer Science Departments through a joint Computer Engineering Committee. Student records are kept in the Electrical Engineering Department.

1300 S. W. Mudd, MC 4712
450 Computer Sciences
Phone: 212-854-3105
compeng.columbia.edu

IN CHARGE
Charles A. Zukowski
1026 CEPSR

COMPUTER ENGINEERING COMMITTEE
Luca Carloni,
Associate Professor of Computer Science
Stephen A. Edwards,
Associate Professor of Computer Science
Martha A. Kim,
Assistant Professor of Computer Science
Vishal Misra,
Associate Professor of Computer Science
Steven M. Nowick,
Professor of Computer Science
Daniel Rubenstein,
Associate Professor of Computer Science
Mingoo Seok,
Assistant Professor of Electrical Engineering
Simha Sethumadhavan,
Associate Professor of Computer Science
Kenneth L. Shepard,
Professor of Electrical Engineering and Biomedical Engineering
Stephen H. Unger,
Professor Emeritus of Computer Science and Electrical Engineering
Charles A. Zukowski,
Professor of Electrical Engineering
Gil Zussman,
Associate Professor of Electrical Engineering

The computer engineering program is run jointly by the Computer Science and Electrical Engineering departments. It offers both B.S. and M.S. degrees.

The program covers some of engineering's most active, exciting, and critical areas, which lie at the interface between CS and EE. The focus of the major is on computer systems involving both digital hardware and software.

Some of the key topics covered are computer design (i.e., computer architecture); embedded systems (i.e., the design of dedicated hardware/software for cell phones, automobiles, robots, games, and aerospace); digital and VLSI circuit design; computer networks; design automation (i.e., CAD); and parallel and distributed systems (including architectures, programming, and compilers).

The undergraduate major includes one substantial senior design course, either designing an entire microprocessor (*EECS E4340*), or an embedded system (*CSEE W4840*) (including both software and hardware components), or providing hands-on experience in designing and using a computer network (*CSEE W4140*).

Students in the programs have two "home" departments. The Electrical Engineering Department maintains student records and coordinates advising appointments.

UNDERGRADUATE PROGRAM

This undergraduate program incorporates most of the core curricula in both electrical engineering and computer science so that students will be well prepared to work in the area of computer engineering, which substantially overlaps both fields. Both hardware and software aspects of computer science are included, and, in electrical engineering, students receive a solid grounding in circuit theory and in electronic circuits. The program includes several electrical engineering laboratory courses as well as the Computer Science Department's advanced programming course. Detailed lists of requirements can be found at compeng.columbia.edu.

Students will be prepared to work on all aspects of the design of digital hardware, as well as on the associated software that is now often an integral part of computer architecture. They will also be well equipped to work in the growing field of telecommunications. Students will have the prerequisites to delve more deeply into either hardware or software areas, and enter graduate programs in computer science, electrical engineering, or computer engineering. For example, they could take more advanced courses in VLSI, communications theory, computer architecture, electronic circuit theory, software engineering, or digital design.

Minors in electrical engineering and computer science are not open to computer engineering majors, due to excessive overlap.

COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS
EARLY-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) and APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3)	C1402 (3)	Lab C1493 (3) **or** chem. lab C1500 (3)	
	C1601 (3.5)	C1602 (3.5)	Lab C1493 (3) **or** chem. lab C1500 (3)	
	C2801 (4.5)	C2802 (4.5)	Lab W3081 (2) **or** chem. lab C1500 (3)	
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 or C3045 **or** C1604 Lab C1500 (3) either semester **or** physics lab C1493 (3)			
CORE REQUIRED COURSES	ELEN E1201 (3.5) Intro. to elec. eng. (either semester)		ELEN E3801 (3.5) Signals and systems	COMS W3134 (3) **or** W3137 (4) Data structures CSEE W3827 (3) Fund. of computer sys.
REQUIRED LABS			ELEN E3084 (1) Signals and systems lab	ELEN E3082 (1) Digital systems lab
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3)			
	Z1003 (0)	C1010 (3)		
	Z0006 (0)	Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES[2]			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)[1]	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3)	COMS W1004 (3) **or** W1007 (3)	COMS W3203 (3) Discrete math.	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101, or MATH V2010, or COMS W3251.

[2] Some of these courses can be postponed to the junior or senior year to make room for taking the required core computer engineering courses.

COMPUTER ENGINEERING: THIRD AND FOURTH YEARS
EARLY-STARTING STUDENTS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES	IEOR E3658 (3) Probability COMS W3157 (4) Advanced programming ELEN E3201 (3.5) Circuit analysis	ELEN E3331 (3) Electronic circuits COMS W3261 (3) Computer sci. theory	COMS W4118 (3) Operating systems	COMS W4115 (3) Programming lang.
		CSEE W4823 (3) Advanced logic design **or**	CSEE W4119 (3) Computer networks	
REQUIRED LABS	ELEN E3081 (1) Circuit analysis lab	ELEN E3083 (1) Electronic circuits lab	CSEE W4840 (3) Embedded sys. design **or** CSEE W4140 (3) Networking lab **or** EECS E4340 (3) Computer hardware design	
ELECTIVES — **TECH**	15 points required; see details below			
ELECTIVES — **NONTECH**	Complete 27-point requirement; see page 10 or seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[1]	17.5	17	15	15

For a discussion about programming languages used in the program, please see compeng.columbia.edu. Check the late-starting student chart for footnotes about various courses.

[1] "Total points" assumes that 20 points of nontechnical electives and other courses are included.

Technical Electives

The Computer Engineering Program includes 15 points of technical electives. Any 3000-level or higher courses listed in the Computer Science or Electrical Engineering sections of this bulletin can be used for this requirement with the following exceptions: *COMS W3101, W3251,* courses used for other computer engineering requirements and courses that have significant overlap with other required or elective courses (e.g., *COMS W3134* and *W3137*), and courses with significant amounts of nontechnical content such as EEHS E3900. Courses at the 3000 level or higher in other areas of engineering, math, and science can be considered for approval, as long as they do not significantly overlap with other required or elective courses. Economics courses cannot be used as technical electives.

Starting Early

Students are strongly encouraged to begin taking core computer engineering courses as sophomores. They start with *ELEN E1201: Introduction to electrical engineering* in the second semester of their first year and may continue with other core courses one semester after that. For sample "early-starting" and "late-starting" programs, see the degree track charts. It must be emphasized that these charts present examples only; actual schedules may be customized in consultation with academic advisers.

GRADUATE PROGRAM

The Computer Engineering Program offers a course of study leading to the degree of Master of Science (M.S.). The basic courses in the M.S. program come from the Electrical Engineering and Computer Science Departments. Students completing the program are prepared to work (or study further) in such fields as digital computer design, digital communications, and the design of embedded computer systems.

Applicants are generally expected to have a bachelor's degree in computer engineering, computer science, or electrical engineering with at least a 3.2 GPA in technical courses. The Graduate Record Examination (GRE), General Test only, is required of all applicants.

Students must take at least 30 points of courses at Columbia University at or above the 4000 level. These must include at least 15 points from the courses listed below that are deemed core to computer engineering. At least 6 points must be included from each department. *CSEE* and *EECS* courses can count toward either department minimum. Other courses may be chosen with the prior approval of a faculty adviser in the Computer Engineering Program.

COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS
LATE-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Lab C1493 (3) **or** chem. lab C1500 (3) Lab C1493 (3) **or** chem. lab C1500 (3) Lab W3081 (2) **or** chem. lab C1500 (3)	
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604 Lab C1500 (3) either semester **or** physics lab C1493 (3)			
CORE REQUIRED COURSES	ELEN E1201 (3.5)[2] Intro. to elec. eng. (either semester)			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3)	COMS W1004 (3) **or** W1007 (3)	W3203 (3) Discrete math.	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101, or MATH V2010, or COMS W3251.

[2] Transfer and combined-plan students are expected to have completed the equivalent of the first- and second-year program listed above before starting their junior year. Note that this includes some background in discrete math (see COMS W3203) and electronic circuits (see ELEN E1201). Transfer and combined-plan students are also expected to be familiar with Java before they start their junior year. If students must take the one-point Java course (COMS W3101-03) junior year, prerequisite constraints make it difficult to complete the remaining computer engineering program by the end of the senior year.

Core Computer Engineering Courses

COMS W4113: Fundamentals of large-scale distributed systems
COMS W4115: Programming languages and translators
COMS W4118: Operating systems, I
CSEE W4119: Computer networks
COMS W4130: Principles and practice of parallel programming
CSEE W4140: Networking laboratory
COMS W4180: Network security
EECS E4321: Digital VLSI circuits
EECS E4340: Computer hardware design
ELEN E4350: VLSI design laboratory*
ELEN E4702: Digital communications
ELEN E4750: Signal processing and communications on mobile multicore processors
ELEN E4810: Digital signal processing
CSEE W4823: Advanced logic design
CSEE W4824: Computer architecture
ELEN E4830: Digital image processing
CSEE W4840: Embedded systems
ELEN E4896: Music signal processing
COMS E6118: Operating systems, II
CSEE E6180: Modeling and performance evaluation
COMS E6181: Advanced Internet services

COMPUTER ENGINEERING: THIRD AND FOURTH YEARS
LATE-STARTING STUDENTS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES	IEOR E3658 (3)[1] Probability COMS W3134 (3) **or** W3137 (4) Data structures ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	COMS W3157 (4) Advanced programming ELEN E3331 (3) Electronic circuits COMS W3261 (3)[2] Models of comp. CSEE W3827 (3) Fund. of computer systems	COMS W4118 (3) Operating systems CSEE W4119 (3) Computer networks **or**	COMS W4115 (3) Programming lang. CSEE W4823 (3) Advanced logic design
REQUIRED LABS	ELEN E3081 (1)[3] Circuit analysis lab ELEN E3084 (1)[3] Signals and systems lab	ELEN E3083 (1)[3] Electronic circuits lab ELEN E3082 (1)[3] Digital systems lab	CSEE W4840 (3) Embedded sys. design **or** CSEE W4140 (3) Networking lab **or** EECS E4340 (3) Computer hardware design	
ELECTIVES: TECH	15 points required; see details on page 105			
ELECTIVES: NONTECH	Complete 27-point requirement; see page 10 or seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[5]	15	18	15	18

For a discussion about programming languages used in the program, please see compeng.columbia.edu.

[1] SIEO W3600, STAT W4105, and SIEO W4150 can be used instead of IEOR E3658, but W3600 and W4150 may not provide enough probability background for elective courses such as ELEN E3701. Students completing an economics minor who want such a background can take IEOR E3658 and augment it with IEOR E4307.

[2] COMS W3261 can be taken one semester later than pictured.

[3] If possible, ELEN E3081 and ELEN E3084 should be taken along with ELEN E3201 and ELEN 3801 respectively, and ELEN E3083 and ELEN E3082 taken with ELEN E3331 and CSEE W3827 respectively.

[4] The total points of technical electives is reduced to 12 if APMA E2101 has been replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101 or MATH V2010, or COMS W3251.

[5] Assuming technical electives taken Semesters VII and VIII, and 9 points of nontechnical electives taken Semesters VI, VII, and VIII.

EECS E6321: Advanced digital electronic circuits
ELEN E6350: VLSI design laboratory
ELEN E6488: Optical interconnects and interconnection networks
ELEN E6761: Computer communication networks, I
ELEN E6762: Computer communication networks, II*
EECS E6765: Internet of things
ELEN E6770: Topic: Next generation networks
CSEE E6824: Parallel computer architecture
CSEE E6831: Sequential logic circuits*
CSEE E6832: Topics in logic design theory*
CSEE E6847: Distributed embedded systems
ELEN E6850: Visual information systems
ELEN E6860: Advanced digital signal processing
CSEE E6861: Computer-aided design of digital systems
CSEE E6868: System-on-chip platforms
ELEN E6950: Wireless and mobile networking, I
ELEN E6951: Wireless and mobile networking, II
COMS E6998: Topic: Embedded scalable platforms
COMS E6998: Topic: Advanced distributed systems
COMS E6998: Topic: Resilient hardware systems
COMS E6998: Topic: Formal verification of hardware/software systems

* Occasionally offered

The overall program must include at least 15 points of 6000-level *ELEN, EECS, CSEE*, or *COMS* courses (exclusive of seminars). No more than 9 points of research may be taken for credit. No more than 3 points of a nontechnical elective (at or above the 4000 level) may be included. A minimum GPA of at least 2.7 must be maintained, and all degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

COMPUTER SCIENCE

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Adam Cannon

LECTURER IN DISCIPLINE
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Paul Blaer
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Dana Pe'er
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Vladimir Vapnik*
Henryk Wozniakowski**
Yechiam Yemini, Professor Emeritus

SPECIAL RESEARCH SCIENTIST
Henryk Wozniakowski

SENIOR RESEARCH SCIENTISTS
Arthur G. Werschulz
Moti Yung

RESEARCH SCIENTISTS
Rebecca Passonneau
Owen Rambow*

ASSOCIATE RESEARCH SCIENTISTS
Mohit Gupta
Nizar Habash*

*Columbia Center for Computational Learning Systems
**Professor Emeritus

The function and influence of the computer is pervasive in contemporary society. Today's computers process the daily transactions of international banks, the data from communications satellites, the images in video games, and even the fuel and ignition systems of automobiles.

Computer software is as commonplace in education and recreation as it is in science and business. There is virtually no field or profession that does not rely upon computer science for the problem-solving skills and the production expertise required in the efficient processing of information. Computer scientists, therefore, function in a wide variety of roles, ranging from pure theory and design to programming and marketing.

The computer science curriculum at Columbia places equal emphasis on theoretical computer science and mathematics and on experimental computer technology. A broad range of upper-level courses is available in such areas as artificial intelligence, computational complexity and the analysis of algorithms, combinatorial methods, computer architecture, computer-aided digital design, computer communications, databases, mathematical models for computation, optimization, and software systems

Laboratory Facilities

The department has well-equipped lab areas for research in computer graphics, computer-aided digital design, computer vision, databases and digital libraries, data mining and knowledge discovery, distributed systems, mobile and wearable computing, natural-language processing, networking, operating systems, programming systems, robotics, user interfaces, and real-time multimedia.

The computer facilities include a shared infrastructure of Linux multiprocessor servers, NetApp file servers, a student interactive teaching and research lab of high-end multimedia workstations, a load balanced web cluster with 6 servers and business process servers, a large student laboratory, featuring 17 Mac-mini machines and 33 Linux towers each with 8 cores and 24GB memory; a remote Linux cluster with 17 servers, a large Linux computer cluster and a number of computing facilities for individual research labs. In addition, the data center houses a computer cluster consisting of a Linux cloud with 43 servers each with 2 Nehalem processors, 8 cores and 24GB memory. This cloud can support approximately 5000 of VMware instances.

The labs for research in image processing, vision, graphics, and robotics contain specialized equipment such as Baxter Research Robot, PR2 mobile robot manipulator, Staubli RX-60L Robot arm, Kinova, MICO arm, custom-built overhead XYZ gantry robot, Toshiba FMA manipulator, Barrett Technology robotic hand, 2 RWI Pioneer mobile robots, 1 Evolution ER-1 robot, 1 RWI ATRV-2 mobile robot with RTK GPS, Leica HDS-500 and HDS-3000 100 meter range scanners, and real-time Imaging boards; a networking testbed with Cisco backbone routers,

<table>
<tr><th colspan="5">COMPUTER SCIENCE PROGRAM: FIRST AND SECOND YEARS</th></tr>
<tr><th></th><th>SEMESTER I</th><th>SEMESTER II</th><th>SEMESTER III</th><th>SEMESTER IV</th></tr>
<tr><td>MATHEMATICS</td><td>MATH V1101 (3)</td><td>MATH V1102 (3)</td><td>MATH V1201 (3)</td><td></td></tr>
<tr><td>PHYSICS
(three tracks, choose one)</td><td>C1401 (3) →
C1601 (3.5) →
C2801 (4.5) →</td><td>C1402 (3)
C1602 (3.5)
C2802 (4.5)</td><td rowspan="2">Chemistry or physics lab:
PHYS C1493 (3) or
PHYS W3081 (2) or
CHEM W1500 (3) or
CHEM W2507 (3) or
CHEM C3085 (4)</td><td></td></tr>
<tr><td>CHEMISTRY/ BIOLOGY
(choose one course)</td><td colspan="2">CHEM C1403 (3) or higher or
EEEB W2001 (4) or C2005 (4) or higher
either semester</td><td></td></tr>
<tr><td>ENGLISH COMPOSITION
(three tracks, choose one)</td><td>C1010 (3)
Z1003 (0) →
Z0006 (0) →</td><td>C1010 (3)
Z1003 (0) →</td><td>C1010 (3)</td><td></td></tr>
<tr><td rowspan="3">REQUIRED NONTECHNICAL ELECTIVES</td><td colspan="4">ECON W1105 (4) and W1105 recitation (0) any semester</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">HUMA C1001 or
COCI C1101 or
Major Cultures (3–4)</td><td>HUMA C1002 or
COCI C1102 or
Major Cultures (3–4)</td></tr>
<tr><td>HUMA W1121 or
W1123 (3)</td></tr>
<tr><td>REQUIRED TECH ELECTIVES</td><td colspan="2">ENGI E1006 Computing for EAS (3) either semester</td><td></td><td></td></tr>
<tr><td>COMPUTER SCIENCE</td><td colspan="2">COMS W1004 (3)
Intro. to computer science
or
COMS W1007 (3)
Object-oriented programming
either semester</td><td>COMS W3134 (3) or
COMS W3137 (4)
Data structures
and
COMS W3203 (3)
Discrete math</td><td>COMS W3157 (4)
Adv. programming
and
CSEE W3827 (3)
Fund. of computer systems</td></tr>
<tr><td>PHYSICAL EDUCATION</td><td>C1001 (1)</td><td>C1002 (1)</td><td></td><td></td></tr>
<tr><td>THE ART OF ENGINEERING</td><td colspan="2">ENGI E1102 (4) either semester</td><td></td><td></td></tr>
</table>

traffic generators; an IDS testbed with secured LAN, Cisco routers, EMC storage, and Linux servers; a simulation testbed with several Linux servers and Cisco Catalyst routers. The department uses a SIP IP phone system. The protocol was developed in the department.

The department's computers are connected via a switched 1 Gb/s Ethernet network, which has direct connectivity to the campus OC-3 Internet and Internet2 gateways. The campus has 802.11b/g wireless LAN coverage.

The research facility is supported by a full-time staff of professional system administrators and programmers.

UNDERGRADUATE PROGRAM

Computer science majors at Columbia study an integrated curriculum, partially in areas with an immediate relationship to the computer, such as programming languages, operating systems, and computer architecture, and partially in theoretical computer science and mathematics. Thus, students obtain the background to pursue their interests both in applications and in theoretical developments.

Practical experience is an essential component of the computer science program. Undergraduate students are often involved in advanced faculty research projects using state-of-the-art computing facilities. Qualified majors sometimes serve as consultants at Columbia University Information Technology (CUIT), which operates several computer labs at convenient locations on the campus.

Upper-level students in computer

COMPUTER SCIENCE: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		COMS W3251 (3) Computational lin. algebra **and** COMS W3261 (3) Computer sci. theory **and** SIEO W4150 (3) **or** SIEO W3600 (4) Prob. and stat.			
ELECTIVES	**NONTECH**		3 points	6 points	3 points
	TECH	6 points	12 points	9 points	9 points
TOTAL POINTS		15–16	15	15	12

The primary programming languages for the undergraduate major are Python, C, and Java, and students are expected to learn all three at an early stage. The language for COMS W1004-W3134 and COMS W1007-3137 is Java. COMS W1004 may be waived for students who have scored 4 or 5 on the AP computer science exam.

science may assist faculty members with research projects, particularly in the development of software. Ongoing faculty projects include algorithmic analysis, computational complexity, software tool design, distributed computation, modeling and performance evaluation, computer networks, computer architecture, CAD for digital systems, computer graphics, programming environments, expert systems, natural language processing, computer vision, robotics, computational biology, computer security, multicomputer design, user interfaces, VLSI applications, artificial intelligence, combinatorial modeling, virtual environments, and microprocessor applications. Students are strongly encouraged to arrange for participation by consulting individual faculty members and by attending the Computer Science Research Fair held at the beginning of each semester.

Most graduates of the computer science program at Columbia step directly into career positions in computer science with industry or government, or continue their education in graduate degree programs. Many choose to combine computer science with a second career interest by taking additional programs in business administration, medicine, or other professional studies.

For further information on the undergraduate computer science program, please see the home page (cs.columbia.edu/education/undergrad) and the Quick Guide (cs.columbia.edu/education/undergrad/seasguide).

Technical Electives

Students are encouraged to select one of the following six preapproved groupings of electives called "tracks." An advanced version of each track is available by invitation for qualified students who wish an extra opportunity for advanced learning. An additional 15 points of technical elective points beyond those used to satisfy the track requirements are also required.

The following courses are required as a preparation for all tracks: *COMS W1004* or *W1007, W3134* or *W3137, W3157, W3203, W3251, W3261, CSEE W3827*, and *SIEO W4150* (*SIEO W3600* is an acceptable substitute for *W4150*). Collectively these courses are called the CS Core Curriculum. In addition, all students are required to take *ENGI E1006 Introduction to computing for engineers and applied scientists* in their first year. Students considering a career in scientific computing or finance are encouraged to take *COMS W3210 Scientific computation*.

All technical electives except those noted in each track must be approved by the faculty adviser. Technical electives not noted in the track must be at the 3000 level or above and in mathematics, science, engineering or closely related disciplines.

Students who pass the Computer Science Advanced Placement (AP) Exam with a 4 or 5 will receive 3 points of credit and exemption from *COMS W1004.*

Note: A maximum of one course worth no more than 4 points passed with a grade of D may be counted toward the major or minor.

Track 1: Foundations of CS Track

The foundations track is suitable for students who plan to concentrate on theoretical computer science in graduate school or in mathematical topics such as communications security or scientific computation in their career plans. Register for track course *COMS E0001.*

REQUIRED: 9 points

CSOR W4231: Analysis of algorithms
COMS W4236: Introduction to computational complexity
COMS W4241: Numerical algorithms and complexity

ELECTIVES: 12 points from the following list:

COMS W3902: Undergraduate thesis*
COMS W3998: Projects in Computer Science*
IEOR E4010: Graph theory: A combinatorial view
COMS W4203: Graph theory
COMS W4205: Combinatorial theory
COMS W4252: Computational learning theory
COMS W4261: Introduction to cryptography
COMS W4281: Quantum computing
COMS W4444: Programming and problem solving
COMS W4771: Machine learning
COMS W4772: Advanced machine learning
COMS W4901: Projects in Computer Science*
COMS W4995: Math foundations of machine learning
COMS E6232: Analysis of algorithms, II
COMS E6261: Advanced cryptography
ELEN E6717: Information theory
COMS E6901: Projects in Computer Science*
COMS E6998: Approximation algorithms

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901**, and **E6901**) can count toward the major.

Track 2: Software Systems Track

The software systems track is for students interested in networks, programming languages, operating systems, and software systems. Register for track course *COMS E0002.*

REQUIRED: 9 points

COMS W4115: Programming languages and translators
COMS W4118: Operating systems
CSEE W4119: Networking

ELECTIVES: 12 points from the following list:

COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
Any **COMS W41xx** course
COMS W4444: Programming and problem solving
Any **COMS W48xx** course
COMS W4901: Projects in computer science*
COMS W4995-W4996: Special topics in computer science
Any **COMS E61xx** or **E68xx** course (with adviser approval)
COMS E6901: Projects in computer science*

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901**, **E6901**) can count toward the major.

Track 3: Intelligence Track

The intelligence track is for students interested in machine learning, robots, and systems capable of exhibiting "human-like" intelligence. A total of seven required breadth and elective courses are to be chosen from the following schedule. Register for track course *COMS E0003.*

REQUIRED: 9 Points from:

COMS W4701: Artificial intelligence
COMS W4705: Natural language processing
COMS W4706: Spoken language processing
COMS W4731: Computer vision
COMS W4733: Computational aspects of robotics
COMS W4771: Machine learning

ELECTIVES: 12 points required
Up to 12 points from the following list:

Any **COMS W40xx** course with adviser approval
COMS W4165: Pixel processing
COMS W4252: Computational learning theory
Any **COMS W47xx** course if not used as a required course
COMS W4995: Special topics, I*
COMS W4996: Special topics, II*
Any **COMS W67xx** course
COMS E6998: Topics in computer science, I (with adviser approval)
COMS E6999: Topics in computer science, II (with adviser approval)

Up to 6 points from the following list:

COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
COMS W4901: Projects in computer science*
COMS E6901: Projects in computer science*

Up to 3 points from the following list:

COMS W4111: Database systems
COMS W4160: Computer graphics
COMS W4170: User interface design
COMS W4999: Computing and the humanities

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901**, **E6901**) can count toward the major.

Track 4: Applications Track

The applications track is for students interested in the implementation of interactive multimedia applications for the Internet and wireless networks. Register for track course *COMS E0004.*

REQUIRED: 6 points

COMS W4115: Programming languages and translators
COMS W4170: User interface design

ELECTIVES: 15 points from the following list:

COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
Any **COMS W41xx** course
Any **COMS W47xx** course
COMS W4901: Projects in computer science*
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
COMS E6901: Projects in computer science* or other **COMS E69xx** course (with adviser approval)
Any **COMS E69xx** course (with adviser approval)

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901**, **E6901**) can count toward the major.

Track 5: Vision and Graphics Track

The vision and graphics track exposes students to interesting new fields and focuses on visual information with topics in vision, graphics, human-computer interaction, robotics, modeling, and learning. Students learn about fundamental ways in which visual information is captured, manipulated, and experienced. Register for track course *COMS E0005.*

REQUIRED: 6 points from:

COMS W4160: Computer graphics
COMS W4731: Computer vision
COMS W4761: Computer animation

ELECTIVES: 15 points from the following list:

COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
COMS W4162: Advanced computer graphics
COMS W4165: Pixel processing
COMS W4167: Computer animation
COMS W4170: User interface design
COMS W4172: 3D user interface design
COMS W4701: Artificial intelligence
COMS W4733: Computational aspects of robotics
COMS W4735: Visual interfaces to computers
COMS W4771: Machine learning
COMS W4901: Projects in computer science*
COMS W4995: Video game technology and design
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
COMS E6901: Projects in computer science*
Any **COMS E691x** course (with adviser approval)

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901, E6901**) can count toward the major.

Track 6: Digital Systems Track

The digital systems track is for students interested in working at the interface of hardware and software. Subjects include digital design, computer architecture (both sequential and parallel) and embedded systems. Register for track course *COMS E0006.*

REQUIRED: 3 points

CSEE W4824: Computer architecture

Plus 3 points from:

EECS E4340: Computer hardware design
CSEE W4823: Advanced logic design
CSEE W4840: Embedded systems

Plus 3 points from:

COMS W4115: Programming languages and translators
COMS W4118: Operating systems
COMS W4130: Parallel programming

ELECTIVES: 12 points from the following list:

COMS W3902: Undergraduate thesis
COMS E3998: Undergraduate projects in computer science
Any **COMS/CSEE W41xx** course
Any **COMS/CSEE W48xx** course
COMS E4901: Projects in computer science
CSEE E6824: Parallel computer architecture*
CSEE E6827: Distributed embedded systems*
CSEE E6861: CAD of digital systems*
CSEE E6868: System-on-chip platforms
COMS E6901: Projects in computer science

* With adviser approval, may be repeated for credit

Note: No more than 6 units of project/thesis courses (**COMS W3902**, **W3998**, **W4901**, **E6901**) can count toward the major.

Track 7: Advanced

The advanced track of the B.S. in Computer Science provides extra opportunity for advanced learning. It comprises accelerated versions of the other six tracks. Entry is only by collective faculty invitation, extended to students who have already completed the core courses and the required courses for one of those tracks.

REQUIRED TRACK COURSES

A student designates one of the six other track areas and completes the set of required track courses for that track, prior to entry into the Advanced Track. There are two or three courses, depending on the designated area.

ELECTIVES

At least 6 points of 4000-level lecture courses from the menu for the designated track, plus 6 points of 6000-level courses in the designated track area.

THESIS

There is a required 6-point senior thesis.

INVITATION

Only the top 20 percent of computer science majors in course performance in computer science courses will be considered for invitation during the junior year. (A student in the advanced track who does not maintain this status may be required to return to his or her previously selected track area.)

GRADUATE PROGRAMS

The Department of Computer Science offers graduate programs leading to the degree of Master of Science and the degree of Doctor of Philosophy.

The Graduate Record Examination (GRE) is required for admission to the department's graduate programs. Applicants for September admission should take the GREs by October of the preceding year. Applicants for January admission should take these exams by April of the preceding year.

The course requirements in all programs are flexible, and each student is urged to design his or her own program under the guidance of a faculty adviser. The student's program should focus on a particular field of computer science. Among the fields of graduate study in computer science are analysis of algorithms, artificial intelligence, expert systems, natural language understanding, computer vision, multicomputer design, VLSI applications, combinatorial modeling, combinatorial optimization, computational complexity, computer architecture and design, computer communications networks, computer graphics, database machines and systems, microprocessors, parallel computation, programming environments, programming languages, robotics, user interfaces, software design, computational biology, computer security, and machine learning.

Graduate students are encouraged actively to pursue research. Faculty members of the Department of Computer Science are engaged in experimental and theoretical research in most of the fields in which courses are offered. The degree of doctor of philosophy requires a dissertation based on the candidate's original research, which is supervised by a faculty member.

For information on the M.S. program, please see cs.columbia.edu/education/MS and for information on the Ph.D. program, see cs.columbia.edu/education/phd.

DUAL DEGREE PROGRAM IN JOURNALISM AND COMPUTER SCIENCE

The Graduate School of Journalism and the School of Engineering and Applied Science offer a dual degree program leading to the M.S. degree from the Graduate School of Journalism and the M.S. degree in Computer Science from the School of Engineering and Applied Science.

Admitted students will enroll for a total of four semesters. In addition to taking classes already offered at the journalism and engineering schools, students will attend a seminar and workshop designed specifically for the joint program. The seminar will teach students about the impact of digital techniques on journalism; the emerging role of citizens in the news process; the influence of social media; and the changing business models that will support newsgathering. In the workshop, students will use a hands-on approach to delve deeply into information design, focusing on how to build a site, section, or application from concept to development, ensuring the editorial goals are kept uppermost in mind.

COURSES IN COMPUTER SCIENCE

In the listing below, the designator COMS (Computer Science) is understood to precede all course numbers for which no designator is indicated. NOTE: Students may receive credit for only one of the following two courses: *COMS W1004 and W1005*. Likewise, students may receive credit for only one of the following three courses: *COMS W3134, W3136,* or *W3137*.

COMS W1001x and y Introduction to information science
3 pts. Lect: 3. Instructor to be announced.
Basic Introduction to concepts and skills in Information Sciences: human-computer interfaces, representing information digitally, organizing and searching information on the World Wide Web, principles of algorithmic problem solving, introduction to database concepts, introduction to programming in Python.

COMS W1002y Computing in context
4 pts. Lect: 4. Professor Cannon.
Introduction to elementary computing concepts and Python programming with domain-specific applications. Shared CS concepts and Python programming lectures with track-specific sections. Track themes will vary but may include computing for the social sciences, computing for economics and finance, digital humanities, and more. Intended for nonmajors. Students may only receive credit for one of ENGI E1006 and COMS W1002.

COMS W1004x and y Introduction to computer science and programming in Java
3 pts. Lect: 3. Professor Cannon.
A general introduction to computer science for science and engineering students interested in majoring in computer science or engineering. Covers fundamental concepts of computer science, algorithmic problem-solving capabilities, and introductory Java programming skills. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: 1004 and 1005.

COMS W1005x and y Introduction to computer science and programming in MATLAB
3 pts. Lect: 3. Professor Blaer.
Prerequisites: None. Corequisites: None. A general introduction to computer science concepts, algorithmic problem-solving capabilities, and programming skills in MATLAB. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: 1004 and 1005.

ENGI E1006x and y Introduction to computing for engineers and applied scientists
3 pts. Lect: 3. Professor Cannon.
Prerequisite: None. An interdisciplinary course in computing intended for first year SEAS students. Introduces computational thinking, algorithmic problem solving and Python programming with applications in science and engineering. Assumes no prior programming background.

COMS W1007x Honors introduction to computer science
3 pts. Lect: 3. Professor Kender.
Prerequisite: AP Computer Science with a grade of 4 or 5 or similar experience. An honors-level introduction to computer science, intended primarily for students considering a major in computer science. Computer science as a science of abstraction. Creating models for reasoning about and solving problems. The basic elements of computers and computer programs. Implementing abstractions using data structures and algorithms. Taught in Java.

COMS W1404x and y Emerging scholars program seminar
1 pt. Sem: 1. Professor Cannon.
Corequisite: COMS W1004/1007 or ENGI E1006. Enrollment with instructor permission only. Peer-led weekly seminar intended for first- and second-year undergraduates considering a major in computer science. Pass/Fail only.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E4060, but the work requirements differ somewhat.

COMS W3101x and y Programming languages
1 pt. Lect: 1.
Prerequisite: Fluency in at least one programming language. Introduction to a programming language. Each section is devoted to a specific language. Intended only for those who are already fluent in at least one programming language. Sections may meet for one hour per week for the whole term, for three hours per week for the first third of the term, or for two hours per week for the first six weeks. May be repeated for credit if different languages are involved.

COMS W3134x and y Data structures in Java
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: COMS W1004 or knowledge of Java. Data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Rudiments of the analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3136y Data structures with C/C++
4 pts. Lect: 3. Professor Lee.
Prerequisite: COMS W1004, W1005, W1007, or ENGI E1006. A second programming course intended for nonmajors with at least one semester of introductory programming experience. Basic elements of programming in C and C++, array-based data structures, heaps, linked lists, C programming in UNIX environment, object-oriented programming in C++, trees, graphs, generic programming, hash tables. Due to significant overlap, students may only receive credit for either COMS W3134, W3136, or W3137.

COMS W3137y Honors data structures and algorithms
4 pts. Lect: 3. Instructor to be announced.
Prerequisite: COMS W1004 or W1007. Corequisite: COMS W3203. An honors introduction to data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Design and analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3157x and y Advanced programming
4 pts. Lect: 4. Professor Lee.
Prerequisite: Two terms of programming experience. Practical, hands-on introduction to programming techniques and tools for professional software construction, including learning how to write code to given specifications as well as document the results. Provides introductory overview of C and C++ in a UNIX environment, for students with Java background. Also introduces scripting languages (Perl) and basic web programming. UNIX programming utilities are also covered. Lab required.

COMS W3203x and y Discrete mathematics: introduction to combinatorics and graph theory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: Any introductory course in computer programming. Logic and formal proofs, sequences and summation, mathematical induction, binomial coefficients, elements of finite probability, recurrence relations, equivalence relations and partial orderings, and topics in graph theory (including isomorphism, traversability, planarity, and colorings).

COMS W3210y Scientific computation
3 pts. Lect: 3. Professor Traub.
Prerequisites: Two terms of calculus. Introduction to computation on digital computers. Design and analysis of numerical algorithms. Numerical solution of equations, integration, recurrences, chaos, differential equations. Introduction to Monte Carlo methods. Properties of floating point arithmetic. Applications to weather prediction, computational finance, computational science, and computational engineering.

COMS W3251x Computational linear algebra
3 pts. Lect: 3. Professor Papageorgiou.
Prerequisites: Two terms of calculus. Computational linear algebra, solution of linear systems, sparse linear systems, least squares, eigenvalue problems, and numerical solution of other multivariate problems as time permits.

COMS W3261x and y Computer science theory
3 pts. Lect: 3. Professor Yannakakis.
Prerequisite: COMS W3203. Corequisite: COMS W3134, W3136, or W3137. Regular languages: deterministic and nondeterministic finite automata, regular expressions. Context-free languages: context-free grammars, push-down automata. Turing machines, the Chomsky hierarchy, and the Church-Turing thesis. Introduction to complexity theory and NP-completeness.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professors Rubenstein and Kim.
Prerequisite: An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flip-flops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language,

instruction sets, ALUs, single-cycle and multi-cycle processor design, introduction to pipelined processors, caches, and virtual memory.

COMS W3902x and y Undergraduate thesis
1–6 pts.
Prerequisite: Agreement by faculty member to serve as thesis adviser. An independent theoretical or experimental investigation by an undergraduate major of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written report is mandatory and an oral presentation may also be required. May be taken over more than one term, in which case the grade is deferred until all 6 points have been completed. Consult the department for section assignment.

COMS W3995x or y Special topics in computer science
3 pts. Lect: 3.
Prerequisite: Instructor's permission. Consult the department for section assignment. Special topics arranged as the need and availability arise. Topics are usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit.

COMS W3998x and y Undergraduate projects in computer science
1–3 pts.
Prerequisite: Approval by a faculty member who agrees to supervise the work. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit, but not for a total of more than 3 points of degree credit. Consult the department for section assignment.

ECBM E4060x Introduction to genomic information
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function, and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E3060, but the work requirements differ somewhat.

COMS W4111x and y Introduction to databases
3 pts. Lect: 3. Professor Biliris.
Prerequisites: COMS W3134, W3136, or W3137, fluency in Java; or instructor's permission. The fundamentals of database design and application development using databases: entity-relationship modeling, logical design of relational databases, relational data definition and manipulation languages, SQL, XML, query processing, physical database tuning, transaction processing, security. Programming projects are required.

COMS W4112y Database system implementation
3 pts. Lect: 2.5. Professor Ross.
Prerequisites: COMS W4111; fluency in Java or C++. CSEE W3827 is recommended. The principles and practice of building large-scale database management systems. Storage methods and indexing, query processing and optimization, materialized views, transaction processing and recovery, object-relational databases, parallel and distributed databases, performance considerations. Programming projects are required.

COMS W4113x Fundamentals of large-scale distributed systems
3 pts. Lect: 3. Professor Geambasu.
Prerequisites: COMS W3134, W3136, or W3137. COMS W3157 or good working knowledge of C and C++. COMS W4118 or CSEE W4119. Design and implementation of large-scale distributed and cloud systems. Abstractions, design, and implementation techniques that enable the building of fast, scalable, fault-tolerant distributed systems. Topics include distributed communication models (e.g., sockets, remote procedure calls, distributed shared memory), distributed synchronization (clock synchronization, logical clocks, distributed mutex), distributed file systems, replication, consistency models, fault tolerance, distributed transactions, agreement and commitment, Paxos-based consensus, MapReduce infrastructures, scalable distributed databases. Combines concepts and algorithms with descriptions of real-world implementations at Google, Facebook, Yahoo, Microsoft, Linkedin, etc.

COMS W4115x and y Programming languages and translators
3 pts. Lect: 3. Professor Edwards.
Prerequisites: COMS W3134, W3136, or W3137 (or equivalent), W3261, and CSEE W3827, or instructor's permission. Modern programming languages and compiler design. Imperative, object-oriented, declarative, functional, and scripting languages. Language syntax, control structures, data types, procedures and parameters, binding, scope, run-time organization, and exception handling. Implementation of language translation tools including compilers and interpreters. Lexical, syntactic, and semantic analysis; code generation; introduction to code optimization. Teams implement a language and its compiler.

COMS W4117x or y Compilers and interpreters
3 pts. Lect: 3. Professor Aho.
Prerequisite: COMS W4115 or instructor's permission. Continuation of COMS W4115, with broader and deeper investigation into the design and implementation of contemporary language translators, be they compilers or interpreters. Topics include: parsing, semantic analysis, code generation and optimization, run-time environments, and compiler-compilers. A programming project is required.

COMS W4118x and y Operating systems, I
3 pts. Lect: 3. Professor Nieh.
Prerequisites: CSEE W3827 and knowledge of C and programming tools as covered in W3136, W3157, or W3101, or instructor's permission. Design and implementation of operating systems. Topics include process management, process synchronization and interprocess communication, memory management, virtual memory, interrupt handling, processor scheduling, device management, I/O, and file systems. Case study of the UNIX operating system. A programming project is required.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Chaintreau or Misra.
Corequisite: SIEO W3600 or IEOR E3658 or equivalent. Introduction to computer networks and the technical foundations of the Internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

COMS W4130x Principles and practice of parallel programming
3 pts. Lect: 2.5. Professor Kim.
Prerequisites: Experience in Java, basic understanding of analysis of algorithms. COMS W3134, W3136, or W3137 (or equivalent). Principles of parallel software design. Topics include task and data decomposition, load-balancing, reasoning about correctness, determinacy, safety, and deadlock-freedom. Application of techniques through semester-long design project implementing performant, parallel application in a modern parallel programming language.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite: CSEE 4119 or equivalent. In this course, students will learn how to put "principles into practice," in a hands-on networking lab course. The course will cover the technologies and proctocols of the Internet using equipment currently available to large Internet service providers such as CISCO routers and end systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and will familiarize students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP, and application-level protocols (FTP, TELNET, SMTP).

COMS W4156x Advanced software engineering
3 pts. Lect: 3. Professor Kaiser.
Prerequisite: COMS W3157 or equivalent. Software lifecycle from the viewpoint of designing and implementing N-tier applications (typically

utilizing web browser, web server, application server, database). Major emphasis on quality assurance (code inspection, unit and integration testing, security and stress testing). Centers on a student-designed team project that leverages component services (e.g., transactions, resource pooling, publish/subscribe) for an interactive multi-user application such as a simple game.

COMS W4160y Computer graphics
3 pts. Lect: 3. Professor Zheng.
Prerequisite: COMS W3134, W3136, or W3137; W4156 is recommended. Strong programming background and some mathematical familiarity including linear algebra is required. Introduction to computer graphics. Topics include 3D viewing and projections, geometric modeling using spline curves, graphics systems such as OpenGL, lighting and shading, and global illumination. Significant implementation is required: the final project involves writing an interactive 3D video game in OpenGL.

COMS W4162x or y Advanced computer graphics
3 pts. Lect: 3.
Prerequisite: COMS W4160 or equivalent, or instructor's permission. A second course in computer graphics covering more advanced topics including image and signal processing, geometric modeling with meshes, advanced image synthesis including ray tracing and global illumination, and other topics as time permits. Emphasis will be placed both on implementation of systems and important mathematical and geometric concepts such as Fourier analysis, mesh algorithms and subdivision, and Monte Carlo sampling for rendering. Note: Course will be taught every two years.

COMS W4167x or y Computer animation
3 pts. Lect: 3. Professor Grinspun.
Prerequisite: Multivariable calculus, linear algebra, C++ programming proficiency. COMS W4156 recommended. Theory and practice of physics-based animation algorithms, including animated clothing, hair, smoke, water, collisions, impact, and kitchen sinks. Topics covered: integration of ordinary differential equations, formulation of physical models, treatment of discontinuities including collisions/contact, animation control, constrained Lagrangian Mechanics, friction/dissipation, continuum mechanics, finite elements, rigid bodies, thin shells, discretization of Navier-Stokes equations. General education requirement: quantitative and deductive reasoning (QUA).

COMS W4170x User interface design
3 pts. Lect: 3. Professor Feiner.
Prerequisite: COMS W3134, W3136, or W3137. Introduction to the theory and practice of computer user interface design, emphasizing the software design of graphical user interfaces. Topics include basic interaction devices and techniques, human factors, interaction styles, dialogue design, and software infrastructure. Design and programming projects are required.

COMS W4172y 3D user interfaces and augmented reality
3 pts. Lect: 3. Professor Feiner.
Prerequisite: COMS W4160 or W4170 or instructor's permission. Design, development, and evaluation of 3D user interfaces. Interaction techniques and metaphors, from desktop to immersive. Selection and manipulation. Travel and navigation. Symbolic, menu, gestural, and multimodal interaction. Dialogue design. 3D software support. 3D interaction devices and displays. Virtual and augmented reality. Tangible user interfaces. Review of relevant 3D math.

COMS W4180x or y Network security
3 pts. Lect: 3. Professor Keromytis.
Prerequisites: COMS W3134, W3136, or W3137, and W4119, or instructor's permission. Introduction to network security concepts and mechanisms. Foundations of network security and an in-depth review of commonly used security mechanisms and techniques, security threats and network-based attacks, applications of cryptography, authentication, access control, intrusion detection and response, security protocols (IPsec, SSL, Kerberos), denial of service, viruses and worms, software vulnerabilities, web security, wireless security, and privacy.

COMS W4187x or y Security architecture and engineering
3 pts. Lect: 3. Professor Bellovin.
Prerequisite: COMS W4118; W4180 and/or W4119 recommended. Secure programming. Cryptograhic engineering and key handling. Access controls. Trade-offs in security design. Design for security.

COMS W4203y Graph theory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: COMS W3203. General introduction to graph theory. Isomorphism testing, algebraic specification, symmetries, spanning trees, traversability, planarity, drawings on higher-order surfaces, colorings, extremal graphs, random graphs, graphical measurement, directed graphs, Burnside-Polya counting, voltage graph theory.

COMS W4205x Combinatorial theory
3 pts. Lect: 3. Professor Gross.
Prerequisites: COMS W3203 and course in calculus. Sequences and recursions, calculus of finite differences and sums, elementary number theory, permutation group structures, binomial coefficients, Stilling numbers, harmonic numbers, generating functions.

CSOR W4231x Analysis of algorithms, I
3 pts. Lect: 3. Professor Yannakakis, Chen, or Stein.
Prerequisites: COMS W3134, W3136 or W3137, and W3203. Introduction to the design and analysis of efficient algorithms. Topics include models of computation, efficient sorting and searching, algorithms for algebraic problems, graph algorithms, dynamic programming, probabilistic methods, approximation algorithms, and NP-completeness.

COMS W4236y Introduction to computational complexity
3 pts. Lect: 3. Professor Servedio.
Prerequisite: COMS W3261. Develops a quantitative theory of the computational difficulty of problems in terms of the resources (eg., time, space) needed to solve them. Classification of problems into complexity classes, reductions and completeness. Power and limitations of different modes of computation such as nondeterminism, randomization, interaction and parallelism.

COMS W4241y Numerical algorithms and complexity
3 pts. Lect: 3. Professor Traub.
Prerequisite: Knowledge of a programming language. Some knowledge of scientific computation is desirable. Modern theory and practice of computation on digital computers. Introduction to concepts of computational complexity. Design and analysis of numerical algorithms. Applications to computational finance, computational science, and computational engineering.

STCS W4242x or y Introduction to data science
3 pts. Lect: 3. Professor Salleb-Aouissi.
Practical techniques for working with large-scale data. Topics include statistical modeling and machine learning, data pipelines, programming languages, "big data" tools, and real-world topics and case studies. Statistical and data manipulation software required. Intended for nonquantitative graduate-level disciplines.

COMS W4252x or y Introduction to computational learning theory
3 pts. Lect: 3. Professor Servedio.
Prerequisites: CSOR W4231 or COMS W4236 or W3203 and instructor's permission or COMS W3261 and instructor's permission. Possibilities and limitations of performing learning by computational agents. Topics include computational models of learning, polynomial time learnability, learning from examples and learning from queries to oracles. Computational and statistical limitations of learning. Applications to Boolean functions, geometric functions, automata.

COMS W4261x or y Introduction to cryptography
3 pts. Lect: 2.5. Professor Malkin.
Prerequisites: Comfort with basic discrete math and probability. Recommended: COMS W3261 or CSOR W4231. An introduction to modern cryptography, focusing on the complexity-theoretic foundations of secure computation and communication in adversarial environments; a rigorous approach, based on precise definitions and provably secure protocols. Topics include private and public key encryption schemes, digital signatures, authentication, pseudorandom generators and functions, one-way functions, trapdoor functions, number theory and

computational hardness, identification and zero knowledge protocols.

COMS W4281x or y Introduction to quantum computing
3 pts. Lect: 3. Professor Papageorgiou.
Prerequisite: Knowledge of linear algebra. Prior knowledge of quantum mechanics is not required although helpful. Introduction to quantum computing. Shor's factoring algorithm, Grover's database search algorithm, the quantum summation algorithm. Relationship between classical and quantum computing. Potential power of quantum computers.

EECS E4340x Computer hardware design
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisites: ELEN E3331 plus ELEN E3910 or CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, piplelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis. Lab required.

COMS W4444x Programming and problem solving
3 pts. Lect: 3. Professor Ross.
Prerequisites: COMS W3134, W3136, or W3137, and CSEE W3827. Hands-on introduction to solving open-ended computational problems. Emphasis on creativity, cooperation, and collaboration. Projects spanning a variety of areas within computer science, typically requiring the development of computer programs. Generalization of solutions to broader problems, and specialization of complex problems to make them manageable. Team-oriented projects, student presentations, and in-class participation required.

COMS W4460y Principles of innovation and entrepreneurship
3 pts. Lect: 3. Professor Yemini.
Prerequisites: COMS W3134, W3136, or W3137 (or equivalent), or instructor's permission. Team project-centered course focused on principles of planning, creating, and growing a technology venture. Topics include: identifying and analyzing opportunities created by technology paradigm shifts, designing innovative products, protecting intellectual property, engineering innovative business models.

COMS W4560x Introduction to computer applications in health care and biomedicine
3 pts. Lect: 3.
Prerequisites: Experience with computers and a passing familiarity with medicine and biology. Undergraduates in their senior or junior years may take this course only if they have adequate background in mathematics and receive permission from the instructor An overview of the field of biomedical informatics, combining perspectives from medicine, computer science, and social science. Use of computers and information in health care and the biomedical sciences, covering specific applications and general methods, current issues, capabilities and limitations of biomedical informatics. Biomedical Informatics studies the organization of medical information, the effective management of information using computer technology, and the impact of such technology on medical research, education, and patient care. The field explores techniques for assessing current information practices, determining the information needs of health care providers and patients, developing interventions using computer technology, and evaluating the impact of those interventions.

COMS W4701x or y Artificial intelligence
3 pts. Lect: 3. Professor Pasik.
Prerequisite: COMS W3134, W3136, or W3137. Provides a broad understanding of the basic techniques for building intelligent computer systems. Topics include state-space problem representations, problem reduction and and-or graphs, game playing and heuristic search, predicate calculus, and resolution theorem proving, AI systems and languages for knowledge representation, machine learning and concept formation, and other topics such as natural language processing may be included as time permits.

COMS W4705x Natural language processing
3 pts. Lect: 3. Professor Collins.
Prerequisite: COMS W3134, W3136, or W3137 (or equivalent), or instructor's permission. Computational approaches to natural language generation and understanding. Recommended preparation: Some previous or concurrent exposure to AI or machine learning. Topics include information extraction, summarization, machine translation, dialogue systems, and emotional speech. Particular attention is given to robust techniques that can handle understanding and generation for the large amounts of text on the web or in other large corpora. Programming exercises in several of these areas.

COMS W4706y Spoken language processing
3 pts. Lect: 3. Professor Hirschberg.
Prerequisite: COMS W3134, W3136, or W3137 (or equivalent), or instructor's permission. Computational approaches to speech generation and understanding. Topics include speech recognition and understanding, speech analysis for computational linguistics research, and speech synthesis. Speech applications including dialogue systems, data mining, summarization, and translation. Exercises involve data analysis and building a small text-to-speech system.

COMS W4725x or y Knowledge representation and reasoning
3 pts. Lect: 3.
Prerequisite: **COMS W4701.** General aspects of knowledge representation (KR). The two fundamental paradigms (semantic networks and frames) and illustrative systems. Topics include hybrid systems, time, action/plans, defaults, abduction, and case-based reasoning. Throughout the course particular attention is paid to design trade-offs between language expressiveness and reasoning complexity, and issues relating to the use of KR systems in larger applications.

COMS W4731x or y Computer vision
3 pts. Lect: 3. Professor Nayar.
Prerequisites: The fundamentals of calculus, linear algebra, and C programming. Students without any of these prerequisites are advised to contact the instructor prior to taking the course. Introductory course in computer vision. Topics include image formation and optics, image sensing, binary images, image processing and filtering, edge extraction and boundary detection, region growing and segmentation, pattern classification methods, brightness and reflectance, shape from shading and photometric stereo, texture, binocular stereo, optical flow and motion, 2D and 3D object representation, object recognition, vision systems and applications.

COMS W4733x or y Computational aspects of robotics
3 pts. Lect: 3. Professor Allen.
Prerequisite: COMS W3134, W3136, or W3137. Introduction to robotics from a computer science perspective. Topics include coordinate frames and kinematics, computer architectures for robotics, integration and use of sensors, world modeling systems, design and use of robotic programming languages, and applications of artificial intelligence for planning, assembly, and manipulation.

COMS W4735x or y Visual interfaces to computers
3 pts. Lect: 3. Professor Kender.
Prerequisite: COMS W3134, W3136, or W3137. Visual input as data and for control of computer systems. Survey and analysis of architecture, algorithms, and underlying assumptions of commercial and research systems that recognize and interpret human gestures, analyze imagery such as fingerprint or iris patterns, generate natural language descriptions of medical or map imagery. Explores foundations in human psychophysics, cognitive science, and artificial intelligence.

COMS W4737x or y Biometrics
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite: A background at the sophomore level in computer science, engineering, or like discipline. Corequisites: None. In this course we will explore the latest advances in biometrics as well as the machine learning techniques behind them. Students will learn how these technologies work and how they are sometimes defeated.

Grading will be based on homework assignments and a final project. There will be no midterm or final exam. This course shares lectures with COMS E6737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

CBMF W4761x or y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisites: Introductory probability and statistics and basic programming skills. Provides comprehensive introduction to computational techniques for analyzing genomic data including DNA, RNA and protein structures; microarrays; transcription and regulation; regulatory, metabolic and protein interaction networks. The course covers sequence analysis algorithms, dynamic programming, hidden Markov models, phylogenetic analysis, Bayesian network techniques, neural networks, clustering algorithms, support vector machines, Boolean models of regulatory networks, flux based analysis of metabolic networks and scale-free network models. The course provides self-contained introduction to relevant biological mechanisms and methods.

COMS W4771y Machine learning
3 pts. Lect: 3. Professor Jebara.
Prerequisites: Any introductory course in linear algebra and any introductory course in statistics are both required. Highly recommended: COMS W4701 or knowledge of artificial intelligence. Topics from generative and discriminative machine learning including least squares methods, support vector machines, kernel methods, neural networks, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models and hidden Markov models. Algorithms implemented in MATLAB.

COMS W4772x Advanced machine learning
3 pts. Lect: 3. Professors Jebara and Hsu.
Prerequisites: COMS W4771 or instructor's permission; knowledge of linear algebra and introductory probability or statistics is required. An exploration of advanced machine learning tools for perception and behavior learning. How can machines perceive, learn from, and classify human activity computationally? Topics include appearance-based models, principal and independent components analysis, dimensionality reduction, kernel methods, manifold learning, latent models, regression, classification, Bayesian methods, maximum entropy methods, real-time tracking, extended Kalman filters, time series prediction, hidden Markov models, factorial HMMs, input-output HMMs, Markov random fields, variational methods, dynamic Bayesian networks, and Gaussian/Dirichlet processes. Links to cognitive science.

COMS W4776x Machine learning for data science
3 pts. Lect: 3. Professor Jebara.
Prerequisites: SIEO W3600 or W4150 or equivalent, COMS W3251 or equivalent. Introduction to machine learning, emphasis on data science. Topics include least square methods, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models, hidden Markov models, support vector machines kernel methods. Emphasizes methods and problems relevant to big data. Students may not receive credit for both COMS W4771 and W4776.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3. Professor Nowick.
Prerequisite: CSEE W3827, or a half-semester introduction to digital logic, or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modelling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modelling and simulation; design examples.

CSEE W4824x Computer architecture
3 pts. Lect: 3. Professor Carloni.
Prerequisite: CSEE W3827 or equivalent. Focuses on advanced topics in computer architecture, illustrated by case studies from classic and modern processors. Fundamentals of quantitative analysis. Pipelining. Memory hierarchy design. Instruction-level and thread-level parallelism. Data-level parallelism and graphics processing units. Multiprocessors. Cache coherence. Interconnection networks. Multi-core processors and systems-on-chip. Platform architectures for embedded, mobile, and cloud computing.

CSEE W4840y Embedded systems
3 pts. Lect: 3. Professor Edwards.
Prerequisite: CSEE W4823. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required. Lab required.

COMS W4901x and y Projects in computer science
1–3 pts.
Prerequisite: Approval by a faculty member who agrees to supervise the work. A second-level independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit, but not for a total of more than 3 points of degree credit. Consult the department for section assignment.

COMS W4995x or y Special topics in computer science, I
3 pts. Lect: 3.
Prerequisite: Instructor's permission. Special topics arranged as the need and availability arises. Topics are usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit. Consult the department for section assignment.

COMS W4996x or y Special topics in computer science, II
3 pts. Lect: 3.
Prerequisite: Instructor's permission. A continuation of COMS W4995 when the special topic extends over two terms.

COMS E6111y Advanced database systems
3 pts. Lect: 2. Professor Gravano.
Prerequisites: COMS W4111 and knowledge of Java or instructor's permission. Continuation of COMS W4111, covers latest trends in both database research and industry: information retrieval, web search, data mining, data warehousing, OLAP, decision support, multimedia databases, and XML and databases. Programming projects required.

COMS E6113y Topics In database systems
3 pts. Lect: 2.
Prerequisite: COMS W4111. Concentration on some database paradigm, such as deductive, heterogeneous, or object-oriented, and/or some database issue, such as data modeling, distribution, query processing, semantics, or transaction management. A substantial project is typically required. May be repeated for credit with instructor's permission.

COMS E6117x or y Topics in programming languages and translators
3 pts. Lect: 2. Professor Aho.
Prerequisite: COMS W4115 or instructor's permission. Concentration on the design and implementation of programming languages, and tools focused on advanced applications in new areas in software verification, distributed systems, programming in the large, and web computing. A substantial project is typically required. May be repeated for credit.

COMS E6118y Operating systems, II
3 pts. Lect: 2.
Prerequisite: COMS W4118. Corequisite: COMS W4119. Continuation of COMS W4118, with emphasis on distributed operating systems. Topics include interfaces to network protocols, distributed run-time binding, advanced virtual memory issues, advanced means of interprocess communication, file system design, design for extensibility, security in a distributed environment. Investigation is deeper and more hands-on than in COMS W4118. A programming project is required.

COMS E6121x Reliable software
3 pts. Lect: 3. Professor Yang.
Prerequisite: at least one of COMS W4118, W4115, or W4117, or significant software

development experiences. Topics include automated debugging, automated software repair, concurrent software reliability, software error detection, and more.

COMS E6123x or y Programming environments and software tools (PEST)
3 pts. Lect: 2. Professor Kaiser.
Prerequisite: COMS W4156 or equivalent. Software methodologies and technologies concerned with development and operation of today's software systems. Reliability, security, systems management and societal issues. Emerging software architectures such as enterprise and grid computing. Term paper and programming project. Seminar focus changes frequently to remain timely.

COMS E6125y Web-enhanced information management (WHIM)
3 pts. Lect: 2. Professor Kaiser.
Prerequisites: At least one COMS W41xx or COMS E61xx course and/or COMS W4444, or instructor's permission. Strongly recommended: COMS W4111. History of hypertext, markup languages, groupware and the web. Evolving web protocols, formats and computation paradigms such as HTTP, XML and Web Services. Novel application domains enabled by the web and societal issues. Term paper and programming project. Seminar focus changes frequently to remain timely.

COMS E6160x or y Topics in computer graphics
3 pts. Lect: 2. Professor Belhumeur.
Prerequisite: COMS W4160 or instructor's permission. An advanced graduate course, involving study of an advanced research topic in Computer Graphics. Content varies between offerings, and the course may be repeated for credit. Recent offerings have included appearance models in graphics, and high quality real-time rendering.

COMS E6174y Interaction design: a perceptual approach
3 pts. Lect: 3.
Prerequisite: COMS W4170 or instructor's permission. Design methology for special-purpose user interfaces. Emphasis on how psychology and perception inform good design. Interviewing and task modeling, participatory design, and low-fidelity prototyping. Applications of brain research, graphic design and art to develop custom user interfaces components, screen layouts, and interaction techniques for application-specific systems.

COMS E6176x or y User interfaces for mobile and wearable computing
3 pts. Lect: 2. Professor Feiner.
Prerequisite: COMS W4170 or instructor's permission. Introduction to research on user interfaces for mobile and wearable computing through lectures, invited talks, student-led discussions of important papers, and programming projects. Designing and authoring for mobility and wearability. Ubiquitous/pervasive computing. Collaboration with other users. Display, interaction, and communication technologies. Sensors for tracking position, orientation, motion, environmental context, and personal context. Applications and social consequences.

CSEE E6180x or y Modeling and performance
3 pts. Lect: 2. Professor Misra.
Prerequisites: COMS W4118 and SIEO W4150. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

COMS E6181x or y Advanced Internet services
3 pts. Lect: 2. Professor Schulzrinne.
In-depth survey of protocols and algorithms needed to transport multimedia information across the Internet, including audio and video encoding, multicast, quality-of-service, voice-over IP, streaming media and peer-to-peer multimedia systems. Includes a semester-long programming project.

COMS E6183x or y Advanced topics in network security
3 pts. Lect: 3. Professor Keromytis.
Prerequisites: COMS W4180, CSEE W4119 and COMS W4261 recommended. Review the fundamental aspects of security, including authentication, authorization, access control, confidentiality, privacy, integrity, and availability. Review security techniques and tools, and their applications in various problem areas. Study the state of the art in research. A programming project is required.

COMS E6184y Seminar on anonymity and privacy
3 pts. Lect: 3.
Prerequisite: COMS W4261 or W4180 or CSEE W4119 or instructor's permission. This course covers the following topics: Legal and social framework for privacy. Data mining and databases. Anonymous commerce and Internet usage. Traffic analysis. Policy and national security considerations. Classes are seminars with students presenting papers and discussing them. Seminar focus changes frequently to remain timely.

COMS E6185x or y Intrusion and anomaly detection systems
2 pts. Lect: 2. Professor Stolfo.
Pre- or corequisite: COMS W4180 Network security. The state of threats against computers, and networked systems. An overview of computer security solutions and why they fail. Provides a detailed treatment for network and host-based intrusion detection and intrusion prevention systems. Considerable depth is provided on anomaly detection systems to detect new attacks. Covers issues and problems in e-mail (spam, and viruses) and insider attacks (masquerading and impersonation).

COMS E6204x or y Topics in graph theory
3 pts. Lect: 2. Professor Gross.
Prerequisite: COMS W4203 or instructor's permission. Content varies from year to year. This course may be repeated for credit. Concentration on some aspect of graph theory, such as topological graph theory, algebraic graph theory, enumerative graph theory, graphical optimization problems, or matroids.

COMS E6206x or y Topics in combinatorial theory
3 pts. Lect: 2. Professor Gross.
Prerequisite: COMS W4203 or W4205, or instructor's permission. Concentration on some aspect of combinatorial theory. Content varies from year to year. This course may be repeated for credit.

COMS E6232x or y Analysis of algorithms, II
3 pts. Lect: 2.
Prerequisites: CSOR W4231. Continuation of CSOR W4231.

COMS E6253y Advanced topics in computational learning theory
3 pts. Lect: 3.
Prerequisite: CSOR W4231 or equivalent; COMS W4252 or W4236 helpful but not required. In-depth study of inherent abilities and limitations of computationally efficient learning algorithms. Algorithms for learning rich Boolean function classes in online, Probably Approximately Correct, and exact learning models. Connections with computational complexity theory emphasized. Substantial course project or term paper required.

COMS E6261x or y Advanced cryptography
3 pts. Lect: 3. Professor Malkin or Lewko.
Prerequisite: COMS W4261. A study of advanced cryptographic research topics such as: secure computation, zero knowledge, privacy, anonymity, cryptographic protocols. Concentration on theoretical foundations, rigorous approach, and provable security. Content varies between offerings. May be repeated for credit.

COMS E6291x or y Theoretical topics in computer science
3 pts. Lect: 3.
Prerequisite: Instructor's permission. Concentration on some theoretical aspect of computer science. Content varies from year to year. May be repeated for credit.

COMS E6732x or y Computational imaging
3 pts. Lect: 3. Professor Nayar.
Prerequisite: COMS W4731 or instructor's permission. Computational imaging uses a combination of novel imaging optics and a computational module to produce new forms of visual information. Survey of the state of art in computational imaging. Review of recent papers on: omnidirectional and panoramic imaging, catadioptric imaging, high dynamic

range imaging, mosaicing and superresolution. Classes are seminars with the instructor, guest speakers, and students presenting papers and discussing them.

COMS E6733x or y 3D photography
3 pts. Lect: 2. Professor Allen.
Prerequisite: Experience with at least one of the following topics: Computer graphics, computer vision, pixel processing, robotics or computer-aided design, or permission of instructor. Programming proficiency in C, C++, or JAVA. 3D Photography—the process of automatically creating 3D, texture-mapped models of objects in detail. Applications include robotics, medicine, graphics, virtual reality, entertainment and digital movies etc. Topics include 3D data acquisition devices, 3D modeling systems and algorithms to acquire, create, augment, manipulate, render, animate and physically build such models.

COMS E6734y Computational photography
3 pts. Lect: 3. Professor Belhumeur.
Prerequisites: COMS W4160, W4731, or a working knowledge of photography are recommended. Students should have knowledge in any of three core areas: computer vision, computer graphics, or photography. Computational techniques are used to produce a new level of images and visual representations. Topics include HDR imaging, feature matching using RANSAC, image mosaics, image-based rendering, motion magnification, camera lens arrays, programmable lighting, face detection, single and multiview geometry, and more.

COMS E6735y Visual databases
3 pts. Lect: 3.
Prerequisite: COMS W3134, W3136, or W3137 (or equivalent). COMS W4731 and W4735 helpful but not required. Contact instructor if uncertain. The analysis and retrieval of large collections of image and video data, with emphasis on visual semantics, human psychology, and user interfaces. Low-level processing: features and similarity measures; shot detection; key frame selection; machine learning methods for classification. Middle-level processing: organizational rules for videos, including unedited (home, educational), semiedited (sports, talk shows), edited (news, drama); human memory limits; progressive refinement; visualization techniques; incorporation of audio and text. High-level processing: extraction of thematic structures; ontologies, semantic filters, and learning; personalization of summaries and interfaces; detection of pacing and emotions. Examples and demonstrations from commercial and research systems throughout. Substantial course project or term paper required.

COMS E6737x or y Biometrics
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite: Background at the sophomore level in computer science, engineering, or like discipline. Corequisites: None In this course we will explore the latest advances in biometrics as well as the machine learning techniques behind them. Students will learn how these technologies work and how they are sometimes defeated. Grading will be based on homework assignments and a final project. There will be no midterm or final exam. This course shares lectures with COMS W4737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisite: CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6831y Sequential logic circuits
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. Generation and manipulation of flow table descriptions to asynchronous sequential functions. Coding of flow tables to satisfy various design criteria. Delays, races, hazards, metastability. Analysis of latches to determine key parameters. Bounds of input rates. Clocking schemes for synchronous systems. Synthesis of self-timed systems using 4-phase or 2-phase handshakes.

CSEE E6832x or y Topics in logic design theory
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. A list of topics for each offering of the course is available in the department office one month before registration. May be taken more than once if topics are different Iterative logic circuits applied to pattern recognition. Finite state machines; alternative representations, information loss, linear circuits, structure theory. Reliability and testability of digital systems.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite: Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor's permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

CSEE E6861y Computer-aided design of digital systems
3 pts. Lect: 2. Professor Nowick.
Prerequisites: (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor's permission); and (ii) a basic course in data structures and algorithms COMS W3134, W3136, W3137, W3157, or equivalent, and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include: modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multilevel logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6868x or y System-on-chip platforms
3 pts. Lect: 3. Professor Carloni.
Prerequisites: COMS 3157 and CSEE 3827 Design and programming of system-on-chip (SoC) platforms. Topics include: overview of technology and economic trends, methodologies and supporting CAD tools for system-level design and verification, software simulation and virtual platforms, models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, memory organization, device drivers, on-chip communication architectures, power management and optimization, integration of programmable cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

EECS E6870x or y Speech recognition
3 pts. Lect: 3.
Prerequisites: Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

COMS E6900x and y Tutorial in computer science
1–3 pts.
Prerequisite: Instructor's permission. A reading course in an advanced topic for a small number of students, under faculty supervision.

COMS E6901x Projects in computer science
1–12 pts.
Prerequisite: Instructor's permission. Software or hardware projects in computer science. Before registering, the student must submit a written proposal to the instructor for review. The proposal should give a brief outline of the project, estimated

schedule of completion, and computer resources needed. Oral and written reports are required. May be taken over more than one semester, in which case the grade will be deferred until all 12 points have been completed. No more than 12 points of COMS E6901 may be taken. Consult the department for section assignment.

COMS E6902x and y Thesis
1–9 pts.
Available to M.S. and CSE candidates. An independent investigation of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written report is essential and an oral presentation may also be required. May be taken over more than one semester, in which case the grade will be deferred until all 9 points have been completed. No more than 9 points of COMS E6902 may be taken. Consult the department for section assignment.

COMS E6910x and y Fieldwork
1 pt. Members of the faculty.
Prerequisites: Obtained internship and approval from faculty adviser. Only for M.S. students in the Computer Science Department who need relevant work experience as part of their program of study. Final report required. This course may not be taken for pass/fail credit or audited.

COMS E6915y Technical writing for computer scientists and engineers
3 pts. Members of the faculty.
Available to M.S. or Ph.D. candidates in CS/CE. Topics to help CS/CE graduate students' communication skills. Emphasis on writing, presenting clear, concise proposals, journal articles, conference papers, theses, and technical presentations. May be repeated for credit. Credit may not be used to satisfy degree requirements.

COMS E6998x and y Topics in computer science
3 pts. Members of the faculty.
Prerequisite: Instructor's permission. Selected topics in computer science. Content varies from year to year. May be repeated for credit.

COMS E6999x and y Topics in computer science, II
3 pts.
Prerequisite: COMS E6998. Continuation of COMS E6998.

COMS E9800x and y Directed research in computer science
1–15 pts.
Prerequisites: Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of points. May be repeated for credit. This course is only for Eng.Sc.D. candidates.

COMS E9910x and y Graduate research, I
1–6 pts.
Prerequisites: Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. This course is only for M.S. candidates holding GRA or TA appointments. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.

COMS E9911x and y Graduate research, II
1-15 pts.
Prerequisites: Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of points. May be repeated for credit. This course is only for M.S./Ph.D. track and Ph.D. students. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.

Henry Krumb School of Mines
918 S. W. Mudd, MC 4711
Phone: 212-854-2905
eee.columbia.edu

OUR MISSION

Earth and Environmental Engineering at the Henry Krumb School of Mines fosters excellence in education and research for the development and application of science and technology to maximize the quality of life for all, through the sustainable use and responsible management of Earth's resources.

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DEPARTMENT ADMINISTRATOR
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PROFESSORS
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SPECIAL RESEARCH SCIENTIST
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SENIOR RESEARCH SCIENTIST
Vasilis M. Fthenakis

ASSOCIATE RESEARCH SCIENTISTS
Irina Chernyshova
Greeshma Gadikota
Seungbu Park
Partha Patra
Parag Purohit

EARTH RESOURCES AND THE ENVIRONMENT

The Earth and Environmental Engineering program fosters education and research in the development and application of technology for the sustainable development, use, and integrated management of Earth's resources. Resources are identified as minerals, energy, water, air, and land, as well as the physical, chemical, and biological components of the environment. There is close collaboration with other engineering disciplines, the Lamont-Doherty Earth Observatory, the International Research Institute for Climate Prediction, the Center for Environmental Research and Conservation, and other Columbia Earth Institute units.

THE HENRY KRUMB SCHOOL OF MINES AT COLUMBIA UNIVERSITY

The School of Mines of Columbia University was established in 1864 and was the first mining and metallurgy department in the U.S. It became the foundation for Columbia's School of Engineering and Applied Sciences and has been a pioneer in many areas of mining and metallurgy, including the first mining (Peele) and mineral processing (Taggart) handbooks, flotation, chemical thermodynamics and kinetics, surface and colloid chemistry, and materials science.

Nearly 100 years after its formation, the School of Mines was renamed Henry Krumb School of Mines (HKSM) in honor of the generous Columbia benefactor of the same name. The Henry Krumb School of Mines supports three components:

- The **Department of Earth and Environmental Engineering (eee.columbia.edu) (EEE),** one of Columbia Engineering's nine departments.
- Columbia's interdepartmental program in **Materials Science and Engineering (matsci.columbia.edu) (MSE).** This program, administered by the Department of Applied Physics and Applied Mathematics, is described on page 173.
- **The Earth Engineering Center (seas.columbia.edu/earth).** The current research areas include energy, materials, and water resources.

EARTH AND ENVIRONMENTAL ENGINEERING (EEE)

Starting in 1996, the educational programs of Columbia University in mining and mineral engineering were transformed into the present program in Earth and Environmental Engineering (EEE). This program is concerned with the environmentally sound extraction and processing of primary materials (minerals, fuels, water), the management and development of land and water resources, and the recycling or disposal of used materials. EEE offers the Bachelor of Science (B.S.) in Earth and Environmental Engineering, the Master of Science (M.S.) in Earth and Environmental Engineering, and the doctorate degrees (Ph.D., Eng.Sc.D.) in EEE.

The EEE program welcomes Combined Plan students. An EEE minor is offered to all Columbia engineering students who want to enrich their academic record by concentrating some of their technical electives on Earth/Environment subjects. There is close collaboration between EEE and the Departments of Civil Engineering and Earth and Environmental Sciences, including several joint appointments.

RESEARCH CENTERS ASSOCIATED WITH EARTH AND ENVIRONMENTAL ENGINEERING

Columbia Water Center. The Center was established in 2008 to address issues of Global Water Security. It currently has 3 major initiatives:

The Global Water Sustainability Initiative is focused on an assessment of global water scarcity and risk, and innovations across scales, from farmer's field to reservoir optimization to national policy modifications to international trade, to develop real world solutions to an impending global water crisis. This includes the development of new agro-water and chemical sensor systems to improve water use efficiency and reduce non-point-source pollution as well as field studies on how to get farmers to use them; comprehensive modeling and optimization of regional crop and energy facility siting to improve water sustainability and income; field experiments of water/energy pricing policy changes; participatory reservoir management using climate scenarios, elicited stakeholder values, option contracts and insurance; and models for replicable community-managed rural drinking water systems. Active field research projects are in India, China, Brazil, and Peru.

The Global Flood Initiative recognizes that of all natural hazards, floods are responsible for the largest average annual loss of property and life. They are also a significant contributor to pollutant loading and environmental impact in water bodies. In a globalized society the disruption of food, energy, and manufactured goods supply chains by floods has also emerged as an issue. The initiative is developing state-of-the-art climate analyses for global flood risk projection, its mapping onto supply chains, and risk management using novel structural and financial tools.

America's Water is the third major initiative. It is driven by the goal of developing sustainable water management and infrastructure design paradigms for the 21st century, recognizing the linkages between urban functioning, food, water, energy, and climate. It seeks to pull together a comprehensive understanding of the issues facing water infrastructure in the USA. These include the financing of and investment in the replacement of aging infrastructure; pricing and allocating water, given changing values and climate; the mangement of the total urban water cycle through new technologies and network topologies; groundwater depletion and national food and economic futures; and novel opportunities for flood risk management and non-point-source pollution mitigation.

In addition, the department has active research on improving the efficiency of water use, reclamation and recycling in natural resource processing industries, and on the use of environmental microbiology for wastewater treatment and energy conversion. State-of-the-art methods from molecular genomics are being developed and used to address nitrification and denitrification in wastewater treatment and energy production.

Center for Life Cycle Analysis (LCA). The Center for Life Cycle Analysis (CLCA) of Columbia University was formed in the spring of 2006 with the objective of conducting comprehensive life cycle analyses of energy systems. LCA provides a framework for quantifying the potential environmental impacts of material and energy inputs and outputs of a process or product from "cradle to grave." The mission of the Center is to guide technology and energy policy decisions with data-based, well-balanced, and transparent descriptions of the environmental profiles of energy generation and storage systems in current and future electricity grids. Current research thrusts include:

- *Solar energy grid integration:* The CLCA is engaged in model development and technical and environmental systems analyses of renewable energy integration into electricity grids. It is developing models for evaluating and optimizing energy storage units for ramping rate control in photovoltaic power plants, optimizing penetration of solar and wind resources, and unit commitment and economic dispatch of conventional generators to compensate for solar and wind variability in large-scale penetrations.
- *Resource assessment and recycling of critical energy materials variability:* The CLCA, together with the Brookhaven National Laboratory are developing technologies for optimizing recycling of various elements from end-of-life photovoltaic systems and infrastructures for their collection.
- *Life-cycle environmental and environmental health and safety (EH&S) risk assessment:* Risk- and LCA-based comparisons of solar electric and conventional energy tecnologies in collaboration with Brookhaven National Laboratory and several European, South American, and Asian institutions.

For more information: clca.columbia.edu; e-mail: vmf5@columbia.edu.

Earth Engineering Center (EEC). EEC was formed in 1995 with the original mission to direct engineering research at Columbia on processes and products that balance the increasing use of materials by humanity with the need for clean air, water, and soil. EEC introduced the teaching of industrial ecology, was the first engineering unit of Columbia's Earth Institute, and co-organized the 1997 Global Warming International Conference (GW8) at Columbia University. As of 1998, EEC has concentrated on advancing the goals of sustainable waste management in the U.S. and globally. Economic development has resulted in the generation of billions of tons of used materials that can be a considerable resource, but when not managed properly, constitute a major environmental problem both in developed and developing nations. In 2003, in collaboration with the Energy Recovery Council of the U.S., EEC founded the Waste to Energy Research and Technology Council (WTERT). As of 2013, the Global WTERT Council (www.wtert.org) has sister organizations in 14 countries including Canada, China, Germany, Greece, India, Italy, Mexico, and the U.K. Over the years, WTERT research at Columbia has engaged many M.S. and Ph.D. students on all aspects of waste management (see www.wtert.org, Publications, Theses). EEC conducts a biannual survey of waste management in the 50 states of the Union.

Environmental Tracer Group (ETG). The Environmental Tracer Group uses natural and anthropogenic (frequently transient) tracers, as well as deliberately released tracers, to investigate the physics and chemistry of transport in environmental systems. The tracers include natural or anthropogenically produced isotopes (e.g., tritium or radioactive hydrogen, helium and oxygen isotopes, or radiocarbon), as well as noble gases and chemical compounds (e.g., CFCs and SF6). The ETG analytical facilities include four mass spectrometric systems that can be used in the analysis of tritium and noble gases in water, sediments, and rocks. In addition to the mass spectrometric systems, there are several gas chromatographic systems equipped with electron capture detectors that are used for measurements of SF6 in continental waters and CFCs and SF6 in the atmosphere. GC/MS capability is being added to the spectrum of analytical capabilities.

Industry/University Cooperative Research Center for Particulate and Surfactant Systems (CPaSS). CPaSS was established in 1998 by the Henry Krumb School of Mines, Department of Chemical Engineering, and Department of Chemistry at Columbia University. The Center encompasses detailed structure-property assessment of several classes of surface-active molecules, including oligomeric, polymeric, and bio-molecules. The aim of CPaSS is to develop and characterize novel surfactants for industrial applications such as coatings, dispersions, deposition, gas hydrate control, personal care products, soil decontamination, waste treatment, corrosion prevention, flotation, and controlled chemical reactions. The proposed research thus focuses on the design and development of specialty surfactants, characterization of their solution and interfacial behavior, and identification of suitable industrial application for these materials.

The goals of CPaSS are to perform industrially relevant research to address the technological needs in commercial surfactant and polymer systems, develop new and more efficient surface-active reagents for specific applications in the industry and methodologies for optimizing their performance, promote the use of environmentally benign surfactants in a wide array of technological processes, and build a resource center to perform and provide state-of-the-art facilities for characterization of surface-active reagents: columbia.edu/cu/iucrc.

International Research Institute for Climate Prediction (IRI). The IRI is the world's leading institute for the development and application of seasonal to interannual climate forecasts. The mission of the IRI is to enhance society's capability to understand, anticipate, and manage the impacts of seasonal climate fluctuations, in order to improve human welfare and the environment, especially in developing countries. This mission is to be conducted through strategic and applied research, education and capacity building, and provision of forecast and information products, with an emphasis on practical and verifiable utility and partnerships.

Langmuir Center for Colloids and Interfaces (LCCI). This Center brings together experts from mineral engineering, applied chemistry, chemical engineering, biological sciences, and chemistry to probe complex interactions of colloids and interfaces with surfactants and macromolecules. LCCI activities involve significant interaction with industrial sponsors and adopt an interdisciplinary approach toward state-of-the-art research on interfacial phenomena. Major areas of research at LCCI are thin films, surfactant and polymer adsorption, environmental problems, enhanced oil recovery, computer tomography, corrosion and catalysis mechanisms, membrane technology, novel separations of minerals, biocolloids, microbial surfaces, and interfacial spectroscopy.

Lenfest Center for Sustainable Energy. The mission of the Lenfest Center for Sustainable Energy is to develop technologies and institutions to ensure a sufficient supply of environmentally sustainable energy for all humanity. To meet this goal, the Center supports research programs in energy science, engineering, and policy across Columbia University to develop technical and policy solutions that will satisfy the world's future energy needs without threatening to destabilize Earth's natural systems.

The mission of the Lenfest Center is shaped by two global challenges. First, the Center seeks to reduce the emission of carbon dioxide into the atmosphere and to forestall a disruption of global climate systems that would impose negative consequences for human welfare. Second, the Center seeks to create energy options that will meet the legitimate energy demands of a larger and increasingly wealthy world population. In order to meet these two challenges, the Center seeks to develop new sources, technologies, and infrastructures.

The Lenfest Center focuses primarily on the technological and institutional development of the three energy resources sufficient to support the world's projected population in 2100 without increased carbon emissions: solar, nuclear, and fossil fuels combined with carbon capture and storage. Although each of these options can, in theory, be developed on a scale to satisfy global demand, they each face a combination of technological and institutional obstacles that demand research and development before they can be deployed.

The Center's main activities are based within the range of natural science and engineering disciplines. At the same time, it integrates technological research with analysis of the institutional, economic, and political context within which energy technologies are commercialized and deployed. For more information: energy.columbia.edu.

SCHOLARSHIPS, FELLOWSHIPS, AND INTERNSHIPS

The department arranges for undergraduate summer internships after the sophomore and junior years. Undergraduates can also participate in graduate research projects under the work-study program. Graduate research and teaching assistantships, as well as fellowships funded by the Department, are available to qualified graduate students. GRE scores are required of all applicants for graduate studies.

UNDERGRADUATE PROGRAM

The Bachelor of Science (B.S.) degree in Earth and Environmental Engineering prepares students for careers in the public and private sector concerned with primary materials (minerals, fuels, water) and the environment. Graduates are also prepared to continue with further studies in Earth/Environmental sciences and engineering, business, public policy, international studies, law, and medicine. The EEE program is accredited as an environmental engineering program by the Engineering Accreditation Commission of ABET.

What Is Earth and Environmental Engineering?

It is now recognized by the U.S. and other nations that continuing economic development must be accompanied by intelligent use of Earth's resources and that engineers can contribute much to the global efforts for sustainable development. The technologies that have been developed for identifying, extracting, and processing primary materials are also being applied to the twenty-first-century problems of resource recovery from used materials, pollution prevention, and environmental remediation. The EEE undergraduate program encompasses these technologies.

Undergraduate Program Objectives

1. Graduates equipped with the necessary tools (mathematics, chemistry, physics, Earth sciences, and engineering science) will understand and implement the underlying principles used in the engineering of processes and systems.
2. Graduates will be able to pursue careers in industry, government agencies, and other organizations concerned with the environment and the provision of primary and secondary materials and energy, as well as continue their education as graduate students in related disciplines.
3. Graduates will possess the basic skills needed for the practice of Earth and Environmental Engineering, including measurement and control of material flows through the environment; assessment of environmental impact of past, present, and future industrial activities; and analysis and design of processes for remediation, recycling, and disposal of used materials.
4. Graduates will practice their profession with excellent written and communication skills and with professional ethics and responsibilities.

The Curriculum

The first two years of the EEE program are similar to those of other engineering programs. Students are provided with a strong foundation in basic sciences and mathematics, as well as the liberal arts core. Specific to the EEE program is an early and sustained introduction to Earth science and environmental engineering, and options for a number of science courses to meet the specific interests of each student. The junior and senior years of the program consist of a group of required courses in engineering science and a broad selection of technical electives organized into three distinct concentrations, representing major areas of focus within the department.

Several Columbia departments, such as Civil Engineering, Mechanical Engineering, and Earth and Environmental Sciences (Lamont-Doherty Earth Observatory), as well as the Mailman School of Public Health, contribute courses to the EEE program. EEE students are strongly encouraged to work as summer interns in industry or agencies on projects related to Earth and Environmental Engineering. The department helps students get summer internships.

Technical Elective Concentrations

Students majoring in Earth and Environmental Engineering select one of the following three preapproved technical elective concentrations. Note that the eight-course sequence for each preapproved concentration includes two science courses during sophomore year (fall semester) and six technical elective courses during junior and senior years.

Any deviations from a preapproved concentration must be approved by an undergraduate faculty adviser. Alternatives for junior/senior electives within each concentration are listed, and others may be considered among 3000- to 4000-level courses of any Columbia Engineering department, as well as courses listed in the section "Courses in Other Divisions" in this bulletin. However, at least four of the six junior/senior electives must consist of engineering topics. Alternatives for sophomore-year science courses are shown in the EEE program table.

A student may also choose to develop an individual concentration conforming to his/her specific interests, provided that it satisfies ABET engineering accreditation criteria. Therefore, this must be developed in close consultation with and approved by a faculty adviser.

Water Resources and Climate Risks Concentration

Preapproved course sequence:

PHYS C1403: Introduction to classical and quantum waves (SEM III)
EESC V2100: Climate system (SEM III)
EAEE E4006: Field methods for environmental engineering (SEM VI)
EAEE E4009: GIS for resource, environmental, and infrastructure management (SEM VII)
EAEE E4350: Planning and management of urban hydrologic systems (SEM VII)
EAEE E4257: Environmental data analysis and modeling (SEM VIII)
ECIA W4100: Management and development of water systems (SEM VIII)
CIEE E4257: Groundwater contaminant transport and remediation

Alternatives for junior/senior electives:

EAEE E4001: Industrial ecology of Earth resources
EESC W4008: Introduction to atmospheric science
CIEE E4163: Environmental engineering: wastewater
APPH E4200: Physics of fluids
CIEN E4250: Waste containment design and practice
CIEN E4255: Flow in porous media
EESC W4401: Quantitative models of climate-sensitive natural and human systems
EESC W4404: Regional dynamics, climate and climate impacts

Sustainable Energy and Materials Concentration

Preapproved course sequence:

CHEM C3443: Organic chemistry (SEM III)
EESC V2200: Solid earth system (SEM III)
EESC W4001: Advanced general geology (SEM III)
MECE E3311: Heat transfer (SEM VI)
EAEE E4001: Industrial ecology of Earth resources (SEM VII)
EAEE E4361: Economics of Earth resource industries (SEM VII)
EAEE E4190: Photovoltaic systems engineering and sustainability (SEM VII)
MECE E4302: Advanced thermodynamics (SEM VIII)

EARTH AND ENVIRONMENTAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3) **or** MATH V1207 (4)	MATH V1102 (3) MATH V1208 (4)	MATH V1201 (3)	APMA E2101 (3) MATH V2030 (3) ODE
PHYSICS	C1401 (3) **or** C1601 (3.5) **or** C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	CHEM C3443 (3.5) **or** PHYS C1403 (3) **or** PHYS C2601 (3.5) **or** BIOL C2005 (4)	
CHEMISTRY	C1403 (3.5) **and** Lab C1500 (3) either semester **or** C1604 (3.5) **or** C3045 (3.5)	C1404 (3.5) C2507 (3) C3046 (3.5) **and** Lab C2507 (3)		
REQUIRED NONTECHNICAL ELECTIVES	C1010 (3) **or** Z1003 (4) **or** ALP0006 (0)	C1010 (3) Z1003 (4)	HUMA C1001, COCI C1101, **or** Global Core (3–4) **or** C1010 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0) HUMA C1121 **or** C1123 (3)
REQUIRED PROFESSIONAL AND TECHNICAL ELECTIVES			EESC W4001 (4) **or** EESC V2100 (4.5) **or** EESC V2200 (4.5) EEAE E2100 (3) A better planet by design	SIEO W3600 (4) Introduction to probability and statistics
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

EESC W3015: The Earth's carbon cycle (SEM VIII)
MECE E4211: Energy: sources and conversion (SEM VIII)
CHEE E4140: Engineering separations processes

Alternatives for junior/senior electives:
CHEM C3071: Introduction to inorganic chemistry
MSAE E3103: Elements of materials science
CHEN E3110: Transport phenomena, I
CHEN E3120: Transport phenomena, II
EESC W4008: Introduction to atmospheric science
EAEE E4210: Thermal treatment of waste and biomass materials
CHEM G4230: Statistical thermodynamics
EAEE E4550: Catalysis for emissions control
EACE E4560: Particle technology

Environmental Health Engineering Concentration

Preapproved course sequence:
CHEM C3443: Organic chemistry (SEM III)
EESC V2100: Climate system (SEM III)
EAEE E4006: Field methods for environmental engineering (SEM VI)
EAEE E4009: GIS for resource, environmental and infrastructure management (SEM VII)
EHSC P6300: Environmental health sciences (SEM VII)
EAEE E4257: Environmental data analysis and modeling (SEM VIII)
EAEE E4150: Air pollution prevention and control (SEM VIII)

EARTH AND ENVIRONMENTAL ENGINEERING: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	EAEE E3103 (3) Energy, minerals, and material systems	CIEE E3255 (3) Environmental control and pollution reduction systems	EAEE E3998 (2) Undergraduate design project	EAEE E3999 (2) Undergraduate design project
	CIEE E4252 (3) Environmental engineering	CIEE E3250 (3) Hydrosystems engineering	EAEE E4003 (3) Aquatic chemistry	
	EAEE E3200 (3) Applied transportation and chemical rate phenomena	EAEE E4160 (3) Solid and hazardous waste management	EAEE E3801 (2) Earth and environmental engineering lab, II	
	CHEE E3010 (3) Principles of chemical engineering thermodynamics	EAEE E3800 (2) Earth and environmental engineering lab, I		
		EAEE E3901 (3) Environmental microbiology		
TECHNICAL ELECTIVES		3 points	6 points	9 points
NONTECHNICAL ELECTIVES	3 points		3 points	6 points
TOTAL POINTS	15	17	16	17

EHSC P6309: Biochemistry basic to environmental health (SEM VIII)

Alternatives for junior/senior electives:
EAEE E4001: Industrial ecology of Earth resources
CIEE E4163: Environmental engineering: wastewater
CIEE E4257: Groundwater contaminant transport and remediation
EAEE E4900: Applied transport and chemical rate phenomena
EAEE E4950: Environmental biochemical processes

GRADUATE PROGRAMS

M.S. in Earth and Environmental Engineering (M.S.-EEE)

The M.S.-EEE program is designed for engineers and scientists who plan to pursue, or are already engaged in, environmental management/development careers. The focus of the program is the environmentally sound mining and processing of primary materials (minerals, energy, and water) and the recycling or proper disposal of used materials. The program also includes technologies for assessment and remediation of past damage to the environment. Students can choose a pace that allows them to complete the M.S.-EEE requirements while being employed.

M.S.-EEE graduates are specially qualified to work for engineering, financial, and operating companies engaged in mineral processing ventures, the environmental industry, environmental groups in all industries, and for city, state, and federal agencies responsible for the environment and energy/resource conservation. At the present time, the U.S. environmental industry comprises nearly 30,000 big and small businesses with total revenues of more than $150 billion. Sustainable development and environmental quality has become a top priority of government and industry in the United States and many other nations.

This M.S. program is offered in collaboration with the Departments of Civil Engineering and Earth and Environmental Sciences. Many of the teaching faculty are affiliated with Columbia's Earth Engineering Center.

For students with a B.S. in engineering, at least 30 points (ten courses) are required. For students with a nonengineering B.S. or a B.A., preferably with a science major, up to 48 points (total of sixteen courses) may be required for makeup courses. Students may carry out a research project and write a thesis worth 3–6 points. A number of areas of study are available for the M.S.-EEE, and students may choose courses that match their interest and career plans. The areas of study include:

- Alternative energy and carbon management
- Climate risk assessment and management
- Environmental health engineering
- Integrated waste management
- Natural and mineral resource development and management
- Novel technologies: surfacial and colloidal chemistry and nanotechnology
- Urban environments and spatial analysis

Additionally, there are three optional concentrations in the program, in each of which there are a number of required specific core courses and electives. The concentrations are described briefly below; details and the lists of specific courses for each track are available from the department.

Water Resources and Climate Risks

Climate-induced risk is a significant component of decision making for the planning, design, and operation of water resource systems, and related sectors such as energy, health, agriculture, ecological resources, and natural hazards control. Climatic uncertainties can be broadly classified into two areas: (1) those related to anthropogenic climate change; (2) those related to seasonal- to century-scale natural variations. The climate change issues impact the design of physical, social, and financial infrastructure systems to support the sectors listed above. The climate variability and predictability issues impact systems operation, and hence design. The goal of the M.S. concentration in water resources and climate risks is to provide (1) a capacity for understanding and quantifying the projections for climate change and variability in the context of decisions for water resources and related sectors of impact; and (2) skills for integrated risk assessment and management for operations and design, as well as for regional policy analysis and management. Specific areas of interest include:

- Numerical and statistical modeling of global and regional climate systems and attendant uncertainties
- Methods for forecasting seasonal to interannual climate variations and their sectoral impacts
- Models for design and operation of water resource systems, considering climate and other uncertainties
- Integrated risk assessment and management across water resources and related sectors

Sustainable Energy

Building and shaping the energy infrastructure of the twenty-first century is one of the central tasks for modern engineering. The purpose of the sustainable energy concentration is to expose students to modern energy technologies and infrastructures and to the associated environmental, health, and resource limitations. Emphasis will be on energy generation and use technologies that aim to overcome the limits to growth that are experienced today. Energy and economic well-being are tightly coupled. Fossil fuel resources are still plentiful, but access to energy is limited by environmental and economic constraints. A future world population of 10 billion people trying to approach the standard of living of the developed nations cannot rely on today's energy technologies and infrastructures without severe environmental impacts. Concerns over climate change and changes in ocean chemistry require reductions in carbon dioxide emissions, but most alternatives to conventional fossil fuels, including nuclear energy, are too expensive to fill the gap. Yet access to clean, cheap energy is critical for providing minimal resources: water, food, housing, and transportation.

Concentration-specific classes will sketch out the availability of resources, their geographic distribution, the economic and environmental cost of resource extraction, and avenues for increasing energy utilization efficiency, such as cogeneration, district heating, and distributed generation of energy. Classes will discuss technologies for efficiency improvement in the generation and consumption sector; energy recovery from solid wastes; alternatives to fossil fuels, including solar and wind energy, and nuclear fission and fusion; and technologies for addressing the environmental concerns over the use of fossil fuels and nuclear energy. Classes on climate change, air quality, and health impacts focus on the consequences of energy use. Policy and its interactions with environmental sciences and energy engineering will be another aspect of the concentration. Additional specialization may consider region-specific energy development.

Sustainable Waste Management

Humanity generates nearly 2 billion tons of municipal solid wastes (MSW) annually. Traditionally, these wastes have been discarded in landfills that have a finite lifetime and then must be replaced by converting more greenfields to landfills. This method is not sustainable because it wastes land and valuable resources. Also, it is a major source of greenhouse gases and of various contaminants of air and water. In addition to MSW, the U.S. alone generates billions of tons of industrial and extraction wastes. Also, the by-product of water purification is a sludge or cake that must be disposed in some way. The IWM concentration prepares engineers to deal with the major problem of waste generation by exposing them to environmentally better means for dealing with wastes: waste reduction, recycling, composting, and waste-to-energy via combustion, anaerobic digestion, or gasification. Students are exposed not only to the technical aspects of integrated waste management but also to the associated economic, policy, and urban planning issues.

Since the initiation of the Earth and environmental engineering program in 1996, there have been several graduate research projects and theses that exemplify the engineering problems that will be encompassed in this concentration:

- Design of an automated materials recovery facility
- Analysis of the bioreactor landfill
- Generation of methane by anaerobic digestion of organic materials
- Design of corrosion inhibitors
- Flocculation modeling
- Analysis of formation of dioxins in high-temperature processes
- Combination of waste-to-energy and anaerobic digestion
- Application of GIS in siting new WTE facilities
- Corrosion phenomena in WTE
- Combustion chambers
- Mathematical modeling of transport phenomena in a combustion chamber

- Effect of oxygen enrichment on combustion of paper and other types of solid wastes
- Feasibility study and design of WTE facilities

Doctoral Programs

EEE offers two doctoral degrees: (1) the Eng.Sc.D. degree, administered by Columbia Engineering; and (2) the Ph.D. degree, administered by the Graduate School of Arts and Sciences.

Doctoral Qualifying Examination and Research Proposal

Before the end of the first semester in the doctoral program, the student and her/his adviser will set up an advisory committee of two or three faculty members. This committee will meet at least once a semester to assess academic and research progress of the student and to recommend corrective action in case of emerging or existing deficiencies.

Doctoral students are required to pass a qualifying exam soon after the completion of their first year into the program (spring or fall). They will submit and defend their research proposal approximately one year after successful completion of the qualifying exam. Submission of the dissertation and thesis defense will follow general University rules.

The qualifying examination will be an oral exam administered by four faculty members. The adviser of the student will be a member of the exam committee but may not be the chair. The students will be examined in their understanding of fundamentals as they apply in the four general areas of research of the department: water resources, materials processing, energy, and chemical and biochemical processes. It is expected that each question period will last about 20 minutes, of which 15 minutes will be led by the faculty member from the area and the remaining 5 minutes will be open for questions by all faculty present at the exam. There will be a final period of 20 minutes for general questions.

All graduate students are expected to have a background equivalent to the required core of our undergraduate program. They have, of course, an opportunity to make up for any deficiency in their master's program. In order to be prepared for the exam, students can take at least one course in each core area during their first two semesters at Columbia (see website for up-to-date course listing). In case the student declares an explicit minor in another department, the qualifying exam requirements will be modified in consultation with the graduate committee. The minor has to be approved by both departments.

The engineering objectives of EEE research and education include:

- **Provision and disposal of materials:** environmentally sustainable extraction and processing of primary materials; manufacturing of derivative products; recycling of used materials; management of industrial residues and used products; materials-related application of industrial ecology.
- **Management of water resources:** understanding, prediction, and management of the processes that govern the quantity and quality of water resources, including the role of climate; development/operation of water resource facilities; management of water-related hazards.
- **Energy resources and carbon management:** mitigation of environmental impacts of energy production; energy recovery from waste materials; advancement of energy efficient systems; new energy sources; development of carbon sequestration strategies.
- **Sensing and remediation:** understanding of transport processes at different scales and in different media; containment systems; modeling flow and transport in surface and subsurface systems; soil/water decontamination and bioremediation.

COURSES IN EARTH AND ENVIRONMENTAL ENGINEERING

EAEE E2002x Alternative energy resources
3 pts. Lect: 3. Instructor to be announced.
Unconventional, alternative energy resources. Technological options and their role in the world energy markets. Comparison of conventional and unconventional, renewable and non-renewable energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Introduction to carbon dioxide capture and carbon dioxide disposal as a means of sustaining the fossil fuel option.

EAEE E2100x A better planet by design
3 pts. Lect: 3. Professor Lall.
Introduction to design for a sustainable planet. Scientific understanding of the challenges. Innovative technologies for water, energy, food, materials provision. Multiscale modeling and conceptual framework for understanding environmental, resource, human, ecological, and economic impacts and design performance evaluation. Focus on the linkages between planetary, regional, and urban water, energy, mineral, food, climate, economic, and ecological cycles. Solution strategies for developed and developing country settings.

CHEE E3010x Principles of chemical engineering thermodynamics
3 pts. Lect: 3. Professor Kumar.
Prerequisite: CHEM C1403. Corequisite: CHEN E3030. Introduction to thermodynamics. Fundamentals are emphasized: the laws of thermodynamics are derived and their meaning explained and elucidated by applications to engineering problems. Pure systems are treated, with an emphasis on phase equilibrium.

EAEE E3101y Earth resource production systems
3 pts. Lect: 3. Not offered in 2015–2016.
Technologies and equipment common to a wide range of surface and subsurface engineering activities: mine reclamation, hazardous waste remediation, discovering and operating surface and underground mines, detection and removal of hidden underground objects, waste disposal, dredging and harbor rehabilitation, and tunneling for transportation or water distribution systems. These methods and equipment are examined as they apply across the spectrum from mining to environmental engineering projects. The aim is to provide a broad background for earth and environmental engineers in careers involving minerals and industrial, large-scale environmental projects.

EAEE E3103x Energy, minerals, and materials systems
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent Corequisites: MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent. Overview of energy resources, resource management from extraction and processing to recycling and final disposal of wastes. Resources availability and resource processing in the context of the global natural and anthropogenic material cycles; thermodynamic and chemical conditions including nonequilibrium effects that shape the resource base; extractive technologies and their impact on the environment and the biogeochemical cycles; chemical extraction from mineral ores, and metallurgical processes for extraction of metals. In analogy to metallurgical processing, power generation and the refining of fuels are treated as

extraction and refining processes. Large scale of power generation and a discussion of its impact on the global biogeochemical cycles.

EAEE E3112y Introduction to rock mechanics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: EAEE E3101 and ENME 3111, or their equivalents. Rock as an engineering material, geometry and strength of rock joints, geotechnical classification of rock masses, strength and failure of rock, field investigations prior to excavation in rock, rock reinforcement, analysis and support of rock slopes and tunnels, and case histories.

MSAE E3141y Processing of metals and semiconductors
3 pts. Lect: 3. Professor Duby.
Prerequisite: MSAE E3103 or equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

EAEE E3185y Summer fieldwork for Earth and environmental engineers
0.5 pt. Not offered in 2015–2016.
Undergraduates in Earth and environmental engineering may spend up to 3 weeks in the field under staff direction. The course consists of mine, landfill, plant, and major excavation site visits and brief instruction of surveying methods. A final report is required.

EAEE E3200x Applied transport and chemical rate phenomena
3 pts. Lect: 3. Professor Chen.
Prerequisite: APMA E2101. Fluid statics. Basics of flow analysis. Dimensional analysis. Pipe flow. Fluid dynamics, heat and mass transfer. Effects of velocity, temperature, and concentration gradients and material properties on fluid flow, heat and mass transfer. Applications to environmental engineering problems.

EAEE E3221x Environmental geophysics
3 pts. Lect: 3. Not offered in 2015–2016.
Introduction to applied and environmental geophysics methods. Overview of principles of geophysics, geophysical methods and techniques (seismic, ground penetrating radar, resistivity, frequency em, and magnetics), and theory and practical aspects of data processing and inversion. Examination of geophysical case studies for engineering and environmental purposes.

CIEE E3250y Hydrosystems engineering
3 pts. Lect: 3. Professor Gentine.
Prerequisites: CHEN E3110 or ENME E3161 or equivalent, SIEO W3600 or equivalent, or instructor's permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial hydrologic analysis using GIS and watershed models.

CIEE E3255y Environmental control and pollution reduction systems
3 pts. Lect: 3. Professor Farrauto.
Prerequisite: EAEE E3200 or ENME E3161 or MECE E3100. Sources of solid/gaseous air pollution and the technologies used for modern methods of abatement. Air pollution and its abatement from combustion of coal, oil, and natural gas and the thermodynamics of heat engines in power generation. Catalytic emission control is contrasted to thermal processes for abating carbon monoxide, hydrocarbons, oxides of nitrogen and sulfur from vehicles and stationary sources. Processing of petroleum for generating fuels. Technological challenges of controlling greenhouse gas emissions. Biomass and the hydrogen economy coupled with fuel cells as future sources of energy.

EAEE E3800y Earth and environmental engineering laboratory, I
2 pts. Lect: 1. Lab: 3. Professor Duby.
Prerequisite: CHEE E3010. Corequisite: EAEE E3255. Experiments on fundamental aspects of Earth and environmental engineering with emphasis on the applications of chemistry, biology and thermodynamics to environmental processes: energy generation, analysis and purification of water, environmental biology, and biochemical treatment of wastes. Students will learn the laboratory procedures and use analytical equipment firsthand, hence demonstrating experimentally the theoretical concepts learned in class.

EAEE E3801x Earth and environmental engineering laboratory, II
2 pts. Lect: 1. Lab: 3. Professor Duby.
Prerequisite: EAEE E3800. Corequisite: EAEE E4003. A continuation of EAEE E3800, with emphasis on the principles underlying water analysis for inorganic, organic, and bacterial contaminants. Lab required.

EAEE E3900x and y–S3900 Undergraduate research in Earth and environmental engineering
0–3 pts. Directed study. Members of the faculty.
This course may be repeated for credit, but no more than 3 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in Earth and Environmental Engineering, or carry out a special project under the supervision of EAEE faculty. Credit for the course is contingent on the submission of an acceptable thesis or final report. This course cannot substitute for the Undergraduate design project (EAEE E3999 or EAEE E3999).

EAEE E3901y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Prerequisite: CHEM C1404 or equivalent. Fundamentals of microbiology, genetics and molecular biology, principles of microbial nutrition, energetics and kinetics, application of novel and state-of-the-art techniques in monitoring the structure and function of microbial communities in the environment, engineered processes for biochemical waste treatment and bioremediation, microorganisms and public health, global microbial elemental cycles.

EAEE E3998x-E3999y Undergraduate design project
2 pts. (each semester). Lect: 1. Lab: 2. Professor Farrauto.
Prerequisite: senior standing. Students must enroll for both 3998x and 3999y during their senior year. Selection of an actual problem in Earth and environmental engineering, and design of an engineering solution including technical, economic, environmental, ethical, health and safety, social issues. Use of software for design, visualization, economic analysis, and report preparation. Students may work in teams. Presentation of results in a formal report and public presentation.

EAEE E4001x Industrial ecology of earth resources
3 pts. Lect: 3. Professor Chen.
Industrial ecology examines how to reconfigure industrial activities so as to minimize the adverse environmental and material resource effects on the planet. Engineering applications of methodology of industrial ecology in the analysis of current processes and products and the selection or design of environmentally superior alternatives. Home assignments of illustrative quantitative problems.

EAEE E4003x Introduction to aquatic chemistry
3 pts. Lect: 3. Professor Duby.
Prerequisite: CHEE E3010. Principles of physical chemistry applied to equilibria and kinetics of aqueous solutions in contact with minerals and anthropogenic residues. The scientific background for addressing problems of aqueous pollution, water treatment, and sustainable production of materials with minimum environmental impact. Hydrolysis, oxidation-reduction, complex formation, dissolution and precipitation, predominance diagrams; examples of natural water systems, processes for water treatment and for the production of inorganic materials from minerals.

EAEE E4004x Physical processing and recovery of solids
3 pts. Lect: 3. Not offered in 2015–2016.
Generalized treatment of processes for solids separation. Applications to materials processing and handling; mining; solid waste, recycling, and resource recovery; construction materials and debris; scrap materials, yard and park wastes. Economic considerations and context. Relevant materials properties and bulk materials analyses. Process system flow-sheets and analysis. Solid/solid, solid/liquid, and solid/gas separation process. Liberation, concentration, and auxiliary processes. Design of separation machines: types and intensities of force involved; scalling-up factors. Laboratory demonstrations and a field trip will be included.

EAEE E4005x Near-surface engineering geophysics
3 pts. Lect: 3. Not offered in 2015–2016.
Geophysical methods as applicable to engineering problems. Principles of geophysics and noninvasive imaging techniques (inversion technology) and benefits and pitfalls of geophysics vs. direct imaging methods. Discussion of theory of each method. Discussion of data acquisition, processing and interpretation for each method. Treatment of several case studies. Class-wide planning and execution of small-scale geophysical survey.

EAEE E4006y Field methods for environmental engineering
3 pts. Lect: 1.5. Lab: 2. Professor McGillis.
Prerequisite: ENME E3161 or equivalent or instructor's permission Principles and methods for designing, building and testing systems to sense the environment. Monitoring the atmosphere, water bodies and boundary interfaces between the two. Sensor systems for monitoring heat and mass flows, chemicals, and biota. Measurements of velocity, temperature, flux and concentration in the field. The class will involve planning and execution of a study to sense a local environmental system.

EAEE E4007y Environmental geophysics field studies
3 pts. Lect: 3. Not offered in 2015–2016.
Application of geophysical methods to noninvasive assessment of the near surface. First part consists of series of two-hour lectures of physics and math involved in instrumental methods and data acquisition and processing. the field (nine field days) students plan surveys; collect and analyze geophysical data in teams; learn how to integrate geophysical data with invasive data, hydrological, geological, engineering, and contaminant transport models; and develop a comprehensive and justifiable model of the subsurface. Geophysical methods include GPR (Ground Penetrating Radar), conductivity, and magnetic and seismic methods. Field applications include infrastructure/environmental assessment, archeological studies, and high resolution geology.

EAEE E4009x Geographic information systems (GIS) for resource, environmental and infrastructure management
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Permission of the instructor. Basic concepts of geomatics, spatial data representation and organization, and analytical tools that comprise GIS are introduced and applied to a variety of problems including watershed protection, environmental risk assessment, material mass balance, flooding, asset management, and emergency response to natural or man-made hazards. Technical content includes geography and map projections, spatial statistics, database design and use, interpolation and visualization of spatial surfaces and volumes from irregularly spaced data, and decision analysis in an applied setting. Taught in a laboratory setting using ArcGIS. Access to New York City and other standard databases. Term projects emphasize information synthesis toward the solution of a specific problem.

EAEE E4010y Remote sensing and environmental change
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E4009 or EESC W4050 or instructor's permission. Practical and theoretical foundations for the application of remote sensing techniques to identification and monitoring of environmental change. Designing and applying spectral indices for assessment and monitoring, time series analysis of remote sensing data for analyzing environmental problems. Discussions of published literature relevant to the central topic covered in class. Analysis of remote sensing data using IRI data library.

EAEE E4011y Industrial ecology for manufacturing
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E4001 or instructor's permission. Application of industrial ecology to Design for Environment (DFE) of processes and products using environmental indices of resources consumption and pollution loads. Introduction of methodology for Life Cycle Assessment (LCA) of manufactured products. Analysis of several DFE and LCA case studies. Term project required on use of DFE/LCA on a specific product/process: (a) product design complete with materials and process selection, energy consumption, and waste loadings; (b) LCA of an existing industrial or consumer product using a commercially established method.

CHEE E4050x Industrial and environmental electrochemistry
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEN E3010 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications illustrated by means of laboratory experiments: electroplating, refining, and winning in aqueous solutions and in molten salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

ECIA W4100y Management and development of water systems
3 pts. Lect: 3. Professors Gentine and Lall.
Decision analytic framework for operating, managing, and planning water systems, considering changing climate, values and needs. Public and private sector models explored through U.S.-international case studies on topics ranging from integrated watershed management to the analysis of specific projects for flood mitigation, water and wastewater treatment, or distribution system evaluation and improvement.

CHEE E4140x Engineering separations processes
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEN E3100, E3120, and E3210 or permission of instructor. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

EAEE E4150y Air pollution prevention and control
3 pts. Lect: 3. Professor Fthenakis.
Adverse effects of air pollution, sources and transport media, monitoring and modeling of air quality, collection and treatment techniques, pollution prevention through waste minimalization and clean technologies, laws, regulations, standards, and guidelines.

EAEE E4160y Solid and hazardous waste management
3 pts. Lect: 3. Professor Somasundaran.
Generation, composition, collection, transport, storage and disposal of solid and hazardous waste. Impact on the environment and public health. Government regulations. Recycling and resource recovery.

CIEE E4163x Sustainable water treatment and reuse
3 pts. Lect: 3. Professor Becker.
Prerequisites: Introductory chemistry (with lab) and fluid mechanics, or the equivalent. Theory and application of the physical and chemical processes for treating potable water and reusing wastewater. Disinfection/oxidation, coagulation and floccuation, clarification, filtration, ion exchange, adsorption, membrane processes, advanced oxidation processes, activated sludge, and anaerobic sludge digestion.

EAEE E4190x Photovoltaic systems engineering and sustainability
3 pts. Lect: 3. Professor Fthenakis.
Prerequisite: Senior standing or instructor's permission. A systems approach for intermittent renewable energy involving the study of resources, generation, demand, storage, transmission, economics and politics. Study of current and emerging photovoltaic technologies, with focus on basic sustainability metrics (e.g., cost, resource

availability, and life-cycle environmental impacts). The status and potential of first- and second-generation photovoltaic technologies (e.g., crystalline and amorphous Si, CdTe, CIGS) and emerging third-generation ones. Storage options to overcome the intermittency constraint. Large scales of renewable energy technologies and plug-in hybrid electric cars.

EAEE E4200y Production of inorganic materials
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEE E3010 or equivalent. Production and recycling of inorganic materials in aqueous and high temperature systems. Industrial and environmental applications of hydrometallurgy, pyrometallurgy, and electrometallurgy. Reactor systems for, e.g., leaching, precipitation, and solvent extraction, bath and flash smelting reactors, rotary kilns, and fluid bed reactors. Thermodynamic and kinetic factors and materials/energy balances involved in the design and performance of such reactors in typical applications.

EAIA E4200y Alternative energy resources
3 pts. Lect: 3. Instructor to be announced.
Unconventional, alternative energy resources. Technological options and their role in the world energy markets. Comparison of conventional and unconventional, renewable and nonrenewable, energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Introduction to carbon dioxide disposal as a means of sustaining the fossil fuel option. Recitation section required.

EAEE E4210x Thermal treatment of waste and biomass materials
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEE E3010 or the equivalent or instructor's permission. Origins, quantities generated, and characterization of solid wastes. Chemical and physical phenomena in the combustion or gasification of wastes. Application of thermal conversion technologies, ranging from combustion to gasification and pyrolysis. Quantitative description of the dominant waste to energy processes used worldwide, including feedstock preparation, moving grate and fluid bed combustion, heat transfer from combustion gases to steam, mitigation of high-temperature corrosion, electricity generation, district heating, metal recovery, emission control, and beneficial use of ash residues.

EAEE E4241x Solids handling and transport systems
3 pts. Lect: 3. Not offered in 2015–2016.
Analysis and design of transportation systems for bulk solids in tunnels, mines, and large excavations. Design of hoisting, cable transport, rail and trackless haulage systems, conveyor belts, selection of loaders, excavators, off-highway trucks, and draglines for large excavations.

CIEE E4250y Hydrosystems engineering
3 pts. Lect: 2.5. Professors Lall and Gentine.
Prerequisites: CHEN E3110 or ENME E3161 or equivalent, SIEO W3600 or equivalent, or the instructor's permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial hydrologic analysis using GIS and watershed models.

CHEE E4252x Introduction to surface and colloid chemistry
3 pts. Lect: 3. Professor Somasundaran.
Prerequisite: Elementary physical chemistry. Thermodynamics of surfaces, properties of surfactant solutions and surface films, electrostatic and electrokinetic phenomena at interfaces, adsorption; interfacial mass transfer and modern experimental techniques.

CIEE E4252y Environmental engineering
3 pts. Lect: 3. Professor Chandran.
Prerequisites: CHEM C1403, or equivalent; ENME E3161 or equivalent. Engineering aspects of problems involving human interaction with the natural environment. Review of fundamental principles that underlie the discipline of environmental engineering, i.e., constituent transport and transformation processes in environmental media such as water, air, and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollution emissions, and hazardous waste remediation. Presented in the context of current issues facing the practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management.

EAEE E4255x River and coastal hyrdrodynamics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEN E3110 or ENME E3161 or the equivalent. Dynamics of flow and waves in rivers and coastal settings, with applications to flooding and mixing of saline and fresh waters, sediment transport. Integrative hydrodynamics modeling experience using numerical and analytical tools applied to complex real world setting, including concerns of anthropogenic change in rivers and estuaries and sea level fluctuations at the river-estuary boundary.

CIEE E4257y Groundwater contaminant transport and remediation
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CIEE E3250 or equivalent. Sources and types of groundwater contamination. Groundwater hydrology. Groundwater contaminant rate and transport. Flow and transport in the unsaturated zone. Nonaqueous phase liquids and multiphase flow. Physical and numerical models for contaminant transport. Characterization and assessment of contaminated sites. Groundwater remediation alternatives. Regulations.

EAEE E4257y Environmental data analysis and modeling
3 pts. Lect: 3. Professor Lall.
Prerequisite: SIEO W3600 or W4250 or equivalent. Statistical methods for the analysis of the space and time structure in environmental data. Application to problems of climate variation and change; hydrology; air, water and soil pollution dynamics; disease propagation; ecological change; and resource assessment. Applications are developed using the ArcView Geographical Information System (GIS), integrated with currently available statistical packages. Team projects that lead to publication-quality analyses of data in various environmental fields of interest. An interdisciplinary perspective is emphasized in this applications-oriented class.

EAEE E4300x or y Introduction to carbon management
3 pts. Lect: 3. Professor Schlosser.
Prerequisites: Undergraduate level mathematics and science, or instructor's permission. Introduction to natural and anthropogenic carbon cycle, and carbon and climate. Rationale and need to manage carbon and tools with which to do so (basic science, psychology, economics and policy background, negotiations and society; emphasis on interdisciplinary and inter-dependent approach). Simple carbon emission model to estimate the impacts of a specific intervention with regard to national, per capita, and global emissions. Student-led case studies (e.g., reforestation, biofuels, CCS, efficiency, alternative energy) to illustrate necessary systems approach required to tackle global challenges.

EAEE E4301y Carbon storage
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Undergraduate level mathematics and science, or instructor's permission. Major technologies to capture carbon dioxide via new or retro-fitted power plant designs, during industrial processes, and from ambient air. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4302x or y Carbon capture
3 pts. Lect: 3. Professor Meinrenken.
Prerequisites: Undergraduate level math and science or instructor's permission. Major technologies to store carbon dioxide, geological, ocean, and in the carbon chemical pool. Carbon

dioxide transport technologies also covered. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4303x or y Carbon measurement and monitoring
3 pts. Lect: 3. Professor Meinrenken.
Prerequisites: Undergraduate level math and science or instructor permission. Sources of various GHGs (whether fossil/industrial or biogenic), their chemical behavior, interactions, and global warming potential once airborne; available measurement, monitoring, and detection technologies to track gas emissions, including leakage from storage sites. Carbon accounting and reporting methodologies such as life cycle analysis, and corporate carbon footprinting. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE W4304x Closing the carbon cycle
3 pts. Lect: 3. Professor Eisenberger.
Prerequisites: Calculus, basic inorganic chemistry, and basic physics, including thermodynamics, or instructor's permission. Introduction to complex systems, their impact on our understanding and predictability of the carbon cycle, the use of systems analysis and modeling tools, as well as Bayesian statistics and decision theory for evaluating various solutions to close the carbon cycle, a detailed examination of the geochemical carbon cycle, major conceptual models that couple its changes to climate change, analysis of the anthropogenic carbon sources and sinks and role of carbon in energy production, closing the carbon cycle impacts on energy security, economic development and climate change protection, analysis of solutions to close the carbon cycle.

EAEE E4350x Planning and management of urban hydrologic systems
3 pts. Lect: 3. Professor Rangarajan.
Prerequisite: ENME E3161 or equivalent. Introduction to runoff and drainage systems in an urban setting, including hydrologic and hydraulic analyses, flow and water quality monitoring, common regulatory issues, and mathematical modeling. Applications to problems of climate variation, land use changes, infrastructure operation and receiving water quality, developed using statistical packages, public-domain models, and Geographical Information Systems (GIS). Team projects that can lead to publication quality analyses in relevant fields of interest. Emphasis on the unique technical, regulatory, fiscal, policy, and other interdisciplinary issues that pose a challenge to effective planning and management of urban hydrologic systems.

EAEE E4361y Economics of earth resource industries
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E3103 or instructor's permission. Definition of terms. Survey of Earth resource industries: resources, reserves, production, global trade, consumption of mineral commodities and fuels. Economics of recycling and substitution. Methods of project evaluation: estimation of operating costs and capital requirements, project feasibility, risk assessment, and environmental compliance. Cost estimation for reclamation/remediation projects. Financing of reclamation costs at abandoned mine sites and waste-disposal post-closure liability.

CHEE E4530y Corrosion of metals
3 pts. Lect: 3. Professor Duby.
Prerequisite: CHEN E3010 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

EAEE E4550x Catalysis for emissions control
3 pts. Lect: 3. Professor Farrauto.
Prerequisite: One year of general college chemistry. Fundamentals of heterogeneous catalysis including modern catalytic preparation techniques. Analysis and design of catalytic emissions control systems. Introduction to current industrial catalytic solutions for controlling gaseous emissions. Introduction to future catalytically enabled control technologies.

EACE E4560y Particle technology
3 pts. Lect: 3. Professor Park.
Prerequisites: ENME E3161 and MSAE E3111 or equivalent. Introduction to engineering processes involving particulates and powders. The fundamentals of particle characterization, multiphase flow behavior, particle formation, processing and utilization of particles in various engineering applications with examples in energy and environment related technologies. Engineering of functionalized particles and design of multiphase reactors and processing units with emphasis on fluidization technology. Particle technology is an interdisciplinary field. Due to the complexity of particulate systems, particle technology is often treated as art rather than science. In this course, the fundamental principles governing the key aspects of particle science and technology are introduced along with various industrial examples.

EAEE E4901y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Basic microbiological principles; microbial metabolism; identification and interactions of microbial populations responsible for the biotransformation of pollutants; mathematical modeling of microbially mediated processes; biotechnology and engineering applications using microbial systems for pollution control.

EAEE E4950x Environmental biochemical processes
3 pts. Lect: 3. Professor Chandran.
Prerequisite: EAEE 4901, E4003, CIEE E4252, or instructor's approval. Qualitative and quantitative considerations in engineered environmental biochemical processes. Characterization of multiple microbial reactions in a community and techniques for determining associated kinetic and stoichiometric parameters. Engineering design of several bioreactor configurations employed for biochemical waste treatment. Mathematical modeling of engineered biological reactors using state-of-the-art simulation packages.

EAEE E4951x Engineering systems for water treatment and reuse
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CIEE E4163 and EAEE 3901, or the instructor's permission. Application of fundamental principles to designing water treatment and reuse plants. Development of process designs for a potable water treatment plant, a biological wastewater treatment plant, or a water reclamation and reuse facility by students working in teams. Student work in evaluation of water quality and pilot plant data, screeening process alternatives, conducting regulatory reviews and recommending a process for implementation, supported by engineering drawings and capital operating costs. Periodic oral progress reports and a full engineering report are required. Presentations by practicing engineers, utility personnel, and regulators; and field trips to water, wastewater, and water reuse facilities.

EAEE E4980 Urban environmental technology and policy
3 pts. Lect: 3. Not offered in 2015–2016.
Progress of urban pollution engineering via contaminant abatement technology, government policy, and public action in urban pollution. Pollutant impact on modern urban environmental quality, natural resources, and government, municipal, and social planning and management programs. Strong emphasis on current and twentieth-century waste management in New York City.

EAEE E4999x and y Fieldwork
1pt. Members of faculty.
Prerequisite: Instructor's written permission. Only EAEE graduate students who need relevant off-campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. This course may not be taken for pass/fail credit or audited. International students must also consult with the International Students and Scholars Office..

EAEE E6132y Numerical methods in geomechanics
3 pts. Lect: 3. Professor Chen.
Prerequisites: EAEE E3112 and CIEN E4241 or instructor's permission. A detailed survey of numerical methods used in geomechanics,

emphasizing the Finite Element Method (FEM). Review of the behavior of geological materials. Water and heat flow problems. FEM techniques for solving nonlinear problems, and simulating incremental excavation and loading on the surface and underground.

EAEE E6150y Industrial catalysis
3 pts. Lect: 3. Professor Farrauto.
Prerequisite: EAEE E4550 or equivalent, or instructor's permission. Fundamental principles of kinetics, characterization and preparation of catalysts for production of petroleum products for conventional transportation fuels, specialty chemicals, polymers, food products, hydrogen and fuel cells and the application of catalysis in biomass conversion to fuel. Update of the ever changing demands and challenges in environmental applications, focusing on advanced catalytic applications as described in modern literature and patents.

EAEE E6151y Applied geophysics
3 pts. Lect: 3. Not offered in 2015–2016.
Potential field data, prospecting, wave equations. Huygens' principle, Green's functions, Kirchoff equation, WKB approximation, ray tracing. Wave propagation, parameters. Computer applications. Wavelet processing, filters and seismic data. Stratified Earth model, seismic processing and profiling. Radon transform and Fourier migration. Multidimensional geological interpretation.

EAEE E6200y Theory and applications of extreme value statistics in engineering and earth sciences
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: STAT W4107 or equivalent background in probability and statistical inference, or instructor's permission. Introduction of fundamental concepts in extreme value statistics. The exact and asymptotic theory of extremes. Development of statistical methodology for estimating the parameters of asymptotic extremal distributions from experimental data. Examples of applications of extreme value statistics to regional and global earthquake forecasting, laboratory testing of rocks and metals, fatigue failure, floods, droughts, extreme wind velocities, and rainfalls.

EAIA W6201x or y Complexity science
4 pts. Lect: 4. Professors Castner, Dumas, Lall, Mutter, and Rising.
Prerequisites: Graduate standing and instructor's permission. Survey of techniques, applications, and implications of complexity science and complex systems. Topics include systems dynamics, chaos, scaling, fat-tailed distributions, fractals, information theory, emergence, criticality, agent-based models, graph theory, and social networks. Applications will cover climate science, ecology, conflict, hydrology, geomorphology, physics, social theory, epidemiology, and governance.

EAEE E6208y Combustion chemistry and processes
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E4900 or equivalent or instructor's permission. The fundamentals of combustion phenomena and the intrinsic chemistry of combustion processes. The theory of the essential combustion processes such as ignition, sustained reaction, stability and flame quenching. Processes that govern reactant consumption and product formation, in particular by-products that are formed that result in pollutant emissions, and the impacts and implications that combustion has locally and globally on the environment. Detailed examination of the entire range of combustion systems from diffusion flame processes to current developing technologies including millisecond catalytic combustion processes, noncarbon fueled combustion, fuel cells, and plasma combustion.

EAEE E6210x Quantitative environmental risk analysis
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E3101, SIEO W4150, or equivalent. Comprises the tools necessary for technical professionals to produce meaningful risk analyses. Review of relevant probability and statistics; incorporation of probability in facility failure analysis. Availability, assessment, and incorporation of risk-related data. Contaminant transport to exposed individuals; uptake, morbidity, and mortality. Computational tools necessary to risk modeling. Use and applicability of resulting measurements of risk, and their use in public policy and regulation.

EAEE E6212y Carbon sequestration
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E4900 or equivalent or instructor's permission. New technologies for capturing carbon dioxide and disposing of it away from the atmosphere. Detailed discussion of the extent of the human modifications to the natural carbon cycle, the motivation and scope of future carbon management strategies and the role of carbon sequestration. Introduction of several carbon sequestration technologies that allow for the capture and permanent disposal of carbon dioxide. Engineering issues in their implementation, economic impacts, and the environmental issues raised by the various methods.

CHEE E6220y Equilibria and kinetics in hydrometallurgical systems
3 pts. Lect: 3. Professor Duby.
Prerequisite: CHEE E4050 or EAEE E4003. Detailed examination of chemical equilibria in hydrometallurgical systems. Kinetics and mechanisms of homogeneous and heterogeneous reactions in aqueous solutions.

EAEE E6220x Remedial and corrective action
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EAEE E4160 or equivalent. Integrates the engineering aspects of cleanup of hazardous materials in the environment. Site assessment/investigation. Site closure, containment, and control techniques and technologies. Techniques used to treat hazardous materials in the environment, in situ and removal for treatment, focusing on those aspects that are unique to the application of those technologies in an uncontrolled natural environment. Management, safety, and training issues.

EAEE E6228y Theory of flotation
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: CHEE E4252 or instructor's permission. A detailed study of the physicochemical principles of the flotation process.

EAEE E6240x or y Physical hydrology
3 pts. Lect: 3. Professor Gentine.
Prerequisite: Engineering hydrology or equivalent. Spatial/temporal dynamics of the hydrologic cycle and its interactions with landforms and vegetation. Hydroclimatology at regional to planetary scales, focusing on mechanisms of organization and variation of water fluxes as a function of season, location, reservoir (ocean, atmosphere, land), and time scale. Land-atmosphere interaction and the role of vegetation and soil moisture. Topography as an organizing principle for land water fluxes. Geomorphology and the evolution of river networks. Sedimentation, erosion and hill slope hydrology. Dynamics of water movement over land, in rivers and in the subsurface, with an emphasis on modeling interfaces. Integrated models and the scale problem. Emphasis on data-based spatial/temporal modeling and exploration of outstanding theoretical challenges.

CHEE E6252y Advanced surface and colloid chemistry
3 pts. Lect: 2. Lab: 3. Professor Somasundaran.
Prerequisite: CHEE E4252. Applications of surface chemistry principles to wetting, flocculation, flotation, separation techniques, catalysis, mass transfer, emulsions, foams, aerosols, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects. Lab required.

EAEE E6255x-E6256y Methods and applications of analytical decision making in mineral industries
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Instructor's permission. Advanced study of decision-making problems with critical survey and applications of quantitative decision-making techniques in mineral industries. Systematic development of methods of the formulation, analysis, and resolution of these problems.

EAEE P6329 Water, sanitation, and human health
3 pts. Lect: 3. Professor Shaman.
Prerequisite: Instructor's permission. In-depth analysis of issues relating to water, sanitation, and hygiene in both the developed and developing worlds. Hydrologic cycle, major causes of enteric morbidity and mortality, and design, financing and implementation of sanitation systems. For both engineering and public health students; intended to foster dialog between the two communities.

EAEE E8229x Selected topics in processing minerals and wastes
3 pts. Lect: 2. Lab: 3. Not offered in 2015–2016.

Prerequisite: CHEE E4252 or instructor's permission. Critical discussion of current research topics and publications in the area of flotation, flocculation, and other mineral processing techniques, particularly mechanisms of adsorption, interactions of particles in solution, thinning of liquid films, and optimization techniques.

EAEE E8231y Selected topics in hydro- and electrometallurgy
3 pts. Lect: 3. Professor Duby.
Prerequisites: EAEE E4003 and CHEE E4050, or instructor's permission. Review of current research and literature in the field of hydrometallurgy, electrometallurgy, and corrosion. Topics will be selected by the instructor to illustrate the application of thermodynamics and rate phenomena to the design and control of electrochemical engineering processes.

EAEE E8233x and y Research topics in particle processing
0 pts. Professor Somasundaran.
Emergent findings in the interactions of particles with reagents and solutions, especially inorganics, surfactants, and polymers in solution, and their role in grinding, flotation, agglomeration, filtration, enhanced oil recovery, and other mineral processing operations.

EAEE E8273x-E8274y Mining engineering reports
0–4 pts. Not offered in 2015–2016.
May substitiute for formal thesis, EAEE E9271, upon recommendation of the student's adviser.

EAEE E9271x and y–S9271 Earth and environmental engineering thesis
0–6 pts. Members of the faculty.
Research work culminating in a creditable dissertation on a problem of a fundamental nature selected in conference between student and adviser. Wide latitude is permitted in choice of a subject, but independent work of distinctly graduate character is required in its handling.

EAEE E9273x-E9274y Earth and environmental engineering reports
0–4 pts.
May substitute for the formal master's thesis, EAEE E9271, upon recommendation of the department.

EAEE E9280x and y Earth and environmental engineering colloquium
0 pts. Lect: 1.5. Professor Gentine.
All graduate students are required to attend the departmental colloquium as long as they are in residence. Advanced doctoral students may be excused after three years of residence. No degree credit is granted.

EAEE E9281x Prospects for nuclear energy–earth and environmental engineering seminar
0–1 pt. Lect: 1.5. Not offered in 2015–2016.
This seminar course examines the prospects for nuclear energy as a source of safe, secure, and environmentally sustainable energy both in the U.S. and internationally. In particular, it analyzes the four key issues that limit the expansion of nuclear energy: cost, safety, proliferation concerns, and long-term disposal of radioactive wastes. Through readings, research, and class discussions, it engages students to critically evaluate arguments both for and against nuclear power. The course builds basic literacy in nuclear technology and is open to students with technical, policy, or economic backgrounds.

EAEE E9302x and y Mining engineering research
0–4 pts. Not offered in 2015–2016..
Graduate research directed toward solution of technicoscientific problems in mining.

EAEE E9305x and y–S9305 Earth and environmental engineering research
0–12 pts. Members of the faculty.
Graduate research directed toward solution of a problem in mineral processing or chemical metallurgy.

EAEE E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in mineral engineering must register for 12 points of doctoral research instruction. Registration in EAEE E9800 may not be used to satisfy the minimum residence requirement for the degree.

EAEE E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the student's course work has been completed, and until the dissertation has been accepted.

ELECTRICAL ENGINEERING

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Sefi Vernick
Ziliang Ye

POSTDOCTORAL RESEARCH FELLOW
Omer Yaffe

Contemporary electrical engineering is a broad discipline that encompasses a wide range of activities. A common theme is the use of electrical and electromagnetic signals for the generation, transmission, processing, storage, conversion, and control of information and energy. An equally important aspect is the human interface and the role of individuals as the sources and recipients of information. The rates at which information is transmitted today range from megabits per second to gigabits per second and in some cases, as high as terabits per second. The range of frequencies over which these processes are studied extends from direct current (i.e., zero frequency), to microwave and optical frequencies.

The need for increasingly faster and more sophisticated methods of handling information poses a major challenge to the electrical engineer. New materials, devices, systems, and network concepts are needed to build the advanced communications and information handling systems of the future. Previous innovations in electrical engineering have had a dramatic impact on the way in which we work and live: the transistor, integrated circuits, computers, radio and television, satellite transmission systems, lasers, fiber optic transmission systems, and medical electronics.

The faculty of the Electrical Engineering Department at Columbia University is dedicated to the continued development of further innovations through its program of academic instruction and research. Our undergraduate academic program in electrical engineering is designed to prepare the student for a career in industry or business by providing her or him with a thorough foundation of the fundamental concepts and analytical tools of contemporary electrical engineering. A wide range of elective courses permits the student to emphasize specific disciplines such as telecommunications, microelectronics, digital systems, or photonics. Undergraduates have an opportunity to learn firsthand about current research activities by participating in a program of undergraduate research projects with the faculty.

A master's level program in electrical engineering permits the graduate student to further specialize her/his knowledge and skills within a wide range of disciplines. For those who are interested in pursuing a career in teaching or research, our Ph.D. program offers the opportunity to conduct research under faculty super-vision at the leading edge of technology and applied science. Research seminars are offered in a wide range of areas, including telecommunications, very large scale integrated circuits, photonics, and microelectronics.

The Electrical Engineering Department, along with the Computer Science Department, also offers B.S. and M.S. programs in computer engineering. Details on those programs can be found in the Computer Engineering section in this bulletin.

Research Activities

The research interests of the faculty encompass a number of rapidly growing areas, vital to the development of future technology, that will affect almost every aspect of society: communications and information processing; solid-state devices; ultrafast optics and photonics; microelectronic circuits, integrated systems and computer-aided design; systems biology; and electromagnetics and plasmas. Details on all of these areas can be found at ee.columbia.edu/research.

Communications research focuses on wireless communication, multimedia networking, real-time Internet, lightwave (fiber optic) communication networks, optical signal processing and switching, service architectures, network management and control, the processing of image and video information, and media engineering. Current studies include wireless and mobile computing environments, broadband kernels, object-oriented network management, real-time monitoring and control, lightwave network architectures, lightweight protocol design, resource allocation and networking games, real-time Internet services, future all-digital HDTV systems, coding and modulation.

Solid-state device research is conducted in the Columbia Microelectronics Sciences Laboratories. This is an interdisciplinary facility, involving aspects of electrical engineering and applied physics. It includes the study of semiconductor physics and devices, optical electronics, and quantum optics. The emphasis is on laser processing and diagnostics for submicron electronics, fabrication of compound semiconductor optoelectronic devices by molecular beam epitaxy, physics of superlattices and quantum wells, and interface devices such as Schottky barriers, MOS transistors, heterojunctions, and bipolar transistors. Another area of activity is the physics and chemistry of microelectronics packaging.

Research in photonics includes development of semi conductor light sources such as LEDs and injection lasers, fabrication and analysis of quantum confined structures, photo conductors, pin diodes, avalanche photodiodes, optical interconnects, and quantum optics. A major effort is the picosecond optoelectronics program, focusing on the development of new devices and their applications to high-speed optoelectronic measurement systems, photonic switching, and optical logic. In addition, research is being performed in detection techniques for optical communications and radar. Members of the photonics group play a leading role in a multi-university consortium: The National Center for Integrated Photonics Technology.

Integrated systems research involves the analysis and design of analog, digital, and mixed-signal microelectronic circuits and systems. These include novel signal processors and related systems, data converters, radio frequency circuits, low noise and low power circuits, and fully integrated analog filters that share the same chip with digital logic. VLSI architectures for parallel computation, packet switching, and signal processing are also under investigation. Computer-aided design research involves the development of techniques for the analysis and design of large-scale integrated circuits and systems.

Electromagnetics research ranges from the classical domains of microwave generation and transmission and wave propagation in various media to modern applications involving lasers, optical fibers, plasmas, and solid-state devices. Problems relevant to controlled thermonuclear fusion are under investigation.

Laboratory Facilities

Current research activities are fully supported by more than a dozen well-equipped research laboratories run by the department. Specifically, laboratory research is conducted in the following laboratories: Multimedia Networking Laboratory, Lightwave Communications Laboratory, Systems Laboratory, Image and Advanced Television Laboratory, Laser Processing Laboratory, Molecular Beam Epitaxy Laboratory, Surface Analysis Laboratory, Microelectronics Fabrication Laboratory, Device Measurement Laboratory, Ultrafast Optoelectronics Laboratory, Columbia Integrated Systems Laboratory (CISL), Lightwave Communications Laboratory, Photonics Laboratory, Plasma Physics Laboratory (in conjunction with the Department of Applied Physics).

Laboratory instruction is provided in the Introduction to Electrical Engineering Laboratory, Marcellus-Hartley Electronics Laboratory, Microprocessor Laboratory, Microwave Laboratory, Optical Electronics Laboratory, Solid-State Laboratory, VLSI Design Laboratory, and Student Projects Laboratory, all on the twelfth floor of the S. W. Mudd Building.

UNDERGRADUATE PROGRAM

The educational objective of the Electrical Engineering program, in support of the mission of the School, is to prepare graduates to achieve success in one or more of the following within a few years after graduation:

A. Graduate or professional studies—as evidenced by admission to a top-tier program, attainment of advanced degrees, research contributions, or professional recognition.
B. Engineering practice—as evidenced by entrepreneurship; employment in industry, government, academia, or nonprofit organizations in engineering; patents; or professional recognition.
C. Careers outside of engineering that take advantage of an engineering education—as evidenced by contributions appropriate to the chosen field.

The B.S. program in electrical engineering at Columbia University seeks to provide a broad and solid foundation in the current theory and practice of electrical engineering, including familiarity with basic tools of math and science, an ability to communicate ideas, and a humanities background sufficient to understand the social implications of engineering practice. Graduates should be qualified to enter the profession of engineering, to continue toward a career in engineering research, or to enter other fields in which engineering knowledge is essential. Required nontechnical courses cover civilization and culture, philosophy, economics, and a number of additional electives. English communication skills are an important aspect of these courses. Required science courses cover basic

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS EARLY-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) → C1601 (3.5) → C2801 (4.5) →	C1402 (3) C1602 (3.5) C2802 (4.5)		
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604			
CORE REQUIRED COURSES	ELEN E1201 (3.5) Introduction to electrical engineering (either semester)		ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	ELEN E3331 (3) Electronic circuits CSEE E3827 (3) Fund. of computer sys.
REQUIRED LABS			ELEN E3081 (1)[2] Circuit analysis lab ELEN E3084 (1)[2] Signals and systems lab	ELEN E3083 (1)[2] Electronic circuits lab ELEN E3082 (1)[2] Digital systems lab
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) → Z0006 (0) →	C1010 (3) Z1003 (0) →	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	HUMA C1001, COCI C1101, **or** Major Cultures (3–4); HUMA W1121 **or** W1123 (3); HUMA C1002, COCI C1102, **or** Global Core (3–4); ECON W1105 (4) **and** W1155 recitation (0); some of these courses can be postponed to the junior or senior year, to make room for taking the above electrical engineering courses.			
COMPUTER SCIENCE	ENGI E1006 (3) either semester[3]			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101 or MATH V2010.
[2] If possible, these labs should be taken along with their corresponding lecture courses.
[3] ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.

chemistry and physics, whereas math requirements cover calculus, differential equations, probability, and linear algebra. Basic computer knowledge is also included, with an introductory course on using engineering workstations and two rigorous introductory computer science courses. Core electrical engineering courses cover the main components of modern electrical engineering and illustrate basic engineering principles. Topics include a sequence of two courses on circuit theory and electronic circuits, one course on semiconductor devices, one on electromagnetics, one on signals and systems, one on digital systems, and one on communications or networking. Engineering practice is developed further through a sequence of laboratory courses, starting with a first-year course to introduce hands-on experience early and to motivate theoretical work. Simple creative design experiences start immediately in this first-year course. Following this is a sequence of lab courses that parallel the core lecture courses. Opportunities for exploring design can be found both within these lab courses and in the parallel lecture courses, often coupled with experimentation and computer simulation, respectively. The culmination of the laboratory sequence

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS EARLY-STARTING STUDENTS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
PHYSICS (tracks continued)		C1403 (3) → C2601 (3.5) → Lab W3081 (2)	Lab C1494 (3)[1] Lab C2699 (3)		
EE CORE REQUIRED COURSES		ELEN E3106 (3.5) Solid-state devices and materials	ELEN E3401 (4) Electromagnetics ELEN E3701 (3)[2] Intro. to communication systems **or** CSEE W4119 (3)[2] Computer networks		
EE REQUIRED LABS				ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[3] Capstone design course
OTHER REQUIRED COURSES		IEOR E3658 **or** STAT 4105[4]; **and** COMS W3136 (**or** W3134 or W3137)[5] (Some of these courses *are not* offered both semesters. Students with an adequate background can take some of these courses in the sophomore year)			
ELECTIVES	**EE DEPTH TECH**	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking (For details, see ee.columbia.edu)			
	BREADTH TECH	(at least 6 points total) At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)			
	OTHER TECH	Additional technical electives (consisting of more depth or breadth courses, or further options listed at ee.columbia.edu/ee-undergraduate-program) as required to bring the total points of technical electives to 18[6]			
	NONTECH	Complete 27-point requirement; see page 10 or seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[7]		16.5	17	16	18

[1] Chemistry lab (CHEM 1500) may be substituted for physics lab, although this is not generally recommended.
[2] These courses can be taken in the sophomore year if the prerequisites/corequisites are satisfied.
[3] The capstone design course provides ELEN majors with a "culminating design experience." As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.
[4] SIEO W3600 and W4150 cannot generally be used to replace IEOR E3658 or STAT W4105.
[5] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.
[6] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101 or MATH V2010.
[7] "Total points" assumes that 20 points of nontechnical electives and other courses are included.

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS LATE-STARTING STUDENTS				
	SEMESTER I	**SEMESTER II**	**SEMESTER III**	**SEMESTER IV**
MATHEMATICS	MATH V1101(3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5) Lab W3081 (2)	Lab C1494 (3)[2] Lab C2699 (3)
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604			
ELECTRICAL ENGINEERING	ELEN E1201 (3.5) either semester[3]			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3) any semester[4]			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101 or MATH V2010.
[2] Chemistry lab (CHEM C1500) may be substituted for physics lab, although this is not generally recommended.
[3] Transfer students and 3-2 Combined Plan students who have not taken ELEN E1201 prior to the junior year are expected to have taken a roughly equivalent course when they start ELEN E3201.
[4] ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.

and the design experiences introduced throughout earlier courses is a senior design course (capstone design course), which includes a significant design project that ties together the core program, encourages creativity, explores practical aspects of engineering practice, and provides additional experience with communication skills in an engineering context. Finally, several technical electives are required, chosen to provide both breadth and depth in a specific area of interest. More detailed program objectives and outcomes are posted at ee.columbia.edu.

The program in electrical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET.

There is a strong interaction between the Department of Electrical Engineering and the Departments of Computer Science, Applied Physics and Applied Mathematics, Industrial Engineering and Operations Research, Physics, and Chemistry.

EE Core Curriculum

All electrical engineering (EE) students must take a set of core courses, which collectively provide the student with fundamental skills, expose him/her to the breadth of EE, and serve as a springboard for more advanced work, or for work in areas not covered in the core. These courses are shown on the charts in Undergraduate Degree Tracks. A full curriculum checklist is also posted at ee.columbia.edu.

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS LATE-STARTING STUDENTS					
		SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
EE CORE REQUIRED COURSES		ELEN E3106 (3.5) Solid-state devices and materials ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	CSEE W3827(3) Fund. of computer sys. ELEN E3331 (3) Electronic circuits ELEN E3401 (4) Electromagnetics ELEN E3701 (3) Intro. to communication systems **or** CSEE W4119 (3) Computer networks		
EE REQUIRED LABS		ELEN E3081 (1)[1] Circuit analysis lab ELEN E3084 (1)[1] Signals and systems lab	ELEN E3083 (1)[1] Electronic circuits lab ELEN E3082 (1)[1] Digital systems lab	ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[2] Capstone design course
OTHER REQUIRED COURSES		IEOR E3658 **or** STAT W4105[3]; **and** COMS W3136 (**or** W3134 or W3137)[4] (Some of these courses are *not* offered both semesters)			
ELECTIVES	**EE DEPTH TECH**	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. (For details, see ee.columbia.edu.)			
	BREADTH TECH	(at least 6 points total) At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)			
	OTHER TECH	Additional technical electives (consisting of more depth or breadth courses, or further options listed at ee.columbia.edu/ee-undergraduate-program) as required to bring the total points of technical electives to 18[5]			
	NONTECH	Complete 27-point requirement; see page 10 or seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[6]		15.5	18	16	18

Note: This chart shows one possible schedule for a student who takes most of his or her major program in the final two years. Please refer to the previous chart for a recommended earlier start.

[1] If possible, these labs should be taken along with their corresponding lecture courses.

[2] The capstone design course provides ELEN majors with a "culminating design experience." As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.

[3] SIEO W3600 and W4150 cannot generally be used to replace IEOR E3658 or STAT W4105.

[4] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.

[5] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH V2030 (formerly MATH E1210) and either APMA E3101 or MATH V2010.

[6] "Total points" assumes that 9 points of nontechnical electives are included.

Technical Electives

The 18-point technical elective requirement for the electrical engineering program consists of three components: depth, breadth, and other. A general outline is provided here, and more specific course restrictions can be found at ee.columbia.edu. For any course not clearly listed there, adviser approval is necessary.

The *depth* component must consist of at least 6 points of electrical engineering courses in one of four defined areas: (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. The depth requirement provides an opportunity to pursue particular interests and exposure to the process of exploring a discipline in depth—an essential process that can be applied later to other disciplines, if desired.

The *breadth* component must consist of at least 6 additional points of courses that are outside of the chosen depth area and have significant engineering content. These courses can be from other departments within the School. The breadth requirement precludes overspecialization. Breadth is particularly important today, as innovation requires more and more of an interdisciplinary approach, and exposure to other fields is known to help one's creativity in one's own main field. Breadth also reduces the chance of obsolescence as technology changes.

Any remaining technical elective courses, beyond the minimum 12 points of depth and breadth, do not have to be engineering courses (except for students without *ELEN E1201* or approved transfer credit for *ELEN E1201*) but must be technical. Generally, math and science courses that do not overlap with courses used to fill other requirements are allowed.

Starting Early

The EE curriculum is designed to allow students to start their study of EE in their first year. This motivates students early and allows them to spread nontechnical requirements more evenly. It also makes evident the need for advanced math and physics concepts, and motivates the study of such concepts. Finally, it allows more time for students to take classes in a chosen depth area, or gives them more time to explore before choosing a depth area. Students can start with *ELEN E1201: Introduction to electrical engineering* in the second semester of their first year, and can continue with other core courses one semester after that, as shown in the "early-starting students" chart. It is emphasized that both the early- and late-starting sample programs shown in the charts are examples only; schedules may vary depending on student preparation and interests.

Transfer Students

Transfer students coming to Columbia as juniors with sufficient general background can complete all requirements for the B.S. degree in electrical engineering. Such students fall into one of two categories:

Plan 1: Students coming to Columbia without having taken the equivalent of *ELEN E1201* must take this course in their junior year. This requires postponing the core courses in circuits and electronics until the senior year, and thus does not allow taking electives in that area; thus, such students cannot choose circuits and electronics as a depth area.

Plan 2: This plan is for students who have taken a course equivalent to *ELEN E1201* at their school of origin, including a laboratory component. See the bulletin for a description of this course. Many pre-engineering programs and physics departments at four-year colleges offer such courses. Such students can start taking circuits at Columbia immediately, and thus can choose circuits and electronics as a depth area.

It is stressed that *ELEN E1201* or its equivalent is a key part of the EE curriculum. The preparation provided by this course is essential for a number of other core courses.

Sample programs for both Plan 1 and Plan 2 transfer students can be found at ee.columbia.edu.

B.S./M.S. Program

The B.S./M.S. degree program is open to a select group of undergraduate students. This double degree program makes possible the earning of both the Bachelor of Science and Master of Science degrees in an integrated fashion. Up to 6 points may be credited to both degrees, and some graduate classes taken in the senior year may count toward the M.S. degree. Interested students can find further information at ee.columbia.edu and can discuss options directly with their faculty adviser. Students must be admitted prior to the start of their seventh semester at Columbia Engineering. Students in the 3-2 Combined Plan undergraduate program are not eligible for admission to this program.

GRADUATE PROGRAMS

The Department of Electrical Engineering offers graduate programs leading to the degree of Master of Science (M.S.) and the degrees of Doctor of Engineering Science (Eng.Sc.D.) and Doctor of Philosophy (Ph.D.). The Graduate Record Examination (General Test only) is required of all applicants except special students. An undergraduate grade-point average equivalent to B or better from an institution comparable to Columbia is expected.

Applicants who, for good reasons, are unable to submit GRE test results by the deadline date but whose undergraduate record is clearly superior may file an application without the GRE scores. An explanatory note should be added to ensure that the application will be processed even while incomplete. If the candidate's admissibility is clear, the decision may be made without the GRE scores; otherwise, it may be deferred until the scores are received.

There are no prescribed course requirements in any of the regular graduate degree programs. Students, in consultation with their faculty advisers, design their own programs, focusing on particular fields of electrical engineering. Among the fields of graduate study are microelectronics, communications and signal processing, integrated circuit and system analysis and synthesis, photonics, electromagnetic theory and applications, plasma physics, and quantum electronics.

Graduate course charts for several focus areas can be found at ee.columbia.edu.

Master of Science Degree

Candidates for the M.S. degree in electrical engineering must complete 30 points of credit beyond the bachelor's degree. A minimum of 15 points of credit must be at the 6000 level or higher. No credit will be allowed for undergraduate courses (3000 or lower). At least 15 points must be in electrical engineering, defined as including all courses with an ELEN designator or a joint designator containing electrical engineering as a member, e.g., EECS, CSEE, EEME, ECBM, etc. And it is expected that at least 12 of the first 24 points taken will be in electrical engineering.

Not all technical courses can be applied toward the M.S. degree, and some have restrictions. Also, no more than 6 points of research (such as ELEN E4998, ELEN E6001, and ELEN E6002) can be used, and no more than 3 points of approved courses that do not contain primarily engineering, math, or science content can be used. Any course that is not on the list of standard courses specified at ee.columbia.edu/masters-program requires prior written department approval, including during the summer session.

The general school requirements listed earlier in this bulletin, such as minimum GPA, must also be satisfied. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

More details and a requirements checklist for approvals can be found at ee.columbia.edu/masters-program.

Doctoral Degree

The requirements for the Ph.D. and Eng.Sc.D. degrees are identical. Both require a dissertation based on the candidate's original research, conducted under the supervision of a faculty member. The work may be theoretical or experimental or both.

Students who wish to become candidates for the doctoral degree in electrical engineering have the option of applying for admission to the Eng.Sc.D. program or the Ph.D. program. Students who elect the Eng.Sc.D. degree register in the School of Engineering and Applied Science; those who elect the Ph.D. degree register in the Graduate School of Arts and Sciences.

Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor's degree. A master's degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master's degree must be earned while in residence in the doctoral program.

More detailed information regarding the requirements for the doctoral degree may be obtained in the department office and at ee.columbia.edu.

Optional M.S. Concentrations

Students in the electrical engineering M.S. program often choose to use some of their electives to focus on a particular field. Students may pick one of a number of optional, formal concentration templates or design their own M.S. program in consultation with an adviser. These concentrations are not degree requirements. They represent suggestions from the faculty as to how one might fill one's programs so as to focus on a particular area of interest. Students may wish to follow these suggestions, but they need not. The degree requirements are quite flexible and are listed in the Master of Science Degree section, above. All students, whether following a formal concentration template or not, are expected to include breadth in their program. Not all of the elective courses listed here are offered every year. For the latest information on available courses, visit the Electrical Engineering home page at ee.columbia.edu.

Concentration in Multimedia Networking

Advisers: Professors Henning Schulzrinne, Predrag Jelenkovic

1. Satisfy M.S. degree requirements.
2. Both *ELEN E6761: Computer communication networks, I* and *ELEN E6950: Wireless and mobile networking, I.*
3. Either *COMS W4118: Operating systems* or *COMS W4111: Database systems.*
4. *COMS E6181: Advanced Internet services* or *ELEN E6776: Topic: content distribution networks.*

With an adviser's approval, any of the courses above can be replaced by the following closely related subjects: *CSEE E4140: Networking laboratory; CSEE W4119: Computer networks; COMS W4180: Network security; ELEN E6762: Computer communication networks, II; ELEN E6850: Visual information systems; ELEN E6951: Wireless and mobile networking, II.*

Concentration in Telecommunications Engineering

Advisers: Professors Henning Schulzrinne, Pedrag Jelenkovic, Ed Coffman, Nicholas Maxemchuk, Gil Zussman

1. Satisfy M.S. degree requirements.
2. One basic hardware or software course such as: *EECS E4321: Digital VLSI circuits; ELEN E4411: Fundamentals of photonics; COMS W4118: Operating systems, I; COMS W4111: Database systems.*
3. One basic systems course such as: *ELEN E4702: Communication theory; ELEN E4703: Wireless communications; CSEE W4119: Computer networks; ELEN E6761: Computer communication networks, I.*
4. At least two approved courses from a focus area such as Signal/Image Processing and Telecommunications/Multimedia Networks.

Concentration in Lightwave (Photonics) Engineering

Advisers: Professors Keren Bergman, Paul Diament, Richard Osgood, Amiya Sen, Tony Heinz, Ioannis (John) Kymissis

1. Satisfy M.S. degree requirements.
2. Take both *ELEN E4411: Fundamentals of photonics* and *ELEN E6412: Lightware devices* (or an E&M course, such as *APPH E4300: Applied electrodynamics* or *PHYS G6092: Electromagnetic theory).*
3. One more device/circuits/photonics course such as: *ELEN E6413: Lightwave systems; ELEN E6414: Photonic integrated circuits; ELEN E4314: Communication circuits; ELEN E4488: Optical systems; ELEN E6488: Optical interconnects and interconnection networks; ELEN E4193: Modern display science and technology.*
4. At least two additional approved courses in photonics or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.*

Concentration in Wireless and Mobile Communications

Adviser: Professors Gil Zussman, Predrag Jelenkovic, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. One basic circuits course such as: *ELEN E4312: Analog electric circuits; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6312: Advanced analog ICs.*
3. Two communications or networking courses such as: *CSEE W4119: Computer networks; ELEN E4702: Digital communications; ELEN E4703: Wireless communications; ELEN E6711: Stochastic signals and noise; ELEN E4810: Digital signal processing; ELEN E6950: Wireless and mobile networking, I; ELEN E6951: Wireless and mobile networking, II; ELEN E6761: Computer communication networks, I; ELEN E6712: Communication theory; ELEN E6713: Topics in communications; ELEN E6717: Information theory; ELEN E677x: Topics in telecommunication networks.*
4. At least two additional approved courses in wireless communications or a related area.

Concentration in Integrated Circuits and Systems

Advisers: Professors Peter Kinget, Harish Krishnaswamy, Mingoo Seok, Kenneth Shepard, Yannis Tsividis, Charles Zukowski

1. Satisfy M.S. degree requirements.
2. One digital course from: *EECS E4321: Digital VLSI circuits* or *EECS E6321: Advanced digital electronic circuits.*
3. One analog course from: *ELEN E4312: Analog electronic circuits; ELEN E6312: Advanced analog integrated circuits; ELEN E6316: Analog circuits and systems in VLSI; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6320: Millimeter-wave IC design.*
4. Two additional courses such as: Other courses from 2. and 3.; *ELEN E6350: VLSI design laboratory; ELEN E6304: Topics in electronic circuits;*

ELEN E6318: Microwave circuit design; ELEN E9303: Seminar in electronic circuits.

5. At least one additional approved course in integrated circuits and systems or a related area.

Concentration in Microelectronic Devices

Advisers: Professors Wen Wang, Richard Osgood, Ioannis (John) Kymissis

1. Satisfy M.S. degree requirements.
2. One basic course such as: *ELEN E4301: Introduction to semiconductor devices* or *ELEN E4411: Fundamentals of photonics.*
3. One advanced course such as: *ELEN E4193: Modern display science and technology; ELEN E4944: Principles of device microfabrication; ELEN E4503: Sensors, actuators, and electromechanical systems; ELEN E6151: Surface physics and analysis of electronic materials; ELEN E6331: Principles of semiconductor physics, I; ELEN E6332: Principles of semiconductor physics, II; ELEN E6333: Semiconductor device physics; ELEN E6945: Nanoscale fabrication and devices.*
4. At least two other approved courses in devices or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.*

Concentration in Systems Biology and Neuroengineering

Advisers: Professors Dimitris Anastassiou, Christine Fleming, Pedrag Jelenkovic, Aurel Lazar, Nima Mesgarani, Kenneth Shepard, Xiaodong Wang, Charles Zukowski

1. Satisfy M.S. degree requirements.
2. Take both *ECBM E4060: Introduction to genomic information science and technology* and *BMEB W4020: Computational neuroscience, I: circuits in the brain*
3. Take at least one course from *BMEE E4030: Neural control engineering; CBMF W4761: Computational genomics; BIST P8139: Theoretical genetic modeling* (Biostatistics); *ELEN E6010: Systems biology*; *EEBM E6020: Methods in computational neuroscience*; *BMEE E6030: Neural modeling and neuroengineering*; *APMA E4400: Introduction to biophysical modeling*; *CHEN E4700: Principles of genomic technologies*; *CHEN E4760: Genomics sequencing lab; ELEN E4312: Analog electronic circuits*.
4. Take at least one course from *ELEN E608x: Topics in systems biology; ELEN E6717: Information theory; ELEN E6201: Linear systems theory; EEME E6601: Introduction to control theory; ELEN E6711: Stochastic models in information systems; ELEN E6860: Advanced digital signal processing; EEBM E6090: Topics in computational neuroscience and neuroengineering; ELEN E6261: Computational methods of circuit analysis.*

COURSES IN ELECTRICAL ENGINEERING

ELEN E1101x or y The digital information age
3 pts. Lect: 3. Professor Vallancourt.
An introduction to information transmission and storage, including technological issues. Binary numbers; elementary computer logic; digital speech and image coding; basics of compact disks, telephones, modems, faxes, UPC bar codes, and the World Wide Web. Projects include implementing simple digital logic systems and Web pages. Intended primarily for students outside the School of Engineering and Applied Science. The only prerequisite is a working knowledge of elementary algebra.

ELEN E1201x and y Introduction to electrical engineering
3.5 pts. Lect: 3. Lab:1. Professor Vallancourt.
Prerequisite: MATH V1101. Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course. Required of electrical engineering and computer engineering majors.

ELEN E3043x Solid state, microwave, and fiber optics laboratory
3 pts. Lect: 1. Lab: 6. Professor W. Wang.
Prerequisites: ELEN E3106 and ELEN E3401. Optical electronics and communications. Microwave circuits. Physical electronics.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E4060, but the work requirements differ somewhat.

ELEN E3081x Circuit analysis laboratory
1 pt. Lab: 3. Professor Zukowski.
Prerequisite: ELEN E1201 or equivalent. Corequisite: ELEN E3201. Companion lab course for ELEN E3201. Experiments cover such topics as: use of measurement instruments; HSPICE simulation; basic network theorems; linearization of nonlinear circuits using negative feedback; op-amp circuits; integrators; second order RLC circuits. The lab generally meets on alternate weeks.

ELEN E3082y Digital systems laboratory
1 pt. Lab: 3. Professor Shepard.
Corequisite: CSEE W3827. Recommended preparation: ELEN E1201 or equivalent. Companion lab course for CSEE W3827. Experiments cover such topics as logic gates; flip-flops; shift registers; counters; combinational logic circuits; sequential logic circuits; programmable logic devices. The lab generally meets on alternate weeks.

ELEN E3083y Electronic circuits laboratory
1 pt. Lab: 3. Professor Vallancourt.
Prerequisite: ELEN E3081. Corequisite: ELEN E3331. Companion lab course for ELEN

E3331. Experiments cover such topics as macromodeling of nonidealities of opamps using SPICE; Schmitt triggers and astable multivibrations using opamps and diodes; logic inverters and amplifiers using bipolar junction transistors; logic inverters and ring oscillators using MOSFETs; filter design using op-amps. The lab generally meets on alternate weeks.

ELEN E3084x Signals and systems laboratory
1 pt. Lab: 3. Professor X. Wang.
Corequisite: ELEN E3801. Companion lab course for ELEN E3801. Experiments cover topics such as: introduction and use of MATLAB for numerical and symbolic calculations; linearity and time invariance; continuous-time convolution; Fourier-series expansion and signal reconstruction; impulse response and transfer function; forced response. The lab generally meets on alternate weeks.

ELEN E3106x Solid-state devices and materials
3.5 pts. Lect: 3. Recit: 1. Professor Kymissis.
Prerequisite: MATH V1201 or equivalent. Corequisite: PHYS C1403 or PHYS C2601 or equivalent. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices.

ELEN E3201x Circuit analysis
3.5 pts. Lect: 3. Recit: 1. Professor Zukowski.
Prerequisite: ELEN E1201 or equivalent. Corequisite: MATH V1201. A course on analysis of linear and nonlinear circuits and their applications. Formulation of circuit equations. Network theorems. Transient response of first and second order circuits. Sinusoidal steady state-analysis. Frequency response of linear circuits. Poles and zeros. Bode plots. Two-port networks.

ELEN E3331y Electronic circuits
3 pts. Lect: 3. Professor Vallancourt.
Prerequisites: ELEN E3201. Operational amplifier circuits. Diodes and diode circuits. MOS and bipolar junction transistors. Biasing techniques. Small-signal models. Single-stage transistor amplifiers. Analysis and design of CMOS logic gates. A/D and D/A converters.

ELEN E3390y Electronic circuit design laboratory
3 pts. Lab: 6. Professor Vallancourt.
Prerequisites: ELEN E3082, E3083, E3331, E3401, E3801. Advanced circuit design laboratory. Students work in teams to specify, design, implement and test an engineering prototype. The work involves technical as well as non-technical considerations, such as manufacturability, impact on the environment, and economics. The projects may change from year to year.

ELEN E3399x Electrical engineering practice
1 pt. Professor Vallancourt.
Design project planning, written and oral technical communication, practical aspects of engineering as a profession, such as career development and societal and environmental impact. Generally taken senior year.

ELEN E3401y Electromagnetics
4 pts. Lect: 3. Professor Diament.
Prerequisite: MATH V1201, PHYS C1402 or PHYS C1602, or equivalents. Basic field concepts. Interaction of time-varying electromagnetic fields. Field calculation of lumped circuit parameters. Transition from electrostatic to quasistatic and electromagnetic regimes. Transmission lines. Energy transfer, dissipation, and storage. Waveguides. Radiation.

EEME E3601x Classical control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware; implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

ELEN E3701y Introduction to communication systems
3 pts. Lect: 3. Professor Kalet.
Prerequisite: ELEN E3801. Corequisite: IEOR E3658. A basic course in communication theory, stressing modern digital communication systems. Nyquist sampling, PAM and PCM/DPCM systems, time division multipliexing, high frequency digital (ASK, OOK, FSK, PSK) systems, and AM and FM systems. An introduction to noise processes, detecting signals in the presence of noise, Shannon's theorem on channel capacity, and elements of coding theory.

ELEN E3801x Signals and systems
3.5 pts. Lect: 3. Professor X. Wang.
Corequisite: MATH V1201. Modeling, description, and classification of signals and systems. Continuous-time systems. Time domain analysis, convolution. Frequency domain analysis, transfer functions. Fourier series. Fourier and Laplace transforms. Discrete-time systems and the Z transform.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professors Kim and Rubenstein.
Prerequisites: An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flipflops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multicycle processor design, introduction to pipelined processors, caches, and virtual memory.

ELEN E3998x and y Projects in electrical engineering
0 to 3 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

BMEB W4020x Computational neuroscience: circuits in the brain
3 pts. Lect: 3. Professor Lazar.
Prerequisite: ELEN E3801 or BIOL W3004. The biophysics of computation: modeling biological neurons, the Hodgkin-Huxley neuron, modeling channel conductances and synapses as memristive systems, bursting neurons and central pattern generators, I/O equivalence and spiking neuron models. Information representation and neural encoding: stimulus representation with time encoding machines, the geometry of time encoding, encoding with neural circuits with feedback, population time encoding machines. Dendritic computation: elements of spike processing and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and spike time-dependent plasticity, basic dendritic integration. Projects in MATLAB.

BMEE E4030 y Neural control engineering
3 pts. Lect: 3.
Prerequisite: ELEN E3801. Topics include: Basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson's disease treatment, motor neural prostheses, and sensory neural prostheses.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and

visualization using simple computer programming. This course shares lectures with ECBM E3060, but the work requirements differ somewhat.

ECBM E4090x or y Brain computer interfaces (BCI) laboratory
3 pts. Lect: 2. Lab: 3. Professor Mesgarani.
Prerequisites: ELEN E3801. Hands-on experience with basic neural interface technologies. Recording EEG (electroencephalogram) signals using data acquisition systems (noninvasive, scalp recordings). Real-time analysis and monitoring of brain responses. Analysis of intention and perception of external visual and audio signals.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Misra.
Corequisite: IEOR E3658 or SIEO W3600 or equivalents. Introduction to computer networks and the technical foundations of the Internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite: CSEE W4119 or equivalent. In this course, students learn how to put “principles into practice,” in a hands-on-networking lab course. The technologies and protocols of the Internet are covered, using equipment currently available to large Internet service providers such as CISCO routers and end-systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and familiarizes students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP), and application-level protocols (FTP, TELNET, SMTP).

ELEN E4193x or y Modern display science and technology
3 pts. Lect: 3. Professor Kymissis.
Prerequisites: Linear algebra, differential equations, and basic semiconductor physics. Introduction to modern display systems in an engineering context. The basis for visual perception, image representation, color space, metrics of illumination. Physics of luminescence, propagation and manipulation of light in anisotropic media, emissive displays, and spatial light modulators. Fundamentals of display addressing, the Alt-Pleshko theorem, multiple line addressing. Large area electronics, fabrication, and device integration of commercially important display types. A series of short laboratories will reinforce material from the lectures. Enrollment may be limited.

ELEN E4301y Introduction to semiconductor devices
3 pts. Lect: 3. Professor Laibowitz.
Prerequisite: ELEN E3106 or equivalent. Semiconductor physics. Carrier injection and recombination. P-n junction and diodes: Schottky barrier and heterojunctions, solar cells and light-emitting diodes. Junction and MOS field-effect transistors, bipolar transistors. Tunneling and charge-transfer devices.

ELEN E4312x Analog electronic circuits
3 pts. Lect: 3. Professor Tsividis.
Prerequisites: ELEN E3331 and E3801. Differential and multistage amplifiers; small-signal analysis; biasing techniques; frequency response; negative feedback; stability criteria; frequency compensation techniques. Analog layout techniques. An extensive design project is an integral part of the course.

ELEN E4314y Communication circuits
3 pts. Lect: 3. Professor Tsividis.
Prerequisite: ELEN E4312. Principles of electronic circuits used in the generation, transmission, and reception of signal waveforms, as used in analog and digital communication systems. Nonlinearity and distortion; power amplifiers; tuned amplifiers; oscillators; multipliers and mixers; modulators and demodulators; phase-locked loops. An extensive design project is an integral part of the course.

EECS E4321x Digital VLSI circuits
3 pts. Lect: 3. Professor Shepard.
Recommended preparation: ELEN E3106, E3331, and CSEE W3827. Design and analysis of high speed logic and memory. Digital CMOS and BiCMOS device modeling. Integrated circuit fabrication and layout. Interconnect and parasitic elements. Static and dynamic techniques. Worst-case design. Heat removal and I/O. Yield and circuit reliability. Logic gates, pass logic, latches, PLAs, ROMs, RAMs, receivers, drivers, repeaters, sense amplifiers.

EECS E4340x Computer hardware design
3 pts. Lect: 2. Lab: 3. Professor Sethumadhavan.
Prerequisites: ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

BMEE E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3.
Prerequisites: APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include: frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation and classification methods for computer aided diagnosis.

ELEN E4401x Wave transmission and fiber optics
3 pts. Lect: 3. Professor Diament.
Prerequisite: ELEN E3401 or equivalent. Waves and Maxwell’s equations. Field energetics, dispersion, complex power. Waves in dielectrics and in conductors. Reflection and refraction. Oblique incidence and total internal reflection. Transmission lines and conducting waveguides. Planar and circular dielectric waveguides; integrated optics and optical fibers. Hybrid and LP modes. Graded-index fibers. Mode coupling; wave launching.

ELEN E4411x Fundamentals of photonics
3 pts. Lect: 3. Professor Osgood.
Prerequisite: ELEN E3401 or equivalent. Planar resonators. Photons and photon streams. Photons and atoms: energy levels and band structure; interactions of photons with matter; absorption, stimulated and spontaneous emission; thermal light, luminescence light. Laser amplifiers: gain, saturation, and phase shift; rate equations; pumping. Lasers: theory of oscillation; laser output characteristics. Photons in semiconductors: generation, recombination, and injection; heterostructures; absorption and gain coefficients. Semiconductor photon sources: LEDs; semiconductor optical amplifiers; homojunction and heterojunction laser diodes. Semiconductor photon detectors: p-n, p-i-n, and heterostructure photo diodes; avalanche photodiodes.

ELEN E4488x Optical systems
3 pts. Lect: 3. Professor Bergman.
Prerequisite: ELEN E3401 or equivalent. Introduction to optical systems based on physical design and engineering principles. Fundamental geometrical and wave optics with specific emphasis on developing analytical and numerical tools used in optical engineering design. Focus on applications that employ optical systems and networks, including examples in holographic imaging, tomography, Fourier imaging, confocal microscopy, optical signal processing, fiber optic communication systems, optical interconnects and networks.

ELEN E4501x Electromagnetic devices and energy conversion
3 pts. Lect: 3. Professor Sen.
Prerequisite: ELEN E3401. Linear and nonlinear magnetic circuits. Electric and magnetic energy storage, loss, and transfer. Circuit behavior of energy storage and transfer devices. Field theory of moving bodies. Dynamical equations of an electromechanical system. Electromechanical and thermo-electric sensors and actuators. Rotating electric energy converters. Superconductivity and applications.

ELEN E4503x Sensors, actuators and electromechanical systems
3 pts. Lect: 3.
Prerequisites: ELEN E3201 and E3401, or equivalents. Electromagnetic energy storage, loss, and transfer. Dynamics of electromechanical systems. Linearization of nonlinear coupled dynamical equations and equivalent circuits. Electromechanical actuators: acoustic, IC processed micromachines. Electromechanical sensors: acoustic, pressure, and acceleration. Thermal sensors: polysilicon thermopiles and bipolar transistor temperature sensors. Electro-optic sensors: visible light, infrared, and X-ray.

ELEN E4510x or y Solar energy and smart grid power systems
3 pts. Lect: 3. Professors Kymissis and Schwartz.
Prerequisite: Background in circuits. Inorganic solar cell semiconductor physics. Single and tandem junction design. Measures of spectral and energy efficiency. Introduction to organic solar cells and thin film inorganic cells. Batteries and other energy storage systems. Introduction to legacy power networks: Single phase equivalents to three-phase networks. Reactive and real power. Equivalent circuits of synchronous machines, transformers, and transmission lines. Smart grid technology: Control and management of distributed solar energy and other intermittent renewable power sources connected to legacy power networks. Microgrid concept. “Small world” networks and fault management. Communication over power lines. Smart metering.

ELEN E4511x or y Power systems analysis and control
3 pts. Lect: 3. Professor Lavaei.
Prerequisites: ELEN E3201 and E3401, or equivalents, or instructor’s permission. Modeling of power networks, steady-state and transient behaviors, control and optimization, electricity market, and smart grid.

EEME E4601y Digital control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: ELEN E3801 or EEME E3601, or equivalent. Real-time control using digital computers. Solving scalar and state-space difference equations. Discrete equivalents of continuous systems fed by holds. Z-transfer functions. Creating closed-loop difference equation models by Z-transform and state variable approaches. The Nyquist frequency and sample rate selection. Classical- and modern-based digital control laws. Digital system identification.

EEOR E4650x or y Convex optimization for electrical engineering
3 pts. Lect: 3. Professor Lavaei.
Prerequisite: ELEN E3801 or instructor’s permission. Theory of convex optimization; numerical algorithms; applications in circuits, communications, control, signal processing and power systems.

ELEN E4702x or y Digital communications
3 pts. Lect: 3. Professor Cvijetic.
Prerequisite: ELEN E3701 or equivalent. Digital communications for both point-to-point and switched applications is further developed. Optimum receiver structures and transmitter signal shaping for both binary and M-ary signal transmission. An introduction to block codes and convolutional codes, with application to space communications.

ELEN E4703y Wireless communications
3 pts. Lect: 3. Professor Diament.
Prerequisite: ELEN E3701 or equivalent. Wireless communication systems. System design fundamentals. Trunking theory. Mobile radio propagation. Reflection of radio waves. Fading and multipath. Modulation techniques; signal space; probability of error, spread spectrum. Diversity. Multiple access.

BMEE E4740y Bioinstrumentation
3 pts. Lect: 1. Lab: 3. Professor Kyle.
Prerequisites: COMS W1005, ELEN E1201. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data scquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker. Lab required.

ELEN E4750x or y Signal processing and communications on mobile multicore processors
3 pts. Lect: 2. Lab: 3. Professor Kostic.
Prerequisite: ELEN E4702 or E4810 or instructor’s permission. Methods for deploying signal processing and communications algorithms on contemporary mobile processors with heterogeneous computing infrastructures consisting of a mix of general purpose, graphics, and digital signal processors. Using programming languages such as OpenCL and CUDA for computational speedup in audio, image, and video processing and computational data analysis. Significant design project.

ELEN E4810x Digital signal processing
3 pts. Lect: 3. Professor Ellis.
Prerequisite: ELEN E3801. Digital filtering in time and frequency domain, including properties of discrete-time signals and systems, sampling theory, transform analysis, system structures, IIR and FIR filter design techniques, the discrete Fourier transform, fast Fourier transforms.

ELEN E4815y Random signals and noise
3 pts. Lect: 3.
Prerequisite: IEOR E3658 or equivalent. Characterization of stochastic processes as models of signals and noise; stationarity, ergodicity, correlation functions, and power spectra. Gaussian processes as models of noise in linear and nonlinear systems; linear and nonlinear transformations of random processes; orthogonal series representations. Applications to circuits and devices, to communication, control, filtering, and prediction.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3. Professor Nowick.
Prerequisite: CSEE W3827 or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modeling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples.

CSEE W4824x or y Computer architecture
3 pts. Lect: 3. Professor Carloni.
Prerequisite: CSEE W3827 or equivalent. Focuses on advanced topics in modern computer architecture, illustrated by recent case studies. Fundamentals of quantitative analysis. Pipelined, out-of-order, and speculative execution. Superscalar, VLIW and vector processors. Embedded processors. Memory hierarchy design. Multiprocessors and thread-level parallelism. Synchronization and cache coherence protocols. Interconnection networks.

ELEN E4830y Digital image processing
3 pts. Lect: 3.
Introduction to the mathematical tools and algorithmic implementation for representation and processing of digital pictures, videos, and visual sensory data. Image representation, filtering, transform, quality enhancement, restoration, feature extraction, object segmentation, motion analysis, classification, and coding for data compression. A series of

programming assignments reinforces material from the lectures.

ELEN E4835 Introduction to adaptive signal representations
3 pts. Lect: 2. Professor Wright.
Prerequisites: Linear algebra (APMA E3101, MATH V2010, or equivalent), probability (IEOR E3658 or equivalent), and signals and systems (ELEN E3801), or instructor's permission. Introduces numerical tools for adaptive processing of signals. Signal representations, sparsity in overcomplete bases. Techniques for sparse recovery, applications to inpainting and denoising. Adaptive representations: principal component analysis, clustering and vector quantization, dictionary learning. Source separation: independent component analysis and matrix factorizations. Signal classification: support vector machines and boosting, learning with invariances. Hashing and signal retrieval. Case studies from image processing, audio, multimedia.

CSEE W4840y Embedded systems
3 pts. Lect: 3.
Prerequisite: CSEE W4823 or equivalent. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required.

ELEN E4896y Music signal processing
3 pts. Lect: 3.
Prerequisite: ELEN E3801, E4810, or the equivalent. An investigation of the applications of signal processing to music audio, spanning the synthesis of musical sounds (including frequency modulation [FM], additive sinusoidal synthesis, and linear predictive coding [LPC]), the modification of real and synthetic sounds (including reverberation and time/pitch scaling), and the analysis of music audio to extract musical information (including pitch tracking, chord transcription, and music matching). Emphasis on practical, hands-on experimentation, with a wide range of software implementations introduced and modified within the class.

ELEN E4900-4909x or y Topics in electrical and computer engineering
3 pts. Lect: 2. Instructor to be announced.
Prerequisite: Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 4900 to 4909.

ELEN E4944x or y Principles of device microfabrication
3 pts. Lect: 3. Professor Yardley.
Science and technology of conventional and advanced microfabrication techniques for electronics, integrated and discrete components. Topics include diffusion; ion implantation, thin-film growth including oxides and metals, molecular beam and liquid-phase epitaxy; optical and advanced lithography; and plasma and wet etching.

ELEN E4998x or y Intermediate projects in electrical engineering
0–3 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Substantial independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

ELEN E6001x-E6002y Advanced projects in electrical engineering
1–4 pts. Members of the faculty.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for up to 6 points of credit. Graduate-level projects in various areas of electrical engineering and computer science. In consultation with an instructor, each student designs his or her project depending on the student's previous training and experience. Students should consult with a professor in their area for detailed arrangements no later than the last day of registration.

ELEN E6010y Systems biology: design principles for biological circuits
4.5 pts. Lect: 3.
Prerequisite: ECBM E4060 or instructor's permission. Beyond bioinformatics, cells as systems. Metabolic networks, transcription regulatory networks, signaling networks. Deterministic and stochastic kinetics. Mathematical representation of reconstructed networks. Network motifs. Signal transduction and neuronal networks. Robustness. Bacterial chemotaxis and patterning in fruit fly development. Kinetic proofreading. Optimal gene circuit design. Rules for gene regulation. Random networks and multiple time scales. Biological information processing. Numerical and simulation techniques. Major project(s) in MATLAB.

EEBM E6020y Methods of computational neuroscience
4.5 pts. Lect: 3.
Prerequisite: BMEB W4020 or instructor's permission. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Professor Sajda.
Prerequisites: ELEN E3801 and either APMA E2101 or E3101, or equivalent, or instructor's permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course will include a computer simulation laboratory.

ECBM E6040y Neural networks and deep learning
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: BMEB W4020 or BMEE E4030 or ECBM E4090 or ELEN E4750 or COMS W4771 or the equivalent. Developing features and internal representations of the world, artificial neural networks, classifying handwritten digits with logistical regression, multilayer perceptron, convolutional neural networks, autoencoders and denoising autoencoders, recurrent neural networks, restricted Boltzmann machines, deep belief networks, deep learning in speech, and object recognition.

ELEN E6080–6089x or y Topics in systems biology
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected advanced topics in systems biology. Content varies from year to year, and different topics rotate through the course numbers 6080 to 6089.

EEBM E6090–6099x or y Topics in computational neuroscience and neuroengineering
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected advanced topics in computational neuroscience and neuroengineering. Content varies from year to year, and different topics rotate through the course numbers 6090 to 6099.

CSEE E6180x or y Modeling and performance evaluation
3 pts. Lect: 2.
Prerequisites: COMS W4118 and SIEO W4150 or permission of the instructor. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

ELEN E6201x Linear system theory
3 pts. Lect: 3. Professor Fishler.
Prerequisites: ELEN E3801 and APMA E3101, or equivalents. Abstract objects, the concepts of state. Definition and properties of linear systems. Characterization of linear continuous-time and discrete-time, fixed, and time-varying systems. State-space description; fundamental matrix, calculation by computer and matrix methods. Modes in linear systems. Adjoint systems. Controllability and observability. Canonical forms and decompositions. State estimators. Lyapunov's method and stability.

ELEN E6312y Advanced analog integrated circuits
3 pts. Lect: 2.
Prerequisite: ELEN E4312. Integrated circuit device characteristics and models; temperature- and supply-independent biasing; IC operational amplifier analysis and design and their applications; feedback amplifiers, stability and frequency compensation techniques; noise in circuits and low-noise design; mismatch in circuits and low-offset design. Computer-aided analysis techniques are used in homework or a design project.

ELEN E6314x Advanced communication circuits
3 pts. Lect: 2.
Prerequisites: ELEN E4314 and E6312. Overview of communication systems, modulation and detection schemes. Receiver and transmitter architectures. Noise, sensitivity, and dynamic range. Nonlinearity and distortion. Low-noise RF amplifiers, mixers, and oscillators. Phase-locked loops and frequency synthesizers. Typical applications discussed include wireless RF transceivers or data links. Computer-aided analysis techniques are used in homework(s) or a design project.

ELEN E6316y Analog systems in VLSI
3 pts. Lect: 3.
Prerequisite: ELEN E4312. Analog-digital interfaces in very large scale integrated circuits. Precision sampling; A/D and D/A converter architectures; continuous-time and switched capacitor filters; system considerations. A design project is an integral part of this course.

ELEN E6318x or y Microwave circuit design
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and E3401, or equivalents. Introduction to microwave engineering and microwave circuit design. Review of transmission lines. Smith chart, S-parameters, microwave impedance matching, transformation and power combining networks, active and passive microwave devices, S-parameter-based design of RF and microwave amplifiers. A microwave circuit design project (using microwave CAD) is an integral part of the course.

ELEN E6320x or y Millimeter-wave IC design
3 pts. Lect: 3. Professor Krishnaswamy.
Prerequisites: ELEN E3401 or equivalent, ELEN E4314 and E6312. Principles behind the implementation of millimeter-wave (30GHz-300GHz) wireless circuits and systems in silicon-based technologies. Silicon-based active and passive devices for millimeter-wave operation, millimeter-wave low-noise amplifiers, power amplifiers, oscillators and VCOs, oscillator phase noise theory, mixers and frequency dividers for PLLs. A design project is an integral part of the course.

EECS E6321y Advanced digital electronic circuits
4.5 pts. Lect: 3. Professor Seok.
Prerequisite: EECS E4321. Advanced topics in the design of digital integrated circuits. Clocked and non-clocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

ELEN E6331y Principles of semiconductor physics, I
3 pts. Lect: 2.
Prerequisite: ELEN E4301. Designed for students interested in research in semiconductor materials and devices. Topics include energy bands: nearly free electron and tight-binding approximations, the k.p. method, quantitative calculation of band structures and their applications to quantum structure transistors, photodetectors, and lasers; semiconductor statistics, Boltzmann transport equation, scattering processes, quantum effect in transport phenomena, properties of heterostructures. Quantum mechanical treatment throughout.

ELEN E6332y Principles of semiconductor physics, II
3 pts. Lect: 2.
Prerequisites: ELEN E6331. Optical properties including absorption and emission of radiation, electron-phonon interactions, radiative and phonon-mediated processes, excitons, plasmons, polaritons, carrier recombination and generation, and related optical devices, tunneling phenomena, superconductivity. Quantum mechanical treatment throughout, heavy use of perturbation theory.

ELEN E6333y Semiconductor device physics
3 pts. Lect: 2.
Prerequisites: ELEN E4301 or equivalent. Physics and properties of semiconductors. Transport and recombination of excess carriers. Schottky, P-N, MOS, and heterojunction diodes. Field effect and bipolar junction transistors. Dielectric and optical properties. Optical devices including semiconductor lamps, lasers, and detectors.

ELEN E6412y Lightwave devices
3 pts. Lect: 2.
Prerequisites: ELEN E4411. Electro-optics: principles; electro-optics of liquid crystals and photo-refractive materials. Nonlinear optics: second-order nonlinear optics; third-order nonlinear optics; pulse propagation and solitons. Acousto-optics: interaction of light and sound; acousto-optic devices. Photonic switching and computing: photonic switches; all-optical switches; bistable optical devices. Introduction to fiber-optic communications: components of the fiber-optic link; modulation, multiplexing and coupling; system performance; receiver sensitivity; coherent optical communications.

ELEN E6413y Lightwave systems
3 pts. Lect: 2.
Prerequisites: ELEN E4411. Recommended preparation: ELEN E6412. Fiber optics. Guiding, dispersion, attenuation, and nonlinear properties of fibers. Optical modulation schemes. Photonic components, optical amplifiers. Semiconductor laser transmitters. Receiver design. Fiber optic telecommunication links. Nonregenerative transmission using erbium-doped fiber amplifier chains. Coherent detection. Local area networks. Advanced topics in light wave networks.

ELEN E6414y Photonic integrated circuits
3 pts. Lect: 3.
Photonic integrated circuits are important subsystem components for telecommunications, optically controlled radar, optical signal processing, and photonic local area networks. An introduction to the devices and the design of these circuits. Principle and modelling of dielectic waveguides (including silica on silicon and InP based materials), waveguide devices (simple and star couplers), and surface diffractive elements. Discussion of numerical techniques for modelling circuits, including beam propagation and finite difference codes, and design of other devices: optical isolators, demultiplexers.

ELEN E6430x or y Applied quantum optics
3 pts. Lect: 2.
Prerequisites: Background in electromagnetism (ELEN E3401, E4401, E4411, or PHYS G6092) and quantum mechanics (APPH E3100,

E4100, or PHYS G402x). An introduction to fundamental concepts of quantum optics and quantum electrodynamics with an emphasis on applications in nanophotonic devices. The quantization of the electromagnetic field; coherent and squeezed states of light; interaction between light and electrons in the language of quantum electrodynamics (QED); optical resonators and cavity QED; low-threshold lasers; and entangled states of light.

ELEN E6488y Optical interconnects and interconnection networks
3 pts. Lect: 2. Professor Bergman.
Prerequisite: ELEN E4411 or E4488 or an equivalent photonics course. Introduction to optical interconnects and interconnection networks for digital systems. Fundamental optical interconnects technologies, optical interconnection network design, characterization, and performance evaluation. Enabling photonic technologies including free-space structures, hybrid and monolithic integration platforms for photonic on-chip, chip-to-chip, backplane, and node-to-node interconnects, as well as photonic networks on-chip.

EEME E6601x Introduction to control theory
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models, and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed-loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability, observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

EEME E6602y Modern control theory
3 pts. Lect: 3.
Prerequisite: EEME E6601 or E4601 or ELEN E6201, or instructor's permission. Singular value decomposition. ARX model and state-space model system identification. Recursive least squares filters and Kalman filters. LQR, H, linear robust control, predictive control. Learning control, repetitive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEOR E6616x or y Convex optimization
3 pts. Lect: 2.5.
Prerequisites: IEOR E6613 and EEOR E4650. Convex sets and functions, and operations preserving convexity. Convex optimization problems. Convex duality. Applications of convex optimization problems ranging from signal processing and information theory to revenue management. Convex optimization in Banach spaces. Algorithms for solving constrained convex optimization problems.

ELEN E6711x Stochastic models in information systems
4.5 pts. Lect: 3. Professor Baryshnikov.
Prerequisite: IEOR E3658. Foundations: probability review, Poisson processes, discrete-time Markov models, continuous-time Markov models, stationarity, and ergodicity. The course presents a sample-path (time domain) treatment of stochastic models arising in information systems, including at least one of the following areas: communications networks (queueing systems), biological networks (hidden Markov models), Bayesian restoration of images (Gibbs fields), and electric networks (random walks).

ELEN E6712x Communication theory
3 pts. Lect: 3.
Prerequisite: ELEN E4815, or equivalent, or instructor's permission. Representation of bandlimited signals and systems. Coherent and incoherent communications over Gaussian channels. Basic digital modulation schemes. Intersymbol inference channels. Fading multipath channels. Carrier and clock synchronization.

ELEN E6713y Topics in communications
3 pts. Lect: 3.
Prerequisite: ELEN E6712 or E4702 or E4703 or equivalent, or instructor's permission. Advanced topics in communications, such as turbo codes, LDPC codes, multiuser communications, network coding, cross-layer optimization, cognitive radio. Content may vary from year to year to reflect the latest development in the field.

ELEN E6717x Information theory
3 pts. Lect: 2.
Prerequisite: IEOR E3658 or a course in stochastic processes. Corequisite: ELEN E4815. Mutual information and entropy. The source coding theorem. The capacity of discrete memoryless channels and the noisy channel coding theorem. The rate distortion function. Discrete memoryless sources and single-letter distortion measures. Bhattacharya bounds, convolutional codes, and the Viterbi algorithm.

ELEN E6718y Algebraic coding theory
3 pts. Lect: 2.
Prerequisite: IEOR E3658. Elementary concepts of error control codes. Linear block codes. Elements of algebra: Galois fields. Cyclic codes: BCH, Reed Solomon, Goppa codes. Coder, decoder implementation. Decoding algorithms based on spectral techniques. Convolutional codes.

ELEN E6761x Computer communication networks I
3 pts. Lect: 3. Professor Maxemchuk.
Prerequisites: IEOR E3658 and CSEE W4119 or equivalent, or instructor's permission. Focus on architecture protocols and performance evaluation of geographically distributed and local area data networks. Emphasis on layered protocols. Data link layer. Network layer: flow and congestion control routing. Transport layer. Typical Local and Metropolitan Area Network standards: Ethernet, DQDB, FDDI. Introduction to Internetting. Review of relevant aspects of queueing theory to provide the necessary analytical background.

EECS E6765x or y Internet of things
3 pts. Lect: 3. Professor Kostic.
Prerequisites: One of the following is recommended: ELEN E4703, CSEE W4119, E4823, E4840, or related courses and knowledge of programming. Broad study of technical aspects of Internet of things: architecture, algorithms, channels, devices, networks, protocols, communication, power, data processing, security, and standards. In-depth analysis of several selected use cases across systems, software, and hardware. Focus on a significant design project.

ELEN E6767x or y Internet economics, engineering, and the implications for society
3 pts. Lect: 2. Professor Mitra.
Prerequisites: CSEE W4119 or ELEN E6761 recommended, and ability to comprehend and track development of sophisticated models. Mathematical models, analyses of economics and networking interdependencies in the Internet. Topics include microeconomics of pricing and regulations in communications industry, game theory in revenue allocations, ISP settlements, network externalities, two-sided markets. Economic principles in networking and network design, decentralized vs. centralized resource allocation, "price of anarchy," congestion control. Case studies of topical Internet issues. Societal and industry implications of Internet evolution.

ELEN E6770–6779x or y Topics in networking
3 pts. Lect: 2.
Further study of areas such as communication protocols and architectures, flow and congestion control in data networks, performance evaluation in integrated networks. Content varies from year to year, and different topics rotate through the course numbers 6770 to 6779.

ELEN E6820y Speech and audio processing and recognition
4.5 pts. Lect: 3.
Prerequisite: ELEN E4810 or instructor's permission. Fundamentals of digital speech processing and audio signals. Acoustic and perceptual basics of audio. Short-time Fourier analysis. Analysis and filterbank models. Speech and audio coding, compression, and reconstruction. Acoustic feature extraction and classification. Recognition techniques for speech and other sounds, including hidden Markov models.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2.
Prerequisite: CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite: Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor's permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

ELEN E6850x Visual information systems
3 pts. Lect: 2.
Prerequisite: ELEN E4830 or instructor's permission. Introduction to critical image technologies in advanced visual information systems, such as content-based image databases, video servers, and desktop video editors. Intended for graduate students. Topics include visual data representation and compression, content-based visual indexing and retrieval, storage system design (data placement, scheduling, and admission control), compressed video editing, and synchronization issues of stored video/audio signals. Programming projects and final presentations are required.

ELEN E6860y Advanced digital signal processing
3 pts. Lect: 2. Professor Nguyen.
Prerequisite: ELEN E4810. This course is designed as an extension to ELEN E4810, with emphasis on emerging techniques in the area of digital signal processing. Topics include multirate signal processing, multidimensional signal processing, short-time Fourier transform, signal expansion in discrete and continuous time, filter banks, multiresolution analysis, wavelets, and their applications to image compression and understanding. Other topics may be included to reflect developments in the field.

CSEE E6861y Computer-aided design of digital systems
3 pts. Lect: 2.
Prerequisites: (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor's permission); and (ii) a basic course in data structures and algorithms (COMS W3133, 3134, 3137, 3139 or 3157, or equivalent, and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multi-level logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6868x or y System-on-chip platforms
3 pts. Lect: 3.
Prerequisites: COMS W3157 and CSEE W3827. Design and programming of system-on-chip (SoC) platforms. Topics include: overview of technology and economic trends, methodologies and supporting CAD tools for system-level design and verification, software simulation and virtual platforms, models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, memory organization, device drivers, on-chip communication architectures, power management and optimization, integration of programmable cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

EECS E6870x or y Speech recognition
3 pts. Lect: 2.
Prerequisites: Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

ELEN E6873x or y Detection and estimation theory
3 pts. Lect: 2.
Prerequisite: ELEN E4815. Introduction to the fundamental principles of statistical signal processing related to detection and estimation. Hypothesis testing, signal detection, parameter estimation, signal estimation, and selected advanced topics. Suitable for students doing research in communications, control, signal processing, and related areas.

ELEN E6880-6889x or y Topics in signal processing
3 pts. Lect: 2.
Prerequisite: ELEN E4810. Advanced topics in signal processing, such as multidimensional signal processing, image feature extraction, image/video editing and indexing, advanced digital filter design, multirate signal processing, adaptive signal processing, and wave-form coding of signals. Content varies from year to year, and different topics rotate through the course numbers 6880 to 6889.

EECS E6890-6899x or y Topics in information processing
3 pts. Lect: 2.
Advanced topics spanning electrical engineering and computer science such as speech processing and recognition, image and multimedia content analysis, and other areas drawing on signal processing, information theory, machine learning, pattern recognition, and related topics. Content varies from year to year, and different topics rotate through the course numbers 6890 to 6899.

ELEN E6900–6909x or y Topics in electrical and computer engineering
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 6900 to 6909.

ELEN E6945x or y Device nanofabrication
3 pts. Lect: 3.
Prerequisites: ELEN E3106 and E3401, or equivalents. Recommended: ELEN E4944. This course provides an understanding of the methods used for structuring matter on the nanometer length: thin-film technology; lithographic patterning and technologies including photon, electron, ion and atom, scanning probe, soft lithography, and nanoimprinting; pattern transfer; self-assembly; process integration; and applications.

ELEN E6950x Wireless and mobile networking, I
4.5 pts. Lect: 2. Lab: 1. Professor Jelenkovic.
Corequisite: ELEN E6761 or instructor's permission. Overview of mobile and wireless networking. Fundamental concepts in mobile wireless systems: propagation and fading, cellular systems, channel assignment, power control, handoff. Examples of second-generation circuits-switched systems and standards. Quantitative homework assignments may require use of a mathematical software package.

ELEN E6951y Wireless and mobile networking, II
3 pts. Lect: 2. Lab: 1. Professor Zussman.
Prerequisite: CSEE W4119, ELEN E6761, or instructor's permission. Third-generation packet switched systems, wireless LANs, mobile computing and communications. Study of some

current research topics. Quantitative homework assignments may require use of a mathematical software package. A project based on readings from the literature will be required.

ELEN E6999 Fieldwork
0.5–1.5 pts.
Prerequisites: Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for electrical engineering and computer engineering graduate students who include relevant off-campus work experience as part of their approved program of study. Final report required. May not be taken for pas/faill credit or audited.

EEME E8601y Advanced topics in control theory
3 pts. Lect: 3.
See entry under "Courses in Mechanical Engineering" for description.

ELEN E9001x and y–E9002 Research
0–6 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Requires submission of an outline of the proposed research for approval by the faculty member who is to supervise the work of the student. The research facilities of the department are available to qualified students interested in advanced study.

ELEN E9011x and y–E9012 Doctoral research
0–6 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Open only to doctoral students who have passed the qualifying examinations. Requires submission of an outline of the proposed research for the approval of the faculty member who is to supervise the work of the student.

ELEN E9800x and y Doctoral research instruction
3, 6, 9 or 12 pts.
A candidate for the Eng.Sc.D. degree in electrical engineering must register for 12 points of doctoral research instruction. Registration in ELEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

ELEN E9900x and y–9900 Doctoral dissertation
0 pts.
A candidate for the doctorate may be required to register for this course every term after the student's course work has been completed, and until the dissertation has been accepted.

COURSES IN ELECTRICAL ENGINEERING OFFERED OCCASIONALLY

EEHS E3900y History of telecommunications: from the telegraph to the Internet
3 pts. Lect: 3.
Historical development of telecommunications from the telegraphy of the mid-1800s to the Internet at present. Included are the technologies of telephony, radio, and computer communications. The coverage includes both the technologies themselves and the historical events that shaped, and in turn were shaped by, the technologies. The historical development, both the general context and the particular events concerning communications, is presented chronologically. The social needs that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are explained as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking principles. There are no prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective. The course shares lectures with EEHS E4900, but the work requirements differ somewhat.

ELEN E3999x or y Electrical engineering design challenge
1 pt.
Prerequisite: Approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Short-term design project organized as a faculty-led team competition. Particular design targets are set that vary by semester. A set of hardware and software constraints is specified. The project takes place over an advertised subset of the semester, beginning around the third week.

ELEN E4215y Analog filter synthesis and design
3 pts. Lect: 3.
Prerequisites: ELEN E3201 and ELEN E3801, or equivalent. Approximation techniques for magnitude, phase, and delay specifications , transfer function realization sensitivity, passive LC filters, active RC filters, MOSFET-C filters, Gm-C filters, switched-capacitor filters, automatic tuning techniques for integrated filters. Filter noise. A design project is an integral part of the course.

ELEN E4302x or y Magnetic sensors and instruments for medical imaging
3 pts. Lect: 2.5, Lab: 0.5.
Prerequisite: ELEN E3106, ELEN E3401, or instructor's permission. Physics of nuclear magnetic resonance (NMR) and superconducting quantum interference device (SQUID). Design and operation of superconducting DC magnet, RF receiver, Josephson junction, and integrated SQUID. Principles of biomedical sensoring systems including Magnetic Resonance Imaging (MRI), SQUID magnetometer, and NMR spectroscopy. Medical image formation and processing.

ELEN E4350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisites: ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E6350, but the complexity requirements of integrated circuits are lower.

ELEN E4405x Classical nonlinear optics
3 pts. Lect: 3.
Prerequisite: ELEN E4401. Waves in anisotropic media. Maxwell's equations and constitutive relations. Fresnel equations. Optical waves in anisotropic crystals. Birefringence. Waves in nonlinear media. Plasma model. Electro-optic, Pockels, and Kerr effects. Second harmonic generation and phase matching. Parametric amplification. Backward-wave oscillator. Acousto-optic beam deflection and light modulation.

ELEN E4420x Topics in electromagnetics
3 pts. Lect: 3.
Prerequisites: Undergraduate electromagnetic theory. Selected topics in the theory and practice of electromagnetics, varying from year to year. Topic for current term will be available in the department office one month before registration. This course may be taken more than once when topics are different. Possible topics: microwave theory and design (generalized waveguides, excitation and coupling of waveguides, junctions, microwave networks, periodic structures, optical fibers); antennas (filamentary antennas, arrays, aperture radiation, system properties, pattern synthesis); electrodynamics (special relativity, radiation by charged particles, relativistic beams, free electron lasers).

ELEN E4741x Introduction to biological sensory systems
3 pts. Lect: 3.
Corequisite: IEOR E3658. Introduction to vision and hearing using engineering principles. Nature of sound and light; minimum detectable energy for human observers; excitation of the visual and hearing systems; rods, cones, and hair-cell receptors; the experiment of Hecht, Shlaer, and Pirenne; Poisson counting statistics; stimulus-based modeling; detection and false-alarm probabilities; de Vries-Rose square-root law; Weber's law; relation of sensory and communication systems.

ELEN E6140x Gallium arsenide materials processing
3 pts. Lect: 3.
Prerequisite: ELEN E4301 or instructor's permission. Materials and device aspects of GaAs and compound technologies, electronic properties of GaAs, growth techniques (bulk and epitaxial), surface and etching properties, implantation, MESFETS, transferred electron devices, Impatt diodes, HEMTS, HBTs.

ELEN E6151y Surface physics and analysis of electronic materials
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Basic physical principles of methods of surface analysis, surfaces of electronic materials including structure and optical properties (auger electron spectroscopy, X-ray photoemission, ultraviolet photoelectron spectroscopy, electron energy loss spectroscopy, inverse photoemission, photo stimulated desorption, and low energy electron diffraction), physical principles of each approach.

ELEN E6211x or y Circuit theory
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and ELEN E3801. An axiomatic development of circuit theory. Circuit theorems, circuit topology, general methods of circuit analysis. Normal form characterizations. Scattering characterization and sensitivity function. Basic network synthesis methods: immittance and transfer function realization, multiport realization, approximation techniques.

ELEN E6261y Computational methods of circuit analysis
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and APMA E3101. Computational algorithms for DC, transient, and frequency analysis of linear and nonlinear circuits. Formulation of equations: state equations, hybrid equations, sparse tableaux. Solution techniques: iterative methods to solve nonlinear algebraic equations; piecewise linear methods; sparse matrix techniques; numerical integration of stiff, nonlinear differential equations, companion network models; waveform relaxation.

ELEN E6302x or y MOS transistors
3 pts. Lect: 2.
Prerequisite: ELEN E3106 or equivalent. Operation and modelling of MOS transistors. MOS two- and three-terminal structures. The MOS transistor as a four-terminal device; general charge-sheet modelling; strong, moderate, and weak inversion models; short-and-narrow-channel effects; ion-implanted devices; scaling considerations in VLSI; charge modelling; large-signal transient and small-signal modelling for quasistatic and nonquasistatic operation.

ELEN E6304x or y Topics in electronic circuits
3 pts. Lect: 3.
Prerequisite: Instructor's permission. State-of-the-art techniques in integrated circuits. Topics may change from year to year.

ELEN E6350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisites: ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E4350 but the complexity requirements of integrated circuits are higher.

ELEN E6403y Classical electromagnetic theory
4.5 pts. Lect: 3.
Prerequisite: One term of undergraduate electromagnetic theory. A mathematical physics approach to electromagnetic phenomena. Poisson, Laplace equations; Green's functions. Theorems of electrostatics. Multipole expansions. Energy relations and stress tensor. Maxwell's equations in stationary and moving media. The wave equation, energy and momentum theorems, potentials, choice of gauge.

EEME E6610x Optimal control theory
3 pts. Lect: 3.
Prerequisite: ELEN E6201 or EEME E6601. Objectives of optimal control. Continuous and discrete control problems. Calculus of variations: Mayer and Bolza; Pontryagin's maximum principle. Bang-bang and singular controls. Existence of optimal control. Hamilton-Jacobi theory and dynamic programming. Numerical methods. Optimal feedback control regulatory problems. Linear-quadratic-Gaussian estimation. Applications.

ELEN E6731y Satellite communication systems
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisite: ELEN E4702. Introduction to satellite communication, with emphasis on characterization and systems engineering of the transmission channel. Power budgets, antennas, transponders, multiple access, and frequency re-use techniques. Noise, intermodulation, interference, and propagation effects. Modulation methods, earth terminals, and standards. Digital transmission and advanced systems.

ELEN E6762y Computer communication networks, II
3 pts. Lect: 2.
Prerequisite: ELEN E6761. Broadband ISDN, services and protocols; ATM. Traffic characterization and modeling: Markov-modulated Poisson and Fluid Flow processes; application to voice, video, and images. Traffic Management in ATM networks: admission and access control, flow control. ATM switch architectures; input/output queueing. Quality of service (QoS) concepts.

ELEN E6763y Digital circuit switched networks
3 pts. Lect: 2.
Prerequisite: ELEN E6761 or instructor's permission. Current topics in digital circuit switching: introduction to circuit switching, comparison with packet switching, elements of telephone traffic engineering, space and time switching, call processing in digital circuit-switched systems, overload control mechanisms, nonhierarchical routing, common channel signaling, introduction to integrated services digital networks. Examples of current systems are introduced throughout. Emphasis on modeling and quantitative performance analysis. Queueing models introduced where possible.

ELEN E6781y Topics in modeling and analysis of random phenomena
3 pts. Lect: 3.
Prerequisite: ELEN E6711. Recommended preparation: a course on real analysis and advanced probability theory. Current methodology in research in stochastic processes applied to communication, control, and signal processing. Topics vary from year to year to reflect student interest and current developments in the field.

CSEE E6831y Sequential logic circuits
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. Generation and manipulation of flow table descriptions to asynchronous sequential functions. Coding of flow tables to satisfy various design criteria. Delays, races, hazards, metastability. Analysis of latches to determine key parameters. Bounds of input rates. Clocking schemes for synchronous systems. Synthesis of self-timed systems using 4-phase or 2-phase handshakes.

CSEE E6832x or y Topics in logic design theory
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. A list of topics for each offering of the course is available in the department office one month before registration. May be taken more than once if topics are different. Iterative logic circuits applied to pattern recognition. Finite state machines; alternative representations, information loss, linear circuits, structure theory. Reliability and testability of digital systems.

ELEN E6920x or y Topics in VLSI systems design
3 pts. Lect: 2.
Prerequisite: ELEN E4321. Design automation: layout, placement, and routing. Circuit simulation algorithms and optimization of performance and area. Multiprocessor computing systems.

Verification of testing. Topics may change from year to year.

ELEN E8701y Point processes in information and dynamical systems
3 pts. Lect: 3.
Prerequisite: ELEN E6711 or equivalent. Recommended preparation: Course in measure theory or advanced probability theory. Probability and point processes. Random intensity rate, martingales, and the integral representation of point process martingales. Recursive estimation, the theory of innovations, state estimate for queues. Markovian queueing networks. Hypothesis testing, the separation between filtering and detection. Mutual information and capacity for the Poisson-type channel. Stochastic control, dynamic programming for intensity control.

ELEN E9060x or y Seminar in systems biology
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in the field of systems biology.

EEBM E9070x or y Seminar in computational neuroscience and neuroengineering
3 pts. Lect: 2.
Open to doctoral candidates and qualified M.S. candidates with instructor's permission. Study of recent developments in computational neuroscience and neuroengineering.

ELEN E9101x or y Seminar in physical electronics
3 pts. Lect: 2.
Prerequisites: Quantum electronics and ELEN E4944, or instructor's permission. Advanced topics in classical and quantum phenomena that are based on ion and electron beams, gas discharges, and related excitation sources. Application to new laser sources and microelectronic fabrication.

ELEN E9201x or y Seminar in circuit theory
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in linear, nonlinear, and distributed circuit theory and analysis techniques important to the design of very large scale integrated circuits.

ELEN E9301x or y Seminar in electronic devices
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Theoretical and experimental studies of semiconductor physics, devices, and technology.

ELEN E9303x or y Seminar in electronic circuits
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in electronic circuits.

ELEN E9402x or y Seminar in quantum electronics
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent experimental and theoretical developments in various areas of quantum electronics research. Examples of topics that may be treated include novel nonlinear optics, lasers, transient phenomena, and detectors.

ELEN E9403x or y Seminar in photonics
3 pts. Lect: 2.
Prerequisite: ELEN E4411. Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent experimental and theoretical developments in various areas of photonics research. Examples of topics that may be treated include squeezed-light generation, quantum optics, photon detection, nonlinear optical effects, and ultrafast optics.

ELEN E9404x or y Seminar in lightwave communications
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's approval. Recent theoretical and experimental developments in light wave communications research. Examples of topics that may be treated include information capacity of light wave channels, photonic switching, novel light wave network architectures, and optical neural networks.

ELEN E9501x or y Seminar in electrical power networks
3 pts. Lect: 2.
Prerequisites: Open to doctoral candidates, and to qualified M.S. candidates with the instructor's permission. Recent developments in control & optimization for power systems, design of smart grid, and related topics.

ELEN E9701x or y Seminar in information and communication theories
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent developments in telecommunication networks, information and communication theories, and related topics.

ELEN E9801x or y Seminar in signal processing
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's approval. Recent developments in theory and applications of signal processing, machine learning, content analysis, and related topics.

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

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Industrial engineering is the branch of the engineering profession that is concerned with the design, analysis, and control of production and service systems. Originally, an industrial engineer worked in a manufacturing plant and was involved only with the operating efficiency of workers and machines. Today, industrial engineers are more broadly concerned with productivity and all of the technical problems of production management and control. They may be found in every kind of organization: manufacturing, distribution, transportation, mercantile, and service. Their responsibilities range from the design of unit operations to that of controlling complete production and service systems. Their jobs involve the integration of the physical, financial, economic, computer, and human components of such systems to attain specified goals. Industrial engineering includes activities such as production planning and control; quality control; inventory, equipment, warehouse, and materials management; plant layout; and workstation design.

Operations research is concerned with quantitative decision problems, generally involving the allocation and control of limited resources. Such problems arise, for example, in the operations of industrial firms, financial institutions, health care organizations, transportation systems, and government. The operations research analyst develops and uses mathematical and statistical models to help solve these decision problems. Like engineers, they are problem formulators and solvers. Their work requires the formation of a mathematical model of a system and the analysis and prediction of the consequences of alternate modes of operating the system. The analysis may involve mathematical optimization techniques, probabilistic and statistical methods, experiments, and computer simulations.

Management Science and Engineering (also known as Engineering Management Systems) is a multidisciplinary field integrating industrial engineering, operations research, contemporary technology, business, economics, and management. It provides a foundation for decision making and managing risks in complex systems.

Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. The field provides training in the application of engineering methodologies and quantitative methods to finance.

Current Research Activities

In industrial engineering, research is conducted in the area of logistics, routing, scheduling, production and supply chain management, inventory control, revenue management, and quality control.

In operations research, new developments are being explored in mathematical programming, combinatorial optimization, stochastic modeling, computational and mathematical finance, queueing theory, reliability, simulation, and both deterministic and stochastic network flows.

In engineering and management systems, research is conducted in the areas of logistics, supply chain optimization, and revenue and risk management.

In financial engineering, research is being carried out in portfolio management; option pricing, including exotic and real options; computational finance, such as Monte Carlo simulation and numerical methods; as well as data mining and risk management.

Projects are sponsored and supported by leading private firms and government agencies. In addition, our students and faculty are involved in the work of three research and educational centers: the Center for Applied Probability (CAP), the Center for Financial Engineering (CFE), and the Computational and Optimization Research Center (CORC). These centers are supported principally by grants from the National Science Foundation.

The Center for Applied Probability (CAP) is a cooperative center involving the School of Engineering and Applied Science, several departments in the Graduate School of Arts and Sciences, and the Graduate School of Business. Its interests are in four applied areas: mathematical and computational finance, stochastic networks, logistics and distribution, and population dynamics.

The Center for Financial Engineering (CFE) at Columbia University encourages interdisciplinary research in financial engineering and mathematical modeling in finance and promoting collaboration between Columbia faculty and financial institutions, through the organization of research seminars, workshops, and the dissemination of research done by members of the Center.

The Computational Optimization Research Center (CORC) at Columbia University is an interdisciplinary group of researchers from a variety of departments on the Columbia campus. Its permanent members are Professors Daniel Bienstock, Don Goldfarb, Garud Iyengar, Jay Sethuraman, and Cliff Stein, from the Industrial Engineering and Operations Research Department, and Professor David Bayer, from the Department of Mathematics at Barnard College. Researchers at CORC specialize in the design and implementation of state-of-the-art algorithms for the solution of large-scale optimization problems arising from a wide variety of industrial and commercial applications.

BACHELOR OF SCIENCE PROGRAMS

Industrial Engineering

The undergraduate program is designed to develop the technical skills and intellectual discipline needed by our graduates to become leaders in industrial engineering and related professions. The program is distinctive in its emphasis on quantitative, economic, computer-aided approaches to production and service management problems. It is focused on providing an experimental and mathematical problem-formulating and problem-solving framework for industrial engineering work. The curriculum provides a broad foundation in the current ideas, models, and methods of industrial engineering. It also includes a substantial component in the humanities and social sciences to help students understand the societal implications of their work.

The industrial engineering program objectives are:

1. To provide students with the requisite analytical and computational skills to assess practical situations and academic problems, formulate models of the problems represented or embedded therein, design potential solutions, and evaluate their impact;
2. To prepare students for the workplace by fostering their ability to participate in teams, understand and practice interpersonal and organizational behaviors, and communicate their solutions and recommendations effectively through written, oral, and electronic presentations;
3. To familiarize students with the historical development of industrial engineering tools and techniques and with the contemporary state of the art, and to instill the need for lifelong learning within their profession; and
4. To instill in our students an understanding of ethical issues and professional and managerial responsibilities.

Operations Research

The operations research program is one of several applied science programs offered at the School. At the undergraduate level, it offers basic courses in probability, statistics, applied mathematics, simulation, and optimization as well as more professionally oriented operations research courses. The curriculum is well suited for students with an aptitude for mathematics applications.

It prepares graduates for professional employment as operations research analysts, e.g., with management consultant and financial service organizations, as well as for graduate studies in operations research or business. It is flexible enough to be adapted to the needs of future medical and law students.

Operations Research: Engineering Management Systems

This operations research option is designed to provide students with an understanding of contemporary technology and management. It is for students who are interested in a technical-management background rather than one in a traditional engineering field. It consists of required courses in industrial engineering and operations research, economics, business, and computer science, intended to provide a foundation for dealing with engineering and management systems problems. Elective courses are generally intended to provide a substantive core in at least one technology area and at least one management area.

Due to the flexibility of this option, it

INDUSTRIAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	Linear algebra (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Chemistry or physics lab: PHYS C1493 (3) **or** PHYS W3081 (2) **or** CHEM C1500 (3) **or** CHEM C2507 (3) **or** CHEM C3085 (4) **or**	
CHEMISTRY (choose one course)	C1403 (3) **or** C1404 (3) **or** C1604 (3.5) **or** C3045 (3.5)			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	ECON W1105 (4) **and** W1155 recitation (0) either semester		HUMA C1001, COCI C1101, **or** Global core (3–4)	HUMA C1002, COCI C1102, **or** Global core (3–4)
			HUMA W1121 **or** W1123 (3) either semester	
FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS			IEOR E2261 (3)	SIEO W3600 (4)[2]
COMPUTER SCIENCE			COMS W1004 (3) **and** COMS W3134 (3) **or** ENGI E1006 (3) **and** COMS W3136 (3)[3] **or** COMS W1007 (3) **and** COMS W3137 (4)	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] The linear algebra requirement may be filled by either MATH V2010 or APMA E3101.
[2] If taking IEOR E3658, students must take IEOR E4307 to complete the SIEO W3600 requirement.
[3] COMS W3136 will be offered beginning in Spring 2013.

INDUSTRIAL ENGINEERING: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]	MATH E1210 (3) Ordinary diff. equations IEOR E3106 (3) Stochastic models IEOR E3608 (4) Mathematical prog. COMS W4111 (3) Database systems	IEOR E3402 (4) Production planning IEOR E4404 (4) Simulation	IEOR E4003 (3) Industrial econ. IEOR E4207 (3) Human factors IEOR E4205 (3) Studies in operations research	IEOR E4405 (3) Prod. scheduling IEOR E4510 (3) Project management
NONTECH ELECTIVES	Complete 27-point requirement. See page 10 or engineering.columbia.edu for details.			
INDUSTRIAL ENGINEERING ELECTIVES	Choose three (9 pts.): Please consult the list on the departmental website: ieor.columbia.edu			

[1] Taking required courses later than the prescribed semester is not permitted.

OPERATIONS RESEARCH PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	Linear algebra (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Chemistry or physics lab: PHYS C1493 (3) **or** PHYS W3081 (2) **or** CHEM C1500 (3) **or** CHEM C2507 (3) **or** CHEM C3085 (4) **or**	
CHEMISTRY (choose one course)	C1403 (3) **or** C1404 (3) **or** C1604 (3.5) **or** C3045 (3.5)			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	ECON W1105 (4) **and** W1155 recitation (0) either semester		HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4)
			HUMA W1121 **or** W1123 (3) either semester	
FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS			IEOR E2261 (3)	SIEO W3600 (4)[2]
COMPUTER SCIENCE			COMS W1004 (3) **and** COMS W3134 (3) **or** ENGI E1006 (3) **and** COMS W3136 (3)[3] **or** COMS W1007 (3) **and** COMS W3137 (4)	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] The linear algebra requirement may be filled by either MATH V2010 or APMA E3101.
[2] If taking IEOR E3658, students must take IEOR E4307 to complete the SIEO W3600 requirement.
[3] COMS W3136 will be offered beginning in Spring 2013.

OPERATIONS RESEARCH: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]	MATH E1210 (3) Ordinary diff. equations IEOR E3106 (3) Stochastic models IEOR E3608 (4) Mathematical prog. COMS W4111 (3) Database systems	IEOR E3402 (4) Production planning IEOR E4404 (4) Simulation IEOR E4600 (3) Applied integer prog.	IEOR E4003 (3) Industrial econ. IEOR E4407 (3) Game theoretic models of operations	IEOR E4405 (3) Prod. scheduling
			Choose one: IEOR E4505 Operations research for public policy IEOR E4507 Healthcare operations management IEOR E4615 Service engineering IEOR E4700 Introduction to FE	
OPERATIONS RESEARCH ELECTIVES	Choose four OR electives (12 pts. total): Please consult the list on the departmental website: ieor.columbia.edu			
NONTECH ELECTIVES	Complete 27-point requirement. See page 10 or engineering.columbia.edu for details.			

[1] Taking required courses later than the prescribed semester is not permitted.

OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	Linear algebra (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Chemistry or physics lab: PHYS C1493 (3) **or** PHYS W3081 (2) **or** CHEM C1500 (3) **or** CHEM C2507 (3) **or** CHEM C3085 (4) **or**	
CHEMISTRY (choose one course)	C1403 (3) **or** C1404 (3) **or** C1604 (3.5) **or** C3045 (3.5)			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	ECON W1105 (4) **and** W1155 recitation (0) either semester		HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4)
			HUMA W1121 **or** W1123 (3) either semester	
FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS			IEOR E2261 (3)	SIEO W3600 (4)[2]
COMPUTER SCIENCE			COMS W1004 (3) **and** COMS W3134 (3) **or** ENGI E1006 (3) **and** COMS W3136 (3)[3] **or** COMS W1007 (3) **and** COMS W3137 (4)	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] The linear algebra requirement may be filled by either MATH V2010 or APMA E3101.
[2] If taking IEOR E3658, students must take IEOR E4307 to complete the SIEO W3600 requirement.
[3] COMS W3136 will be offered beginning in Spring 2013.

OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]	MATH E1210 (3) Ordinary diff. equations IEOR E3106 (3) Stochastic models IEOR E3608 (4) Mathematical prog. ECON W3211 (3) Microeconomics	IEOR E3402 (4) Production planning ECON W3213 (3) Macroeconomics IEOR E4404 (4) Simulation	IEOR E4003 (3) Industrial econ. COMS W4111 (3) Database systems	Choose one: IEOR E4001 (3) Design and mgmt of prod. and service systems IEOR E4510 (3) Project management
			Choose one: IEOR E4550 Entrepreneurial business creation IEOR E4998 Managing technological innovations	
ELECTIVES: TECH	Technical electives (12 pts. total)[2]			
ELECTIVES: MANAGEMENT	Management electives (9 pts. total): Please consult lists posted on IEOR website: ieor.columbia.edu			
ELECTIVES: NONTECH	Complete 27-point requirement; see page 10 or engineering.columbia.edu for details.			

[1] Taking required courses later than the prescribed semester is not permitted.
[2] At least two technical electives must be chosen from IEOR; the complete list is available at ieor.columbia.edu.

OPERATIONS RESEARCH: FINANCIAL ENGINEERING: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	Linear algebra (3)[1] **and** ODE (3)
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	Physics or chemistry lab: PHYS C1493 (3) **or** PHYS W3081 (2) **or** CHEM C1500 (3) **or** CHEM C2507 (3) **or** CHEM C3085 (4) **or**	
CHEMISTRY (choose one course)	C1403 (3.5) **or** C1404 (3.5) **or** C1604 (3.5) **or** C3045 (3.5)			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	ECON W1105 (4) **and** W1155 recitation (0) either semester		HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4)
			HUMA W1121 **or** W1123 (3) either semester	
FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS			IEOR E2261 (4)	
			IEOR E3658 (3)	IEOR E4307 (3)[2]
COMPUTER SCIENCE			COMS W1004 (3) **and** COMS W3134 (3) **or** ENGI E1006 (3) **and** COMS W3136 (3)[3] **or** COMS W1007 (3) **and** COMS W3137 (4)	
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] The linear algebra requirement may be filled by either MATH V2010 or APMA E3101.
[2] Students may also take STAT W3107 or W4107; however, the department strongly recommends IEOR E4307 in the spring term.

OPERATIONS RESEARCH: FINANCIAL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		ECON W3213 (3) Macroeconomics IEOR E3106 (3) Stochastic models IEOR E3608 (4) Mathematical prog. IEOR E4003 (3) Industrial econ.	IEOR E3402 (4) Production planning IEOR E4404 (4) Simulation IEOR E4700 (3) Intro. to FE COMS W4111 (3) Database systems ECON W3211 (3) Microeconomics	IEOR E4407 (3) Game theoretic models of operations IEOR E4620 (3) Pricing models for FE	IEOR E4630 (3) Asset allocation
				IEOR E4500 (3) Applications prog. for FE ECON E3412 (3) Intro. to econometrics	
ELECTIVES	**FINANCIAL ENGINEERING**	Choose three (9 pts.): Please consult the list on the departmental website: ieor.columbia.edu			
	NONTECH	Complete 27-point requirement; see page 10 or engineering.columbia.edu for details			

can incorporate the varied educational needs of preprofessional students interested in law, medicine, business, and finance. In addition, most students are encouraged to add a minor in economics or computer science to their standard course schedules.

Operations Research: Financial Engineering

The operations research concentration in financial engineering is designed to provide students with an understanding of the application of engineering methodologies and quantitative methods to finance. Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. Students graduating with this concentration are prepared to enter careers in securities, banking, financial management, and consulting industries, and fill quantitative roles in corporate treasury and finance departments of general manufacturing and service firms.

Students who are interested in pursuing the rigorous concentration in financial engineering must demonstrate proficiency in calculus, computer programming, linear algebra, ordinary differential equations, probability, and statistics. Applications to the concentration are accepted during the fall and spring semesters of the sophomore year, and students will be notified of the departmental decision by the end of that spring semester. The department is seeking students who demonstrate strength and consistency in all the above-mentioned areas. Application to this concentration is available online: ieor.columbia.edu /bs-financial-engineering.

Undergraduate Advanced Track

The undergraduate advanced track is designed for advanced undergraduate students with the desire to pursue further higher education after graduation. Students with a minimum cumulative GPA of 3.4 and faculty approval have the opportunity to participate. Students are invited to apply to the track upon the completion of their sophomore year. Advanced track students are required to take higher-level IEOR courses, including the following:

IEOR E4004 instead of *IEOR E3608*
IEOR E4106 instead of *IEOR E3106*
IEOR E4403 instead of *IEOR E4003* and *MATH V2500*

Students successfully completing the requirements of the undergraduate advanced track will receive recognition on their academic record.

Minors

A number of minors are available for students wishing to add them to their programs. These minors are described starting on page 200 of this bulletin.

IEOR program students may want to consider minors in economics or computer science. In addition, operations research and engineering and management systems majors may elect to minor in industrial engineering, and industrial engineering majors may elect to minor in operations research.

The department does not offer a minor in engineering management systems or financial engineering.

MASTER OF SCIENCE PROGRAMS

The Department of Industrial Engineering and Operations Research offers courses and M.S. programs in (1) financial engineering on a full-time basis only; (2) management science and engineering on a full-time basis only; (3) industrial engineering on either a full- or part-time basis; and (4) operations research on either a full- or part-time basis. The Department's M.S. program in Management Science and Engineering is offered in conjunction with the Columbia Graduate School of Business. Lastly, the Department and the Graduate School of Business offer a combined M.S./M.B.A. degree program in industrial engineering.

All degree program applicants are required to take the Aptitude Tests of the Graduate Record Examination (GRE). M.S./M.B.A. candidates are also required to take the Graduate Management Admissions Test (GMAT). A minimum grade-point average of 3.0 (B) or its equivalent in an undergraduate engineering program is required for admission to the M.S. programs. At a minimum, students are expected, on entry, to have completed courses in ordinary differential equations, linear algebra, probability, and a programming language such as C, Java, or Python.

The Department requires that M.S. students achieve grades of B– or higher in each of the fundamental core courses in the discipline of study. Poor performance in core courses is indicative of inadequate preparation and is very likely to lead to serious problems in completing the program. As a result, students failing to meet this criterion may be asked to withdraw.

Courses taken at the School of Continuing Education will not be counted toward the M.S. degree in the IEOR Department (e.g., courses with the following prefixes: ACTU, BUSI, COPR, IKNS, SUMA, FUND, and more). Please consult with your academic adviser regarding electives offered in other departments and schools, prior to registration.

Financial Engineering

The M.S. program in Financial Engineering is offered on a full time basis only. Financial Engineering is intended to provide a unique technical background for students interested in pursuing career opportunities in financial analysis and risk management. In addition to the basic requirements for graduate study, students are expected, on entry, to have attained a high level of mathematical and computer programming skills, particularly in probability, statistics, linear algebra, and the use of a programming language such as C, Python or JAVA. Previous professional experience is highly desirable but not required.

Graduate studies in Financial Engineering consists of 36 points (12 courses), starting the fall semester. Students may complete the program in May, August, or December of the following year. The requirements include six required core courses and additional elective courses chosen from a variety of departments or schools at Columbia. The six required core courses for Financial Engineering are IEOR E4007, E4701, E4703, E4706, E4707, and E4709. In addition, students are required to attend the Financial Engineering Seminar Series and submit learning journals.

Financial Engineering has five concentrations: (1) Computation and Programming; (2) Finance and Economics; (3) Derivatives; (4) Asset Management; and (5) Computational Finance and Trading Systems. A sample schedule is available in the Department office and on the IEOR website: ieor.columbia.edu. Students select electives from a group of specialized offerings in both the fall and spring terms. They may select from a variety of approved electives from the department, the School of Business, and the Graduate School of Arts and Sciences.

Financial Engineering—June or December 2016 Completion (36 points)[1]		
Fall Semester (9 points)[2]	**Spring Semester** (9 points)[2]	**Summer and/or Fall Semester** (For remaining credits)[2]
Required core courses: **IEOR E4007** Optimization models and methods for financial engineering **IEOR E4701** Stochastic models for financial engineering **IEOR E4706** Foundations of financial engineering Plus semi-core electives, 3-6 points [3]	Required core courses: **IEOR E4703** Monte Carlo simulation **IEOR E4707** Continuous time finance **IEOR E4709** Data analysis for financial engineering Plus semi-core electives, 3-6 points [3]	**IEOR E4708** Seminar on important papers in financial engineering **IEOR E4714** (1.5) Risk management, financial systems, and financial crisis **IEOR E4715** Commodity derivatives (1.5) **IEOR E4722** Introduction to algorithmic trading (1.5) **IEOR E4733** Algorithmic trading **IEOR E4734** Foreign exchange and related derivatives instruments (1.5) **IEOR E4735** Introduction to structured and hybrid products

[1] Students may conclude the program in June, August, or December 2016. Please visit the departmental website (ieor.columbia.edu/ms-financial-engineering) for more information.
[2] All courses listed are for 3 points, unless stated otherwise.
[3] The list of semi-core electives can be found at ieor.columbia.edu/ms-financial-engineering

Management Science and Engineering

Management Science and Engineering (MS&E), offered by the IEOR Department in conjunction with Columbia Business School, is the first such program between Columbia Engineering and Columbia Business School. It reflects the next logical step in the longstanding close collaboration between the IEOR Department at the Engineering School and the Decision, Risk, and Operations (DRO) Division at the Business School. Course work emphasize both management and engineering perspectives in solving problems, making decisions, and managing risks in complex systems. Students pursuing this specialization are provided with a rigorous exposure to optimization and stochastic modeling, and a deep coverage of applications in the areas of operations engineering and management.

Graduates of this program are expected to assume positions as analysts and associates in consulting firms, business analysts in logistics, supply chain, operations, or revenue management departments of large corporations, and as financial analysts in various functions (e.g., risk management) of investment banks, hedge funds, credit-card companies, and insurance firms.

Management Science and Engineering (36 points) can be completed in a single calendar year, in three semesters. Students enter in the fall term and can either finish their course work at the end of the following August, or alternatively, have the option to take the summer term off (e.g., for an internship) and complete their course work by the end of the following fall term. Students are required to take the equivalent of 12 3-point courses (36 points).

Students must take at least six courses (18 points) within the IEOR Department, four to six courses at the Business School, and the remaining courses (if any) within the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics. Students in residence during the summer term can take two to four Business School courses in the third (summer) semester in order to complete their program. Additional details regarding these electives are available in the Departmental office and on the MS&E website: mse.ieor.columbia.edu.

Industrial Engineering

Graduate studies in Industrial Engineering enable students with industrial engineering bachelor's degrees to enhance their undergraduate training with studies in special fields such as production planning, inventory control, scheduling, and industrial economics. However, the department also offers a broader master's program for engineers whose undergraduate training is not in industrial engineering. Students may complete the studies on a full-time (12 points per term) or part-time basis.

Industrial Engineers are required to satisfy a core program of graduate courses in production management, probability theory, statistics, simulation, and operations research. Students with B.S. degrees in industrial engineering will usually have satisfied this core in their undergraduate programs. All students must take at least 18 points of graduate work in industrial engineering and at least 30 points of graduate studies at Columbia. Industrial Engineering may include concentrations in: (1) industrial regulation studies and (2) systems engineering. Additional details regarding these concentrations and electives are available in the Departmental office and on IEOR website: ieor.columbia.edu.

Operations Research

Graduate studies in Operations Research enables students to concentrate their studies in methodological areas such as mathematical programming, stochastic models, and simulation. Students may complete the studies on a full time (12 points per term) or part time basis.

Students are required to satisfy a core set of graduate courses in probability, statistics, linear programming, and simulation. All students must complete at least 18 points of operations research courses and at least 30 points of graduate work at Columbia. The Department considers it desirable that students construct balanced programs involving deterministic and stochastic models, as well as substantive areas for application.

Operations Research has five areas of concentrations including: (1) applied probability; (2) business analytics; (3) financial and managerial applications of operations research; (4) logistics and supply chain management and (5) optimization. Students may select from a variety of approved electives from the Department, the School of Business, and the Graduate School of Arts and Sciences. Additional details regarding these concentrations and electives are available in the Departmental office and on IEOR website: ieor.columbia.edu.

JOINT M.S. AND M.B.A.

The department and the Graduate School of Business offer a joint M.S. master's program in Industrial Engineering. Prospective students for this special program must submit separate applications to Columbia Engineering and the Graduate School of Business and be admitted to both schools for entrance into the joint program.

Admissions requirements are the same as those for the regular M.S. program in Industrial Engineering and for the M.B.A. This joint program is coordinated so that both degrees can be obtained after five terms of full-time study (30 points in two terms while registered in Columbia Engineering and 45 points in three terms while registered in the Graduate School of Business).

Students in the joint program must complete certain courses by the end of

Management Science and Engineering (36 points)	
Required Core Courses *(12)*	**IEOR E4004** Intro to OR: deterministic models (first fall semester) **IEOR E4111** Operations consulting (starts first fall semester, all-year course) **IEOR E4101** Probability models for management science and engineering (first fall semester) **IEOR E4102** Stochastic models for management science and engineering (spring semester) Plus Semi-Core Courses (DRO, Analysis, and Management Electives (18)
Decision, Risk, and Operations Electives (9)	**DROM B8106-060** Operations strategy (1.5) (summer—second half) **DROM B8107-060** Service operations (fall semester) **DROM B8108-060** Supply chain management (spring semester) **DROM B8111-060** Analytics for business research (1.5) (summer—second half) **DROM B8122-060** MSE game-theoretic business strategy (spring semester) **DROM B9106-001** Applied multivariate statistics (summer) **DROM B9122-001** Computing for business research (fall semester) **DROM B8510-060** Managerial negotiations (with game theoretical analysis) (fall and spring semester) **MRKT B8617-001** Marketing research (summer)
Analysis and Management Electives (9) *Management Group* *At least one of the following:*	**ECON W4280** Corporate finance (by application, fall and spring semester) **IEME E4310** The manufacturing enterprise (fall semester) **IEOR E4205** Studies in operations research (fall or spring semester) **IEOR E4505** Operations research in public policy (spring semester) **IEOR E4510** Project management (spring semester) **IEOR E4520** Applied systems engineering (fall semester) **IEOR E4521** Systems engineering tools and methods **IEOR E4550** Entrepreneurial business creation for engineers (fall or spring semester) **IEOR E4560** Lean LaunchPad (weeklong course in mid-January, by application only) **IEOR E4573** Design and Agile Project Management Engineerng Lab (fall semester) **IEOR E4711** Global capital markets (fall semester) **IEOR E4998** Managing technological innovation and entrepreneurship (fall or spring semester) **FINC B8307** Advanced corporate finance (spring semester)
Analysis and Management Electives (9) *Analysis Group* *At least one of the following:*	**IEOR E4000** Production and operations management (fall semester) **IEOR E4403** Advanced engineering and corporate economics (fall semester) **IEOR E4404** Simulation (fall or spring semester) **IEOR E4405** Production scheduling (spring semester) **IEOR E4407** Game theoretic models of operations (fall semester) **IEOR E4418** Logistics and transportation management (spring semester) **IEOR E4507** Operations management: with application to healthcare management (fall semester) **IEOR E4570** Machine learning for OR and FE (spring semester) **IEOR E4601** Dynamic pricing and revenue optimization (spring semester) **IEOR E4611** Decision models and applications (spring semester) **IEOR E4615** Service engineering (spring semester)
Breadth Electives: The breadth electives can be selected from the Business School, the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics.	

<table>
<tr><th colspan="4">Operations Research (30 points)</th></tr>
<tr><td>Required Core Courses
(12 points)</td><td colspan="3">SIEO W4150 Intro to probability and statistics
IEOR E4106 Intro to OR: stochastic models
IEOR E4004 Intro to OR: deterministic models
IEOR E4404 Simulation</td></tr>
<tr><th colspan="4">ELECTIVES FOR CONCENTRATION</th></tr>
<tr><td>Applied Probability
The department recommends taking at least three of the following elective courses:</td><td colspan="3">IEOR E4000 Production and operations management
IEOR E4407 Game theoretic models of operation
IEOR E4602 Quantitative risk management
DROM B8108 Supply chain management
IEOR E4210 Supply chain management
IEOR E4601 Dynamic pricing and revenue management
IEOR E4700 Intro to financial engineering
DROM B8123 Demand and supply analytics</td></tr>
<tr><td rowspan="2">Business Analytics
The department recommends taking:</td><td colspan="2">Technical Courses</td><td>Management Courses</td></tr>
<tr><td colspan="2">IEOR E4525 Machine learning for OR and FE and
IEOR E4574 Business Analytics for Operations Research
At least two of:
IEOR E4000 Production and operations management
IEOR E4307 Applied statistical models in operations research
IEOR E4500 Applications programming for financial engineering
IEOR E4521 Systems engineering tools and methods
IEOR E4570 Data mining
IEOR E4736 Experimental finance
DROM B8123 Demand and supply analytics
DROM B9122 Computing for business research</td><td>At least two of:
IEOR E4205 Studies in operations research
IEOR E4408 Resources allocation: models, algorithms, and applications
IEOR E4510 Project management
IEOR E4520 Applied systems engineering
IEOR E4550 Entrepreneurial business creation for engineers
IEOR E4560 The Lean Launchpad
IEOR E4561 Dynamic pricing and revenue management
IEOR E4611 Decision models and applications
IEOR E4998 Managing technological innovation and entrepreneurship</td></tr>
<tr><td rowspan="2">Financial and Managerial Applications
The department recommends taking:</td><td>Corporate Finance Courses</td><td>Derivatives Pricing Courses</td><td>Management Courses</td></tr>
<tr><td>IEOR E4403 Adv. engineering and corporate economics

And at least one of:
IEOR E4711 Global capital market
FINC B8307 Advanced corporate finance
ECON W4280 Corporate finance
or INAF U6022 Economics of finance
IEOR E4734 Foreign exchange and related derivatives instruments
IEOR E4735 Introduction to structured and hybrid products</td><td>IEOR E4700 Intro to financial engineering

And at least one of:
IEOR E4602 Quantitative risk management
IEOR E4620 Pricing models
IEOR E4630 Asset allocation
IEOR E4731 Credit risk and credit derivatives
DRAN B8835 Quantitative finance: models and computation</td><td>At least one of:
IEOR E4205 Studies in operations research
IEOR E4505 OR in public policy
IEOR E4507 Healthcare operations management
IEOR E4510 Project management
IEOR E4550 Entrepreneurial business creation for engineers
IEOR E4611 Decision models and applications
IEOR E4998 Managing technological innovation</td></tr>
<tr><td rowspan="2">Logistics and Supply Chain Management
The department recommends taking:</td><td colspan="2">Technical Courses</td><td>Management Courses</td></tr>
<tr><td colspan="2">At least three of:
IEOR E4000 Production and operations management
IEOR E4403 Adv. engineering and corporate economics
IEOR E4405 Production scheduling
IEOR E4418 Logistics and transport management
IEOR E4505 OR in public policy
IEOR E4507 Healthcare operations management
IEOR E4525 Machine learning for OR and FE
IEOR E4600 Applied integer programming
IEOR E4601 Dynamic pricing and revenue management
IEOR E4602 Quantitative risk management
IEOR E4615 Service engineering
DROM B8107 Service operations management
DROM B8108 Supply chain management
DROM B8123 Demand and supply analytics</td><td>At least two of:
IEOR E4205 Studies in operations research
IEME E4310 The manufacturing enterprise
IEOR E4408 Resource allocation: models, algorithms and applications
IEOR E4412 Quality control
IEOR E4510 Project management
IEOR E4520 Applied systems engineering
IEOR E4550 Entrepreneurial business creation for engineers
IEOR E4611 Decision models and applications
IEOR E4998 Managing technological innovation</td></tr>
</table>

Operations Research (30 points)		
Optimization The department recommends taking at least three of the following elective courses:	**IEOR E4000** Production and operations management **IEOR E4205** Studies in operations research **IEOR E4408** Resource allocation: models, algorithms and applications **IEOR E4418** Logistics and transportation management **IEOR E4507** Healthcare operations management **IEOR E4520** Applied systems engineering **IEOR E4521** Systems engineering tools and methods **IEOR E4611** Decision models and applications **IEOR E4630** Asset allocation	**IEOR E4405** Production scheduling **IEOR E4505** Operations research in public policy **IEOR E4510** Project management **IEOR E4600** Applied integer programming **IEOR E4615** Service engineering **DROM B8107** Service operations management **DROM B8108** Supply chain management

their first year of study. If a substantial equivalent has been completed during undergraduate studies, students should consult with a faculty adviser in order to obtain exemption from a required course.

Ph.D. Program

The IEOR Department offers two Ph.D. programs in (1) Industrial Engineering; and (2) Operations Research. The requirements for the Ph.D. in industrial engineering and operations research are identical. Both programs require the student to complete the qualifying procedure and submit and defend a dissertation based on the candidate's original research, conducted under the supervision of the faculty. The dissertation work may be theoretical or computational or both.

The qualifying procedure consists of three components, including: (1) complete the four Ph.D. core courses during the first year with at most one grade of (B+) or worse; (2) conduct research during the first summer, and give a talk based on this research at the beginning of the third semester; and (3) submit a research paper at the end of the third semester. Students in the doctoral programs are reviewed by the Ph.D. committee after each of the three components. A student who fails to complete component (1) may be asked to withdraw from the Ph.D. program at the end of the first year. A student who successfully completes component (1) will typically move on to conduct research during the first summer under the advisement by a faculty member in the Department. In the rare instance the Ph.D. committee is not satisfied with a student's performance in components (2) and (3), they may be asked to withdraw from the program at the end of the second year.

Doctoral students are also required to select a concentration for their studies and complete a certain amount of course work in one of the following fields: applied probability, mathematical programming, financial engineering, or supply chain management and logistics. Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor's degree. A master's degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master's degree must be earned while in residence in the doctoral program. Detailed information regarding the requirements for the doctoral degree may be obtained in the Department office and on IEOR website: ieor.columbia.edu.

COURSES IN INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

For up-to-date course offerings, please visit ieor.columbia.edu.

IEOR E2261x and y Introduction to accounting and finance
3 pts. Lect: 3. Professor Webster.
Prerequisite: ECON W1105 Principles of economics. For undergraduates only. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This course examines the fundamental concepts of financial accounting and finance, from the perspective of both managers and investors. Key topics covered include: principles of accrual accounting; recognizing and recording accounting transactions; preparation and analysis of financial statements; ratio analysis; pro-forma projections; time value of money (present values, future values and interest/discount rates); inflation; discounted-cash-flow (DCF) project evaluation methods; deterministic and probabilistic measures of risk; capital budgeting.

IEOR E3106x Introduction to operations research: stochastic models
3 pts. Lect: 3. Professor Olvera.
Prerequisite: SIEO W3600. For undergraduates only. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This class must be taken during (or before) the fifth semester. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queueing, reliability, inventory, and finance. IEOR E3106 must be completed by the fifth term. Only students with special academic circumstances may be allowed to take these courses in alternative semesters with the consultation of CSA and Departmental advisers.

IEOR E3402y Production inventory planning and control
4 pts. Lect: 3. Recit: 1. Professor Truong.
Prerequisites: SIEO W3600 Probability and Statistics and IEOR E3608 Introduction to OR: Mathematical programming. For undergraduates only. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This class must be taken during (or before) the sixth semester. Inventory management and production planning. Continuous and periodic review models: optimal policies and heuristic solutions, deterministic and probabilistic demands. Material requirements planning. Aggregate planning of production, inventory, and work force. Multi-echelon integrated production-inventory systems. Production scheduling. Term project. Recitation section required.

SIEO W3600y Introduction to probability and statistics
4 pts. Lect: 3. Recit: 1. Professor Dieker.
Prerequisite: Calculus. For undergraduates only. This course is required for undergraduate students majoring in IE, OR:EMS, and OR. This class must be taken during the fourth semester. Fundamentals of probability and statistics used in engineering and applied science. Probability: random variables, useful distributions, expectations, law of large numbers, central limit theorem. Statistics: point and confidence interval estimation, hypothesis tests, linear regression. SIEO W3600 must be completed

by the fourth term. Only students with special academic circumstances may be allowed to take these courses in alternative semesters with the consultation of CSA and Departmental advisers. Recitation section required.

IEOR E3608x Introduction to mathematical programming
4 pts. Lect: 3. Recit: 1. Professor Sethuraman.
Prerequisite: MATH V2010 Linear algebra. Corequisite: COMS W3134 (or COMS W3137 Data structures). For undergraduates only. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This class must be taken during (or before) the fifth semester. Introduction to mathematical programming models and computational techniques. Linear programming and the simplex method, dynamic programming, implicit enumeration for integer programs; production planning applications. IEOR E3608 must be completed by the fifth term. Only students with special academic circumstances may be allowed to take these courses in alternative semesters with the consultation of CSA and Departmental advisers. Recitation section required.

IEOR E3658x Probability
3 pts. Lect: 3. Professor Olvera.
Prerequisite: Calculus. For undergraduates only. This course is required for the OR:FE concentration. This class must be taken during (or before) the third semester. Fundamentals of probability theory. Distributions of one or more random variables. Moments, generating functions, law of large numbers and central limit theorem.

IEOR E3900x and y Undergraduate research or project
1–3 pts. Members of the faculty.
Prerequisite: Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

IEOR E4000x Production and operations management
3 pts. Lect: 3. Professor Gallego.
Prerequisites or Corequisite: Probability theory and linear programming. Required course for MSIE. An introduction to production management for students not having an industrial engineering bachelor's degree. Topics include deterministic inventory models, aggregate production planning, material requirements planning, forecasting, stochastic inventory models and supply chain management. Emphasis is on modeling and its implications for managerial decisions.

IEOR E4001y Design and management of production and service systems
3 pts. Lect: 3. Professor Riccio.
Prerequisite: IEOR E4000 or E3402. This course is required for undergraduate students majoring in OR:EMS. Design and management problems in production and service systems: process design and capacity management, inventory system design and management, aggregate planning, staff scheduling, and quality control system design.

IEOR E4003x Industrial economics
3 pts. Lect: 3. Professor Song.
Prerequisites or corequisites: Probability theory and linear programming. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Introduction to the economic evaluation of industrial projects. Economic equivalence and criteria. Deterministic approaches to economic analysis. Multiple projects and constraints. Analysis and choice under risk and uncertainty.

IEOR E4004x and y Introduction to operations research: deterministic models
3 pts. Lect: 3. Professors Agrawal, Bienstock, and Goldfarb
This graduate course is only for MS&E, IE, and OR students. This is also required for students in the Undergraduate Advanced Track. For students who have not studied linear programming. Some of the main methods used in IEOR applications involving deterministic models: linear programming, the simplex method, nonlinear, integer and dynamic programming.

IEOR E4007x Optimization models and methods for financial engineering
3 pts. Lect: 3. Professor Iyengar.
Prerequisite: Linear algebra. This graduate course is only for M.S. Program in Financial Engineering students. Linear, quadratic, nonlinear, dynamic, and stochastic programming. Some discrete optimization techniques will also be introduced. The theory underlying the various optimization methods is covered. The emphasis is on modeling and the choice of appropriate optimization methods. Applications from financial engineering are discussed.

CSOR E4010y Graph theory: a combinatorial view
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Linear algebra, or instructor's permission. An introductory course in graph theory with emphasis on its combinatorial aspects. Basic definitions, and some fundamental topics in graph theory and its applications. Topics include trees and forests graph coloring, connectivity, matching theory and others.

IEOR E4101x Probability models for MSE
1.5 pts. Lect: 2.5. Professor Zhong.
Prerequisites: Understanding of single- and multivariable calculus. Basic probability theory, including independence and conditioning, discrete and continuous random variable, law of large numbers, central limit theorem, and stochastic simulation, basic statistics, including point and interval estimation, hypothesis testing, and regression; examples from business applications such as inventory management, medical treatments, and finance. This course is a specialized version of SIEO W4150 for MSE students.

IEOR E4102y Stochastic models for MSE
3 pts. Lect: 2.5. Professor Sigman.
Prerequisite: IEOR E4101. Introduction to stochastic processes and models, with emphasis on applications to engineering and management; random walks, gambler's ruin problem, Markov chains in both discrete and continuous time, Poisson processes, renewal processes, stopping times, Wald's equation, binomial lattice model for pricing risky assets, simple option pricing; simulation of simple stochastic processes, Brownian motion, and geometric Browninan motion. This course is a specialized version of IEOR E4106 for MSE students.

IEOR E4106x and y Introduction to operations research: stochastic models
3 pts. Lect: 3. Professors Olvera and Yao.
Prerequisites: SIEO W4150 or probability theory. This graduate course is only for MS&E, IE, and OR students. This is also required for students in the Undergraduate Advanced Track. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queueing, reliability, inventory, and finance.

SIEO W4150x Introduction to probability and statistics
3 pts. Lect: 3. Professor Dieker.
Prerequisite: Calculus. Fundamentals of probability theory and statistical inference used in engineering and applied science. Probabilistic models, random variables, useful distributions, expectations, law of large numbers, central limit theorem. Statistical inference: point and confidence interval estimation, hypothesis tests, linear regression.

IEOR E4205x and y Studies in operations research
3 pts. Lect: 3. Professor Riccio.
Prerequisites: IEOR E3608 or E4004, and IEOR E3106 or E4106, or instructor's permission. Applications of operations research models in practice; examples of successful projects; discussion of difficulties in applying operations research techniques in practice; understanding the factors leading to successful applications. Students will be required to do a project that may involve the following: project management and budgeting, contract preparation, change-order negotiations, progress reporting, organizational and personal dynamics, client communications and relationships, and presentation skills.

IEOR E4207x Human factors: performance
3 pts. Lect: 3. Professor Gold.
This course is required for undergraduate students majoring in IE. Sensory and cognitive (brain) processing considerations in the design, development, and operations of systems, products, and tools. User or operator limits and potential in sensing, perceiving decision making, movement coordination, memory, and motivation.

IEOR E4208y Seminar in human factors design
3 pts. Lect: 3. Professor Gold.
Prerequisite: IEOR E4207 or instructor's permission. This course is an elective undergraduate students majoring in IE. An in-depth exploration of the application potential of human factor principles for the design of products and

processes. Applications to industrial products, tools, layouts, workplaces, and computer displays. Consideration to environmental factors, training and documentation. Term project.

DROM B8108/IEOR E4210y Supply chain management
3 pts. Lect: 3. Members of the faculty.
Prerequisite: IEOR E3402, E4000, or permission of instructor. This is a IE elective for undergraduate students majoring in IE. Major issues in supply chain management, including, definition of a supply chain; role of inventory; supply contracts; bullwhip effect and information sharing; vendor-managed inventories and other distribution strategies; third-party logistics providers; managing product variety; information technology and supply chain management; international issues. Emphasis on quantitative models and analysis.

IEOR E4211x and y Applied consulting
3 pts. Lect: 2.5. Professor Herman.
Prerequisites: Probability at the level of SIEO W3600 or W4150, familiarity with R or SAS. Basic and advanced techniques in commercial and government consulting. Case studies supported by lectures focused on collecting and analyzing skills, client/market data, client interview techniques, and application of quantitative and qualitative methodologies. Exposure to critical skills on workplan development, interview techniques, presentation deck preparation, costing, and application of analytic techniques to solve complex problems.

DROM B8123/IEOR E4220y Demand and supply analytics
3 pts. Lect: 3. Members of the faculty.
Prerequisites: IEOR E4004 (or E3608), IEOR E4106 (or E3608). Tools to efficiently manage supply and demand networks. Topics include service and inventory trade-offs, stock allocation, pricing, markdown management and contracts, timely product distribution to market while avoiding excess inventory, allocating adequate resources to the most profitable products and selling the right product to the right customer at the right price and at the right time.

IEOR E4307y Applied statistical models in operations research
3 pts. Lect: 3. Professor Dieker.
Prerequisites: probability, linear algebra. Descriptive statistics, central limit theorem, parameter estimation, sufficient statistics, hypothesis testing, regression, logistic regression, goodness-of-fit tests, applications to operations research models.

IEME E4310x The manufacturing enterprise
3 pts. Lect: 3. Professor Weinig.
The strategies and technologies of global manufacturing and service enterprises. Connections between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

IEOR E4403x Advanced engineering and corporate economics
3 pts. Lect: 3. Professor Mohebbi.
Prerequisites: Probability theory and linear programming This course is required for students in the Undergraduate Advanced Track. Key measures and analytical tools to assess the financial performance of a firm and perform the economic evaluation of industrial projects. Deterministic mathematical programming models for capital budgeting. Concepts in utility theory, game theory and real options analysis.

IEOR E4404x and y Simulation
4 pts. Lect: 3. Recit: 1. Professors Sigman and Zhong.
Prerequisites: SIEO W3600 or SIEO W4150, computer programming. Corequisite: IEOR E3106 or IEOR E4106. This course is required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This course is also required for MSIE and MSOR. Generation of random numbers from given distributions; variance reduction; statistical output analysis; introduction to simulation languages; application to financial, telecommunications, computer, and production systems. Graduate students must register for 3 points. Undergraduate students must register for 4 points. NOTE: Students who have taken IEOR E4703 Monte Carlo simulation may not register for this course for credit. Recitation section required.

IEOR E4405y Production scheduling
3 pts. Lect: 3. Professor Stein.
Prerequisites: SIEO W3600, IEOR E3608, computer programming. This course is required for undergraduate students majoring in IE and OR. Job shop scheduling: parallel machines, machines in series; arbitrary job shops. Algorithms, complexity, and worst-case analysis. Effects of randomness: machine breakdowns, random processing time. Term project.

IEOR E4407x Game theoretic models of operations
3 pts. Lect: 3. Professor Sethuraman.
Prerequisites: IEOR E4004 (or E3608), IEOR E4106 (or E3106), familiarity with differential equations and computer programming; or instructor's permission. This course is required for undergraduate students majoring in OR:FE and OR. A mathematically rigorous study of game theory and auctions, and their application to operations management. Topics include introductory game theory, private value auction, revenue equivalence, mechanism design, optimal auction, multiple-unit auctions, combinatorial auctions, incentives, and supply chain coordination with contracts. No previous knowledge of game theory is required.

IEOR E4408x Resource allocation: models, algorithms, and applications
3 pts. Lect: 3. Professor Luss.
Prerequisites: Linear programming (IEOR E3608 or E4004), basic knowledge of nonlinear and integer programming. Overview of resource allocation models. Single resource allocation with concave returns; equitable resource allocation; lexicographic minmax/maxmin optimization; extensions to substitutable resources; multi-period resource allocation; equitable allocation in multicommodity network flow models; equitable content distribution in networks; equitable resource allocation with discrete decision variables.

IEOR E4412y Quality control and management
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: SIEO W3600 or W4150. This course is required for undergraduate students majoring in IE. Statistical methods for quality control and improvement: graphical methods, introduction to experimental design and reliability engineering and the relationships between quality and productivity. Contemporary methods used by manufacturing and service organizations in product and process design, production and delivery of products and services.

IEOR E4418y Logistics and transportation management
3 pts. Lect: 3. Professor Truong.
Prerequisite: IEOR E3608 or E4404 or permission of instructor. Introduces quantitative techniques and state-of-the-art practice of operations research relevant to the design and both the tactical and strategic management of logistical and transportation systems. Discusses a wide variety of passenger and freight systems, including air, urban and highway traffic, rail, and maritime systems. Explores the practice of revenue management and dynamic pricing. Through case studies, analyzes successes and failures in third-party logistics, postal, truck and rail pickup and delivery systems. Investigates large-scale integrated logistics and transportation systems and studies the underlying principles governing transportation planning, investment and operations.

IEOR E4500x Applications programming for financial engineering
3 pts. Lect: 3. Professor Bienstock.
Prerequisite: Computer programming or instructor's approval. This course is required for undergraduate students majoring in OR:FE. In this course we will take a hands-on approach to developing computer applications for Financial Engineering. Special focus will be placed on high-performance numerical applications that interact with a graphical interface. In the course of developing such applications we will learn how to create DLLs, how to integrate VBA with C/C++ programs, and how to write multithreaded programs. Examples of problems settings that we consider include simulation of stock price evolution, tracking, evaluation and optimization of a stock portfolio; optimal trade execution. In the course of developing these applications, we review topics of interest to OR:FE in a holistic fashion.

IEOR E4507y Healthcare operations management
3 pts. Lect: 3. Professor Truong.
Prerequisite(s): for senior undergraduate Engineering students: SIEO W3600 and IEOR E3608; for Engineering graduate students (M.S. or Ph.D.): Probability and statistics at the level of SIEO W4150, and deterministic models at the level of IEOR E4004; for Healthcare Management students: P8529 Analytical methods for health services management. Analytic methods for health services management. Develops modeling, analytical, and managerial skills of Engineering and Healthcare Management students. Enables students to master an array of fundamental Operations Management tools adapted to the management of healthcare systems. Through real-world business cases, students learn to identify, model, and analyze operational improvements and innovations in a range of healthcare contexts.

IEOR E4510y Project management
3 pts. Lect: 3. Professor Rosenwein.
Prerequisites: IEOR E4004 (or IEOR E3608). Management of complex projects and the tools that are available to assist managers with such projects. Topics include: project selection, project teams and organizational issues, project monitoring and control, project risk management, project resource management, and managing multiple projects.

IEOR E4520y Applied systems engineering
3 pts. Lect: 3. Professor Jahangir.
Prerequisites: B.S. in engineering or applied sciences; professional experience recommended; Calculus, Probability and Statistics, Linear Algebra. Introduction to fundamental methods used in Systems Engineering. Rigorous process that translates customer needs into a structured set of specific requirements; synthesizes a system architecture that satisfies those requirements and allocates them in a physical system, meeting cost, schedule, and performance objectives throughout the product life-cycle. Sophisticated modeling of requirements optimization and dependencies, risk management, probabilistic scenario scheduling, verification matrices, and systems-of-systems constructs are synthesized to define the meta-workflow at the top of every major engineering project.

IEOR E4521x or y Systems engineering tools and methods
3 pts. Lect: 2.5. Professor Jahangir.
Prerequisites: B.S. in engineering or applied sciences; probability and statistics, optimization, linear algebra, and basic economics. Applications of SE tools and methods in various settings. Encompasses modern complex system development environments, including aerospace and defense, transportation, energy, communications, and modern software-intensive systems.

IEOR E4530x and y Operations research in telecommunications
3 pts. Lect: 2.5. Not offered in 2015–2016.
Prerequisites: IEOR E3608 or E4004 and E3106 or E4106. Operations research models and algorithms to solve diverse, contemporary problems in the telecommunications industry, including routing and design of core networks with an emphasis on IP and optical networks. Exploration of various robust network design methods to survive any failure, including shared mesh restoration, ring networks, and p-cycles.

IEOR E4550x and y Entrepreneurial business creation for engineers
3 pts. Lect: 3. Professor Gulley.
Prerequisite: ENGI W2261. This course is required for undergraduate students majoring in OR:EMS. Introduces the basic concepts and methodologies that are used by the nonengineering part of the world in creating, funding, investing in, relating to, and operating entrepreneurial ventures. The first half of the course focuses on the underpinning principles and skills required in recognizing, analyzing, evaluating, and nurturing a business idea. The second half focuses on basic legal knowledge necessary in creating a business entity, defending your business assets, and in promoting effective interaction with other individuals and organizations.

IEOR E4573x Topics in operations research: Design and Agile Project Management Engineering Lab (DAPME-Lab)
3 pts. Professor Farrokhnia.
Intensive project-based seminar with emphasis on multidisciplinary approach to front-end product design, strategy formulation, implementation, and agile application of tech-driven concepts in actual business settings. Focus on practical development and execution of inventive design-centric solutions coupled with deep industrial, operational, and business analyses. Topics include industrial product and web design, UX and UI, Scrum, Kanban, and the dynamics of entrepreneurial/venture-capital financing relevant to technical (co-)founders. Guest speakers, field trips, and interaction with domain experts. Projects include work with a Fortune 500 corporation and an entrepreneurial portfolio company. Social good project of a New York–based small or not-for-profit business. Best practices in lean start-ups, product development, team management, and business planning. Product Design Sprint and Agile Development, working on all aspects of exploration, ideation, design, refinement, prototype buildup, and validation. Simultaneous work on engineering and tech-driven briefs (including field-testing) addressing real life business challenges. Limited enrollment by application: requires signing of Non-Disclosure Agreement for class projects. Proficiency in math, statistics, coding, and/or database management/analysis recommended.

IEOR E4577y Intellectual property for entrepreneurs and managers
0 pts. Lect: 3. Professors Orin and Sears.
An overview of commercial opportunities in intellectual property, with a focus on technology patents for the business or tech entrepreneur.

IEOR E4600y Applied integer programming
3 pts. Lect: 3. Professor Goyal.
Prerequisites: Linear programming, linear algebra, and computer programming. This course is required for undergraduate students majoring in OR. Applications of mathematical programming techniques, especially integer programming, with emphasis on software implementation. Typical applications: capacity expansion, network design, and scheduling.

IEOR E4601y Dynamic pricing and revenue management
3 pts. Lect: 3. Professor Goyal.
Prerequisites: SIEO W4150 and IEOR E4004. Focus on capacity allocation, dynamic pricing and revenue management. Perishable and/or limited product and pricing implications. Applications to various industries including service, airlines, hotel, resource rentals, etc.

IEOR E4602y Quantitative risk management
3 pts. Lect: 3. Professor Haugh.
Prerequisites: SIEO W4150 and IEOR E4106. Risk management models and tools; measure risk using statistical and stochastic methods, hedging and diversification. Examples include insurance risk, financial risk, and operational risk. Topics covered include VaR, estimating rare events, extreme value analysis, time series estimation of extremal events; axioms of risk measures, hedging using financial options, credit risk modeling, and various insurance risk models.

IEOR E4611y Decision models and applications
3 pts. Lect: 3. Professor Webster.
Prerequisites: For undergraduates: SIEO W3600/SIEO W4150 or equivalent and IEOR E3608/IEOR E4004 or equivalent. For graduate students: Instructor's permission required. Corequisite: IEOR E4404 or equivalent. Introduction to deterministic and stochastic decision tools used by leading corporations and applied researchers. Real-world problems in engineering and finance are discussed.

IEOR E4615y Service engineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite(s): Introductory courses in probability and statistics such as SIEO W3600, and introductory courses in stochastic processes such as IEOR E3106 or IEOR E4106. Focus on service systems viewed as stochastic networks, exploiting the theoretical framework of queueing theory. Includes multidisciplinary perspectives involving Statistics, Psychology, and Marketing. Significant emphasis on data analysis, exploiting data from banks, hospitals, and call centers to demonstrate the use of decision support tools. Analytical models, flow models of service networks, Little's law, measuring methods in face-to-face and

computerized systems, forecasting methods, stability of service systems, operational quality of service, economies of scale, staffing, complex service networks, skill-based routing.

IEOR E4620x Pricing models for financial engineering
3 pts. Lect: 3. Professor DeRosa.
Prerequisite: IEOR E4700. This course is required for undergraduate students majoring in OR:FE. Characteristics of commodities or credit derivatives. Case study and pricing of structures and products. Topics covered include swaps, credit derivatives, single tranche CDO, hedging, convertible arbitrage, FX, leverage leases, debt markets, and commodities.

IEOR E4630y Asset allocation
3 pts. Lect: 3. Members of the faculty.
Prerequisite: IEOR E4700. Models for pricing and hedging equity, fixed-income, credit-derivative securities, standard tools for hedging and risk management, models and theoretical foundations for pricing equity options (standard European, American equity options, Asian options), standard Black-Scholes model (with multiasset extension), asset allocation, portfolio optimization, investments over longtime horizons, and pricing of fixed-income derivatives (Ho-Lee, Black-Derman-Toy, Heath-Jarrow-Morton interest rate model).

IEOR E4700x and y Introduction to financial engineering
3 pts. Lect: 3. Professors Derman and Yao.
Prerequisite: IEOR E4106 or E3106. This course is required for undergraduate students majoring in OR:FE. Introduction to investment and financial instruments via portfolio theory and derivative securities, using basic operations research/engineering methodology. Portfolio theory, arbitrage; Markowitz model, market equilibrium, and the capital asset pricing model. General models for asset price fluctuations in discrete and continuous time. Elementary introduction to Brownian motion and geometric Brownian motion. Option theory; Black-Scholes equation and call option formula. Computational methods such as Monte Carlo simulation.

IEOR E4701 Stochastic models for financial engineering
3 pts. Lect: 3. Professor Blanchet.
Prerequisite: SIEO W4105. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Review of elements of probability theory, Poisson processes, exponential distribution, renewal theory, Wald's equation. Introduction to discrete-time Markov chains and applications to queueing theory, inventory models, branching processes.

IEOR E4703y Monte Carlo simulation
3 pts. Lect: 3. Professor Leung.
Prerequisite: IEOR E4701. This graduate course is only for M.S. Program in Financial Engineering students. Multivariate random number generation, bootstrapping, Monte Carlo simulation, efficiency improvement techniques. Simulation output analysis, Markov-chain Monte Carlo. Applications to financial engineering. Introduction to financial engineering simulation software and exposure to modeling with real financial data. NOTE: Students who have taken IEOR E4404 Simulation may not register for this course for credit.

IEOR E4706 Foundations of financial engineering
3 pts. Lect: 3. Professor Haugh.
Prerequisites: IEOR E4701, E4702, and linear algebra. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Discrete-time models of equity, bond, credit, and foreign-exchange markets. Introduction to derivative markets. Pricing and hedging of derivative securities. Complete and incomplete markets. Introduction to portfolio optimization and the capital asset pricing model.

IEOR E4707y Financial engineering: continuous-time asset pricing
3 pts. Lect: 3. Professor Capponi.
Prerequisites: IEOR E4701. This graduate course is only for MS program in FE students. Modeling, analysis, and computation of derivative securities. Applications of stochastic calculus and stochastic differential equations. Numerical techniques: finite-difference, binomial method, and Monte Carlo.

IEOR E4708y Seminar on important papers in financial engineering
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: IEOR E4703, E4706, probability and statistics. Selected topics of special interest to M.S. students in financial engineering. If topics are different then this course can be taken more than once for credit.

IEOR E4709y Data analysis for financial engineering
3 pts. Lect: 3. Professor Leung.
Prerequisites: Probability and IEOR E4702. Corequisites: IEOR E4706, E4707. This graduate course is only for M.S. Program in Financial Engineering students. Empirical analysis of asset prices: heavy tails, test of the predictability of stock returns. Financial time series: ARMA, stochastic volatility, and GARCH models. Regression models: linear regression and test of CAPM, nonlinear regression and fitting of term structures.

IEOR E4710x Term structure models
3 pts. Lect: 3. Professor He.
Prerequisites: IEOR E4706, E4707, and computer programming. Interest rate models and numerical techniques for pricing and hedging interest rate contracts and fixed income securities.

IEOR E4711x Global capital markets
3 pts. Lect: 3. Professor Dastidar.
Prerequisites: Refer to course syllabus. An introduction to capital markets and investments providing an overview of financial markets and tools for asset valuation. Topics covered include the pricing of fixed-income securities (treasury markets, interest rate swaps futures, etc.), discussions on topics in credit, foreign exchange, sovereign ad securitized markets—private equity and hedge funds, etc.

IEOR E4712x Behavioral finance
1.5 pts. Lect: 3. Professor He.
Prerequisite: IEOR E4700. Behavioral finance is the application of behavioral psychology to financial decision making. Focus on the portfolio aspect of behavioral finance and briefly touches others. Compared with classical theory of portfolio choice, behavioral portfolio choice features human being's psychological biases. It builds both on behavioral preference structures different from mean variance theory and expected utility theory and on systematic biases against rational beliefs such as Bayesian rule.

IEOR E4714x Risk management, financial system and financial crisis
1.5 pts. Professor Malz.
Prerequisites: None. Risk-taking and risk management are at the heart of the financial system, and of the current financial crisis. An introduction to risk management both from an individual financial firm's and from a public policy viewpoint. Overview of the contemporary financial system, focusing on innovations of the past few decades that have changed how financial risk is generated and distributed among market participants, such as the growth of non-bank financial intermediaries, the increased prevalence of leverage and liquidity risk, and the development of structured credit products. Introduction to the basic quantitative tools used in market, credit, and liquidity risk management. The two strands of the course are brought together to help understand how the financial crisis arose and is playing out, examining the mechanics of runs and the behavior of asset prices during crises. Attempt to understand the emergency programs deployed by central bankers and other policy makers to address crises historically and today.

IEOR E4715x Commodity derivatives
1.5 pts. Not offered in 2015–2016.
Commodities markets have been much in the public eye recently as volatility has increased and they changed from markets dominated by physical participants to ones which have a significant investor component. The largest banks either already have profitable commodities franchises or are actively building them, and money managers and funds are increasingly including these assets in their portfolio mix. The end result is a dramatic increase in focus on these markets from all aspects of the financial markets, including the quantitative end.

IEOR E4718y Introduction to the implied volatility smile
3 pts. Lect: 3. Professor Derman.
Prerequisites: IEOR E4706, knowledge of derivatives valuation models. During the past 15 years the behavior of market options prices have shown systematic deviations from the classic Black-Scholes model. The course examines

the empirical behavior of implied volatilities, in particular the volatility smile that now characterizes most markets, the mathematics and intuition behind new models that can account for the smile, and their consequences for hedging and valuation.

IEOR E4720x and y–E4729 Topics in quantitative finance
1.5–3 pts. Lect: 2–2.5. Members of the faculty.
Prerequisites: IEOR E4700; additional prerequisites will be announced depending on offering. Selected topics of interest in the area of quantitative finance. Offerings vary each year; some topics include: energy derivatives, experimental finance, foreign exchange and related derivative instruments, inflation derivatives, hedge fund management, modeling equity derivatives in Java, mortgage-backed securities, numerical solutions of partial differential equations, quantitative portfolio management, risk management, trade and technology in financial markets.

IEOR E4731s Credit risk modeling and credit derivatives
3 pts. Lect: 3. Professor Capponi.
Prerequisites: IEOR E4701 and E4707. Introduction to quantitative modeling of credit risk, with a focus on the pricing of credit derivatives. Focus on the pricing of single-name credit derivatives (credit default swaps) and collateralized debt obligations (CDOs). Detail topics include default and credit risk, multiname default barrier models and multiname reduced form models.

IEOR E4732x Computational methods in derivatives pricing
3 pts. Professor Hirsa.
Prerequisite: IEOR E4700. Introduction and application of various computational techniques in pricing derivatives and risk management. Transform techniques, numerical solutions of partial differential equations (PDEs) and partial integro-differential equations (PIDEs) via finite differences, Monte-Carlo simulation techniques, calibration techniques, and parameter estimation and filtering techniques. The computational platform will be Java/C++. The primary application focus will be pricing of financial derivatives and calibration. These techniques are useful for various other problems in financial modeling and practical implementations from the theory of mathematical finance.

IEOR E4733y Algorithmic trading
3 pts. Professor Kani.
Prerequisite: IEOR E4700. Large and amorphous collection of subjects ranging from the study of market microstructure, to the analysis of optimal trading strategies, to the development of computerized, high-frequency trading strategies. Analysis of these subjects, the scientific and practical issues they involve, and the extensive body of academic literature they have spawned. Attempt to understand and uncover the economic and financial mechanisms that drive and ultimately relate them.

IEOR E4734s Foreign exchange and related derivatives instruments
1.5 pts. Lect: 1.5. Professor DeRosa.
Prerequisite: IEOR E4700. Foreign exchange market and its related derivative instruments—the latter being forward contracts, futures, options, and exotic options. What is unusual about foreign exchange is that although it can rightfully claim to be the largest of all financial markets, it remains an area where very few have any meaningful experience. Virtually everyone has traded stocks, bonds, and mutual funds. Comparatively few individuals have ever traded foerign exchange. In part that is because foreign exchange is an interbank market. Ironically the foreign exchange markets may be the best place to trade derivatives and to invent new derivatives—given the massive two-way flow of trading that goes through bank dealing rooms virtually twenty-four hours a day. And most of that is transacted at razor-thin margins, at least comparatively speaking, a fact that makes the foreign echange market an ideal platform for derivatives. The emphasis is on familiarizing the student with the nature of the foreign exchange market and those factors that make it special among financial markets, enabling the student to gain a deeper understanding of the related market for derivatives on foreign exchange.

IEOR E4735x Introduction to structured and hybrid products
3 pts. Lect: 3. Professor Kani.
Prerequisite: IEOR E4700. Conceptual and practical understanding of structured and hybrid products from the standpoint of relevant risk factors, design goals and characteristics, pricing, hedging, and risk management. Detailed analysis of the underlying cash-flows, embedded derivative instruments, and various structural feautures of these transactions, both from the investor and issuer perspectives, and analysis of the impact of the prevailing market conditions and parameters on their pricing and risk characteristics. Numerical methods for valuing and managing risk of structured/hybrid products and their imbedded derivatives and their application to equity, interest rates, commodities and currencies, inflation, and credit-related products. Conceptual and mathematical principles underlying these techniques, and practical issues that arise in their implementations in the Microsoft Excel/VBA and other programming environments. Special contractual provisions encountered in structured and hybrid transactions, and incorporation of yield curves, volatility smile, and other features of the underlying processes into pricing and implementation framework for these products.

IEOR E4736y Experimental finance
3 pts. Lect: 2.5. Professors Lipkin and Stanton.
Prerequisites: IEOR E4700 or equivalent. Intense laboratory to introduce students to event-driven finance using SQL query language to perform data explorations in the Optionmetrics IVY database.

IEOR E4738x Programming for FE 1: tools for building financial data and risk systems
3 pts. Lect: 2.5. Not offered in 2015–2016.
Prerequisite: Familiarity with object-oriented programming. Object-oriented programming and database development for building financial data and risk systems; Python and Pythons scientific libraries; basic database theory, querying and constructing databases; basic risk management and design of risk systems.

IEOR E4739y Programming for FE 2: implementing high-performance financial systems
3 pts. Lect: 2.5. Professor Bienstock.
Prerequisites: IEOR E4738 and instructor's permission. Developing effective software implementations in C programming language; modeling of portfolio optimization; modeling of price impact trading models; review of synchronization of programs using the file system; review of synchronization of programs using threads; review of synchronization of programs using sockets; implementation of high-performance simulations in finance.

IEOR E4900x and y Master's research or project
1–3 pts. Members of the faculty.
Prerequisite: Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

IEOR E4998x and y Managing technological innovation and entrepreneurship
3 pts. Lect: 3. Professor Neumann.
This is a required course for undergraduate students majoring in OR:EMS. Focus on the management and consequences of technology-based innovation. Explores how new industries are created, how existing industries can be transformed by new technologies, the linkages between technological development and the creation of wealth and the management challenges of pursuing strategic innovation.

IEOR E4999x and y Fieldwork
1–3 pts. Professor Derman.
Prerequisites: Obtained internship and approval from faculty adviser. Only for IEOR graduate students who need relevant work experience as part of their program of study. Final reports required. This course may not be taken for pass/fail credit or audited.

MSIE W6408y Inventory theory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Probability theory, dynamic programming. Construction and analysis of mathematical models used in the design and analysis of inventory systems. Deterministic and stochastic demands and lead times. Optimality of (s, S) policies. Multiproduct and multiechelon systems. Computational methods.

IEOR E6602y Nonlinear programming
3 pts. Lect: 3.
Prerequisite: Ph.D.-level linear programming. Convex sets and functions, convex duality and optimality conditions. Computational methods: steepest descent, Newton and quasi-newton methods for unconstrained problems, active set, penalty set, interior point, augmented Lagrangian and sequential quadratic programming methods for constrained problems. Introduction to nondifferentiable optimization and bundle methods.

IEOR E6613x Optimization, I
4.5 pts. Lect: 3. Professor Goldfarb.
Prerequisite: Linear algebra. Theory and geometry of linear programming. The simplex method. Duality theory, sensitivity analysis, column generation and decomposition. Interior point methods. Introduction to nonlinear optimization: convexity, optimality conditions, steepest descent, and Newton's method, active set, and barrier methods.

IEOR E6614y Optimization, II
4.5 pts. Lect: 3. Professor Stein.
Prerequisite: Linear algebra. An introduction to combinatorial optimization, network flows and discrete algorithms. Shortest path problems, maximum flow problems. Matching problems, bipartite and cardinality nonbipartite. Introduction to discrete algorithms and complexity theory: NP-completeness and approximation algorithms.

IEOR E6703y Advanced financial engineering
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisites: Probability theory and advanced stochastic models at the SIEO W6501 level. Review of basic mathematics, including renewal theory and stochastic calculus. Martingale approach to Black-Scholes formula. Optimal stopping and American options. Pricing of continuous and discrete exotic options. Term structure models and pricing of bond options. Jump diffusion models. Applications, including pricing of real and electricity options and hedging of real options.

IEOR E6711x Stochastic models, I
4.5 pts. Lect: 3. Professor Blanchet.
Prerequisite: SIEO W4105 or equivalent. Advanced treatment of stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering and other engineering applications. Review of elements of probability theory; exponential distribution; renewal theory; Wald's equation; Poisson processes. Introduction to both discrete and continuous-time Markov chains; introduction to Brownian motion.

IEOR E6712y Stochastic models, II
4.5 pts. Lect: 3. Professor Yao.
Prerequisite: IEOR E6711 or equivalent. Continuation of IEOR E6711, covering further topics in stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering, and other engineering applications. Topics from among generalized semi-Markov processes; processes with a nondiscrete state space; point processes; stochastic comparisons; martingales; introduction to stochastic calculus.

IEOR E8100x and y Advanced topics in IEOR
1–3 pts. Members of the faculty.
Prerequisite: Faculty adviser's permission. Selected topics of current research interest. May be taken more than once for credit.

IEOR E9101x and y Research
1–6 pts. Members of the faculty.
Before registering, the student must submit an outline of the proposed work for approval by the supervisor and the chair of the Department. Advanced study in a specialized field under the supervision of a member of the department staff. This course may be repeated for credit.

IEOR E9800x and y Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in industrial engineering or operations research must register for 12 points of doctoral research instruction. Registration in IEOR E9800 may not be used to satisfy the minimum residence requirement for the Ph.D. degree.

MATERIALS SCIENCE AND ENGINEERING PROGRAM

Program in the Department of Applied Physics and Applied Mathematics, sharing teaching and research with the faculty of the Henry Krumb School of Mines.

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IN CHARGE OF SOLID-STATE SCIENCE AND ENGINEERING
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208 S. W. Mudd

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Professor of Physics

Latha Venkataraman
Associate Professor of Applied Physics

Wen I. Wang
Professor of Electrical Engineering

Materials Science and Engineering (MSE) focuses on understanding, designing, and producing technology-enabling materials by analyzing the relationships among the synthesis and processing of materials, their properties, and their detailed structure. This includes a wide range of materials such as metals, polymers, ceramics, and semiconductors. Solid-state science and engineering focuses on understanding and modifying the properties of solids from the viewpoint of the fundamental physics of the atomic and electronic structure.

The undergraduate and graduate programs in materials science and engineering are coordinated through the MSE Program in the Department of Applied Physics and Applied Mathematics. This program promotes the interdepartmental nature of the discipline and involves the Departments of Applied Physics and Applied Mathematics, Chemical Engineering and Applied Chemistry, Electrical Engineering, and Earth and Environmental Engineering (EEE) in the Henry Krumb School of Mines (HKSM) with advisory input from the Departments of Chemistry and Physics.

Students interested in materials science and engineering enroll in the materials science and engineering program in the Department of Applied Physics and Applied Mathematics. Those interested in the solid-state science and engineering specialty enroll in the doctoral program within Applied Physics and Applied Mathematics or Electrical Engineering.

The faculty in the interdepartmental committee constitute but a small fraction of those participating in this program, who include Professors Bailey, Barmak, Billinge, Chan, Gaeta, Herman, Im, Marianetti, Noyan, Pinczuk, and Venkataraman from Applied Physics and Applied Mathematics; Brus, Durning, Flynn, Koberstein, and O'Shaughnessy from Chemical Engineering; Duby, Somasundaran, and Themelis from EEE; Lipson, Osgood, and Wang from Electrical Engineering.

Materials science and engineering uses optical, electron, and scanning probe microscopy and diffraction techniques to reveal details of structure, ranging from the atomic to the macroscopic scale—details essential to understanding properties such as mechanical strength, electrical conductivity, and technical magnetism. These studies also give insight into problems of the deterioration of materials in service, enabling designers to prolong the useful life of their products. Materials science and engineering also focus on new ways to synthesize and process materials, from bulk samples to ultrathin films to epitaxial heterostructures to nanocrystals. This involves techniques such as UHV sputtering; molecular beam epitaxy; plasma etching; laser ablation, chemistry, and recrystallization; and other nonequilibrium processes. The widespread use of new materials and the new uses of existing materials in electronics, communications, and computers have intensified the demand for a systematic approach to the problem of relating properties to structure and necessitates a multidisciplinary approach.

Solid-state science and engineering uses techniques such as transport measurements, X-ray photoelectron spectroscopy, inelastic light scattering, luminescence, and nonlinear optics to understand electrical, optical, and magnetic properties on a quantum mechanical level. Such methods are used to investigate exciting new types of structures, such as two-dimensional electron gases in semiconductor heterostructures, superconductors, and semiconductor surfaces and nanocrystals.

Current Research Activities

Current research activities in the materials science and engineering program at Columbia focus on thin films and electronic materials that enable significant advances in information technologies. Specific topics under investigation include interfaces, stresses, and grain boundaries in thin films; lattice defects and electrical properties of semiconductors; laser processing and ultrarapid solidification of thin films; nucleation in condensed systems; optical and electrical properties of semiconductors and metals; synthesis of nanocrystals, carbon nanotubes, and nanotechnology-related materials; deposition, in-situ characterization, electronic testing, and ultrafast spectroscopy of magnetoelectronic ultrathin films and heterostructures. In addition, there is research in surface and colloid chemistry involving both inorganic and organic materials such as surfactants, polymers, and latexes, with emphasis on materials/environment interactions.

The research activities in solid-state science and engineering are described later in this section.

LABORATORY FACILITIES

Facilities and research opportunities also exist within the interdepartmental Columbia Nanotechnology Initiative (CNI). Modern clean room facilities with optical and e-beam lithography, thin film deposition, and surface analytical probes (STM, SPM, XPS) are available. More specialized equipment exists in individual research groups in solid state engineering and materials science and engineering. The research facilities in solid-state science and engineering are listed in the sections for each host department. Facilities, and research opportunities, also exist within the interdepartmental clean room, shared materials characterization laboratories, and electron microscopy facility (SEM, S/TEM).

UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE

The objectives of the undergraduate program in the Materials Science Program of the Department of Applied Physics and Applied Mathematics are as follows:

1. Professional employment in industry, including materials production, automotive, aerospace, microelectronics, information storage, medical devices, energy production, storage and conversion, and in engineering consulting firms;
2. Graduate studies in materials science and engineering or related fields;

The undergraduate curriculum is designed to provide the basis for developing, improving, and understanding materials and processes for application in engineered systems. It draws from physics, chemistry and other disciplines to provide a coherent background for immediate application in engineering or for subsequent advanced study. The emphasis is on fundamentals relating atomic-to-microscopic-scale phenomena to materials properties and processing, including design and control of industrially important materials processes. Core courses and electives combine rigor with flexibility and provide opportunities for focusing on such areas as nanomaterials, materials for green energy, materials for infrastructure and manufacturing, materials for health and biotechnology, and materials for next generation electronics.

The unifying theme of understanding and interrelating materials synthesis, processing, structure, and properties forms the basis of our program and is evident in the undergraduate curriculum and in faculty research activities. These activities include work on polycrystalline silicon for flat panel displays; high-temperature superconductors for power transmission and sensors; semiconductors for lasers and solar cell applications, magnetic heterostructures for information storage and novel computation architectures; electronic ceramics for batteries, gas sensors and fuel cells; electrodeposition and corrosion of metals; and the analysis and design of high-temperature reactors and first principles calculations. Through involvement with our research groups, students gain valuable hands-on experience and are often engaged in joint projects with industrial and government laboratories.

Students are strongly encouraged to take courses in the order specified in the course tables; implications of deviations should be discussed with a departmental adviser before registration. The first two years provide a strong grounding in the physical and chemical sciences, materials fundamentals, and mathematics. This background is used to provide a unique physical approach to the study of materials. The last two years of the undergraduate program provide substantial exposure to modern materials science and include courses in processing, structure and properties of materials that extend the work of the first two years. Graduates of the program are equipped for employment in the large industrial sector that includes materials production, automotive, aerospace, microelectronics, information storage, medical devices, and energy production, storage and conversion. Graduates are prepared for graduate study in materials science and engineering and related fields.

Required Materials Science Courses

Students are required to take 15 Materials Science courses for a total of 43 points. The required courses are MSAE E3010, E3011, E3012, E3013, E4100, E4102, E3111, E4200, E4201, E4250, E3156, E4206, E3157, E4202 and E4215.

Technical Elective Requirements

Students are required to take six technical electives (18 points) from the list given below, which offers significant flexibility in allowing students to tailor their degree program to their interests.

a. All 3000-level or higher courses in the Materials Science program of the Department of Applied Physics and Applied Mathematics, except those MSAE courses that are required.
b. All 3000-level or higher courses in Applied Physics or Applied Math Programs of the Department of Applied Physics and Applied Mathematics
c. All 3000-level or higher courses in the Department of Biomedical Engineering Civil Engineering and Engineering Mechanics program, Department of Chemical Engineering, Department of Computer Science, Earth and Environmental Engineering program, Department of Electrical

MATERIALS SCIENCE PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS[1]	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3)	APMA E2101 (3)
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3) C2601 (3.5) Lab W3081 (2)	C1494 (3) Lab C2699 (3)
CHEMISTRY (three tracks, choose one)	C1403 (3.5) → Lab C1500 (3) either semester C1604 (3.5) → C3045 (3.5)	C1404 (3) C2507 (3) C3046 (3.5), Lab C2507 (3)	C3545 (3)	
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
NONTECHNICAL REQUIREMENTS		HUMA W1121 (3) **or** W1123 (3)	HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
TECHNICAL REQUIREMENTS			MSAE E3010 (3) Intro to mat. sci. I MSAE E3012 (3) Laboratory in mat. sci. I	MSAE E3011 (3) Intro to mat. sci. II MSAE E3013 (3) Laboratory in mat. sci. II
TOTAL POINTS[1]	16	17	16	16

[1] Estimated

Engineering, Department of Industrial Engineering and Operations Research, and Department of Mechanical Engineering, except for courses that require graduate standing

d. Courses in the Department of Chemistry listed in the Focus Areas below.

Focus Areas for technical electives are listed below. Students may choose from any one area if they so choose. They are not required to do so.

NANOMATERIALS

APPH E3100y: Intro to quantum mechanics
CHEM G4071x: Inorganic chemistry
MSAE E4090y: Nanotechnology
APPH E4100x: Quantum physics of matter
CHEM G4168x: Materials chemistry, I
ELEN E4193x: Modern display technology
MECE E4212x or y: Microelectromechanical systems
BMEN E4550y: Micro- and nanostructures in cellular engineering
ELEN E4944x: Principles of device microfabrication

MATERIALS FOR NEXT GENERATION ELECTRONICS

APPH E3100y: Intro to quantum mechanics
ELEN E3106x: Solid state devices-materials
APPH E4100x: Quantum physics of matter
ELEN E4301y: Intro to semiconductor devices
ELEN E4944x: Principles of device microfabrication

MATERIALS SCIENCE PROGRAM: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	MSAE E 3111 (3) Thermodynamics, kinetic theory, and statistical mechanics MSAE E4100 (3) Crystallography MSAE E4102 (3) Synthesis and processing of materials Technical Electives (3)	MSAE E4200 (3) Theory of crystalline materials MSAE E4201 (3) Materials thermodynamics and phase diagrams MSAE E4250 (3) Ceramics and composites Technical Elective (3)	MSAE E3156 (2) Design project MSAE E4206 (3) Electronic and magnetic properties of solids Technical Electives (9)	MSAE E3157 (2) Design project MSAE E4202 (3) Kinetics of transformations in materials MSAE E4215 (3) Mechanical behavior of materials Technical Elective (3)
NONTECHNICAL ELECTIVES	3 points	3 points	4 points	3 points
TOTAL POINTS[1]	15	15	18	14

[1]Estimated total credit points: 128–130 points, depending on the physics and chemistry tracks chosen in the first and second years

MATERIALS SCIENCE PROGRAM: THIRD AND FOURTH YEARS (TRANSFER STUDENTS)

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	MSAE E3010 (3) Introduction to materials science, I MSAE E3012 (3) Laboratory in materials science, I MSAE E3111 (3) Thermodynamics, kinetic theory, and statistical mechanics MSAE E4102 (3) Synthesis and processing of materials	MSAE E3011 (3) Introduction to materials science, II MSAE E3013 (3) Laboratory in materials science, II MSAE E4201 (3) Materials thermodynamics and phase diagrams MSAE E4250 (3) Ceramics and composites	MSAE E3156 (2) Design project MSAE E4100 (3) Crystallography MSAE E4206 (3) Electronic and magnetic properties of solids Technical Electives (6)	MSAE E3157 (2) Design project MSAE E4200 (3) Theory of crystalline materials MSAE E4202 (3) Kinetics of transformations in materials MSAE E4215 (3) Mechanical behavior of materials
NONTECHNICAL ELECTIVES	3 points	3 points	4 points	3 points
TOTAL POINTS	15	15	18	14

[1]Estimated total credit points: 128–130 points, depending on the physics and chemistry tracks chosen in the first and second years. Students following this chart will need four additional technical electives in order to complete the requirements for the degree and should consult the guidelines for technical electives detailed above.

MATERIALS FOR GREEN ENERGY

EAEE E3103x: Energy, minerals, materials systems
EAEE E4004x: Physical processing and recovery of solids
CHEE E4050x: Industrial and environmental electrochemistry
CHEM G4071x: Inorganic chemistry
APPH E4130: Physics of solar energy
EAEE E4190x: Photovoltaic systems engineering and sustainability
EAIA E4200y: Alternative energy resources
MECE E4210x: Energy infrastructure planning
MECE E4211y: Energy: sources and conversion
EAEE E4550x: Catalysis for emissions control

MATERIALS FOR 21ST CENTURY INFRASTRUCTURE AND MANUFACTURING

CIEE E3255y: Environmental control and pollution reduction systems
CIEE E3260y: Engineering for developing communities
ENME E3114y: Experimental mechanics of materials
MECE E3610y: Materials and processes in manufacturing
ENME E4113x: Advanced mechanics of solids
ENME E4114y: Mechanics of fracture and fatigue
ENME E4115y: Micromechanics of composite materials
CIEN E4226y: Advanced design of steel structures
CHEE E4530x: Corrosion of metals

MATERIALS FOR HEALTH AND BIOTECHNOLOGY

CHEM C3443x-C3444y: Organic chemistry
APPH E4300y: Physics of the human body
CHEM G4168: Materials chemistry, I
BMEN E4300: Solid biomechanics
BMEN E4301x: Structure, mechanics, and adaptation of bone
BMEN E4450y: Dental and craniofacial tissue engineering
BMEN E4501x: Tissue engineering, I: biomaterials and scaffold design
CHEE E4530: Corrosion of metals
BMEN E4550x: Micro- and nanostructures in cellular engineering

* **BMEN E4210y:** *Thermodynamics of biological systems accepted as substitute for* **MSAE E3111** *in this track.*

*** Note that* **BIOL C2005x:** *Introductory biology, I and* **BIOL C2006y:** *Introductory biology, II are prerequisites for a number courses in this track.*

MATERIALS CHEMISTRY/SOFT MATERIALS

CHEM C3443x-C3444y: Organic chemistry
CHEN E4201: Applications of electrochemistry
CHEE E4252: Intro surface & colloid chemistry
CHEN E4620: Intro polymers / soft materials
CHEN E4640: Polymer surfaces and interfaces

Nontechnical Elective Requirements

All materials science students are also expected to register for nontechnical electives, both those specifically required by the School of Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

Transfer Students

3-2/Transfer students and students transferring from another SEAS department into the Materials Science Program in the junior year (upon approval of the Materials Science Undergraduate Transfer Committee) will take the following courses to satisfy the degree requirements: The required courses are *MSAE E3010, E3011, E3012, E3013, E4100, E4102, E3111, E4200, E4201, E4250, E3156, E4206, E3157, E4202, and E4215*.

3-2/Transfer Students will be guided by their academic advisers to avoid duplication of courses previously taken. The course tables describe the eight-semester degree program schedule of courses leading to the bachelor's degree in the Materials Science Program of the Department of Applied Physics and Applied Mathematics.

GRADUATE PROGRAMS IN MATERIALS SCIENCE AND ENGINEERING

Master of Science Degree

Candidates for the Master of Science degree in Materials Science and Engineering will follow a program of study formulated in consultation with and approved by a faculty adviser. Thirty points of credit are required at a minimum.

The following five courses (15 points) are required for the degree:

15 points:

MSAE E4100: Crystallography
MSAE E4201: Materials thermodynamics and phase diagram
MSAE E4202: Kinetics of transformations in materials
MSAE E4206: Electronic and magnetic properties of solids
MSAE E4215: Mechanical behavior of structural materials

If a candidate has already taken one or more of these courses at Columbia University, substitutions from the Type I Elective list may be approved.

The remaining 15 points will be chosen from elective courses, 9 points of which must be Type I and 6 points of which may be Type I or Type II:

- **Type I Electives:**

MSAE E4090: Nanotechnology
MSAE E4101: Structural analysis of materials
MSAE E4102: Synthesis and processing of materials
MSAE E4132: Fundamentals of polymers and ceramics
MSAE E4207: Lattice vibrations and crystal defects
MSAE E4250: Ceramics and composites
MSAE E4990: Special topics in materials science and engineering
MSAE E6085: Computing the electronics structure of complex materials
MSAE E6091: Magnetism and magnetic materials
MSAE E6100: Transmission electron microscopy
MSAE E6225: Techniques in X-ray and neutron diffraction
MSAE E6229: Energy and particle beam processing of materials
MSAE E6230: Kinetics of phase transformations
MSAE E6251: Thin films and layers
MSAE E6273: Materials science reports
MSAE E8235: Selected topics in materials science
MSAE E4000-, 6000- or 8000-level courses not listed here

- **Type II Electives:**

BMEN E4300: Solid biomechanics
BMEN E4301: Structure, mechanics, and adaptation of bone
BMEN E4501: Tissue engineering, I
APPH E4100: Quantum physics of matter
APPH E4110: Modern optics
APPH E4130: Physics of solar energy
APPH E6081: Solid state physics, I
APPH E6082: Solid state physics, II
ELEN E4301: Intro to semiconductor devices
ELEN E4411: Fundamentals of photonics
ELEN E4944: Principles of device microfabrication
EAEE E4001: Industrial ecology of earth resources
EAEE E4160: Solid and hazardous waste management
ENME E4113: Advanced mechanics of solids
ENME E4114: Mechanics of fracture and fatigue
ENME E4608: Manufacturing processes
CHEE E4252: Intro to surface and colloid chemistry
CHEE E4530: Corrosion of metals
CHEN E4620: Intro to polymers and soft materials
CHEN E4640: Polymer surfaces and interfaces
CHEM G4168: Materials chemistry
MECE E4211: Energy sources and conversion
APMA E4101: Intro to dynamical systems
APMA E4200: Partial differential equations
APMA E4300: Intro to numerical methods
APMA E4400: Intro to biophysical modeling

Columbia Video Network (CVN) students may have their programs approved by faculty. Special reports (3 points) are required of CVN students.

All degree requirements must be completed within five years. A candidate is required to maintain at least a 2.5 GPA. Applicants for admission are required to take the Graduate Record Examinations.

Doctoral Program

At the end of the first year of graduate study in the doctoral program, candidates are required to take a comprehensive written qualifying examination, which is designed to test the ability of the candidate to apply course work in problem solving and creative thinking. The standard is first-year graduate level. There are two four-hour examinations over a two-day period.

Candidates in the program must take an oral examination within one year of taking the qualifying examination. Within two years of taking the qualifying examination, candidates must submit a written proposal and defend it orally before a Thesis Proposal Defense Committee consisting of three members of the faculty, including the adviser. Doctoral candidates must submit a thesis to be defended before a Dissertation Defense Committee consisting of five faculty members, including two professors from outside the doctoral program. Requirements for the Eng.Sc.D. (administered by the School of Engineering and Applied Science) and the Ph.D. (administered by the Graduate School of Arts and Sciences) are listed elsewhere in this bulletin.

Areas of Research

Materials science and engineering is concerned with synthesis, processing, structure, and properties of metals, ceramics, polymers, and other materials, with emphasis on understanding and exploiting relationships among structure, properties, and applications requirements. Our graduate research programs encompass projects in areas as diverse as polycrystalline silicon, electronic ceramics grain boundaries and interfaces, microstructure and stresses in microelectronics thin films, oxide thin films for novel sensors and fuel cells, optical diagnostics of thin-film processing, ceramic nanocomposites, electrodeposition and corrosion processes, structure, properties, and transmission electron microscopy and crystal orientation mapping, magnetic thin films for giant and colossal magnetoresistance, chemical synthesis of nanoscale materials, nanocrystals, carbon nanotubes, nanostructure analysis using X-ray and neutron diffraction techniques, and electronic structure calculation of materials using density functional and dynamical mean-field theories. Application targets for polycrystalline silicon are thin film transistors for active matrix displays and silicon-on-insulator structures for ULSI devices. Novel applications are being developed for oxide thin films, including uncooled IR focal plane arrays and integrated fuel cells for portable equipment. Long-range applications of high-temperature superconductors include efficient power transmission and highly sensitive magnetic field sensors.

Thin film synthesis and processing in this program include evaporation, sputtering, electrodeposition, and plasma and laser processing. For analyzing materials structures and properties, faculty and students employ electron microscopy, scanning probe microscopy, cathodoluminescence and electron beam–induced current imaging, photoluminescence, dielectric and anelastic relaxation techniques, ultrasonic methods, magnetotransport measurements, and X-ray diffraction techniques. Faculty members have research collaborations with Lucent, Exxon, IBM, and other New York area research and manufacturing centers, as well as major international research centers. Scientists and engineers from these institutions also serve as adjunct faculty members at Columbia. The National Synchrotron Light Source at Brookhaven National Laboratory is used for high-resolution X-ray diffraction and absorption measurements.

Entering students typically have undergraduate degrees in materials science, metallurgy, physics, chemistry, or other science and engineering disciplines. First-year graduate courses provide a common base of knowledge and technical skills for more advanced courses and for research. In addition to course work, students usually begin an association with a research group, individual laboratory work, and participation in graduate seminars during their first year.

GRADUATE SPECIALTY IN SOLID-STATE SCIENCE AND ENGINEERING

Solid-state science and engineering is an interdepartmental graduate specialty that provides coverage of an important area of modern technology that no single department can provide. It encompasses the study of the full range of properties of solid materials, with special emphasis on electrical, magnetic, optical, and thermal properties. The science of solids is concerned with understanding these properties in terms of the atomic and electronic structure of the materials in question. Insulators (dielectrics), semiconductors, ceramics, and metallic materials are all studied from this viewpoint. Quantum and statistical mechanics are key background subjects. The engineering aspects deal with the design of materials to achieve desired properties and the assembling of materials into systems to produce devices of interest to modern technology, e.g., for computers and for energy production and utilization.

Areas of Research

The graduate specialty in solid-state science and engineering includes research programs in semiconductor nanocrystals (Professor Brus, Chemistry/Chemical Engineering); optics of semiconductors and nanomaterials (Professor Herman, Applied Physics and Applied Mathematics); chemical physics of surfaces and photoemission (Professor Osgood, Electrical Engineering/Applied Physics and Applied Mathematics); molecular beam epitaxy leading to semi-conductor devices (Professor Wang, Electrical Engineering/Applied Physics and Applied Mathematics); metamaterials and infrared optoelectronic devices (Professor Yu, Applied Physics and Applied Mathematics); and inelastic light scattering in low-dimensional electron gases within semiconductors

(Professor Pinczuk, Applied Physics and Applied Mathematics/Physics); large-area electronics and thin-film transistors (Professor Im, Henry Krumb School of Mines/Applied Physics and Applied Mathematics); structural analysis and high Tc superconductors (Professor Chan, Henry Krumb School of Mines/Applied Physics and Applied Mathematics); X-ray microdiffraction and stresses (Professor Noyan, Henry Krumb School of Mines/Applied Physics and Applied Mathematics); electronic and magnetic metal thin films (Professor Barmak, Applied Physics and Applied Mathematics); magnetic properties of thin films (Professor Bailey, Applied Physics and Applied Mathematics); the structure of nanomaterials (Professor Billinge, Applied Physics and Applied Mathematics); and electronic structure calculations of materials (Professor Marianetti, Applied Physics and Applied Mathematics).

Program of Study

The applicant for the graduate specialty must be admitted to one of the participating programs: applied physics and applied mathematics, or electrical engineering. A strong undergraduate background in physics or chemistry and in mathematics is important.

The doctoral student must meet the formal requirements for the Eng.Sc.D. or Ph.D. degree set by the department in which he or she is registered. However, the bulk of the program for the specialty will be arranged in consultation with a member of the interdepartmental Committee on Materials Science and Engineering/ Solid-State Science and Engineering. At the end of the first year of graduate study, doctoral candidates are required to take a comprehensive written examination concentrating on solid-state science and engineering.

The following are regarded as core courses of the specialty:

APPH E4100: Quantum physics of matter
APPH E4110: Modern optics
APPH E4112: Laser physics

APPH-MSAE E6081-E6082: Solid state physics, I and II
CHEM G4230: Statistical thermodynamics

or
CHAP E4120: Statistical mechanics
ELEN E4301: Intro to semiconductor devices
ELEN E4944: Principles of device microfabrication
ELEN E6331-E6332: Principles of semiconductor physics
ELEN E6403: Classical electromagnetic theory

or
PHYS G6092: Electromagnetic theory, I
MSAE E4100: Crystallography
MSAE E4206: Electronic and magnetic properties of solids
MSAE E4207: Lattice vibrations and crystal defects
MSAE E6220: Crystal physics
MSAE E6240: Impurities and defects in semiconductor materials
MSAE E6241: Theory of solids
PHYS G6018: Physics of the solid state
PHYS G6037: Quantum mechanics

COURSES IN MATERIALS SCIENCE AND ENGINEERING

For related courses, see also Applied Physics and Applied Mathematics, Chemical Engineering, Earth and Environmental Engineering, and Electrical Engineering.

MSAE E1001y Atomic-scale engineering of new materials
3 pts. Lect: 3. Not offered in 2015–2016.
An introduction to the nanoscale science and engineering of new materials. The control and manipulation of atomic structure can create new solids with unprecedented properties. Computer hard drives, compact disc players, and liquid crystal displays (LCDs) are explored to understand the role of new materials in enabling technologies. Group problem-solving sessions are used to develop understanding.

MSAE E3010x Introduction to materials science, I
3 pts. Lect: 3. Professor Noyan.
Prerequisites: CHEM C1404, PHYS C1011. Introduction to quantum mechanics: atoms, electron shells, bands, bonding; introduction to group theory: crystal structures, symmetry, crystallography; introduction to materials classes: metals, ceramics, polymers, liquid crystals, nanomaterials; properties of single crystals: optical properties, electrical properties, magnetic properties, thermal properties, mechanical properties.

MSAE E3011y Introduction to materials science, II
3 pts. Lect: 3. Professor Noyan.
Prerequisite: MSAE E3010. Introduction to polycrystals and disordered materials; noncrystalline and amorphous structures; grain boundary structures, diffusion; phase transformations; phase diagrams, time-temperature-transformation diagrams; properties of polycrystalline and amorphous materials: mechanical properties and failure, the Drude model of electrical properties, thermal properties; corrosion; materials selection for engineering design.

MSAE E3012x Laboratory in materials science, I
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: MSAE E3010. Measurement of electrical, thermal, and magnetic properties of single crystals. Single crystal diffraction analysis, polarized light microscopy, and infrared microscopy in Si single crystals, written and oral reports.

MSAE E3013y Laboratory in materials science, II
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: MSAE E3011. Metallographic sample preparation, optical microscopy, quantitative metallography, hardness and tensile testing, plastic deformation, annealing, phase diagrams, brittle fracture of glass, temperature and strain-rate dependent deformation of polymers; written and oral reports. This is the second of a two-semester sequence materials laboratory course.

MSAE E3103x Elements of materials science
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: CHEM C1404 and PHYS C1011. Atomic and crystal structures, structural defects, alloying and phase diagrams. The influence of microstructure on the strength and physical properties of metals and alloys, semiconductors, ceramics, glasses, and polymers.

MSAE E3104y Laboratory in materials science
3 pts. Lect: 1. Lab: 4. Not offered in 2015–2016.
Corequisite: MSAE E3103. Metallographic specimen preparation, optical microscopy, quantitative metallography, hardness and tensile testing, plastic deformation, annealing, phase diagrams, brittle fracture of glass, temperature and strain rate dependent deformation of polymers, written and oral reports.

MSAE E3111x Thermodynamics, kinetic theory and statistical mechanics
3 pts. Lect: 3. Professor Billinge.
An introduction to the basic thermodynamics of systems, including concepts of equilibrium, entropy, thermodynamic functions, and phase changes. Basic kinetic theory and statistical mechanics, including diffusion processes, concept of phase space, classical and quantum statistics, and applications thereof.

MSAE E3141y Processing of metals and semiconductors
3 pts. Lect: 3. Professor Duby.
Prerequisite: MSAE E3103 or the equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

MSAE E3142y Processing of ceramics and polymers
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E3103 or equivalent. Established and novel methods involved in the processing of polymers and ceramics. The fundamental aspects of the structure and properties of polymers and ceramic materials; strategy in the preparatory, synthesis,, and processing methods for obtaining them. Topics include polymer synthesis, elastomers, thermoplastics, thermoset materials, design and molding processes. Ceramics: inorganic glasses and composites, materials production and principle inorganic chemistry. Processing methodology, conditioning, drying, forming, sintering, and microstructure development. Relevant aspects of transport phenomena, colloid and sol-gel science, contemporary issues in modern polymer and ceramic processing.

MSAE E3156x-E3157y Design project
2 pts (each semester). Lect.: 3. Professor Im.
Prerequisite: Senior standing. Written permission from instructor and approval from adviser. E3156: A design problem in materials science or metallurgical engineering selected jointly by the student and a professor in the department. The project requires research by the student, directed reading, and regular conferences with the professor in charge. E3157: Completion of the research, directed reading, and conferences, culminating in a written report and an oral presentation to the department.

MSAE E3900x and y Undergraduate research in materials science
0–4 pts. Members of the faculty.
Prerequisite: Written permission from instructor and approval from adviser. This course may be repeated for credit, but no more than 6 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in materials science or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report.

MSAE E4090y Nanotechnology
3 pts. Lect: 3. Professor Wind.
Prerequisites: APPH E3100 and MSAE E3103 or their equivalents with instructor's permission. The science and engineering of creating materials, functional structures and devices on the nanometer scale. Carbon nanotubes, nanocrystals, quantum dots, size dependent properties, self-assembly, nanostructured materials. Devices and applications, nanofabrication. Molecular engineering, bionanotechnology. Imaging and manipulating at the atomic scale. Nanotechnology in society and industry. Offered in alternate years.

MSAE E4100x Crystallography
3 pts. Lect: 3. Professor Barmak.
Prerequisites: CHEM C1403, PHYS C1403, APMA E2101, or equivalent. A first course on crystallography. Crystal symmetry, Bravais lattices, point groups, space groups. Diffraction and diffracted intensities. Exposition of typical crystal structures in engineering materials, including metals, ceramics, and semiconductors. Crystalline anisotropy.

MSAE E4101x Structural analysis of materials
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites or corequisite: MSAE E3103 or instructor's permission. Geometry of crystals, basic diffraction theory. X-ray diffraction. Techniques and theory of electron microscopy. Analysis of crystal structures and orientations. Microstructure characterization and analysis of crystalline defects.

MSAE E4102x Synthesis and processing of materials
3 pts. Lect: 3. Professor Im.
Prerequisite: MSAE E3011 or equivalent or instructor's permission. A course on synthesis and processing of engineering materials. Established and novel methods to produce all types of materials (including metals, semiconductors, ceramics, polymers, and composites). Fundamental and applied topics relevant to optimizing the microstructure of the materials with desired properties. Synthesis and processing of bulk, thin-film, and nano materials for various mechanical and electronic applications.

MSAE E4132y Fundamentals of polymers and ceramics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E3103 or instructor's permission. The science and engineering of polymer, ceramic and composite inorganic materials. Fundamental aspects of structure, processing and properties. Polymers: classification, synthesis, elastomers, thermoplastics, thermosets; ceramics: Crystal structure, morphology, classification, oxides, nitrides, carbides, silicates. Electrical, mechanical, thermal and optical properties. Common and advanced technological applications, electrical/optical devices, catalytic and environmental applications.

MSAE E4200y Theory of crystalline materials
3 pts. Lect: 3. Professor Marianetti.
Prerequisite: MSAE E4100 or instructor's permission. Electronic and vibrational properties of crystalline materials from the atomic scale using classical and quantum mechanics. Introduction to the theory of groups: irreducible representations, Great Orthogonality Theorem, Character tables, degeneration, and product groups. Use of translational and point symmetry to block diagonalize the Hamiltonian, including Bloch's Theorem. Covers band structures and the concept of band gap formation. Derive elastic constants from vibrational spectra. Tight binding and nearly free electron limits. Survey of electronic and phonon band structures in real materials.

MSAE E4201y Materials thermodynamics and phase diagrams
3 pts. Lect: 3. Professor Barmak.
Prerequisite: MSAE E3011 or equivalent or instructor's permission. Review of laws of thermodynamics, thermodynamic variables and relations, free energies and equilibrium in thermodynamic system. Unary, binary, and ternary phase diagrams, compounds and intermediate phases, solid solutions and Hume-Rothery rules, relationship between phase diagrams and metastability, defects in crystals. Thermodynamics of surfaces and interfaces, effect of particle size on phase equilibria, adsorption isotherms, grain boundaries, surface energy, electrochemistry.

MSAE E4202y Kinetics of transformation in materials
3 pts. Lect: 3. Professor Im.
Prerequisite: MSAE E4201. Review of thermodynamics, irreversible thermodynamics, diffusion in crystals and noncrystalline materials, phase transformations via nucleation and growth, overall transformation analysis and time-temperature-transformation (TTT) diagrams, precipitation, grain growth, solidification, spinodal and order-disorder transformations, martensitic transformation.

MSAE E4206x Electronic and magnetic properties of solids
3 pts. Lect: 3. Professor Bailey.
Prerequisite: PHYS C1401-3 or equivalent. A survey course on the electronic and magnetic properties of materials, oriented toward materials for solid state devices. Dielectric and magnetic properties, ferroelectrics and ferromagnets. Conductivity and superconductivity. Electronic band theory of solids: classification of metals, insulators, and semiconductors. Materials in devices: examples from semiconductor lasers, cellular telephones, integrated circuits, and magnetic storage devices. Topics from physics are introduced as necessary.

MSAE E4207y Lattice vibrations and crystal defects
3 pts. Lect: 3. Not offered in 2015–2016.
An introductory course in topics of solid state physics other than electronics and magnetic properties. Elastic waves in solids. Phonons and lattice vibrations. Brillouin zones. Thermal properties of solids. Defects, such as point defects in metals, ionic crystals, semiconductors, and ceramics.

MSAE E4215y Mechanical behavior of structural materials
3 pts. Lect: 3. Professor Bailey.
Prerequisite: MSAE E3103. Recommended preparation: A course in mechanics of materials. Review of states of stress and strain and their relations in elastic, plastic, and viscous materials. Dislocation and elastic-plastic concepts introduced to explain work hardening, various materials-strengthening mechanisms, ductility,

and toughness. Macroscopic and microstructural aspects of brittle and ductile fracture mechanics, creep and fatigue phenomena. Case studies used throughout, including flow and fracture of structural alloys, polymers, hybrid materials, composite materials, ceramics, and electronic materials devices. Materials reliability and fracture prevention emphasized.

MSAE E4250x Ceramics and composites
3 pts. Lect: 3. Professor Martin.
Prerequisites or corequisites: MSAE E3142 and E3104, or instructor's permission. The course will cover some of the fundamental processes of atomic diffusion, sintering and microstructural evolution, defect chemistry, ionic transport, and electrical properties of ceramic materials. Following this, we will examine applications of ceramic materials, specifically, ceramic thick and thin film materials in the areas of sensors and energy conversion/storage devices such as fuel cells, and batteries. The course work level assumes that the student has already taken basic courses in the thermodynamics of materials, diffusion in materials, and crystal structures of materials.

MSAE E4301x and y Materials science laboratory
1–3 pts. Members of the faculty.
Prerequisite: Instructor's permission. Materials science laboratory work so conducted as to fulfill particular needs of special students.

MSAE E4990x and y Special topics in materials science and engineering
1–3 pts. Instructor to be announced.
Prerequisite: Instructor's permission. This course may be repeated for credit. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

MSAE E4999x or y–S4999 Supervised internship
1 pt. Members of the faculty.
Prerequisite: Internship and approval from adviser must be obtained in advance. Only for master's students in the Department of Applied Physics and Applied Mathematics who may need relevant work experience as part of their program of study. Final report required. This course may not be taken for pass/fail or audited.

MSAE E6020y Electronic ceramics
3 pts. Lect: 3. Not offered in 2015–2016.
Structure and bonding of ceramics and glasses. Point defects and diffusion. Electronic and ionic conduction. Dielectric, ferroelectric, magnetic, and optical ceramics.

MSAE 86081x Solid state physics, I
3 pts. Lect: 3. Professor Pinczuk.
Prerequisite: APPH E3100 or equivalent. Knowledge of statistical physics on the level of MSAE E3111 or PHYS G4023 strongly recommended. Crystal structure; reciprocal lattices; classification of solids; lattice dynamics; anharmonic effects in crystals; stress and strain; classical electron models of metals; and periodic, nearly periodic, and more advanced analysis of electron band structure.

MSAE E6082y Solid state physics, II
3 pts. Lect: 3. Professor Altshuler.
Prerequisite: MSAE E6081 or instructor's permission. Semiclassical and quantum mechanical electron dynamics and conduction; dielectric properties of insulators; semiconductors; defects; magnetism; superconductivity; low-dimensional structures; and soft matter.

MSAE E6085x Computing the electronic structure of complex materials
3 pts. Lect: 3. Professor Marianetti.
Prerequisite: APPH E3100 or equivalent. Basics of density functional theory (DFT) and its application to complex materials. Computation of electronics and mechanical properties of materials. Group theory, numerical methods, basis sets, computing, and running open source DFT codes. Problem sets and a small project.

MSAE E6091y Magnetism and magnetic materials
3 pts. Lect. 3. Not offered in 2015–2016.
Prerequisite: MSAE E4206, APPH E6081, or equivalent. Types of magnetism. Band theory of ferromagnetism. Magnetic metals, insulators, and semiconductors. Magnetic nanostructures: ultrathin films, superlattices, and particles. Surface magnetism and spectroscopies. High speed magnetization dynamics. Spin electronics. Offered in alternate years.

MSAE E6100y Transmission electron microscopy
3 pts. Lect: 3. Professor Barmak.
Prerequisite: permission of the instructor. Theory and practice of transmission electron microscopy (TEM): principles of electron scattering, diffraction, and microscopy; analytical techniques used to determine local chemistry; introduction to sample preparation; laboratory and in-class remote access demonstrations, several hours of hands-on laboratory operation of the microscope; the use of simulation and analysis software; guest lectures on cryomicroscopy for life sciences and high resolution transmission electron microscopy for physical sciences; and, time permitting, a visit to the electron microscopy facility in the Center for Functional Nanomaterials (CFN) at the Brookhaven National Laboratory (BNL).

MSAE E6120x Grain boundaries and interfaces
3 pts. Lect: 2. Not offered in 2015–2016.
Prerequisites: the instructor's permission. Suggested background: basic knowledge of materials science, dislocations and point defects. The course gives an overview of the classic approaches in studying grain boundaries. Topics include boundary geometry and structure, boundary interactions with crystal defects, boundaries as short-circuit diffusion paths, applications of boundary concepts to interfaces, and roles of grain boundaries in material properties and in kinetic phenomena in polycrystalline materials.

MSAE E6220x Crystal physics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E4206 or instructor's permission. The course develops the idea of a tensor and applies it to stress and, together with considerations of crystal symmetry, to the study of the physical constants of crystals, such as diamagnetic and paramagnetic susceptibility, dielectric constants, thermal expansivity, piezoelectric constants, and others. The physical properties are also studied against the background material of MSAE E4206.

MSAE E6221x Introduction to dislocation theory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E4215 or course in theory of elasticity, or instructor's permission. Point and line imperfections. Theory of dislocations. Relation between imperfections and structure-sensitive properties.

MSAE E6225y Techniques in X-ray and neutron diffraction
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E4101. Crystal symmetry, diffraction, reciprocal space and Ewald sphere construction, radiation sources, analytical representation of diffraction peaks, diffraction line broadening, Fourier analysis of peak shape, texture analysis, diffraction analysis of stress and strain, diffraction analysis of order-disorder thermal diffuse scattering, small angle scattering, instrumentation in diffraction experiments, error analysis.

MSAE E6229x Energy and particle beam processing of materials
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MSAE E4202 or instructor's permission. Laser-, electron-, and ion-beam modification of materials to achieve unique microstructures and metastable phases for electronic and structural applications. Fundamentals of energy deposition and heat flow during laser- and electron-beam irradiation. Atomic displacement processes in ion-irradiated materials. Beam-induced microstructural evolution, crystallization, surface alloying, rapid solidification, and metastable phase formation. Review of current industrial applications.

MSAE E6230y Kinetics of phase transformations
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MSAE E4202 or instructor's permission. Principles of nonequilibrium thermodynamics; stochastic equations; nucleation, growth, and coarsening reactions in solids; spinodal decomposition; eutectic and eutectoid transformations.

MSAE E6251y Thin films and layers
3 pts. Lect: 3. Professor Chan.
Vacuum basics, deposition methods, nucleation and growth, epitaxy, critical thickness, defects properties, effect of deposition procedure, mechanical properties, adhesion, interconnects, and electromigration.

MSAE E6273x and y–S6273x Materials science reports
0 to 6 pts. Members of the faculty.
Prerequisite: Written permission from instructor and approval from adviser. Formal written reports and conferences with the appropriate member of the faculty on a subject of special interest to the student but not covered in the other course offerings.

MSAE E8235x and y Selected topics in materials science
3 pts. Lect: 3. Professor Noyan.
This course may be repeated for credit. Selected topics in materials science. Topics and instructors change from year to year. For students in engineering, physical sciences, biological sciences, and related fields.

MSAE E8236y Anelastic relaxations in crystals
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Instructor's permission. Formal theory of anelastic relaxation phenomena. Detailed study of the mechanisms of anelasticity and internal friction in crystals, including the role of point defects, dislocations, grain boundaries, electron-phonon interactions, and ferromagnetic domain effects.

MSAE E9000x and y Materials science and engineering colloquium
0 pts. Professor Marianetti.
Speakers from industry are invited to speak on the recent impact of materials science and engineering innovations.

MSAE E9259x-E9260y Research topics in materials science and metallurgical engineering
1 pt. Lect: 1. Members of the faculty.
Discussion of a group of technical papers related to a topic of current research interest.

MSAE E9301x-S9301 Doctoral research
0–15 pts. Members of the faculty.
Prerequisite: Qualifying examination for doctorate. Required of doctoral candidates.

MSAE E9309x and y–S9309 Proposal of Research for the Doctorate
0–3 pts. Members of the faculty.
A written report prepared by the prospective doctoral candidate defining the proposed research for the dissertation, and oral defense of the proposal at the time of the qualifying examinations.

MSAE E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Professor Barmak.
A candidate for the Eng.Sc.D. degree must register for 12 points of doctoral research instruction. Registration in MSAE E9800 may not be used to satisfy the minimum residence requirement for the degree.

MSAE E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the course work has been completed and until the dissertation has been accepted.

MECHANICAL ENGINEERING

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Mechanical engineering is a diverse subject that derives its breadth from the need to design and manufacture everything from small individual parts/devices (e.g., micro-scale sensors, inkjet printer nozzles) to large systems (e.g., spacecraft and machine tools). The role of a mechanical engineer is to take a product from an idea to the marketplace. In order to accomplish this, a broad range of skills are needed. The particular skills in which the mechanical engineer acquires deeper knowledge are the ability to understand the forces and the thermal environment that a product, its parts, or its subsystems will encounter; design them for functionality, aesthetics, and the ability to withstand the forces and the thermal environment they will be subjected to; determine the best way to manufacture them and ensure they will operate without failure. Perhaps the one skill that is the mechanical engineer's exclusive domain is the ability to analyze and design objects and systems with motion.

Since these skills are required for virtually everything that is made, mechanical engineering is perhaps the broadest and most diverse of engineering disciplines. Hence mechanical engineers play a central role in such industries as automotive (from the car chassis to its every subsystem—engine, transmission, sensors); aerospace (airplanes, aircraft engines, control systems for airplanes and spacecraft); biotechnology (implants, prosthetic devices, fluidic systems for pharmaceutical industries); computers and electronics (disk drives, printers, cooling systems, semiconductor tools); microelectromechanical systems, or MEMS (sensors, actuators, micro power generation); energy conversion (gas turbines, wind turbines, solar energy, fuel cells); environmental control (HVAC, air-conditioning, refrigeration, compressors); automation (robots, data/image acquisition, recognition, and control); manufacturing (machining, machine tools, prototyping, microfabrication).

To put it simply, mechanical engineering deals with anything that moves. Mechanical engineers learn about materials, solid and fluid mechanics, thermodynamics, heat transfer, control, instrumentation, design, and manufacturing to realize/understand mechanical systems. Specialized mechanical engineering subjects include biomechanics, cartilage tissue engineering, energy conversion, laser-assisted materials processing, combustion, MEMS, microfluidic devices, fracture mechanics, nanomechanics, mechanisms, micropower generation, tribology (friction and wear), and vibrations. The American Society of Mechanical Engineers (ASME) currently lists thirty-six technical divisions, from advanced energy systems and aerospace engineering to solid waste engineering and textile engineering.

The breadth of the mechanical engineering discipline allows students a variety of career options beyond some of the industries listed above. Regardless of the particular future path they envision for themselves after they graduate, their education would have provided them with the creative thinking that allows them to design an exciting product or system, the analytical tools to achieve their design goals, the ability to meet several sometimes conflicting constraints, and the teamwork needed to design, market, and produce a system. These skills also prove to be valuable in other endeavors and can launch a career in medicine, law, consulting, management, banking, finance, and so on.

For those interested in applied scientific and mathematical aspects of the discipline, graduate study in mechanical engineering can lead to a career of research and teaching.

Current Research Activities

Current research activities in the Department of Mechanical Engineering are in the areas of controls and robotics, energy and micropower generation, fluid mechanics, heat/mass transfer, mechanics of materials, manufacturing, material processing, MEMS, nanotechnology, and orthopedic biomechanics.

Biomechanics and Mechanics of Materials. Some of the current research in biomechanics is concerned with the application of continuum theories of mixtures to problems of electromechanical behavior of soft biological tissues, contact mechanics, lubrication of diarthrodial joints, and cartilage tissue engineering. (Ateshian)

In the area of the mechanics of materials, research is performed to better understand material constitutive behavior at the micro- and mesolength scales. This work is experimental, theoretical, and computational in nature. The ultimate goal is to formulate constitutive relationships that are based on physical concepts rather than phenomenology, as in the case of plasticity power-law hardening. In addition, the role that the constitutive relations play in the fracture and failure of materials is emphasized. (Kysar)

Other areas of biomechanics include characterizing the structure-function behavior of the cervix during the remodeling events of pregnancy and characterizing the mechanical properties of the eye-wall in relation to glaucoma. Research in our lab includes the mechanical testing of biological soft tissues, the biochemical analysis of tissue microstructure, and material modeling based on structure-mechanical property relationships. In collaboration with clinicians, our goal is to understand the etiologies of tissue pathology and disease. (Myers)

Control, Robotics, Design, and Manufacturing. Control research emphasizes iterative learning control (ILC) and repetitive control (RC). ILC creates controllers that learn from previous experience performing a specific command, such as robots on an assembly line, aiming for high-precision mechanical motions. RC learns to cancel repetitive disturbances, such as precision motion through gearing, machining, satellite precision pointing, particle accelerators, etc. Time optimal control of robots is being studied for increased productivity on assembly lines through dynamic motion planning. Research is also being conducted on improved system identification, making mathematical models from input-output data. The results can be the starting point for designing controllers, but they are also studied as a means of assessing damage in civil engineering structures from earthquake data. (Longman)

Robotics research focuses on design of novel rehabilitation machines and training algorithms for functional rehabilitation of neural impaired adults and children. The research also aims to design intelligent machines using nonlinear system theoretic principles, computational algorithms for planning, and optimization.

Robotic Systems Engineering (ROSE) Lab develops technology capable of solving difficult design problems, such as cable-actuated systems, under-actuated systems, and others. Robotics and Rehabilitation (ROAR) Lab focuses on developing new and innovative technologies to improve the quality of care and patient outcomes. The lab designs novel exoskeletons for upper and lower limbs training of stroke patients, and mobile platforms to improve socialization in physically impaired infants (Agrawal).

The Robotic Manipulation and Mobility (ROAM) Lab focuses on versatile manipulation and mobility in robotics, aiming for robotic applications pervasive in everyday life. Research areas include manipulation and grasping, interactive or Human-in-the-Loop robotics, dynamic simulators and virtual environments, machine perception and modeling, and many more. We are interested in application domains such as versatile automation in manufacturing and logistics, assistive and rehabilitation robotics in health care, space robotics, and mobile manipulation in unstructured environments. (Ciocarlie)

At the Creative Machines Lab (CreativeMachines.org) we are interested in robots that create and robots that are themselves creative. We develop novel autonomous systems that can design and make other machines - automatically. We are working on a self-replicating robots, self-aware robots, robots that improve themselves over time, and robots that compete and cooperate with other robots. We build robots that paint art, cook food, build bridges and fabricate other robots. Our work is inspired from biology, as we seek new biological concepts for engineering and new engineering insights into biology. (Lipson)

In the area of advanced manufacturing processes and systems, current research concentrates on laser materials processing. Investigations are being carried out in laser micromachining; laser forming of sheet metal; microscale laser shock-peening, material processing using improved laser-beam quality. Both numerical and experimental work is conducted using state-of-the-art equipment, instruments, and computing facilities. Close ties with industry have been established for collaborative efforts. (Yao)

Energy, Fluid Mechanics, and Heat/ Mass Transfer. In the area of energy, one effort addresses the design of flow/mass transport systems for the extraction of carbon dioxide from air. Another effort addresses the development of distributed sensors for use in micrositing and performance evaluation of energy and environmental systems. The design and testing of components and systems for micropower generation is part of the thermofluids effort as well as part of the MEMS effort. (Modi)

In the area of fluid mechanics, study of low-Reynolds-number chaotic flows is being conducted both experimentally and numerically, and the interactions with molecular diffusion and inertia are presently being investigated. Other areas of investigation include the fluid mechanics of inkjet printing, drop on demand, the suppression of satellite droplets, shock wave propagation, and remediation in high-frequency printing systems. (Modi)

In the area of nanoscale thermal transport, our research efforts center on the enhancement of thermal radiation transport across interfaces separated by a nanoscale gap. The scaling behavior of nanoscale radiation transport is measured using a novel heat transfer measurement technique based on the deflection of a bimaterial atomic force microscope cantilever. Numerical simulations are also performed to confirm these measurements. The measurements are also used to infer extremely small variations of van der Waals forces with temperature. This enhancement of radiative transfer will ultimately be used to improve the power density of thermophotovoltaic energy conversion devices. (Narayanaswamy)

Also in the area of energy, research is being performed to improve the thermochemical models used in accelerating development of cleaner, more fuel-efficient engines through computational design. In particular, data-driven approaches to creating high-accuracy, uncertainty-quantified thermochemicals models are being developed that utilize both theoretical and experimental data. Special emphasis is placed on the generation and analysis of data across the full range of relevant scales—from the small-scale electronic behavior that governs molecular reactivity to the large-scale turbulent, reactive phenomena that govern engine performance. (Burke)

MEMS and Nanotechnology. In these areas, research activities focus on power generation systems, nanostructures for photonics, fuel cells and photovoltaics, and microfabricated adaptive cooling skin and sensors for flow, shear, and wind speed. Basic research in fluid dynamics and heat/mass transfer phenomena at small scales also support these activities. (Hone, Kysar, Lin, Modi, Narayanaswamy)

We study the dynamics of microcantilevers and atomic force microscope cantilevers to use them as microscale thermal sensors based on the resonance frequency shifts of vibration modes of the cantilever. Bimaterial microcantilever-based sensors are used to determine the thermophysical properties of thin films. (Narayanaswamy)

Research in the area of nanotechnology focuses on nanomaterials such as nanotubes and nanowires and their applications, especially in nanoelectromechanical systems (NEMS). A laboratory is available for the synthesis of graphene and other two-dimensional materials using chemical vapor deposition (CVD) techniques and to build devices using electron-beam lithography and various etching techniques. This effort will seek to optimize the fabrication, readout, and sensitivity of these devices for numerous applications, such as sensitive detection of mass, charge, and magnetic resonance. (Hone, Kysar, Modi)

Research in BioMEMS aims to design and create MEMS and micro/nanofluidic systems to control the motion and measure the dynamic behavior of biomolecules in solution. Current efforts involve modeling and understanding the physics of micro/nanofluidic devices and systems, exploiting polymer structures to enable micro/nanofluidic manipulation, and integrating MEMS sensors with microfluidics for measuring physical properties of biomolecules. (Lin)

Biological Engineering and Biotechnology. Active areas of research in the musculoskeletal biomechanics laboratory include theoretical and experimental analysis of articular cartilage mechanics; theoretical and experimental analysis of cartilage lubrication, cartilage tissue engineering, and bioreactor design; growth and remodeling of biological tissues; cell mechanics; and mixture theory for biological tissues with experiments and computational analysis (Ateshian).

The Hone group is involved in a number of projects that employ the tools of micro- and nanofabrication toward the study of biological systems. With collaborators in biology and applied physics, the group has developed techniques to fabricate metal patterns on the molecular scale (below 10 nanometers) and attach biomolecules to create biofunctionalized nanoarrays. The group is currently using these arrays to study molecular recognition, cell spreading, and protein crystallization. The project seeks to understand and modify at the nanoscale force- and geometry-sensing pathways in health and disease. The Hone group fabricates many of the tools used by the researchers to measure and apply force on a cellular level. (Hone)

Microelectromechanical systems (MEMS) are being exploited to enable and facilitate the characterization and manipulation of biomolecules. MEMS technology allows biomolecules to be studied in well-controlled micro/nanoenvironments of miniaturized, integrated devices, and may enable novel biomedical investigations not attainable by conventional techniques. The research interests center on the development of MEMS devices and systems for label-free manipulation and interrogation of biomolecules. Current research efforts primarily involve microfluidic devices that exploit specific and reversible, stimulus-dependent binding between biomolecules and receptor molecules to enable selective purification, concentration, and label-free detection of nucleic acid, protein, and small molecule analytes; miniaturized instruments for label-free characterization of thermodynamic and other physical properties of biomolecules; and subcutaneously implantable MEMS affinity biosensors for continuous monitoring of glucose and other metabolites. (Kysar, Lin)

The Kasza group studies the physical principles underlying the mechanics and self-organization of biological materials by combining quantitative approaches from engineering, biology, and physics. The group builds tools to measure and manipulate the behaviors of protein, cells, and tissues in order to uncover the mechanisms by which living multicellular tissues change shape, move, and grow to build functional tissues and organs. For example, the group is currently using the Drosophila (fruit fly) embryo as a model system for understanding how mechanical forces shape tissues during embryonic development. These studies combine confocal microscopy, genetics, and biomechanical measurements.

Mass radiological triage is critical after a large-scale radiological event because of the need to identify those individuals who will benefit from medical intervention as soon as possible. The goal of the ongoing NIH-funded research project is to design a prototype of a fully automated, ultra high throughput biodosimetry. This prototype is supposed to accommodate multiple assay preparation protocols that allow the determination of the levels of radiation exposure that a patient received. The input to this fully autonomous system is a large number of capillaries filled with blood of patients collected using finger sticks. These capillaries are processed by the system to distill the micronucleus assay in lymphocytes, with all the assays being carried out in situ in multiwell plates. The research effort on this project involves the automation system design and integration including hierarchical control algorithms, design and control of custom built robotic devices, and automated image acquisition and processing for sample preparation and analysis. (Yao)

A technology that couples the power of multidimensional microscopy (three spatial dimensions, time, and multiple wavelengths) with that of DNA array technology is investigated in an NIH-funded project. Specifically, a system is developed in which individual cells selected on the basis of optically detectable multiple features at critical time points in dynamic processes can be rapidly and robotically micromanipulated into reaction chambers to permit amplified DNA synthesis and subsequent array analysis. Customized image processing and pattern recognition techniques are developed, including Fisher's linear discriminant preprocessing with neural net, a support vector machine with improved training, multiclass cell detection with error correcting output coding, and kernel principal component analysis. (Yao)

Facilities for Teaching and Research

The undergraduate laboratories, occupying an area of approximately 6,000 square feet of floor space, are the site of experiments ranging in complexity from basic instrumentation and fundamental exercises to advanced experiments in such diverse areas as automatic controls, heat transfer, fluid mechanics, stress analysis, vibrations, microcomputer-based data acquisition, and control of mechanical systems.

Equipment includes microcomputers and microprocessors, analog-to-digital and digital-to-analog converters, lasers and optics for holography and interferometry, a laser-Doppler velocimetry system, a Schlieren system, dynamic strain indicators, a servohydraulic and servoelectric material testing machines, a photoelastic and servoelectric testing machine, Digital Image Correlation (DIC) capabilities, a dynamometer, subsonic and supersonic wind tunnels, a cryogenic apparatus, computer numerically controlled vertical machine centers (VMC), a coordinate measurement machine (CMM), and three-dimensional printers as well as a laser cutter. A CNC wire electrical discharge machine (EDM) is also available for the use of specialized projects for students with prior arrangement. The undergraduate laboratory also houses experimental setups for the understanding and performance evaluation of a complete small steam power generation system, a heat exchanger, a solar cell system, a fuel cell system, and a compressor. Part of the undergraduate laboratory is a staffed machine shop with machining tools such as standard vertical milling machines, engine and bench lathes, programmable surface grinder, band saw, drill press, tool grinders, and a power hacksaw. The shop also has a tig welder.

A mechatronics laboratory affords the opportunity for hands-on experience with microcomputer-embedded control of electromechanical systems. Facilities for the construction and testing of analog and digital electronic circuits aid the students in learning the basic components of the microcomputer architecture. The laboratory is divided into work centers for two-person student laboratory teams. Each work center is equipped with several power supplies (for low-power electronics and higher power control), a function generator, a multimeter, a protoboard for building circuits, a microcomputer circuit board (which includes the microcomputer and peripheral components), a microcomputer programmer, and a personal computer that contains a data acquisition board. The data acquisition system serves as an oscilloscope, additional function generator, and spectrum analyzer for the student team. The computer also contains a complete microcomputer software development system, including editor, assembler, simulator, debugger, and C compiler. The laboratory is also equipped with a portable oscilloscope, an EPROM eraser (to erase microcomputer programs from the erasable chips), a logic probe, and an analog filter bank that the student teams share, as well as a stock of analog and digital electronic components.

The department maintains a modern computer-aided design laboratory equipped with thirty computer work stations with state-of-the-art design software. The research facilities are located within individual or group research laboratories in the department, and these facilities are being continually upgraded. To view the current research capabilities please visit the various laboratories within the research section of the department website. The students and staff of the department can, by prior arrangement, use much of the equipment in these research facilities. Through their participation in the NSF-MRSEC center, the faculty also have access to shared instrumentation and the clean room located in the Schapiro Center for Engineering and Physical Science Research. Columbia University's extensive library system has superb scientific and technical collections.

E-mail and computing services are maintained by Columbia University Information Technology (CUIT) (columbia.edu/cuit).

UNDERGRADUATE PROGRAM

The objectives of the undergraduate program in mechanical engineering are as follows:

The Mechanical Engineering Department at Columbia University is dedicated to graduating mechanical engineers who:

1. Practice mechanical engineering in a broad range of industries
2. Pursue advanced education, research and development, and other creative and innovative efforts in science, engineering, and technology, as well as other professional careers
3. Conduct themselves in a responsible, professional, and ethical manner
4. Participate as leaders in their fields of expertise and in activities that support service and economic development nationally and throughout the world

Highly qualified students are permitted to pursue an honors course consisting of independent study under the guidance of a member of the faculty.

Upon graduation the student may wish to enter employment in industry or government, or continue with graduate study. Alternatively, training in mechanical engineering may be viewed as a basis for a career in business, patent law, medicine, or management. Thus, the department's undergraduate program provides a sound foundation

MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS STANDARD TRACK

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) APMA E2101 (3)[1] **or** Linear Algebra (3)[2] **and** ODE (3)[3]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3)[4] C2601 (3.5)[4]	
CHEMISTRY	one semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604	Lab C1500 (3)[5]		
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL COURSES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
REQUIRED TECHNICAL COURSES	(3) Student's choice, see list of first- and second-year technical electives		ENME-MECE E3105 (4) either semester	
COMPUTER SCIENCE	Computer language: COMS W1005 (3) or ENGI E1006 (3) (in semester I or III)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students who take APMA E2101 must additionally purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[2] Linear algebra may be fulfilled by either APMA E3101 or MATH V2010.
[3] Ordinary differential equations may be fulfilled by either MATH V2030 or MATH V3027.
[4] May substitute EEEB W2001, BIOL C2005, or higher.
[5] May substitute Physics Lab C1493 (3), C1494 (3), or W3081 (2).

for a variety of professional endeavors.

The program in mechanical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET.

Undergraduates who wish to declare mechanical engineering as their major should do so prior to the start of their junior year. Students who wish to declare during or after the fall semester of their junior year must first obtain approval from the Mechanical Engineering Department.

Of the 21 points of elective content in the third and fourth years, at least 12 points of technical courses, including at least 6 points from the Department of Mechanical Engineering, must be taken. Those prior remaining points of electives are intended primarily as an opportunity to complete the four-year, 27-point nontechnical requirement. Consistent with professional accreditation standards, courses in engineering science and courses in design must have a combined credit of 48 points. Students should see their advisers for details.

Undergraduate students are strongly encouraged to take the combination

MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS STANDARD TRACK	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	MECE E3018 (3) Lab I MECE E3100 (3) Fluids I MECE E3301 (3) Thermodynamics ENME E3105 (4)[1] Mechanics ENME E3113 (3) Mechanics of solids	MECE E3028 (3) Lab II MECE E3408 (3) Graphics and design MECE E3311 (3) Heat transfer MECE E3610 (3) Materials and processes in manufacturing ELEN E1201 (3.5) Intro. elec. eng.	MECE E3038 (3) Lab III MECE E3409 (3) Machine design MECE E3420 (1) Engineering design: concept EEME E3601 (3) Classical control sys.	MECE E3430 (3) Engineering design: creation
TECHNICAL ELECTIVES[2]			6 points	6 points
NONTECH ELECTIVES				6 points
TOTAL POINTS[3]	16	15.5	16	15

[1] Strongly recommended to be taken in Semester III or IV.
[2] If APMA E2101 is taken instead of Linear algebra and ODE, students must purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[3] Students must complete 128 points to graduate.

of a stand-alone course in linear algebra (either APMA E3101 or MATH V2010) and a stand-alone course in ordinary differential equations (either MATH V2030 or V3027), instead of the combined topics course APMA E2101. In addition, such students are encouraged to take a course in partial differential equations (APMA E3102 or E4200) as well as a course in numerical methods (APAM E3105 or APMA E4300) as technical electives. Ideally, planning for these courses should start at the beginning of the sophomore year.

Fundamentals of Engineering (FE) Exam

The FE exam is a state licensing exam and the first step toward becoming a Professional Engineer (P.E.). P.E. licensure is important for engineers to obtain—it shows a demonstrated commitment to professionalism and an established record of abilities that will help a job candidate stand out in the field. Ideally, the FE exam should be taken in the senior year while the technical material learned while pursuing the undergraduate degree is still fresh in the student's mind. In addition to the FE exam, achieving P.E. licensure requires some years of experience and a second examination, which tests knowledge gained in engineering practice. For more information, please see http://ncees.org/exams/fe-exam/.

The Mechanical Engineering Department strongly encourages all seniors to take this exam and offers a review course covering material relevant to the exam, including a practice exam to simulate the testing experience. The FE exam is given in the fall and spring of each year. The review course is offered in the spring semester, concluding before the spring exam.

Integrated B.S./M.S. Program

The Integrated B.S./M.S. degree program is open to a qualified group of Columbia juniors and makes possible the earning of both the B.S. and M.S. degree in an integrated fashion. Benefits of this program include optimal matching of graduate courses with corresponding undergraduate prerequisites, greater ability to plan ahead for most advantageous course planning, opportunities to do research for credit during the summer after senior year, and up to 6 points of 4000-level technical electives from the B.S. requirement may count toward the fulfillment of the point requirement of the M.S. degree. Additional benefits include simplified application process, no GRE is required, and no reference letters are required. To qualify for this program, students must have a cumulative GPA of at least 3.5 and strong recommendations from within the Department. Students should apply for the program by April 30 in their junior year. For more information on requirements and access to an application form, please visit me.columbia.edu/integrated-bsms-program.

MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS STANDARD TRACK (CLASS OF 2018 AND BEYOND)

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) APMA E2101 (3)[1] **or** Linear Algebra (3)[2] **and** ODE (3)[3]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3)[4] C2601 (3.5)[4]	
CHEMISTRY	one semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604	Lab C1500 (3)[5]		
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL COURSES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
REQUIRED TECHNICAL COURSES	(3) Student's choice, see list of first- and second-year technical electives			ENME E3105 (4)
COMPUTER SCIENCE	Computer language: COMS W1005 (3) or ENGI E1006 (3) (in semester I or III)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students who take APMA E2101 must additionally purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[2] Linear algebra may be fulfilled by either APMA E3101 or MATH V2010.
[3] Ordinary differential equations may be fulfilled by either MATH V2030 or MATH V3027.
[4] May substitute EEEB W2001, BIOL C2005, or higher.
[5] May substitute Physics Lab C1493 (3), C1494 (3), or W3081 (2).

GRADUATE PROGRAMS

Master of Science Degree Program

The program leading to the Master of Science degree in mechanical engineering requires completion of a minimum of 30 points of approved course work consisting of no fewer than ten courses. A thesis based on either experimental, computational, or analytical research is optional and may be counted in lieu of up to 6 points of course work. In general, attainment of the degree requires one academic year of full-time study, although it may also be undertaken on a part-time basis over a correspondingly longer period. A minimum grade-point average of 2.5 is required for graduation.

The M.S. degree in mechanical engineering requires a student to take a sequence of courses that shows a "clearly discernible specialty or concentration." In consultation with his/her adviser an M.S. student can develop a concentration specifically tailored to his/her interests and objectives, and we refer to this as the standard track. Alternatively, M.S. students can pick

MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS STANDARD TRACK (CLASS OF 2018 AND BEYOND)				
	SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
REQUIRED COURSES	MECE E3018 (3) Lab I MECE E3100 (3) Fluids I MECE E3301 (3) Thermodynamics ENME E3106 (3) Dynamics and Vibrations ENME E3113 (3) Mechanics of solids	MECE E3028 (3) Lab II MECE E3408 (3)[1] Graphics and design MECE E3311 (3) Heat transfer MECE E3610 (3) Materials and processes in manufacturing ELEN E1201 (3.5)[1] Intro. elec. eng.	MECE E3409 (3) Machine design MECE E3420 (1) Engineering design: concept EEME E3601 (3) Classical control sys.	MECE E3430 (3) Engineering design: creation
	MECE E1008 (1) Intro to machining (either semester)			
TECHNICAL ELECTIVES[2]			6 points	6 points
NONTECH ELECTIVES				6 points
TOTAL POINTS[3]	15–16	16.5–17.5	13	15

[1] Strongly recommended to be taken in Semester III or IV.
[2] If APMA E2101 is taken instead of Linear algebra and ODE, students must purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[3] Students must complete 128 points to graduate.

from a set of predefined concentrations, or special tracks.

Typical choices of concentration in the standard track include such subjects as mechanics of solids and fluids, thermodynamics, heat transfer, manufacturing engineering, robotics, kinematics, dynamics and vibrations, controls, and power generation. Nevertheless, the following guidelines must be adhered to:

1. The sequence of courses selected must not be haphazard but rather show a clearly discernible specialty.
2. All courses must be at the graduate level, i.e., numbered 4000 or higher, with at least two 6000-level courses included.
3. Every program must contain at least one course in mathematics (APMA, MATH, STAT, SIEO course designations) covering material beyond what the student has taken previously. It should appear early in the sequence in order to serve as a basis for the technical course work.
4. Out-of-department study is encouraged, but at least five courses should be in mechanical engineering.

Rather than apply for the standard track, students can apply for a special track in either energy systems or in micro/nanoscale engineering. The requirements for a special track are identical to those of the standard track, with one exception: a special track student must take at least 15 of his/her points from a list determined by a special track adviser in consultation with a special track advisory committee. The name of the special track will be listed on a student's transcript. The currently available special tracks are listed below.

M.S. in Mechanical Engineering with Concentration in Energy Systems

Advisers: Professors Vijay Modi and Arvind Narayanaswamy

The concentration in energy systems provides the M.S. candidate with a global understanding of current energy challenges. Advanced thermofluidic knowledge is provided to design and optimize energy systems, with a strong emphasis on renewable energies. Courses related to energy and environmental policy, two strong areas of Columbia as a global university, can be integrated into the course sequence. This concentration is a suitable preparation for careers in energy production and energy consultation.

Requirements: 30 points of graduate level course work, i.e., courses numbered 4000-level or higher, at least

MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
EARLY DECISION TRACK

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) APMA E2101 (3)[1] **or** Linear algebra (3)[2] **and** ODE (3)[3]
PHYSICS (three tracks, choose one)	C1401 (3) C1601 (3.5) C2801 (4.5)	C1402 (3) C1602 (3.5) C2802 (4.5)	C1403 (3)[4] C2601 (3.5)[4]	
CHEMISTRY	one semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604	Lab C1500 (3)[5]		
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) Z0006 (0)	C1010 (3) Z1003 (0)	C1010 (3)	
REQUIRED NONTECHNICAL COURSES			HUMA C1001, COCI C1101, **or** Global Core (3–4)	HUMA C1002, COCI C1102, **or** Global Core (3–4)
REQUIRED TECHNICAL COURSES	(3) Student's choice, see list of first- and second-year technical electives	ENME E3105 (4) Mechanics	ENME E3113 (3) Mechanics of solids	ELEN E1201 (3.5) Intro. to elec. eng. MECE E3408 (3) Graphics and design
COMPUTER SCIENCE	Computer language: COMS W1005 (3) or ENGI E1006 (3) (in semester I and III)			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students who take APMA E2101 must additionally purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[2] Linear algebra may be fulfilled by either APMA E3101 or MATH V2010.
[3] Ordinary differential equations may be fulfilled by either MATH V2030 or MATH V3027.
[4] May substitute EEEB W2001, BIOL C2005, or higher.
[5] May substitute Physics Lab C1493 (3), C1494 (3), or W3081 (2).

two of which must be a 6000-level (*MECE E6100 Advanced mechanics of fluids* and *MECE E6313 Advanced heat transfer* are strongly recommended). Furthermore, students must take one course in statistics (*STAT/SIEO* designations) and at least five courses from the following list*:

MECE E4210: Energy infrastructure planning
MECE E4211: Energy: sources and conversion
MECE E4302: Advanced thermodynamics
MECE E4304: Turbomachinery
MECE E4305: Mechanics and thermodynamics propulsion
MECE E4312: Solar thermal engineering
MECE E4314: Energy dynamics of green buildings
MECH E4320: Intro to combustion
MECE E4330: Thermofluid systems design
MECE E6100: Advanced mechanics of fluids
MECE E6104: Case studies in computational fluid dynamics
MECE E6313: Advanced heat transfer
EAEE E6126: Carbon sequestration

*One 3-point research course can be counted toward the concentration if the research is approved by the student's adviser and is energy related.

MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS EARLY DECISION TRACK				
	SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
REQUIRED COURSES	MECE E3018 (3) Lab I MECE E3100 (3) Fluids I MECE E3301 (3) Thermodynamics	MECE E3028 (3) Lab II MECE E3311 (3) Heat transfer MECE E3610 (3) Materials and processes in manufacturing	MECE E3038 (3) Lab III MECE E3409 (3) Machine design MECE E3420 (1) Engineering design: concept EEME E3601 (3) Classical control sys	MECE E3430 (3) Engineering design: creation
REQUIRED NONTECHNICAL COURSES	HUMA W1121 **or** W1123 (3)	ECON W1105 (4) **and** W1155 recitation (0)		
TECHNICAL ELECTIVES[1]		3 points	3 points	6 points
NONTECH ELECTIVES			3 points	6 points
TOTAL POINTS[2]	12	16	16	15

[1] If APMA E2101 is taken instead of Linear Algebra and ODE, students must purpose 3 points of their 12 points of technical elective requirement toward a course with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, SIEO, or EEEB.
[2] Students must complete a minimum of 128 points to graduate.

M.S. in Mechanical Engineering with Concentration in Micro/Nanoscale Engineering

Advisers: Professors James Hone and Jeff Kysar

The concentration in micro/nanoscale engineering provides the M.S. candidate with an understanding of engineering challenges and opportunities in micro- and nanoscale systems. The curriculum addresses fundamental issues of mechanics, fluid mechanics, optics, heat transfer, and manufacturing at small-size scales. Application areas include MEMS, bio-MEMS, microfluidics, thermal systems, and carbon nanostructures.

Requirements: While satisfying the general mechanical engineering requirements, take at least five courses from:

MECE E4212: Microelectromechanical systems
MECE E4213: BioMEMS
MECE E6105: Transport phenomena in the presence of interfaces
MECE E6700: Carbon nanotubes
MECE E6710: Nanofabrication laboratory
MECE E6720: Nano/microscale thermal transport processes
MECE E8990: Small scale mechanical behavior
ELEN E4503: Sensors, actuators, and electromechanical systems
ELEN E6945: Device nanofabrication
BMEN E4590: BioMEMS: cellular and molecular applications
MSAE E4090: Nanotechnology

M.S. in Mechanical Engineering with Concentration in Robotics and Control

Advisers: Professors Sunil Agrawal, Matei Ciocarlie, Hod Lipson, Richard Longman, and Fred Stolfi

The field of robotics is seeing unprecedented growth, in areas as diverse as manufacturing, logistics, transportation, health care, space exploration, and more. This program prepares students for a career in robotics and its many applications in society. Students perform in-depth study of topics such as robotic manipulation, navigation, perception, human interaction, medical robotics, assistance and rehabilitation. This concentration is a suitable preparation for joining established companies, information-age dominant players investing heavily in this field, or the new wave of robotics start-ups aiming to provide disruptive innovations. Many of the acquired skills can be applied in other fields as diverse as automation, manufacturing, computer graphics or machine vision. This program can also be a foundation for a research career in robotics and related areas, in both academia and industry.

Candidates for the M.S. with concentration in Robotics and Control should simultaneously satisfy these two sets of requirements:

Take at least five courses from the list below during their M.S. (courses taken during undergraduate studies do not count):

Courses in the Mechanical Engineering Department
MECE E4058: Mechanics and embedded microcomputer control
MECE E4601: Digital control systems

MECE E4602: Intro to robotics
MECE E6400: Advanced machine dynamics
MECE E6601: Intro to control theory
MECE E6602: Modern control theory
MECE E6610: Optimal control theory
MECE E6614: Advanced topics in robotics and mechanism synthesis
MECE E4606: Digital manufacturing

Courses in the other Departments in the School of Engineering and Applied Science
ELEN E4501: Sensors, actuators and electromechanical systems
BMME E4702: Advanced musculoskeletal biomechanics
COMS W4731: Computer vision
COMS W4733: Computational aspects of robotics
ELEN E4810: Digital signal processing
COMS E6733: 3D photography

Satisfy the general requirements for the MS in mechanical engineering requirements, which are:

a. All courses must be at the graduate level, i.e., numbered 4000 or higher, with at least two 6000-level courses included.
b. Five (5) courses at least within the Mechanical Engineering department.
c. At least one math course (APMA or MATH designator), covering material beyond what the student has taken previously. Examples of suitable courses are: APMA E4001y Principles of applied mathematics; APMA E4300y, Introduction to numerical methods; APMA E4301x Numerical methods for partial differential equations; and APMA E4204x Functions for complex variables.
d. A total of 30 credits are required.

Express M.S. Application

The Express M.S. Application is offered to current seniors, including 3-2 students, who are enrolled in the BS program. In the Express M.S. Application, a master's degree can be earned seamlessly. Graduate classes are available for seniors to apply toward their M.S. degree and the advanced courses that will be taken have been designed to have the exact prerequisites completed as an undergraduate. Other advantages include the opportunity for better course planning and creating a streamlined set of courses more possible. Additional benefits include simplified application process, no GRE is required and no reference letters are required. To qualify for this program, your cumulative GPA should be at least 3.5. For more information on requirements and access to an application, please visit me.columbia.edu/ms-express-application-1.

Doctoral Degree Program

When a student becomes a prospective candidate for either the Doctor of Engineering Science (Eng.Sc.D.) or Doctor of Philosophy (Ph.D.) degree, a faculty adviser is assigned whose task is to help choose a program of courses, provide general advice on academic matters, and monitor academic performance.

The doctoral candidate is expected to attain a level of mastery in some area of mechanical engineering, and must therefore choose a field and concentrate in it by taking the most advanced courses offered. This choice of specialty is normally made by the time the student has completed 30 points of credit beyond the bachelor's degree, at which time a complete course program is prepared and submitted to the departmental doctoral committee for approval. The student must maintain a grade-point average of 3.2 or better in graduate courses.

The department requires the prospective candidate to pass a qualifying examination. Given once a year, in May, it is usually taken after the student has completed 30 points beyond the bachelor's degree. However, it may not be delayed past the next examination given after completion of 45 points. The examination comprises a written test, given in two parts over two days, in which questions may be selected from a broad set in all areas of mechanical engineering and applied mathematics, devised to test the candidate's ability to think creatively. There is also an oral examination based on some research project the student has undertaken. A candidate who fails the examination may be permitted to repeat it once in the following year.

After passing the qualifying examination, the student chooses a faculty member in the pertinent area of specialization who then serves as the research adviser. This adviser helps select a research problem and supervises the research, writing, and defense of the dissertation. Once a specific problem has been identified and a tentative plan for the research prepared, the student submits a research proposal and presents it to a faculty committee. The committee considers whether the proposed problem is suitable for doctoral research, whether the plan of attack is well formulated and appropriate to the problem, and whether the student is adequately prepared. It may approve the plan without reservation, or it may recommend modifications or additions. This is the last formal requirement until the dissertation is submitted for approval.

All doctoral students are required to successfully complete four semesters of the mechanical engineering seminar *MECE E9500.*

COURSES IN MECHANICAL ENGINEERING

MECE E1001x Mechanical engineering: micromachines to jumbo jets
3 pts. Lect: 3. Professor Myers.
Corequisite: MATH V1101 Calculus I. This introductory course explores the role of Mechanical Engineering in developing many of the fundamental technological advances on which today's society depends. Students will be exposed to several mature and emerging technologies through a series of case studies. Topics include: airplanes, automobiles, robots, modern manufacturing methods as well as the emerging fields of microelectromechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the art innovations in each case study.

MECE E1008x or y Introduction to machining
1 pt. Instructor to be announced.
Introduction to the manual machine operation, CNC fabrication and usage of basic hand tools, band/hack saws, drill presses, grinders and sanders.

MECE E1304x or y Naval ship systems, I
3 pts. Lect: 3. Instructor to be announced.
Students are strongly advised to consult with the ME Department prior to registering for this course. A study of ship characteristics and types including ship design, hydrodynamic forces, stability, compartmentation, propulsion, electrical and auxiliary systems, interior communications, ship control, and damage control; theory and design of steam, gas turbine, and nuclear propulsion; shipboard safety and firefighting. This course is part of the Naval ROTC program at Columbia but

will be taught at SUNY Maritime. Enrollment may be limited; priority is given to students participating in Naval ROTC. This course will not count as a technical elective. Students should see a faculty adviser as well as Columbia NROTC staff (nrotc@columbia.edu) for more information.

MECE E3018x Mechanical engineering laboratory, I
3 pts. Lect: 3. Professor Kysar.
Experiments in instrumentation and measurement: optical, pressure, fluid flow, temperature, stress, and electricity; viscometry, cantilever beam, digital data acquisition. Probability theory: distribution, functions of random variables, tests of significance, correlation, ANOVA, linear regression. A lab fee of $50.00 is collected.

MECE E3028y Mechanical engineering laboratory, II
3 pts. Lect: 3. Professor Akbari.
Experiments in engineering and physical phenomena: aerofoil lift and drag in wind tunnels, laser Doppler anemometry in immersed fluidic channels, supersonic flow and shock waves, Rankine thermodynamical cycle for power generation, and structural truss mechanics and analysis. A lab fee of $50.00 is collected.

MECE E3038x Mechanical engineering laboratory, III
3 pts. Lect: 3. Professor Stolfi.
Mechatronic control of mechanical and electromechanical systems. Control of various thermodynamic cycles, including internal combustion engine (Otto cycle). Reverse engineering of an electromechanical product. A lab fee of $50.00 is collected.

MECE E3100x Introduction to mechanics of fluids
3 pts. Lect: 3. Professor Vukelic.
Prerequisite: ENME E3105. Basic continuum concepts. Liquids and gases in static equilibrium. Continuity equation. Two-dimensional kinematics. Equation of motion. Bernoulli's equation and applications. Equations of energy and angular momentum. Dimensional analysis. Two-dimensional laminar flow. Pipe flow, laminar, and turbulent. Elements of compressible flow.

ENME E3105x and y Mechanics
4 pts. Lect: 4. Professor Hone.
Prerequisites: PHYS C1401 and MATH V1101, V1102, and V1201. Elements of statics, dynamics of a particle, and systems of particles.

ENME E3113x Mechanics of solids
3 pts. Lect: 3. Professor Deodatis.
Pre- or corequisite: ENME E3105 or equivalent. Stress and strain. Mechanical properties of materials. Axial load, bending, shear, and torsion. Stress transformation. Deflection of beams. Buckling of columns. Combined loadings. Thermal stresses.

MECE E3301x Thermodynamics
3 pts. Lect: 3. Professor Vukelic.
Classical thermodynamics. Basic properties and concepts, thermodynamic properties of pure substances, equation of state, work, heat, the first and second laws for flow and nonflow processes, energy equations, entropy, and irreversibility. Introduction to power and refrigeration cycles.

MECE E3311y Heat transfer
3 pts. Lect: 3. Professor Narayanaswamy.
Steady and unsteady heat conduction. Radiative heat transfer. Internal and external forced and free convective heat transfer. Change of phase. Heat exchangers.

MECE E3401x Mechanics of machines
3 pts. Lect: 3. Professor Lin.
Prerequisites: ENME E3105 and MECE E3408. Introduction to mechanisms and machines, analytical and graphical synthesis of mechanism, displacement analysis, velocity analysis, acceleration analysis of linkages, dynamics of mechanism, cam design, gear and gear trains, and computer-aided mechanism design.

MECE E3408y Computer graphics and design
3 pts. Lect: 3. Instructor to be announced.
Introduction to drafting, engineering graphics, computer graphics, solid modeling, and mechanical engineering design. Interactive computer graphics and numerical methods applied to the solution of mechanical engineering design problems. A laboratory fee of $175 is collected.

MECE E3409x Machine design
3 pts. Lect: 3. Professor Agrawal.
Prerequisite: MECE E3408. Computer-aided analysis of general loading states and deformation of machine components using singularity functions and energy methods. Theoretical introduction to static failure theories, fracture mechanics, and

fatigue failure theories. Introduction to conceptual design and design optimization problems. Design of machine components such as springs, shafts, fasteners, lead screws, rivets, welds. Modeling, analysis, and testing of machine assemblies for prescribed design problems. Problems will be drawn from statics, kinematics, dynamics, solid modeling, stress analysis, and design optimization.

MECE E3411y Fundamentals of engineering
1 pt. Lect: 3. Professor Stolfi.
Prerequisite: Senior standing. Review of core courses in mechanical engineering, including mechanics, strength of materials, fluid mechanics, thermodynamics, heat transfer, materials and processing, control, and mechanical design and analysis. Review of additional topics, including engineering economics and ethics in engineering. The course culminates with a comprehensive examination, similar to the Fundamentals of Engineering examination. This course meets the first 4.5 weeks only.

MECE E3420x Engineering concept and design
1 pt. Lect: 1. Professor Stolfi.
Prerequisite: Senior standing. Corequisite: MECE E3409. A preliminary design for an original project is a prerequisite for the capstone design course. This course will focus on the steps required for generating a preliminary design concept. Included will be a brainstorming concept generation phase, a literature search, and the production of a layout drawing of the proposed capstone design project in a Computer Aided Design (CAD) software package (i.e., ProEngineer).

MECE E3430y Engineering design
3 pts. Lect: 2. Lab: 4. Professor Stolfi.
Prerequisite: MECE E3420. Building on the preliminary design concept, the detailed elements of the design process are completed: systems synthesis, design analysis optimization, and Computer Aided Design (CAD) component part drawings. Execution of a project involving the design, fabrication, and performance testing of an actual engineering device or system. A laboratory fee of $125 is collected.

MECE E3450x or y Computer-aided design
3 pts. Lect: 3. Professor Ateshian.
Prerequisites: ENME E3105, E3113, MECE E3408, E3311. Introduction to numerical methods and their applications to rigid body mechanics for mechanisms and linkages. Introduction to finite element stress analysis for deformable bodies. Computer-aided mechanical engineering design using established software tools and verifications against analytical and finite difference solutions.

EEME E3601x Classical control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware, implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

MECE 3610y Materials and processes in manufacturing
3 pts. Lect: 3. Professor Yao.
Prerequisites: ENME E3113 or the equivalent. Introduction to microstructures and properties of metals, polymers, ceramics and composites; typical manufacturing processes: material removal, shaping, joining, and property alteration; behavior of engineering materials in the manufacturing processes.

MECE E3900x-E3901y Honors tutorial in mechanical engineering
3 pts. Lect: 3. Members of the faculty.
Individual study; may be selected after the first term of the junior year by students maintaining a 3.2 grade-point average. Normally not to be taken in a student's final semester. Course format may vary from individual tutorial to laboratory work to seminar instruction under faculty supervision. Written application must be made prior to registration outlining proposed study program. Projects requiring machine-shop use must be approved by the laboratory supervisor.

MECE E3998x and y Projects in mechanical engineering
1-3 pts. Members of the faculty.
Prerequisite: Approval by faculty member who agrees to supervise the work. Normally not to be taken in a student's final semester. Independent project involving theoretical, computational, experimental or engineering design work. May be repeated, but no more than 3 points may be counted toward degree requirements. Projects requiring machine-shop use must be approved by the laboratory supervisor.

MECE E4058x and y Mechatronics and embedded microcomputer control
3 pts. Lect: 3. Professor Stolfi.
Prerequisite: ELEN E1201. Recommended: ELEN E3000. Enrollment limited to 12 students. Mechatronics is the application of electronics and microcomputers to control mechanical systems. Systems explored include on/off systems, solenoids, stepper motors, DC motors, thermal systems, magnetic levitation. Use of analog and digital electronics and various sensors for control. Programming microcomputers in Assembly and C. A lab fee of $75.00 is collected. Lab required.

MECE E4100y Mechanics of fluids
3 pts. Lect: 3. Professor Kasza.
Prerequisite: MECE E3100 or equivalent. Fluid dynamics and analyses for mechanical engineering and aerospace applications: boundary layers and lubrication, stability and turbulence, and compressible flow. Turbomachinery as well as additional selected topics.

MECE E4210x or y Energy infrastructure planning
3 pts. Lect: 3. Professor Modi.
Prerequisites: One year each of college level physics, chemistry, and mathematics. Energy infrastructure planning with specific focus on countries with rapidly growing infrastructure needs. Spatiotemporal characteristics, scale, and environmental footprints of energy resources, power generation and storage, modeling demand growth, technology choices and learning for planning. Computer-assisted decision support and network design/optimization tools. Similarities, differences and interactions among electricity, gas, information, transportation and water distribution networks. Penetration of renewable and/or decentralized technologies into existing or new infrastructure. Special guest lectures on infrastructure finance, regulation and public-private partnerships.

MECE E4211x or y Energy: sources and conversion
3 pts. Lect: 3. Professor Modi.
Prerequisite: MECE E3301. Energy sources such as oil, gas, coal, gas hydrates, hydrogen, solar, and wind. Energy conversion systems for electrical power generation, automobiles, propulsion and refrigeration. Engines, steam and gas turbines, wind turbines; devices such as fuel cells, thermoelectric converters, and photovoltaic cells. Specialized topics may include carbon-dioxide sequestration, cogeneration, hybrid vehicles and energy storage devices.

MECE E4212x or y Microelectromechanical systems
3 pts. Lect: 1.5. Lab: 3.
MEMS markets and applications; scaling laws; silicon as a mechanical material; Sensors and actuators; micromechanical analysis and design; substrate (bulk) and surface micromachining; computer aided design; packaging; testing and characterization; microfluidics.

MECE E4213y Biomicroelectromechanical systems (BioMEMS): design, fabrication, and analysis
3 pts. Lect: 3. Professor Lin.
Prerequisites: MECE E3100 and E3311, course in transport phenomena, or instructor's permission. Silicon and polymer micro/nanofabrication techniques; hydrodynamic microfluidic control; electrokinetic microfluidic control; microfluidic separation and detection; sample preparation; micro bioreactors and temperature control; implantable MEMS, including sensors, actuators and drug delivery devices.

MECE E4302y Advanced thermodynamics
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: MECE E3301. Advanced classical thermodynamics. Availability, irreversibility, generalized behavior, equations of state for nonideal gases, mixtures and solutions, phase and chemical behavior, combustion. Thermodynamic properties of ideal gases. Applications to automotive and aircraft engines, refrigeration and air conditioning, and biological systems.

MECE E4304x Turbomachinery
3 pts. Lect: 3. Professor Akbari.
This course will introduce you to the basics of theory, design, selection and applications of turbomachinery. Turbomachines are widely

used in many engineering applications such as energy conversion, power plants, air-conditioning, pumping, refrigeration and vehicle engines, as there are pumps, blowers, compressors, gas turbines, jet engines, wind turbines, etc. Applications are drawn from energy conversion technologies, HVAC and propulsion. The course provides a basic understanding of the different kinds of turbomachines.

MECE E4305y Mechanics and thermodynamics of propulsion
3 pts. Lect: 3. Professor Akbari.
Prerequisites: MECE E3301x Thermodynamics and MECE E3311y Heat transfer; MECE E4304x Turbomachinery (or instructor approval). Principles of propulsion. Thermodynamic cycles of air breathing propulsion systems including ramjet, scramjet, turbojet, and turbofan engine and rocket propulsion system concepts. Turbine engine and rocket performance characteristics. Component and cycle analysis of jet engines and turbomachinery. Advanced propulsion systems. Columbia Engineering interdisciplinary course.

MECE E4306x or y Introduction to aerodynamics
3 pts. Lect: 3. Professor Akbari.
Principles of flight, incompressible flows, compressible regimes. Inviscid compressible aerodynamics in nozzles (wind tunnels, jet engines), around wings (aircraft, space shuttle) and around blunt bodies (rockets, reentry vehicles). Physics of normal shock waves, oblique shock waves, and explosion waves.

IEME E4310x The manufacturing enterprise
3 pts. Lect: 3. Professor Weinig.
The strategies and technologies of global manufacturing and service enterprises. Connections between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

MECE E4312x Solar thermal engineering
3 pts. Lect: 3. Professor Narayanaswamy.
Prerequisite: MECE E3311 (Heat transfer). Fundamentals of solar energy transport: radiation heat transfer, convention, conduction and phase change processes. Heat exchangers and solar collectors: basic methods of thermal design, flow arrangements, effects of variable conditions, rating procedures. Solar energy concentration. Piping Systems: series and parallel arrangements, fluid movers. Thermal response and management of photovoltaic energy conversion. Solar energy storage. Solar cooling, solar thermal power and cogeneration. Applications to the design of solar thermal engineering systems.

MECE E4314y Energy dynamics of green buildings
3 pts. Lect: 3. Professor Naraghi.
Prerequisites: MECE E3301 and E3311. Introduction to analysis and design of heating, ventilating and air-conditioning systems. Heating and cooling loads. Humidity control. Solar gain and passive solar design. Global energy implications. Green buildings. Building-integrated photovoltaics. Roof-mounted gardens and greenhouses. Financial assessment tools and case studies. Open to Mechanical Engineering graduate students only.

MECH E4320x Introduction to combustion
3 pts. Lect: 3. Professor Burke.
Prerequisites: Introductory thermodynamics, fluid dynamics, and heat transfer at the undergraduate level or instructor's permission. Thermodynamics and kinetics of reacting flows; chemical kinetic mechanisms for fuel oxidation and pollutant formation; transport phenomena; conservation equations for reacting flows; laminar nonpremixed flames (including droplet vaporization and burning); laminar premixed flames; flame stabilization, quenching, ignition, extinction, and other limit phenomena; detonations; flame aerodynamics and turbulent flames.

MECE E4330x Thermofluid systems design
3 pts. Lect: 3. Professor Vukelic.
Prerequisites: MECE E3100, E3301, E3311. Theoretical and practical considerations, and design principles, for modern thermofluids systems. Topics include boiling, condensation, phase change heat transfer, multimode heat transfer, heat exchangers, and modeling of thermal transport systems. Emphasis on applications of thermodynamics, heat transfer, and fluid mechanics to modeling actual physical systems. Term project on conceptual design and presentation of a thermofluid system that meets specified criteria.

MECE E4400x and y Computer laboratory access
0 pts. Professor Kysar.
Sign up for this class to obtain a computer account and access to the Department of Mechanical Engineering Computer Laboratory.

MECE E4404x or y Tribology: friction, lubrication, and wear
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E3100, E3311, and ENME E3113, or permission of the instructor. Friction, lubrication, and wear between sliding surfaces. Surface metrology, contact mechanics, and sliding friction. Deformation, wear, and temperature rise of nonlubricated, liquid-lubricated, and solid-lubricated rolling and sliding materials. The theories of boundary, elastohydrodynamic, hydrodynamic, hydrostatic, and solid-phase lubrication. Lubricant flow and load-carrying capacity in bearings. Special applications such as geartrains, cam/tappets, and micro- and nanoscale tribological interfaces.

MECE E4430y Automotive dynamics
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: ENME 3105 or equivalent; recommended: ENME 3106 or equivalent. Automobile dynamic behavior is divided into three subjects: vehicle subsystems, ride, and handling. Vehicle subsystems include: tire, steering, mechanisms, suspensions, gearbox, engine, clutch, etc. Regarding ride, vibrations and ride comfort are analyzed, and suspension optimization of a quarter car model is treated. Regarding handling, vehicle dynamic behavior on the road is analyzed, with emphasis on numerical simulations using planar as well as roll models.

MECE E4431x or y Space vehicle dynamics and control
3 pts. Lect: 3. Professor Longman.
Prerequisite: ENME-MECE E3105; ENME E4202 recommended. Space vehicle dynamics and control, rocket equations, satellite orbits, initial trajectory designs from earth to other planets, satellite attitude dynamics, gravity gradient stabilization of satellites, spin-stabilized satellites, dual-spin satellites, satellite attitude control, modeling, dynamics, and control of large flexible spacecraft.

MEBM E4439x Modeling and identification of dynamic systems
3 pts. Lect: 3. Professor Chbat.
Prerequisite: APMA E2101, ELEN E3801, or corequisite EEME E3601, or permission of instructor. Generalized dynamic system modeling and simulation. Fluid, thermal, mechanical, diffusive, electrical, and hybrid systems are considered. Nonlinear and high order systems. System identification problem and Linear Least Squares method. State-space and noise representation. Kalman filter. Parameter estimation via prediction-error and subspace approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

MECE E4501y Geometrical modeling
3 pts. Lect: 3. Professor Rajan.
Prerequisite: COMS W1005. Relationship between 3D geometry and CAD/CAM; representations of solids; geometry as the basis of analysis, design, and manufacturing; constructive solid geometry and the CSG tree; octree representation and applications; surface representations and intersections; boundary representation and boundary evaluation; applied computational geometry; analysis of geometrical algorithms and associated data structures; applications of geometrical modeling in vision and robotics.

MECE E4502x Computational geometry for CAD/CAM
3 pts. Lect: 3. Professor Rajan.
Prerequisite: COMS W1005 FORTRAN or PASCAL. Analysis of geometric problems and the design of efficient methodologies to obtain solutions to these problems. Algorithms to be studied include geometric searching, convex hulls, triangulations, Voronoi diagrams, intersections,

hidden surfaces. Emphasis will be on practical aspects of these algorithms, and on applications of the solutions in computer-aided product design and manufacturing.

EEME E4601y Digital control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: EEME E3601 or ELEN E3201. Real-time control using digital computers. Solving scalar and state-space difference equations. Discrete equivalents of continuous systems fed by holds. Z-transer functions. Creating closed-loop difference equation models by Z-transform and state variable approaches. The Nyquist frequency and sample rate selection. Classical and modern based digital control laws. Digital system identification.

MECE E4602x Introduction to robotics
3 pts. Lect: 3. Professor Ciocarlie.
Overview of robot applications and capabilities. Linear algebra, kinematics, statics, and dynamics of robot manipulators. Survey of sensor technology: force, proximity, vision, compliant manipulators. Motion planning and artificial intelligence; manipulator programming requirements and languages.

MECE E4604x Product design for manufacturability
3 pts. Lect: 3. Professor Walker.
Prerequisites: Manufacturing process, computer graphics, engineering design, mechanical design. General review of product development process; market analysis and product system design; principles of design for manufacturing; strategy for material selection and manufacturing process choice; component design for machining; casting; molding; sheet metal working and inspection; general assembly processes; product design for manual assembly; design for robotic and automatic assembly; case studies of product design and improvement.

MECE E4606y Digital manufacturing
3 pts. Lect: 3. Professor Lipson.
Prerequisite: Basic programming in any language. Additive manufacturing processes, CNC, Sheet cutting processes, Numerical control, Generative and algorithmic design. Social, economic, legal, and business implications. Course involves both theoretical exercises and a hands-on project.

MECE E4609y Computer-aided manufacturing
3 pts. Lect: 3. Professor Walker.
Prerequisites: Introductory course on manufacturing processes and knowledge of computer-aided design, and mechanical design or instructor's permission. Computer-aided design, free-form surface modeling, tooling and fixturing, computer numeric control, rapid prototyping, process engineering, fixed and programmable automation, industrial robotics.

MECE E4610x Advanced manufacturing processes
3 pts. Lect: 3. Professor Yao.
Prerequisites: Introductory course on manufacturing processes, and heat transfer, knowledge of engineering materials, or instructor's permission. Principles of nontraditional manufacturing, nontraditional transport and media. Emphasis on laser assisted materials processing, laser material interactions with applications to laser material removal, forming, and surface modification. Introduction to electrochemical machining, electrical discharge machining and abrasive water jet machining.

BMME E4702x Advanced musculoskeletal biomechanics
3 pts. Lect: 3. Professor Guo.
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joints kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

MEBM E4703x Molecular mechanics in biology
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: ENME E3105, APMA E2101, or instructor's permission. Mechanical understanding of biological structures including proteins, DNA and RNA in cells and tissues. Force response of protenis and DNA, mechanics of membranes, biophysics of molecular motors, mechanics of protein-protein interactions. Introduction to modeling and simulation techniques, and modern biopohysical techniques such as single molecule FRET, optical traps, AFM, and superresolution imaging, for understanding molecular mechanics and dynamics.

MEIE E4810y Introduction to human spaceflight
3 pts. Lect: 3. Professor Massimino.
Prerequisites: Department permission and knowledge of MATLAB or equivalent. Introduction to human spaceflight from a systems engineering perspective. Historical and current space programs and spacecraft. Motivation, cost, and rationale for human space exploration. Overview of space environment needed to sustain human life and health, including physiological and psychological concerns in space habitat. Astronaut selection and training processes, spacewalking, robotics, mission operations, and future program directions. Systems integration for successful operation of a spacecraft. Highlights from current events and space research, Space Shuttle, Hubble Space Telescope, and International Space Station (ISS). Includes a design project to assist International Space Station astronauts.

MECE E4990x or y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: Permission of the instructor. Topics and Instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

MECE E4999x and y Fieldwork
1 pt. Professor Kysar.
Prerequisite: Instructor's written permission. Only for ME graduate students who need relevant off-campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. May not be taken for pass/fail credit or audited. International students must consult with the International Students and Scholars Office.

MECE E6100x Advanced mechanics of fluids
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: MATH E1210 and MECE E3100. Eulerian and Lagrangian descriptions of motion. Stress and strain rate tensors, vorticity, integral and differential equations of mass, momentum, and energy conservation. Potential flow.

MECE E6102y Computational heat transfer and fluid flow
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E3100 and E3311; COMS W1005 FORTRAN. Mathematical description of pertinent physical phenomena. Basics of finite-difference methods of discretization, explicit and implicit schemes, grid sizes, stability, and convergence. Solution of algebraic equations, relaxation. Heat conduction. Incompressible fluid flow, stream function-vorticity formulation. Forced and natural convection. Use of primitive variables, turbulence modeling, and coordinate transformations.

MECE E6103x Compressible flow
3 pts. Lect: 3. Professor Akbari.
Prerequisites: APMA E4200, MECE E3100 and E3301. Fundamental analysis of compressible flows and its applications for various sonic/ supersonic elements including supersonic airfoils/ projectiles, nozzles, and shock tubes. Steady and unsteady shock/expansion waves, oblique shock waves. Shock reflections, methods of characteristic.

MECE E6104x or y Case studies in computational fluid dynamics
3 pts. Lect: 3. Instructor to be announced.
Prerequisites: APAM E4200 and MECE E6100. Corequisites: APAM E4300 and MECE E4400. Hands-on case studies in computational fluid dynamics, including steady and transient flows, heat and mass transfer, turbulence, compressible flow and multiphase flow. Identifying assumptions, computational domain selection, model creation and setup, boundary conditions, choice of convergence criteria, visualization and interpretation of computed results. Taught in the Mechanical Engineering Computer Laboratory with Computational Fluid Dynamics software.

MECE E6105y Transport phenomena in the presence of interfaces
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E3301 Thermodynamics and MECE E3311 Heat transfer; MECE E4100

Mechanics of fluids, or equivalent or instructor's permission; CHEE E4252 Introduction to surface and colloid chemistry, or the equivalent, or the instructor's permission. Surface energy and capillary phenomena. Wetting and spreading of liquids, wetting line pinning and hysteresis, dynamics of wetting. Surfactants. Bubbles: nucleation, stability, dynamics, microstreaming. Jets and Drops: generation, dynamics, stability and impact with surfaces. Measurement of transport phenomena involving interfaces. Interfacial transport phenomena involvng thermal, chemical or electrical gradients. Applications in microfluidic systems.

MECE E6200y Turbulence
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MECE E6100. Introductory concepts and statistical description. Kinematics of random velocity fields, dynamics of vorticity, and scalar quantities. Transport processes in a turbulent medium. Turbulent shear flows: deterministic and random structures. Experimental techniques, prediction methods, and simulation.

MEBM E6310x-E6311y Mixture theories for biological tissues, I and II
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MECE E6422 and APMA E4200 or equivalent. Development of governing equations for mixtures with solid matrix, interstitial fluid, and ion constituents. Formulation of constitutive models for biological tissues. Linear and nonlinear models of fibrillar and viscoelastic porous matrices. Solutions to special problems, such as confined and unconfined compression, permeation, indentation and contact, and swelling experiments.

MECE E6313x Advanced heat transfer
3 pts. Lect: 3. Professor Naraghi.
Prerequisites: MECE E3311. Corequisites: MECE E6100. Application of analytical techniques to the solution of multidimensional steady and transient problems in heat conduction and convection. Lumped, integral, and differential formulations. Topics include use of sources and sinks, laminar/turbulent forced convection, and natural convection in internal and external geometries.

MECE E6400y Advanced machine dynamics
3 pts. Lect: 3. Professor Chbat.
Prerequisite: MECE E3401. Review of classical dynamics, including Lagrange's equations. Analysis of dynamic response of high-speed machine elements and systems, including mass-spring systems, cam-follower systems, and gearing; shock isolation; introduction to gyrodynamics.

MECE E6422x–E6423y Introduction to the theory of elasticity, I and II
3 pts. Lect: 3. Professors Ateshian and Kysar.
Corequisite: APMA E4200. Analysis of stress and strain. Formulation of the problem of elastic equilibrium. Torsion and flexure of prismatic bars. Problems in stress concentration, rotating disks, shrink fits, and curved beams; pressure vessels, contact and impact of elastic bodies, thermal stresses, propagation of elastic waves.

MECE E6424x Vibrations in machines, I
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: MECE E3401. Review of vibration analysis of systems and mechanisms with one degree of freedom. Natural frequencies. Forced vibrations. Effects of dry and viscous friction. Energy methods of Rayleigh and Ritz. Suppression and elimination of vibration. Vibration isolation. Measuring instruments. Critical speeds in machinery. Synchronous whirl. Half-frequency whirl. Influence of bearing characteristics on critical speeds. Effect of gyroscopic moments. Systems with multiple degrees of freedom. Dynamic vibration absorbers. Self-tuning absorbers of pendulum and roller types. Lagrangian equations of motion as applied to vibrating systems. General equations for transverse critical speeds of shafts. Surging of helical springs.

MEEM E6432y Small-scale mechanical behavior
3 pts. Lect: 3. Professor Kysar.
Prerequisites: ENME E3113 or equivalent; APMA E4200 or equivalent. Mechanics of small-scale materials and structures require nonlinear kinematics and/or nonlinear stress vs. strain constitutive relations to predict mechanical behavior. Topics include: variational calculus, deformation and vibration of beam, strings, plates, and membranes; fracture, delamination, bulging, buckling of thin films, among others. Thermodynamics of solids will be reviewed to provide the basis for a detailed discussion of nonlinear elastic behavior as well as the study of the equilibrium and stability of surfaces.

EEME E6601x Introduction to control theory
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability and observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

EEME E6602y Modern control theory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EEME E6601 or E4601 or ELEN E6201, or instructor's permission. Singular value decomposition. ARX model and state space model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear robust control, predictive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEME E6610y Optimal control theory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: EEME E6601 or E4601 or instructor's permission. Covers topics in calculus of variations, Pontryagin maximum principle, quadratic cost optimal control, predictive control, dynamic programming for optimal control, Kalman filtering, numerical methods for solution. Some applications discussed include: minimum energy subway operation (our solution saved 11% in tests on the Flushing Line, and the method was adopted by the transit authority, saving many millions of dollars per year), minimum time robot optimal control allowing one to run assembly lines faster for increased productivity.

MECE E6614x or y Advanced topics in robotics and mechanism synthesis
3 pts. Lect: 3. Professor Agrawal.
Prerequisites: APMA E2101, E3101, MECE E4602 (or COMS W4733). Recommended: MECE E3401 or instructor's permission. Kinematic modeling methods for serial, parallel, redundant, wire-actuated robots and multifingered hands with discussion of open research problems. Introduction to screw theory and line geometry tools for kinematics. Applications of homotropy continuation methods and symbolic-numerical methods for direct kinematics of parallel robots and synthesis of mechanisms. Course uses textbook materials as well as a collection of recent research papers.

MECE E6620x or y Applied signal recognition and classification
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: MATH E1210, APMA E3101, knowledge of a programming language, or permission of instructor. Applied recognition and classification of signals using a selection of tools borrowed from different disciplines. Applications include human biometrics, imaging, geophysics, machinery, electronics, networking, languages, communications, and finance. Practical algorithms are covered in signal generation, modeling, feature extraction, metrics for comparison and classification, parameter estimation, supervised, unsupervised and hierarchical clustering and learning, optimization, scaling and alignment, signals as codes emitted from natural sources, information, and extremely large-scale search techniques.

MECE E6700x Carbon nanotube science and technology
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: Knowledge of introductory solid state physics (e.g., PHYS G4018, APPH E6081, or MSAE E3103) or instructor's permission. Basic science of solid state systems. Crystal structure, electronic and phonon band structures of nanotubes. Synthesis of nanotubes and other nanomaterials. Experimental determination of nanotube structures and techniques for nanoscale imaging. Theory and measurement of mechanical, thermal, and electronic properties of nanotubes and nanomaterials. Nanofabrication and nanoelectronic devices. Applications of nanotubes.

MECE E6710y Nanofabrication laboratory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: ELEN E6945 or instructor's permission. Laboratory in techniques for fabrication at the nanometer scale. Electron-beam lithography. Plasma etching and 3D nanofabrication. Thin film deposition. Self-assembly and "bottom up" nanofabrication.

Fabrication of and testing of complete nanodevices. A lab fee of $300 is required.

MECE E6720x Nano/microscale thermal transport process
3 pts. Lect: 3. Not offered in 2015–2016.
Nano- and microscale origins of thermal transport phenomena by molecules, electrons, phonons, and photons. Quantum mechanics and statistical physics. Density of states. Kinetic theory of gases. Boltzmann transport equation (BTE), classical and quantum size effects. Landauer formalism for transport via nanostructures. Macroscopic constitutive equations from BTE. Application to electronics cooling, thermoelectric and thermophotovoltaic devices, and energy conversion.

MECE E8020x or E8021y Master's thesis
3–6 pts. Members of the faculty.
Research in an area of mechanical engineering culminating in a verbal presentation and a written thesis document approved by the thesis adviser. Must obtain permission from a thesis adviser to enroll. Recommended enrollment for two terms, one of which can be the summer. A maximum of 6 points of master's thesis may count toward an M.S. degree, and additional research points cannot be counted. On completion of all master's thesis credits, the thesis adviser will assign a single grade. Students must use a department-recommended format for thesis writing.

MECE E8100y Advanced topics in fluid mechanics
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisite: MECE E6100. This course may be taken more than once, since its content has minimal overlap between consecutive years. Selected topics from viscous flow, turbulence, compressible flow, rarefied gas dynamics, computational methods, and dynamical systems theory, non-Newtonian fluids, etc.

MECE E8501y Advanced continuum biomechanics
3 pts. Lect: 2. Professor Myers.
Prerequisite: Instructor's permission. The essentials of finite deformation theory of solids and fluids needed to describe mechanical behavior of biological tissue: kinematics of finite deformations, balance laws, principle of material objectivity, theory of constitutive equations, concept of simple solids and simple fluids, approximate constitutive equations, some boundary-value problems. Topics include one- and two-point tensor components with respect to generalized coordinates; finite deformation tensors, such as right and left Cauchy-Green tensors; rate of deformation tensors, such as Rivlin-Ericksen tensors; various forms of objective time derivatives, such as co-rotational and convected derivatives of tensors; viscometric flows of simple fluids; examples of rate and integral type of constitutive equations.

EEME E8601y Advanced topics in control theory
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: EEME E6601 and E4601 or instructor's permission This course may be taken more than once, since the content changes from year to year, electing different topics from control theory such as learning and repetitive control, adaptive control, system identification, Kalman filtering, etc.

MECE E8990x and y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: Instructor's permission. This course may be taken for credit more than once. The instructor from the Mechanical Engineering Department and the topics covered in the course will vary from year to year. This course is intended for students with graduate standing in Mechanical Engineering and other engineering and applied sciences.

MECE E9000x-E9001y and E9002s Graduate research and study
1–3 pts. Members of the faculty.
Theoretical or experimental study or research in graduate areas in mechanical engineering and engineering science.

MECE E9500x and y Graduate seminar
0 pts. Pass/fail only. Instructor to be announced.
All doctoral students are required to complete successfully four semesters of the mechanical engineering seminar MECE E9500.

MECE E9800x and y Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in mechanical engineering must register for 12 points of doctoral research instruction. Registration in MECE E9800 may not be used to satisfy the minimum residence requirement for the degree.

MECE E9900x and y Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after his/her course work has been completed and until the dissertation has been accepted.

Undergraduate Minors

Undergraduate minors are designed to allow engineering and applied science students to study, to a limited extent, a discipline other than their major. Besides engineering minors offered by Columbia Engineering departments, liberal arts minors are also available.

A minor requires at least 15 points of credit, and no more than one course can be taken outside of Columbia or met through AP or IB credit. This includes courses taken through study abroad. In Engineering departments with more than one major program, a minor in the second program may be permitted, if approved by the department.

No substitutions or changes of any kind from the approved minors are permitted (see lists below). No appeal for changes will be granted. Please note that the same courses may not be used to satisfy the requirements of more than one minor. No courses taken for pass/fail may be counted for a minor. Minimum GPA for the minor is 2.0. Departments outside the Engineering School have no responsibility for nonengineering minors offered by Engineering.

For a student to receive credit for a course taken while studying abroad, the department offering the minor must approve the course in writing, ahead of the student's study abroad.

Students must expect a course load that is heavier than usual. In addition, unforeseen course scheduling changes, problems, and conflicts may occur. The School cannot guarantee a satisfactory completion of the minor.

Students interested in establishing a new minor should consult with the Associate Dean of Undergraduate Student Affairs.

MINOR IN ANTHROPOLOGY

1. **ANTH V1002:** The interpretation of culture (3)
   or ANTH V1008: The rise of civilization (3)

Note: V1002 serves as a preview to sociocultural anthropology, while V1008 serves as a preview to archaeology.

2–5. Any four courses in the Anthropology department, in ethnomusicology, or taught by an Anthropology instructor, regardless of department. No distribution requirement.

MINOR IN APPLIED MATHEMATICS

Prospective students should consult the first- and second-year requirements for applied mathematics majors to ensure that prerequisites for the applied mathematics minor are satisfied in the first two years.

Course work counting toward the applied mathematics minor may not include advanced placement credits. Any substitutions for the courses listed below require the approval of the applied mathematics program adviser.

1. **APMA E3101:** Linear algebra (3)
   or MATH V2010: Linear algebra (3)

2. **APMA E3102:** Partial differential equations (3)
   or MATH V3028: Partial differential equations (3)

3–5. Three of the following courses:
APMA E4300: Intro to numerical methods (3)
APMA E4204: Func of complex variable (3)
APMA E4101: Intro to dynamical systems (3)
MATH V2500: Analysis and optimization (3)
SIEO W4150: Intro to probability and statistics (3)
STAT W4107: Statistical inference (3)
or any other course designated *APMA, MATH, STAT, IEOR,* or *COMS* that is approved by the applied mathematics program adviser.

MINOR IN APPLIED PHYSICS

Prospective students should consult the first- and second-year requirements for applied physics majors to ensure that prerequisites for the applied physics minor are satisfied in the first two years.

Course work counting toward the applied physics minor may not include advanced placement credits.

1. **APPH E4901:** Problems in applied physics (1)

2. **APPH E3200:** Mechanics (3)

3. **APPH E3100:** Intro to quantum mechanics (3)

4. **APPH E3300:** Applied electromagnetism (3)

5. **MSAE E3111:** Thermodynamics, kinetic theory, and statistical mechanics (3)

6. **Two of the following courses**
   APPH E4010: Intro to nuclear science (3)
   APPH E4100: Quantum physics of matter (3)
   APPH E4110: Modern optics (3)
   APPH E4112: Laser physics (3)
   APPH E4300: Applied electrodynamics (3)
   APPH E4301: Intro to plasma physics (3)

MINOR IN ARCHITECTURE

1. **Studio: One of the following courses**
   ARCH V1020: Intro to architectural design and visual culture (3)
   ARCH V3101: Abstraction (4)
   ARCH V3103: Perception (4)

2–4. History/theory courses *(see Note below)*

5. Elective: must be either an approved second design studio or an additional history/theory course

Note: A list of the approved history/theory courses is available at the departmental office each semester.

MINOR IN ART HISTORY

1–7. Seven courses in art history, covering four of the following areas: (a) ancient Mediterranean, (b) medieval Europe, (c) Renaissance and baroque, (d) 18th, 19th, and 20th century, and (e) non-Western

MINOR IN BIOMEDICAL ENGINEERING

The Biomedical Engineering program offers a minor that consists of the following six courses. Participation in the minor is subject to the approval of the major program adviser.

1. **BIOL C2005:** Introduction to biology, I (3)
2. **BIOL C2006:** Introduction to biology, II (3)
2. **BMEN E3010:** Biomedical engineering, I (3)
2. **BMEN E3020:** Biomedical engineering, II (3)
2. **BMEN E4010:** Quantitative physiology (3)
2. **BMEN E4020:** Quantitative physiology, II (3)

MINOR IN CHEMICAL ENGINEERING

Of the six courses required, at least three must have the *CHEN*, *CHEE,* or *CHAP* designator:

1. CHEN E2100: Intro to chemical engineering (3)

2. CHEE E3010: Prin of chemical engineering thermodynamics (3)
or MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)
or MECE E3301: Thermodynamics (3)
or BMEN E4210: Thermodynamics of biological systems (3)

3. CHEN E3110: Transport phenomena, I (3)
or EAEE E4900: Applied transport and chemical rate phenomena (3)
or MECE E3100: Intro to mech of fluids (3)
or ENME E3161: Fluid mechanics (4)
or BMEN E3220: Fluid biomechanics (4)

4. CHEN E4230: Reaction kinetics and reactor design (3)

5–6. Two of the following courses:
Any 3000-level or higher *BMCH, CHEN, CHAP,* or *CHEE* course
APMA E3101: Linear algebra (3)
APMA E3102: Partial differential equations (3)
BMEN E3320: Fluid biomechanics (3)
BMEN E4001: Quantitative physiology, I (3)
BMEN E4002: Quantitative physiology, II (3)
ELEN E3201: Circuit analysis (3.5)
ELEN E3331: Electronic circuits (3)
SIEO W3600: Intro to probability and statistics (4)
IEOR W4105: Probability (3)
IEOR W4106: Stochastic models (3)
MSAE E3103: Elements of mat sci (3)
MSAE E3142: Ceramics and polymers (3)

MINOR IN CIVIL ENGINEERING

1. CIEN E3121: Structural analysis (3)
or ENME E3161: Fluid mechanics (4)
or MECE E3100: Intro to mech of fluids (3)

2. ENME E3105: Mechanics (4)

3. ENME E3113: Mechanics of solids (3)

4–6. Electives: Three of the following courses:
CIEN E1201: Design of buildings, bridges, and spacecraft (3)
ENME E3161: Fluid mechanics (4)
ENME E3114: Exp mechanics of materials (4)
ENME E3332: A first course in finite elements (3)
MECE E3414: Adv strength of materials (3)
CIEN E3125: Structural design (3)
CIEN E4241: Geotech eng fundamentals (3)
CIEE E3250: Hydrosystems engineering (3)
CIEE E4163: Environ eng: wastewater (3)
CIEN E3129: Project mgmt for construction (3)
CIEN E4131: Prin of construction tech (3)

MINOR IN COMPUTER SCIENCE

Students who pass the Computer Science Advanced Placement Exam, either A or AB, with a 4 or 5 will receive 3 points and exemption from *COMS W1004.* Taking *COMS W1007* is recommended but not required for those students exempt from *COMS W1004*. Participation in the minor is subject to the approval of the major program adviser. For further information, please see the QuickGuide at cs.columbia.edu/education/undergrad/seasguide.

1. COMS W1004: Intro to computer science and programming in Java (3)
or COMS W1007: Honors intro to comp sci (3)

2. COMS W3134: Data structures in Java (3)
or COMS W3137: Honors data structures and algorithms (4)

3. COMS W3157: Advanced programming (4)

4. COMS W3203: Discrete mathematics (3)

5. COMS W3261: Comp science theory (3)

6. CSEE W3827: Fund of computer systems (3)
or a 4000-level *COMS* technical elective

7. COMS W3251: Comp linear algebra (3)
or COMS W3210: Scientific computation (3)
or SIEO W3600 (or W4150): Intro to probability and statistics (3)

MINOR IN DANCE

The dance minor consists of five 3-point courses. Please note that no performance/choreography courses below count toward the nontech requirement for Engineering students.

1–2. History/criticism: Two of the following:
DNCE BC2565: World dance history (3)
DNCE BC2570: Dance in New York City (3)
DNCE BC2575: Choreography for the American musical (3)
DNCE BC3000: From the page to the dance stage (3)
DNCE BC3001: Western theatrical dance from the Renaissance to the 1960s (3)
DNCE BC3200: Dance in film (3)
DNCE BC3567: Dance in Asia (3)
DNCE BC3570: Latin American and Caribbean dance (3)
DNCE BC3574: Seminar on contemporary choreographers and their works (3)
DNCE BC3576: Dance criticism (3)
DNCE BC3577: Performing the political (3)
DNCE BC3578: Traditions of African-American dance (3)

3–4. Performance/choreography: Two of the following:
DNCE BC2563: Dance composition: form (3)
DNCE BC2564: Dance composition: content (3)
DNCE BC2567: Music for dance (3)
DNCE BC2580: Tap as an American art form (3)
DNCE BC3565: Composition: collaboration and the creative process (3)
DNCE BC3601-3604: Rehearsal and performance in dance (1–3)

5. One elective

MINOR IN EARTH AND ENVIRONMENTAL ENGINEERING

1–3. Three of the following courses:
EAEE E3103: Energy, minerals, and mat syst (3)
CIEE E3255: Environmental control and pollution reduction systems (3)
EAEE E4001: Industrial ecology of Earth res (3)
EAEE E4003: Intro to aquatic chemistry (3)
EAEE E4004: Physical processing and recovery of solids (3)
EAEE E4006: Field methods for environ eng (3)
EAEE E4009: GIS for resource, environment, and infrastructure management (3)
EAEE E4150: Air pollution prevention and control (3)
EAEE E4160: Solids and hazardous waste management (3)
EAEE E4200: Prod of inorganic materials (3)
EAEE E4257: Environ data analysis and modeling (3)
EAEE E4361: Econ of Earth res industries (3)
EACE E4560: Particle technology (3)

4–6. Three of the following courses:
CHEE E3010: Prin of chemical engineering thermodynamics (3)
CHEE E3110: Transport phenomena, I (3)
CIEN E3141: Soil mechanics (3)
CIEE E3250: Hydrosystems engineering (3)
SIEO W3600: Intro to probability and statistics (4)

ECIA W4100: Mgmt and dev of water systems (3)
CIEE E4163: Environ eng: wastewater (3)
EAEE E4190: Photovoltaic systems eng (3)
MECE E4211: Energy: sources and conv (3)
CIEN E4250: Waste contain design and prac (3)
CHEE E4252: Intro to surface and colloid chem (3)
CIEE E4252: Environmental engineering (3)
CIEE E4257: Groundwater contaminant transport and remediation (3)
CHEN E4410: Environmental control technology (3)

MINOR IN EAST ASIAN STUDIES

1–5. Any two of the survey courses on Chinese, Japanese, Korean, or Tibetan civilization (ASCE V2359, V2361, V2363, V2365), plus three elective courses dealing with East Asia. The elective courses may be taken in departments outside of East Asian Languages and Cultures. The minor does not include a language requirement. However, one semester of an East Asian language class may be used to fulfill one of the three electives, as long as at least two semesters of that language have been taken. Placement exams may not be used in place of these courses.

MINOR IN ECONOMICS

1. **ECON W1105:** Principles of economics (4)
2. **ECON W3211:** Intermediate microeconomics (3)
3. **ECON W3213:** Intermediate macroeconomics (3)
4. **ECON W3412:** Introduction to econometrics (3)

Note: W1105 is a prerequisite for *W3211, W3213,* and *W3412.* Students must have completed Calculus I before taking *W3213,* Calculus III before taking *W3211,* and one of the introductory statistics courses (see list) before taking *W3412.*

5–6. Electives: Two of the following courses:
ECON W2257: Global economy (3)
ECON V3025: Financial economics (3)
ECON V3265: Econ of money and banking (3)
ECON W4020: Econ of uncertainty and info (3)
ECON W4080: Globalization, incomes and inequality (3)
ECON W4211: Advanced microeconomics (3)
ECON W4213: Advanced macroeconomics (3)
ECON W4228: Urban economics (3)
ECON G4235: Historical foundations of modern economics (3)
ECON W4251: Industrial organization (3)
ECON W4280: Corporate finance (3)
ECON G4301: Economic growth and develop (3)
ECON W4321: Economic development (3)
ECON W4329: Economics of sustainable development (3)
ECON W4345: World economic problems (3)
ECON W4370: Political economy (3)
ECON W4400: Labor economics (3)
ECON W4412: Advanced econometrics (3)
ECON W4415: Game theory (3)
ECON W4438: Economics of race in the U.S. (3)
ECON W4457: Industrial organization of art, entertainment and communications (3)
ECON W4465: Public economics (3)
ECON W4480: Gender and applied economics (3)
ECON W4490: Economics of the Internet (3)
ECON W4500: International trade (3)
ECON W4505: Int'l monetary theory and policy (3)
ECON W4615: Law and economics (3)
ECON W4625: Economics of the environment (3)
ECON W4750: Globalization and its risks (3)

Note: Electives may be taken only after the completion of both *W3211* and *W3213,* with the exception of *W2257,* which may be taken after completion of *W1105.* Some of the elective courses listed above have additional prerequisites. Courses may be taken only after the completion of all prerequisites. Please see the Columbia College bulletin for course descriptions and complete lists of prerequisites.

7. Statistics: One of the following three probability and statistics options (course or sequence):
   a. SIEO W3600 (or W4150): Intro to probability and statistics
   b. IEOR E3658: Probablity **and E4307:** Applied statistical models
   c. STAT W3105 (or W4105): Intro to probability and statistics **and STAT W3107 (or W4107):** Stat inference

Notes:
- The statistics course must be finished before taking *W3412,* and it is recommended that students take *W3412* in the semester following the statistics course.
- Some courses done as part of the economics minor may count toward fulfilling the School's nontechnical requirements. However, other courses, such as *W3412: Intro to econometrics,* may not be applied toward satisfaction of the nontechnical course requirements. To determine which economic class can count toward the nontech elective requirement, please consult the nontech elective section of this bulletin for further details.
- Students with AP credit for economics and an exemption for *W1105* may use the credit toward the minor.
- Transfer or study abroad credits may not be applied to fulfill the requirements of the economics minor.

MINOR IN ELECTRICAL ENGINEERING

1. **ELEN E1201:** Intro to electrical eng (3.5)
   (May be replaced by a similar course or roughly equivalent experience)
2. **ELEN E3201:** Circuit analysis (3.5)
3. **CSEE W3827:** Fund of computer systems (3)
4. **ELEN E3081 and ELEN E3082:** Electrical engineering labs (2)
5. **ELEN E3801:** Signals and systems (3.5)
6. **ELEN E3106:** Solid-state dev and mat (3.5)
   or ELEN E3401: Electromagnetics (4)

Note: Not available to computer engineering majors

MINOR IN ENGINEERING MECHANICS

1. **ENME E3105:** Mechanics (4)
2. **ENME E3113:** Mechanics of solids (3)
3. **ENME E3161:** Fluid mechanics (4)
   or MECE E3100: Intro to mech of fluids (3)

4–6. Electives: Three of the following:
ENME E3106: Dynamics and vibrations (3)
ENME E3114: Exp mechanics of materials (4)
or MECE E3414: Adv strength of materials (3)
CIEN E3121: Structural analysis (3)
ENME E4202: Advanced mechanics (3)
ENME E4113: Advanced mechanics of solids (3)
ENME E4114: Mech of fracture and fatigue (3)
ENME E4214: Theory of plates and shells (3)
ENME E4215: Theory of vibrations (3)
MECE E3301: Thermodynamics (3)

MINOR IN ENGLISH AND COMPARATIVE LITERATURE

1–5. Any five courses in the English Department with no distribution requirement. No speech courses, only one writing course as above and excluding ENGL C1010, may be taken; total 15 points.

MINOR IN ENTREPRENEURSHIP AND INNOVATION

Minimum: 15 points

1–2. Required courses:
IEOR E2261: Intro to acct and finance (3)
and IEOR E4998: Managing technological innovation and entrepreneurship (3)

3–5. Electives: Three of the following courses:
BIOT W4180: Entrepreneurship in biotech (3)
BMEN E3998: Projects in biomedical eng (3)
BUSI W3021: Marketing management (3)
CHEN E4020: Protection of industrial and intellectual property (3)
CIEN E4136: Global entrepreneurship in civil engineering (3)
COMS W4444: Program and problem solving (3)

COMS W4460: Principles of innovation in biotechnology (3)
ECON E4280: Corporate finance (3)
IEOR E4003: Industrial economics (3)
IEOR E4510: Project management (3)
IEOR E4550: Entrepreneurial business creation for engineers (3)
IEOR E4573: Design and agile project management (3)
(Fall semester by application only)
IEOR E4573: Lean LaunchPad (3)
(by application only with adviser approval)
IEOR E4705: Studies in operations research (3)
IEME E4310: The manufacturing enterprise (3)

MINOR IN FRENCH

1–2. FREN W3333: Major literary works to 1800 (3)
and W3334: Major literary works since 1800 (3)

3–5. Three additional courses in French beyond satisfaction of the language requirement

MINOR IN FRENCH AND FRANCOPHONE STUDIES

Required: 15 points beyond second-year French

1–2. FREN W3420 and W3421: Intro to French and francophone studies, I and II (3, 3)

3–5. Three additional courses in French beyond satisfaction of the language requirement

MINOR IN GERMAN

Required: 15 points beyond second-year German

1. GERM V3001 or V3002: Adv German, I or II (3)

2. GERM W3333: Intro to German literature (3)

3. One of the period survey courses in German literature and culture, GERM W3442, W3443, W3444, W3445

4–5. Two courses taken from any 3000/4000-level German or CompLit-German courses taught in German or English

MINOR IN GREEK OR LATIN

1–4. A minimum of 13 points in the chosen language at the 1200 level or higher

5. 3 points in ancient history of the appropriate civilization

MINOR IN HISPANIC STUDIES

1. SPAN W3300: Adv language through content (3)

2. SPAN W3330: Intro to the study of Hispanic cultures (3)

3-4. SPAN W3349 and W3350: Hispanic cultures, I and II (3, 3)

5. One additional 3000-level elective course in the Department of Latin American and Iberian Cultures

Note: Please see the director of undergraduate studies in the Department of Latin American and Iberian Cultures for more information and to declare the minor.

MINOR IN HISTORY

1–5. Minimum 15 points in the History Department with no distribution or seminar requirements. Transfer or study-abroad credits may not be applied.

MINOR IN INDUSTRIAL ENGINEERING

1. SIEO W3600: Intro to probability and statistics (4)
or W4150: Intro to probability and statistics (3)

2. IEOR E3608: Intro to math programming (4)
or E4004: Intro to operations research: deterministic models (3)

3. IEOR E3402: Production inventory planning and control (4)

4. IEOR E4003: Industrial economics (3)

5–6. Electives: Two IEOR courses of interest and approved by a faculty adviser

Note: In addition to the required courses, students majoring in operations research and its concentrations (EMS or FE) minoring in industrial engineering must take three industrial engineering courses that are not used to satisfy the requirements of their major.

MINOR IN MATERIALS SCIENCE AND ENGINEERING

1–5. Any five MSAE E3000 or MSAE E4000-level courses, excluding MSAE E3900 (Undergraduate research), and MSAE E3156, E3157 (Design project), and MSAE E4301 (Materials science laboratory).

MINOR IN MECHANICAL ENGINEERING

1–4. Four of the following courses:
MECE E3100: Intro to mechanics of fluids (3)
or ENME E3161: Fluid mechanics (4)
or CHEN E3110: Transport phenomena, I (3)
or EAEE E4900: App transport and chemical rate phenomena (3)
ENME E3105: Mechanics (4)
MECE E3301: Thermodynamics (3)
or CHEE E3010: Principles of chemical engineering thermodynamics (3)
or MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)
ENME E3113: Mechanics of solids (3)
MECE E3408: Comp graphics and design (3)
MECE E3311: Heat transfer (3)
MECE E3610: Materials and processes in manufacturing (3)
MECE E3409: Machine design (3)
EEME E3601: Classical control systems (3)

5–6. Electives: Two additional mechanical engineering courses from either the above list or the following (not all courses in this list are given every year):
MECE E3401: Mechanics of machines (3)
MECE E4058: Mechatronics and embedded microcomputer control (3)
MECE E4100: Mechanics of fluids (3)
MECE E4211: Energy: sources and conversion (3)
MECE E4212: Microelectromechanical sys (3)
MECE E4302: Advanced thermodynamics (3)
MECE E4404: Tribology (3)
MECE E4501: Geometrical modeling (3)
MECE E4502: Comp geometry for CAD/CAM (3)
EEME E4601: Digital control systems (3)
MECE E4602: Intro to robotics (3)
MECE E4604: Product design for manufact (3)
MECE E4609: Computer-aided manufacturing (3)
MECE E4610: Adv manufacturing processes (3)

Note: Equivalent substitution courses require the approval of the Mechanical Engineering Program Adviser.

MINOR IN MIDDLE EASTERN, SOUTH ASIAN, AND AFRICAN STUDIES

1–5. Five courses, to be chosen with the approval of the MESAAS Director of Undergraduate Studies; no elementary or intermediate language courses may be counted.

MINOR IN MUSIC

1. MUSI V2318-V2319: Diatonic harmony, I and II (3, 3)

2. MUSI V1312-V1313: Intro ear training (1)

3. MUSI V2314: Ear training, I (1)

4. One of the following courses:
MUSI V3128: History of Western music, I (3)
MUSI V3129: History of Western music, II (3)

5–6. Any two electives at the 3000 or 4000 level. See also the Engineering-approved nontechnical electives in music (page 12).

Notes:
- Students must successfully place out of *MUSI V1002: Fundamentals of Western music* (3.0 points).
- Steps 4 and 5 must be completed to fulfill the nontechnical elective requirement for graduation.
- Students are strongly encouraged to take *HUMA W1123: Masterpieces of Western music* (3.0 points) from the list of nontechnical electives.

MINOR IN OPERATIONS RESEARCH

1. IEOR E3106: Stochastic models (3)
or E4106: Intro to operations research: stochastic models (3)

2. SIEO W3600: Intro to probability and statistics (4)
or W4150: Intro to probability and statistics (3)

3. IEOR E3608: Intro to math programming (4)
or E4004: Intro to operations research: deterministic models (3)

4. IEOR E4404: Simulation (4)

5–6. Electives: Two IEOR courses of interest and approved by a faculty adviser. IEOR E3402: Production-inventory planning and control is strongly recommended.

Note: In addition to the required courses, students majoring in industrial engineering must take three operations research courses that are not used to satisfy the requirements of their major.

MINOR IN PHILOSOPHY

1–5. Any five courses in the Philosophy Department with no distribution requirement; total 15 points. See also the list of exceptions under Elective Nontechnical Courses.

Note: Please be aware that some philosophy courses may not count as nontechnical electives.

MINOR IN POLITICAL SCIENCE

1–2. Two of the following courses:
POLS W1201: American govt and politics (3)
POLS V1501: Comparative politics (3)
POLS V1601: International politics (3)

3–5. Any three courses in the Political Science Department with no distribution requirement; total 9 points

MINOR IN PSYCHOLOGY

Minimum: 15 points

1. PSYC W1001: The science of psychology (3)

2–5. Any four courses from, at a minimum, two of the three groups below:

I. PERCEPTION AND COGNITION
Courses numbered in the 2200s, 3200s, or 4200s. Also PSYC W1420, W1480, or W1490

II. PSYCHOBIOLOGY AND NEUROSCIENCE
PSYC W1010: Mind, brain, and behavior (3)
Courses numbered in the 2400s, 3400s, or 4400s; also PSYC W1440

III. SOCIAL, PERSONALITY, AND ABNORMAL
Courses numbered in the 2600s, 3600s, or 4600s; also PSYC W1450 or W1455

MINOR IN RELIGION

1–5. Five courses (total 15 points), one of which must be at the 2000 level

MINOR IN SOCIOLOGY

1. SOCI W1000: The social world (3)

2. SOCI W2200: Evaluation of evidence (3)

3. SOCI W3000: Social theory (3)

4–5. Any two 2000-, 3000-, or 4000-level courses offered by the Department of Sociology; total 6 points

MINOR IN STATISTICS

1. STAT W1001: Intro to statistical reason (3)
or W1111: Intro to statistics (w/o calculus) (3)
or W1211: Intro to statistics (w/calculus) (3)

2. STAT W2024: App linear regression analysis (3)

3. STAT W2025: App statistical methods (3)

4. STAT W2026: Stat appl and case studies (3)

5. STAT W3026: Applied data mining (3)

6. STAT W3997: Independent research
or any Statistics Department offering numbered **4201** *or above.*

Notes:

- The curriculum is designed for students seeking practical training in applied statistics; students seeking a foundation for advanced work in probability and statistics should consider substituting *W3105, W3107, W3315,* and *W4606.*
- Students may, with permission of the Director of Undergraduate Studies in Statistics, substitute for courses. Students may count up to two courses toward both the Statistics minor and another Engineering major.

MINOR IN SUSTAINABLE ENGINEERING

Total of six courses from the following lists required with no substitutions allowed:

1–4. Four of the following courses:
EAEE E2002: Alternative energy sources (3)
EAEE E2100: Better planet by design (3)
CIEE 3260: Eng for developing comm (3)
EAEE E3901: Environmental microbiology (3)
EAEE E4001: Industrial ecology (3)
ECIA W4100: Mgmt and dev of water systems (3)
APPH E4130: Physics of solar energy (3)
EAEE E4190: Photovoltaic systems eng and sustainability (3)
MECE E4211: Energy sources and conversion (3)
MECE E4312: Solar thermal engineering (3)
MECE E4314: Dynamics of green buildings (3)
EESC W4404: Regional climate and climate impacts (3)

5. One of the following courses:
ECON W2257: Global economy (3)
PLAN 4151: Found of urban economic analysis (3)
PLAN 4304: Intro to housing (3)
ECON 4321: Economic development (3)
PLAN 4501: Local econ development planning (3)
ECON G4527: Econ org and develop of China (3)
PLAN 4540: Interdisciplinary planning for health (3)
PLAN 4579: Environmental planning (3)
PLAN 4609: Intro to international planning (3)
ECON W4625: Economics of the environment (3)

6. One of the following courses:
POLS V3212: Environmental politics (3)
POLS V3313: American urban politics (3)
SOCI W3235: Social movements (3)
SOCI W3670: Culture markets and consumption (3)
SOCI W4424: Global urbanism (3)

Interdisciplinary Courses and Courses in Other Divisions of the University

Of the following courses, some may be requirements for degree programs, and others may be taken as electives. See your departmental program of study or consult with an adviser for more information.

ENGI E1102x and y The art of engineering
4 pts. Lect: 4. Professor Vallancourt.
Core requirement for all entering SEAS students. This course is a bridge between the science-oriented, high school way of thinking and the engineering point of view. Fundamental concepts of math and science are reviewed and re-framed in an engineering context, with numerous examples of each concept drawn from all disciplines of engineering represented at Columbia. Non-technical issues of importance in professional engineering practice such as ethics, engineering project management, and societal impact are addressed. Lab fee: $350.

IEOR E2261x and y Introduction to accounting and finance
3 pts. Lect: 3. Professor Webster.
Prerequisite: ECON W1105. For undergraduates only. This course examines the fundamental concepts of financial accounting and finance, from the perspective of both managers and investors. Key topics covered include: principles of accrual accounting; recognizing and recording accounting transactions; preparation and analysis of financial statements, including balance sheets, income statements, cash flow statements, and statements of owners' equity; ratio analysis; pro-forma projections; time value of money (present values, future values, and interest/discount rates); inflation; discounted-cash-flow (DCF) project evaluation methods; deterministic and probabilistic measures of risk; capital budgeting. The course is targeted toward students pursuing careers in engineering, economics, finance, or business.

EEHS E3900y History of telecommunications: from the telegraph to the internet
3 pts. Lect: 3.
Historical development of telecommunications from the telegraphy of the mid-1800s to the Internet at present. Included are the technologies of telephony, radio, and computer communications. The coverage includes both the technologies themselves and the historical events that shaped, and in turn were shaped by, the technologies. The historical development, both the general context and the particular events concerning communications, is presented chronologically. The social needs that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are explained as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking principles. There are no prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective.

CHEN E4020y Protection of industrial and intellectual property
3 pts. Lect: 3. Instructor to be announced.
To expose engineers, scientists, and technology managers to areas of the law they are most likely to be in contact with during their career. Principles are illustrated with various case studies together with active student participation.

IEOR E4550x and y Entrepreneurial business creation for engineers
3 pts. Lect: 3. Professor Gulley.
Prerequisite: ENGI W2261. This course is required for undergraduate students majoring in OR:EMS. Introduces the basic concepts and methodologies that are used by the nonengineering part of the world in creating, funding, investing in, relating to, and operating entrepreneurial ventures. The first half of the course focuses on the underpinning principles and skills required in recognizing, analyzing, evaluating, and nurturing a business idea. The second half focuses on basic legal knowledge necessary in creating a business entity, defending your business assets, and in promoting effective interaction with other individuals and organizations.

IEOR E4998x and y Managing technological innovation and entrepreneurship
3 pts. Lect: 3. Professor Neumann.
Focus on the management and consequences of technology-based innovation. Explores how new industries are created, how existing industries can be transformed by new technologies, the linkages between technological development and the creation of wealth, and the management challenges of pursuing strategic innovation.

This listing of courses has been selected with specific engineering program requirements in mind. For information on these courses and additional courses offered by these departments, please consult the bulletins of Columbia College, the School of Continuing Education, the School of General Studies, and the Graduate School of Arts and Sciences.

BIOLOGICAL SCIENCES

BIOL C2005x Introductory biology, I: biochemistry, genetics, and molecular biology
4 pts. Professors Chasin and Mowshowitz.
Prerequisite: one year of college chemistry, or a strong high school chemistry background. Lecture and recitation. Recommended as the introductory biology course for biology and related majors, and for premedical students. Fundamental principles of biochemistry, molecular biology, and genetics. Website: columbia.edu/cu/biology/courses/c2005.

BIOL C2006y Introductory biology, II: cell biology, development, and physiology
4 pts. Professor Mowshowitz.
Prerequisite: EEEB W2001 or BIOL C2005, or the instructor's permission. Lecture and recitation. Recommended second term of biology for majors in biology and related majors, and for premedical students. Cellular biology and development; physiology of cells and organisms. Website: columbia.edu/cu/biology/courses/c2006.

BIOL W2501x or y Contemporary biology laboratory
3 pts. Professor Hazen.
Strongly recommended prerequisite or corequisite: BIOL C2005 or F2401. Experiments focus on genetics and molecular biology, with an emphasis on data analysis and experimental techniques. The class also includes a study of mammalian anatomy and histology. Each section is limited to 28 students. Lab fee: $150.

BIOC C3501 Biochemistry: structure and metabolism
4 pts. Professor Stockwell.
Prerequisites: BIOL W2001 or C2005 and one year of organic chemistry. Lecture and recitation. Students wishing to cover the full range of modern biochemistry should take both BIOC C3501 and C3512. C3501 covers subject matters in modern biochemistry, including chemical biology and structural biology, discussing the structure and function of both proteins and small molecules in biological systems. Proteins are the primary class of biological macromolecules and serve to carry out most cellular functions. Small organic molecules function in energy production and creating building blocks for the components of cells and can also be used to perturb the functions of proteins directly. The first half of the course covers protein structure, enzyme kinetics and enzyme mechanism. The second half of the course explores how small molecules are used endogenously by living systems in metabolic and catabolic pathways; this part of the course focuses on mechanistic organic chemistry involved in metabolic pathways.

BUSINESS

BUSI W3021x and y Marketing management
3 pts. Lect: 3. Professor Jedidi.
Designed to provide students with an understanding of the fundamental marketing concepts and their application by business and non-business organizations. The goal is to expose students to these concepts as they are used in a wide variety of settings, including consumer goods firms, manufacturing and service industries, and small and large businesses. The course gives an overview of marketing strategy issues, elements of a market (company, customers, and competition), as well as the fundamental elements of the marketing mix (product, price, placement/ distribution, and promotion).

CHEMISTRY

Placement Exam

All students must take the placement exam during Orientation week. The results of the placement exam are used to advise students which track to pursue.

Courses of Instruction

Pre-engineering students should refer to the First Year–Sophomore Program to determine the chemistry requirements for admission to particular Junior-Senior Programs. Special attention should be given to the requirements for admission to chemical engineering, biomedical engineering, materials science and metallurgical engineering, and other related fields.

Laboratory Fee

The laboratory fee covers the cost of nonreturnable items, chemicals, and reasonable breakage. In addition, students may be charged for lab handouts and excessive breakage, for cleaning of equipment returned dirty, and for checking out late.

CHEM C1403x-C1404y General chemistry
3.5 pts. Lect: 3.5. Members of the faculty.
Prerequisites: Concurrent registration in MATH V1101; for C1404: CHEM C1403 or W1403. Preparation equivalent to one year of high school chemistry is assumed, and concurrent registration in Calculus I. Students lacking such preparation should plan independent study of chemistry over the summer or take CHEM W0001 before taking C1403. Topics include stoichiometry, states of matter, chemical equilibria, acids and bases, chemical thermodynamics, nuclear properties, electronic structures of atoms, periodic properties, chemical bonding, molecular geometry, introduction to organic and biological chemistry, solid state and materials science, polymer science and

macromolecular structures, chemical kinetics, coordination chemistry, and electrochemistry. Although C1403 and C1404 are separate courses, students are expected to take both terms sequentially. The order of presentation of topics may differ from the order presented here, and from year to year. Recitation section required.

CHEM W1500x or y General chemistry laboratory
3 pts. Lab: 3. Professors Hansen and Ulichny.
Corequisite: CHEM C1403 or W1403. Lab fee: $140. An introduction to basic techniques of modern experimental chemistry, including quantitative procedures and chemical analysis. A lab lecture section is also required for this course (W1501).

CHEM C1604x Second semester general chemistry (intensive)
3.5 pts. Professor Brus.
Prerequisite: A grade of "B" or better in CHEM C1403 or W1403 or acceptable performance on the Department placement exam. Corequisite: Calculus II. Topics include gases (kinetic theory of gases); binary collision model for chemical reactions; chemical kinetics; acid-base equilibria; thermochemistry (Thermodynamics I); spontaneous processes (Thermodynamics II); chemical bonding in polyatomic molecules. Recitation section required.

CHEM W2507x or y Intensive general chemistry laboratory
3 pts. Lab: 3. Professor Avila.
Prerequisite: CHEM C1604 or C3045. Lab fee: $140. An introduction to basic techniques and practices of modern experimental chemistry, including qualitative procedures and chemical analysis. This course differs from CHEM W1500 in its emphasis on instrumentation and methods. Students must also attend the compulsory mentoring session. Please check the Directory of Classes for details.

CHEM C3045x-C3046y Intensive organic chemistry for first-year students (lecture)
3.5 pts. Professors Breslow and Ng.
Prerequisites: A grade of 5 on the Chemistry Advanced Placement exam and an acceptable grade on the Department placement exam. Not open to students who have taken other courses in college-level chemistry. Premedical students may take CHEM C3045, C3046, and C3545 to meet the minimum requirements for admission to medical school. This course covers the same material as CHEM C3443-C3444, but is intended for students who have learned the principles of general chemistry in high school. The level of instruction is appropriate for those who have not had a college course in general chemistry. Students enrolled in CHEM C3045-C3046 are expected to enroll concurrently in CHEM W2507. Recitation section required.

CHEM C3079x-C3080y Physical chemistry, I and II
4 pts. Professors Min and Zhu.
Prerequisites: CHEM C1403 and C1404, or C1604, or C3045 and C3046; PHYS V1201-V1202 is acceptable, PHYS C1401-C1402 is recommended, or the equivalent; and MATH V1101-V1102 or V1207-V1208. Recommended corequisite: CHEM C3085-C3086. Elementary but comprehensive treatment of the fundamental laws governing the behavior of individual atoms and molecules and collections of them. C3079: The thermodynamics of chemical systems at equilibrium and the chemical kinetics of nonequilibrium systems. C3080: The quantum mechanics of atoms and molecules, the quantum statistical mechanics of chemical systems, and the connection of statistical mechanics to thermodynamics. Recitation section required.

CHEM C3085x-C3086y Physical and analytical chemistry laboratory
4 pts. Lab: 4. Professor Avila.
Prerequisite: CHEM C3085 is prerequisite for C3086. Corequisites: CHEM C3079 for CHEM C3085 and C3080 for C3080. Fee: $125 per term. Techniques of experimental physical chemistry and instrumental analysis, including infrared and ultraviolet spectrophotometry, magnetic resonance, electroanalytical methods, calorimetry, reaction kinetics, hydrodynamic methods, and applications of digital computers to the analysis of experimental data.

CHEM C3098x or y Supervised independent research
4 pts. Lab: 4. Professor Gasperov.
Prerequisite: Permission of the professor in charge for entrance and permission of the departmental representative for aggregate points in excess of 12 or less than 4. Laboratory fee: $105 per term. This course may be repeated for credit (see major and concentration requirements). Individual research under the supervision of a member of the staff. Research areas include organic, physical, inorganic, analytical, and biological chemistry.

CHEM C3443x-C3444y Organic chemistry (lecture)
3.5 pts. Professors Campos, Cornish, Doubleday, and Nuckolls.
Prerequisites: CHEM C1404 or W1404 or C1604, and C1500 or W1500. The principles of organic chemistry. The structure and reactivity of organic molecules are examined from the standpoint of modern theories of chemistry. Topics include stereochemistry, reactions of organic molecules, mechanisms of organic reactions, syntheses and degradations of organic molecules, and spectroscopic techniques of structure determination. Recitation section required.

CHEM W3543x or y Organic chemistry laboratory
3 pts. Lab: 3. Professors Ghurbanyan and Sedbrook.
Prerequisite: CHEM W1500. Corequisite: CHEM C3443 or W3343. Lab fee: $125. Students planning to take a full year of laboratory should enroll in CHEM W3543 and W3546. Techniques of experimental organic chemistry, with emphasis on understanding fundamental principles underlying the experiments in methodology of solving laboratory problems involving organic molecules.

CHEM W3545x Intensive organic chemistry laboratory
3 pts. Lab: 3. Professor Ng.
Prerequisites: CHEM C3045 and C3046 and W2507. Lab fee: $125. The course covers the same material as CHEM W3543, but is intended for those students who have taken Intensive Organic Chemistry for First-Year Students, CHEM C3045-C3046.

CHEM W3546y Advanced organic chemistry laboratory
3 pts. Lab: 3. Professor Ng.
Prerequisite: CHEM W3543 or W3545. Corequisite: CHEM C3444 or W3444. Lab fee: $125. A project laboratory with emphasis on complex synthesis and advanced techniques including qualitative organic analysis and instrumentation.

EARTH AND ENVIRONMENTAL SCIENCES

Undergraduates in the four-year course of study in the School of Engineering and Applied Science may take courses numbered up to 4999 but may enter courses of higher numbers only if

(1) the course is expressly included in the prescribed curriculum or
(2) special permission is obtained from the Department of Earth and Environmental Sciences.

EESC W1011x Earth: origin, evolution, processes, future
4 pts. Lect: 3. Lab: 1. Instructor to be announced.
Students who wish to take only the lectures should register for V1411. What is the nature of our planet and how did it form? From geochemical and geophysical perspectives we explore Earth's internal structure, its dynamical character expressed in plate tectonics, and ask if its future behavior can be known. Students who wish to take only the lectures should register for V1411.

EESC W1030x Oceanography
3 pts. Lect: 3. Professor Hoenisch.
Explore the geology of the sea floor, understand what drives ocean currents and how ocean ecosystems operate. Case studies and discussions centered on ocean-related issues facing society.

EESC W1201y Environmental risks and disasters
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: high school science and math. First-years and sophomores will have priority. An introduction to risks and hazards in the environment. Different types of hazards are

analyzed and compared: natural disasters, such as tornados, earthquakes, and meteorite impacts; acute and chronic health effects caused by exposure to radiation and toxic substances such as radon, asbestos, and arsenic; long-term societal effects due to environmental change, such as sea level rise and global warming. Emphasizes the basic physical principles controlling the hazardous phenomena and develops simple quantitative methods for making scientifically reasoned assessments of the threats (to health and wealth) posed by various events, processes, and exposures. Discusses methods of risk mitigation and sociological, psychological, and economic aspects of risk control and management. Discussion section required.

EESC W1600x Earth resources and sustainable development
3 pts. Lect: 3. Professor Kelemen.
Prerequisites: none. High school chemistry recommended. Survey of the origin and extent of mineral resources, fossil fuels, and industrial materials, that are nonrenewable, finite resources, and the environmental consequences of their extraction and use, using the textbook Earth Resources and the Environment, by James Craig, David Vaughan and Brian Skinner. This course provides an overview but includes focus on topics of current societal relevance, including estimated reserves and extraction costs for fossil fuels, geological storage of CO_2, sources and disposal methods for nuclear energy fuels, sources and future for luxury goods such as gold and diamonds, and special, rare materials used in consumer electronics (e.g., “Coltan,” mostly from Congo) and in newly emerging technologies such as superconducting magnets and rechargeable batteries (e.g., heavy rare earth elements, mostly from China). Guest lectures from economists, commodity traders and resource geologists will provide “real world” input. Discussion session required.

EESC W4001x Advanced general geology
4 pts. Lect: 3. Lab: 1. Professor Scholz.
Prerequisites: one term of college-level calculus, physics, and chemistry. A concentrated introduction to the solid Earth, its interior, and near-surface geology. Intended for students with good backgrounds in the physical sciences but none in geology. Laboratory and field trips.

EESC W4008x Introduction to atmospheric science
3 pts. Lect: 3. Professor Polvani.
Prerequisites: advanced calculus and general physics, or the instructor’s permission. Basic physical processes controlling atmospheric structure: thermodynamics; radiation physics and radiative transfer; principles of atmospheric dynamics; cloud processes; applications to Earth’s atmospheric general circulation, climatic variations, and the atmospheres of the other planets.

EESC W4009x. Chemical geology
4 pts. Offered in alternate years. Not offered in 2015–2016.
Prerequisite: physical chemistry or the instructor’s permission. Thermodynamics as applied to earth systems.

EESC W4050x Global assessment and monitoring using remote sensing
3 pts. Professor Small.
Prerequisite: Calculus I and Physics I and II. Enrollment limited to 24 students. General introduction to fundamentals of remote sensing and image analysis. Example applications in the Earth and environmental sciences are explored through the analysis of remote sensing imagery in a state-of-the-art visualization laboratory. Lab required.

EESC W4076y Geologic mapping
3 pts. Lect: 3. Professor Anders.
Prerequisite: Permission of instructor. Fieldwork on weekends in April and two weeks in mid-May, immediately following the end of examinations. Enrollment limited. Estimated expense: $250. The principles and practices of deciphering geologic history through the observation of rocks in the field, mapmaking, construction of geological cross-sections, and short written reports. Please be advised: graduating undergraduate seniors may have to miss graduation.

EESC W4085x Geodynamics
3 pts. Lect: 3. Offered in alternate years. Not offered in 2015–2016.
Prerequisites: calculus, differential equations, introductory physics. An introduction to how the Earth and planets work. The focus is on physical processes that control plate tectonics and the evolution of planetary interiors and surfaces; analytical descriptions of these processes; weekly physical model demonstrations.

EESC W4113x Introduction to mineralogy
4 pts. Not offered in 2015–2016.
Prerequisites: introductory geology or the equivalent, elementary college physics and chemistry, or the instructor’s permission. Elementary crystallography and crystal structures, optical properties of minerals, mineral associations, economic minerals. Laboratory: identification of minerals in hand specimens and use of the petrographic microscope. Lab required.

EESC W4230y Crustal deformation
3 pts. Lect: 3. Professors Holtzman and Scholz.
Prerequisites: introductory geology and one year of calculus. Recommended preparation: higher levels of mathematics. Introduction to the deformation processes in the Earth’s crust. Fundamental theories of stress and strain; rock behavior in both brittle and ductile fields; earthquake processes; ductile deformation; large-scale crustal contractional and extensional events.

EESC W4300x The Earth’s deep interior
3 pts. Lect: 3. Offered in alternate years. Professor Ekstrom.
Prerequisites: calculus, differential equations, one year of college physics, and EESC W4950 or its equivalent. An introduction to properties of the Earth’s mantle, fluid outer core, and solid inner core. Current knowledge of these features is explored, using observations of seismology, heat flow, gravity, and geomagnetism, plus information on the Earth’s bulk composition.

EESC W4600x Earth resources and sustainable development
3 pts. Lect: 3. Professor Kelemen.
Prerequisites: none. High school chemistry recommended. Survey of the origin and extent of mineral resources, fossil fuels, and industrial materials, that are nonrenewable, finite resources, and the environmental consequences of their extraction and use, using the textbook Earth Resources and the Environment, by James Craig, David Vaughan and Brian Skinner. This course provides an overview, but includes focus on topics of current societal relevance, including estimated reserves and extraction costs for fossil fuels, geological storage of CO_2, sources and disposal methods for nuclear energy fuels, sources and future for luxury goods such as gold and diamonds, and special, rare materials used in consumer electronics (e.g., “Coltan,” mostly from Congo) and in newly emerging technologies such as superconducting magnets and rechargeable batteries (e.g., heavy rare earth elements, mostly from China). Guest lectures from economists, commodity traders and resource geologists will provide “real world” input. Required recitation session.

EESC W4701y Introduction to igneous petrology
4 pts. Offered in alternate years. Instructor to be announced.
Prerequisite: introductory geology or the equivalent. Recommended preparation: EESC W4113 and knowledge of chemistry. Compositional characteristics of igneous and metamorphic rocks and how they can be used as tools to investigate earth processes. Development of igneous and metamorphic rocks in a plate-tectonic framework.

EESC W4885y The chemistry of continental waters
3 pts. Lect: 3. Offered in alternate years. Professor Anderson.
Recommended preparation: a solid background in basic chemistry. Introduction to geochemical cycles involving the atmosphere, land, and biosphere; chemistry of precipitation, weathering reactions, rivers, lakes, estuaries, and groundwaters; students are introduced to the use of major and minor ions as tracers of chemical reactions and biological processes that regulate the chemical composition of continental waters.

EESC W4924y Introduction to atmospheric chemistry
3 pts. Lect: 3. Professor Fiore.
Prerequisites: PHYS V1201, CHEM C1403, Calculus III, or equivalent or instructor’s permission. EESC V2100 preferred. Physical and chemical processes determining atmospheric composition and the implications for climate and regional air pollution. Atmospheric evolution and

human influence; basics of greenhouse effect, photolysis, reaction kinetics; atmospheric transport of trace species; stratospheric ozone chemistry; tropospheric hydrocarbon chemistry; oxidizing power, nitrogen, oxygen, sulfur, carbon, mercury cycles; chemistry-climate-biosphere interactions; aerosols, smog, acid rain. Discussion section required.

EESC W4925x Principles of physical oceanography
3 pts. Lect: 3. Professors Abernathey and Gordon.
Recommended preparation: a solid background in mathematics, physics, and chemistry. Physical properties of seawater, water masses and their distribution, sea-air interaction influence on the ocean structure, basic ocean circulation pattern, relation of diffusion and advection with respect to distribution of ocean properties, ocean tides and waves, turbulence, and introduction to ocean dynamics.

EESC W4926y Principles of chemical oceanography
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Instructor's permission for students without one year of chemistry. Course open to undergraduates with one year of chemistry. Recommended preparation: a solid background in mathematics, physics, and chemistry. Factors controlling the concentration and distribution of dissolved chemical species within the sea. Application of tracer and natural radioisotope methods to large-scale mixing of the ocean, the geological record preserved in marine sediments, the role of ocean processes in the global carbon cycle, and biogeochemical processes influencing the distribution and fate of elements in the ocean.

EESC W4930y Earth's oceans and atmosphere
3 pts. Lect: 3. Professor Abernathy.
Recommended preparation: a good background in the physical sciences. Physical properties of water and air. Overview of the stratification and circulation of Earth's oceans and atmosphere and their governing processes; ocean-atmosphere interaction; resultant climate system; natural and anthropogenic forced climate change.

EESC W4947y Plate tectonics
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: A course in solid earth geology or geophysics. Prepares students for research and oral exams with cross-disciplinary analysis of the plate-tectonic cycle. Driving forces and mantle convection, plate kinematics, magmatism, structure, thermal and chemical evolution of mid-ocean ridges and subduction zones, continental rifts and collisions, and hot spots. Includes literature readings of great debates, and emphasizes integration of geophysical, geological and geochemical observations and processes.

EESC W4949x Introduction to seismology
3 pts. Lect: 3. Not offered in 2015–2016.
Prerequisites: Solid Earth dynamics (V3201 or equivalent), differential equations (APMA E3102, E4200, or equivalent). Methods and underpinnings of seismology including seismogram analysis, elastic wafe propogation theory, earthquake sourde characterization, instrumentation, inversion of seismic data to infer Earth structure.

HUMANITIES AND SOCIAL SCIENCES

For listings of additional courses of interest to engineering students, consult the bulletins of Columbia College; the School of General Studies; the Graduate School of Architecture, Planning, and Preservation; the Graduate School of Business; and the Graduate School of Arts and Sciences.

COCI C1101x-C1102y Introduction to contemporary civilization in the West
4 pts. Lect: 4. Members of the faculty.
Taught by members of the Departments of Anthropology, Classics, English and Comparative Literature, French, German, History, Middle East and Asian Languages and Cultures, Philosophy, Political Science, Religion, Slavic Languages, and Sociology; and members of the Society of Fellows. A study in their historical context of major contributions to the intellectual traditions that underpin contemporary civilization. Emphasis is on the history of political, social, and philosophical thought. Students are expected to write at least three papers to complete two examinations, and to participate actively in class discussions.

ECON W1105x and y Principles of economics
4 pts. Professors Gulati, O'Flaherty, Salanie, and Zaniboni.
Corequisites: ECON W1155 recitation section with the same instructor. How a market economy determines the relative prices of goods, factors of production, and the allocation of resources and the circumstances under which it does it efficiently. Why such an economy has fluctuations and how they may be controlled. Recitation section required.

ENGL C1010x or y University writing
3 pts. Members of the faculty.
Teaches general techniques and strategies for academic reading and writing. Students read and discuss a range of published essays, complete regular reading and writing exercises, write several longer essays, and undertake a collaborative research and writing project designed by the class. Students placed in C1010 whose names fall in the first part of the alphabet must take the course in the fall. Students whose names fall in the second part of the alphabet take the course in the spring. The alphabet will be split somewhere between K and O. The exact place for the split will be posted before fall registration.

Global Core
The Global Core requirement asks students to engage directly with the variety of civilizations and the diversity of traditions that, along with the West, have formed the world and continue to interact in it today. Courses in the Global Core typically explore the cultures of Africa, Asia, the Americas, and the Middle East in an historical context. These courses are organized around a set of primary materials produced in these traditions and may draw from texts or other forms of media, as well as from oral sources or performance. Global Core courses fall into two categories: those that focus on a specific culture or civilization, tracing its existence across a significant span of time; and those that address a common theme or set of analytic questions comparatively (and may include Europe and the West).

HUMA C1001x-C1002y Masterpieces of Western literature and philosophy
4 pts. Lect: 4. Members of faculty.
Taught by members of the Departments of Classics, English and Comparative Literature, French, German, Italian, Middle East and Asian Languages and Cultures, Philosophy, Religion, Slavic Languages, and Spanish; and members of the Society of Fellows in the Humanities. Major works by over twenty authors, ranging in time, theme, and genre from Homer to Virginia Woolf. Students are expected to write at least two papers, to complete two examinations each semester, and to participate actively in class discussions.

HUMA W1121x or y Masterpieces of Western art
3 pts. Lect: 3. Members of faculty.
Discussion and analysis of the artistic qualities and significance of selected works of painting, sculpture, and architecture from the Parthenon in Athens to works of the 20th century.

HUMA W1123x or y Masterpieces of Western music
3 pts. Lect: 3. Members of faculty.
Popularly known as "Music Hum," this course aims to instill in students a basic comprehension of the many forms of the Western musical imagination. The course involves students actively in the process of critical listening, both in the classroom and in concerts. Although not a history of Western music, the course is taught in chronological format and includes masterpieces by Josquin des Prez, Monteverdi, Bach, Handel, Mozart, Haydn, Beethoven, Verdi, Wagner, Schoenberg, Stravinsky, Louis Armstrong, and Duke Ellington, among others.

MATHEMATICS

Courses for First-Year Students

Depending on the program, completion of Calculus III or IV satisfies the basic mathematics requirement. Normally students who have taken an AP Calculus course begin with either Calculus II or Calculus III. Refer to the AP guidelines on page 14 for placement information. The sequence ends with *MATH V2030: Ordinary differential equations.*

Students who wish to transfer from one calculus course to another are allowed to do so beyond the date specified on the Academic Calendar. They are considered to be adjusting their level, not changing their program. They must, however, obtain the approval of the new instructor and the Center for Student Advising before reporting to the Registrar.

MATH V1101x or y Calculus, I
3pts. Lect: 3.
Functions, limits, derivatives, introduction to integrals.

MATH V1102x or y Calculus, II
3 pts. Lect: 3.
Prerequisite: MATH V1101 or equivalent. Methods of integration, applications of integral, Taylor's theorem, infinite series.

MATH V1201x or y Calculus, III
3 pts. Lect: 3.
Prerequisite: MATH V1101 with a grade of B or better or V1102 or equivalent. Vectors in dimensions 2 and 3, complex numbers and the complex exponential function with applications to differential equations, Cramer's rule, vector-valued functions of one variable, scalar-valued functions of several variables, partial derivatives, gradients, surfaces, optimization, the method of Lagrange multipliers.

MATH V1202x or y Calculus, IV
3 pts. Lect: 3.
Prerequisite: MATH V1102, V1201, or equivalent. Multiple integrals, Taylor's formula in several variables, line and surface integrals, calculus of vector fields, Fourier series.

MATH V1207x-V1208y Honors math A-B
4 pts. Lect and recit. Professors Gallagher and Thaddeus.
Prerequisite: Score of 5 on the Advanced Placement BC calculus exam. The second term of this course may not be taken without the first. Multivariable calculus and linear algebra from a rigorous point of view.

MATH V2010 x or y Linear algebra
3 pts. Lect: 3. Professors Bayer, Maulik, and Stein.
Prerequisite: MATH V1201 or equivalent. Matrices, vector spaces, linear transformations, eigenvalues and eigenvectors, canonical forms, applications.

MATH V2030x or y Ordinary differential equations
3 pts. Lect: 3. Professors Chang-Lara, Chen, and Gorskity.
Prerequisite: MATH V1102-V1201 or the equivalent. Special differential equations of order one. Linear differential equations with constant and variable coefficients. Systems of such equations. Transform and series solution techniques. Emphasis on applications.

MATH V2500x or y Analysis and optimization
3 pts. Lect: 3. Professors Dubedat and Maulik.
Prerequisites: MATH V1102-V1201 or equivalent, and V2010. Mathematical methods for economics. Quadratic forms, Hessian, implicit functions. Convex sets, convex functions. Optimization, constrained optimization, Kuhn-Tucker conditions. Elements of the calculus of variations and optimal control.

MATH V3007y Complex variables
3 pts. Lect: 3. Professor Gautam.
Prerequisite: MATH V1202. An elementary course in functions of a complex variable. Fundamental properties of the complex numbers, differentiability, Cauchy-Riemann equations, Cauchy integral theorem, Taylor and Laurent series, poles, and essential singularities. Residue theorem and conformal mapping.

MATH V3027x Ordinary differential equations
3 pts. Lect: 3. Professor Daskalopoulos.
Prerequisite: MATH V1201 or equivalent. Corequisite: MATH V2010. Equations of order one, systems of linear equations, second-order equations, series solutions at regular and singular points, boundary value problems, selected applications.

MATH V3028y Partial differential equations
3 pts. Lect: 3. Professor Savin.
Prerequisite: MATH V3027 and V2010 or equivalent. Introduction to partial differential equations. First-order equations. Linear second-order equations, separation of variables, solution by series expansions. Boundary value problems.

MATH W4032x Fourier analysis
3 pts. Lect: 3. Professor Savin.
Prerequisites: three terms of calculus and linear algebra or four terms of calculus. Fourier series and integrals, discrete analogues, inversion and Poisson summation, formulae, convolution, Heisenberg uncertainty principle. Stress on the application of Fourier analysis to a wide range of disciplines.

MATH W4041x-W4042y Introduction to modern algebra
3 pts. Lect: 3. Professors Friedman, Gallagher, Harris, and Khovano.
The second term of this course may not be taken without the first. Prerequisites: MATH V1102-V1202 and V2010 or equivalent. *Groups, homomorphisms, rings, ideals, fields, polynominals, and field extensions, Galois theory.*

MATH W4061x-W4062y Introduction to modern analysis
3 pts. Lect: 3. Professors De Silva, Guo, and Zhang.
The second term of this course may not be taken without the first. Prerequisite: MATH V1202 or equivalent and V2010. Real numbers, metric spaces, elements of general topology. Continuous and differentiable functions. Implicit functions. Integration, change of variables. Function spaces.

MATH W4065x Honors complex variables
3 pts. Lect: 3. Professor Dubedat.
Prerequisite: MATH V1207 and V1208, or W4061. A theoretical introduction to analytic functions. Holomorphic functions, harmonic functions, power series, Cauchy-Riemann equations, Cauchy's integral formula, poles, Laurent series, residue theorem. Other topics as time permits: elliptic functions, the gamma and zeta functions, the Riemann mapping theorem, Riemann surfaces, Nevanlinna theory.

PHYSICS

The general four-term preengineering physics sequence consists of *PHYS C1401, C1402, C1403,* and *C1494 (laboratory);* or *PHYS C1601, C1602, C2601,* and *C2699 (laboratory).*

PHYS W1401x Introduction to mechanics and thermodynamics
3 pts. Lect: 2.5. Instructor to be announced.
Corequisite: MATH V1101 or equivalent. Fundamental laws of mechanics, kinematics and dynamics, work and energy, rotational dynamics, oscillations, gravitation, fluids, temperature and heat, gas laws, first and second laws of thermodynamics.

PHYS W1402y Introduction to electricity, magnetism, and optics
3 pts. Lect: 2.5. Professors Dodd, Hughes, and Zelevinsky.
Prerequisite: PHYS C1401. Corequisite: MATH V1102 or equivalent. Electric fields, direct currents, magnetic fields, alternating currents, electromagnetic waves, polarization, geometrical optics, interference and diffraction.

PHYS W1403x Introduction to classical and quantum waves
3 pts. Lect: 2.5. Professor Brooijmans.
Prerequisite: PHYS C1402. Corequisite: MATH V1201 or equivalent. Classical waves and the wave equation, Fourier series and integrals, normal modes, wave-particle duality, the uncertainty principle, basic principles of quantum mechanics, energy levels, reflection and transmission coefficients, applications to atomic physics.

PHYS W1493x Introduction to experimental physics
3 pts. Lab: 3. Instructor to be announced.
Prerequisites: PHYS C1401 and C1402. Laboratory work associated with the two prerequisite lecture courses. Experiments in mechanics, thermodynamics, electricity, magnetism, optics, wave motion, atomic and nuclear physics. (Students cannot receive credit for both PHYS C1493 and C1494.)

PHYS W1494y Introduction to experimental physics
3 pts. Lab: 3. Professor Clark.
Prerequisites: PHYS C1401 and C1402. Laboratory work associated with the two prerequisite lecture courses. Experiments in mechanics, thermodynamics, electricity, magnetism, optics, wave motion, atomic and nuclear physics. (Students cannot receive credit for both PHYS C1493 and C1494.)

PHYS W1601x Physics, I: mechanics and relativity
3.5 pts. Lect: 2.5. Professor Humensky.
Corequisite: MATH V1102 or equivalent. Fundamental laws of mechanics, kinematics and dynamics, work and energy, rotational dynamics, oscillations, gravitation, fluids, introduction to special relativity and relativistic kinematics. The course is preparatory for advanced work in physics and related fields.

PHYS W1602y Physics, II: thermodynamics, electricity, and magnetism
3.5 pts. Lect: 2.5. Professors Dodd and Zajc.
Prerequisite: PHYS C1601. Corequisite: MATH V1201 or equivalent. Temperature and heat, gas laws, the first and second laws of thermodynamics, kinetic theory of gases, electric fields, direct currents, magnetic fields, alternating currents, electromagnetic waves. The course Is preparatory for advanced work in physics and related fields.

PHYS W2601x Physics, III: classical and quantum waves
3.5 pts. Lect: 2.5. Professor Dodd.
Prerequisite: PHYS C1602 or C1402. Corequisite: MATH V1202 or equivalent. Classical waves and the wave equation, geometrical optics, interference and diffraction, Fourier series and integrals, normal modes, wave-particle duality, the uncertainty principle, basic principles of quantum mechanics, energy levels, reflection and transmission coefficients, the harmonic oscillator. The course is preparatory for advanced work in physics and related fields.

PHYS W2699y Experiments in classical and modern physics
3 pts. Lab: 3. Professor Clark.
Prerequisites: PHYS C1601 (or C1401), C1602 (or C1402), and C2601. Laboratory work associated with the three prerequisite lecture courses. Experiments in mechanics, thermodynamics, electricity, magnetism, optics, wave motion, atomic and nuclear physics.

PHYS W2801x-W2802y Accelerated physics, I and II
4.5 pts. Lect: 3.5. Rec: 1 hour weekly to be arranged. Professor Cole.
Prerequisite: Advanced placement in physics and mathematics, or equivalent, and instructor's permission. (A special placement meeting is held during Orientation.) This accelerated two-semester sequence covers the subject matter of PHYS C1601, C1602, and C2601 and is intended for students who have an exceptionally strong background in both physics and mathematics. The course is preparatory for advanced work in physics and related fields. There is no accompanying laboratory; however, students are encouraged to take the intermediate laboratory, PHYS W3081, in the following year.

PHYS W3002y From quarks to the cosmos: applications of modern physics
3.5 pts. Lect: 3.5. Not offered in 2015–2016.
Prerequisite: PHYS C2601 or C2802. This course reinforces basic ideas of modern physics through applications to nuclear physics, high-energy physics, astrophysics, and cosmology. The ongoing Columbia research programs in these fields are used as practical examples. The course is preparatory for advanced work in physics and related fields.

PHYS W3003x Mechanics
3 pts. Lect: 2.5. Professor Millis.
Prerequisites: General physics; differential and integral calculus. Newtonian mechanics, oscillations and resonance, conservative forces and potential energy, central forces, noninertial frames of reference, rigid body motion, an introduction to Lagrange's formulation of mechanics, coupled oscillators, and normal modes.

PHYS W3007y Electricity and magnetism
3 pts. Lect: 2.5. Professor Pasupathy.
Prerequisite: General physics; differential and integral calculus. Electrostatics and magnetostatics, Laplace's equation and boundary-value problems, multipole expansions, dielectric and magnetic materials, Faraday's law, AC circuits, Maxwell's equations, Lorentz covariance, and special relativity.

PHYS W3008x Electromagnetic waves and optics
3 pts. Lect: 2.5. Professor Metzger.
Prerequisite: PHYS W3007. Maxwell's equations and electromagnetic potentials, the wave equation, propagation of plane waves, reflection and refraction, geometrical optics, transmission lines, wave guides, resonant cavities, radiation, interference of waves, and diffraction.

PHYS W3018y Weapons of mass destruction
3 pts. Lect: 3. Professor Marka.
Prerequisites: high school science and math. A review of the history and environmental consequences of nuclear, chemical, and biological weapons of mass destruction (WMD); of how these weapons work, what they cost, how they have spread, how they might be used, how they are currently controlled by international treaties and domestic legislation, and what issues of policy and technology arise in current debates on WMD. What aspects of the manufacture of WMD are easily addressed, and what aspects are technically challenging? It may be expected that current events/headlines will be discussed in class.

PHYS W3081x or y Intermediate laboratory work
2 pts. Lab: 2. Members of the faculty.
Prerequisite: PHYS C2601 or C2802. Primarily for junior and senior physics majors. Other majors require the instructor's permission. May be repeated for credit by performing different experiments. The laboratory has 15 individual experiments available, of which two are required per 2 points. Each experiment is chosen by the student in consultation with the instructor. Each section meets one afternoon per week, with registration in each section limited by the laboratory capacity. Experiments (classical and modern) cover topics in electricity, magnetism, optics, atomic physics, and nuclear physics.

PHYS W3083y Electronics laboratory
3 pts. Lab: 3. Professor Parsons.
Registration is limited to the capacity of the laboratory. Corequisite or prerequisite: PHYS W3003 or W3007. A sequence of experiments in solid-state electronics, with introductory lectures.

PHYS W4003y Advanced mechanics
3 pts. Lect: 2.5. Professor Rosen.
Prerequisites: Differential and integral calculus, differential equations, and PHYS W3003 or equivalent. Lagrange's formulation of mechanics, calculus of variations and the Action Principle, Hamilton's formulation of mechanics, rigid body motion, Euler angles, continuum mechanics, Introduction to chaotic dynamics.

PHYS W4018y Solid-state physics
3 pts. Lect: 2.5. Professors Pinczuk and Uemura.
Prerequisites: PHYS G4021 and G4023, or equivalent. Introduction to solid-state physics: crystal structures, properties of periodic lattices, electrons in metals, band structure, transport properties, semiconductors, magnetism, and superconductivity.

PHYS W4019x Mathematical methods of physics
3 pts. Lect: 3. Professor Metzger.
Prerequisites: Differential and integral calculus; linear algebra; PHYS W3003 and W3007 or instructor's permission. Presents a wide variety of mathematical ideas and techniques used in the study of physical systems. Topics include: ordinary and partial differential equations, generalized functions, integral transforms, Green's functions, nonlinear equations, chaos and solitons, Hilbert space and linear operators, Feynman path integrals, Riemannian manifolds, tensor analysis, probability and statistics. Discussion of applications to classical mechanics, fluid dynamics, electromagnetism, plasma physics, quantum mechanics, and general relativity.

PHYS W4021x-W4022y Quantum mechanics, I and II
3 pts. Lect: 2.5. Professor Weinberg.
Prerequisite: PHYS C2601 or C2802, or equivalent. Formulation of quantum mechanics in terms of state vectors and linear operators, three-dimensional spherically symmetric potentials, theory of angular momentum and spin, time-independent and time-dependent perturbation theory, scattering theory, and identical particles. Selected phenomena from atomic physics, nuclear physics, and elementary particle physics are described and then interpreted using quantum mechanical models.

PHYS W4023x Thermal and statistical physics
3 pts. Lect: 2.5. Professor Denef.
Prerequisite: PHYS G4021 or equivalent. Thermodynamics, kinetic theory, and methods of statistical mechanics; energy and entropy; Boltzmann, Fermi, and Bose distributions; ideal and real gases; blackbody radiation; chemical equilibrium; phase transitions; ferromagnetism.

PHYS W4040x Introduction to general relativity
3 pts. Lect: 2.5. Professor Beloborodov.
Prerequisites: PHYS W3003 and W3007, or equivalent. Tensor algebra, tensor analysis, introduction to Riemann geometry. Motion of particles, fluid, and fields in curved spacetime. Einstein equation. Schwarzschild solution; test-particle orbits and light bending. Introduction to black holes, gravational waves, and cosmological models.

STATISTICS

Engineering students interested in a survey of the mathematical theory of probability and statistics should consider the pair *STAT W3105: Probability theory* and *W3107: Statistical inference*. Students seeking a quicker overview that focuses more on probability theory should consider *SIEO W4150. STAT W4109* (6 pts) covers the same material as *W3105* and *W3107* in a single semester. *STAT W3315: Linear regression models* takes *W3105* and *W3107* as prerequisites; like other advanced offerings in statistics, it covers both theory and practical aspects of modeling and data analysis.

STAT W4105, *W4107*, and *W4315* are the equivalent of *W3105*, *W3107*, and *W3315*, respectively; but graduate students may not register for *W3105*, *W3107*, or *W3315*.

Advanced offerings in probability theory, stochastic processes, and mathematical finance generally take *STAT W3105* as a prerequisite; advanced offerings in statistical theory and methods generally take *STAT W4107* and, in several cases, *W3315* as prerequisites; an exception is *STAT W4220: Data mining,* which has a course in computer programming as prerequisite and *STAT W3107* as corequisite. *STAT 4201* is an advanced survey of applied statistical methods.

Please note that *STAT W3000* has been renumbered as *W3105* and *STAT W3659* has been renumbered as *W3107.* For a description of the following course offered jointly by the Departments of Statistics and Industrial Engineering and Operations Research, see “Industrial Engineering and Operations Research.”

STAT W2024x Applied linear regression analysis
3 pts. Professor Feng.
Prerequisite: One of STAT W1001, W1111, or W1211. Develops critical thinking and data analysis skills for regression analysis in science and policy settings. Simple and multiple linear regression, nonlinear and logistic models, random-effects models, penalized regression methods. Implementation in a statistical package. Optional computer-lab sessions. Emphasis on real-world examples and on planning, proposing, implementing, and reporting.

STAT W2025y Applied statistical methods
3 pts. Professors Landwehr and Whalen.
Prerequisite: STAT W2024. Classical nonparametric methods, permutation tests; contingency tables, generalized linear models, missing data, causal inference, multiple comparisons. Implementation in statistical software. Emphasis on conducting data analyses and reporting the results. Optional weekly computer-lab sessions.

STAT W2026x Statistical applications and case studies
3 pts. Instructor to be announced.
Prerequisite: STAT W2025. A sample of topics and application areas in applied statistics. Topic areas may include Markov processes and queuing theory; meta-analysis of clinical trial research; receiver-operator curves in medical diagnosis; spatial statistics with applications in geology, astronomy, and epidemiology; multiple comparisons in bio-informatics; causal modeling with missing data; statistical methods in genetic epidemiology; stochastic analysis of neural spike train data; graphical models for computer and social network data.

STAT W3026x Applied data mining
3 pts. Professor Emir.
Data mining is a dynamic and fast growing field at the interface of Statistics and Computer Science. The emergence of massive datasets containing millions or even billions of observations provides the primary impetus for the field. Such datasets arise, for instance, in large-scale retailing, telecommunications, astronomy, computational and statistical challenges. This course will provide an overview of current practice in data mining. Specific topics covered include databases and data warehousing, exploratory data analysis and visualization, descriptive modeling, predictive modeling, pattern and rule discovery, text mining, Bayesian data mining, and causal inference. The use of statistical software will be emphasized.

STAT W3103x Mathematical methods for statistics
6 pts. Professor Hannah.
Prerequisite: MATH V1101 or instructor’s permission. A fast-paced coverage of those aspects of the differential and integral calculus of one and several variables and of the linear algebra required for the core courses in the Statistics major. The mathematical topics are integrated with an introduction to computing. Students seeking more comprehensive background should replace this course with MATH V1102 and V2010, and any COMS course numbered from W1003 to W1009.

STAT W3105x Introduction to probability
3 pts. Professor Lo.
Prerequisites: MATH V1101 and V1102 or equivalent. A calculus-based introduction to probability theory. A quick review of multivariate calculus is provided. Topics covered include random variables, conditional probability, expectation, independence, Bayes’ rule, important distributions, joint distributions, moment generating functions, central limit theorem, laws of large numbers and Markov’s inequality.

STAT W3107y Introduction to statistical inference
3 pts. Professor Neath.
Prerequisite: STAT W3105 or W4105, or equivalent. Calculus-based introduction to the theory of statistics. Useful distributions, law of large numbers and central limit theorem, point estimation, hypothesis testing, confidence intervals maximum likelihood, likelihood ratio tests, nonparametric procedures, theory of least squares, and analysis of variance.

STAT W3315x Linear regression models
3 pts. Professor Zheng.
Prerequisites: STAT W3107 (or W4150) and STAT W3103 (or MATH V1101, V1102, and V2110). Theory and practice of regression analysis. Simple and multiple regression, testing, estimation, prediction, and confidence procedures, modeling, regression diagnostics and plots, polynomial regression, colinearity and confounding, model selection, geometry of least squares. Extensive use of the computer to analyze data. Equivalent to STAT W4315 except that enrollment is limited to undergraduate students.

STAT W3997x and y Independent research
1 pt. Members of the faculty.
Prerequisite: Permission of a member of the department. May be repeated for credit. This course provides a mechanism for students who undertake research with a faculty member from the Department of Statistics to receive academic credit; students should only register for this course with permission of their project mentor.

SIEO W4150x and y Introduction to probability and statistics
3 pts. Members of the faculty.
Prerequisites: MATH V1101 and V1102 or equivalent. A quick calculus-based tour of the fundamentals of probability theory and statistical inference. Probabilistic models, random variables, useful distributions, expectations, laws of large numbers, central limit theorem, point and confidence interval estimation, hypothesis tests, linear regression. Students seeking a more thorough introduction to probability and statistics should consider STAT W3105 and W3107.

STAT W4201x and y Advanced data analysis
3 pts. Professors Alemayehu and Liu.
Prerequisite: STAT W4315. At least one of W4290, W4325, W4330, W4437, W4413, W4543 is recommended. This is a course on getting the most out of data. The emphasis will be on hands-on experience, involving case studies with real data and using common statistical packages. The course covers, at a very high level, exploratory data analysis, model formulation, goodness of fit testing, and other standard and nonstandard statistical procedures, including linear regression, analysis of variance, nonlinear regression, generalized linear models, survival analysis, time series analysis, and modern regression methods. Students will be expected to propose a data set of their choice for use as case study material.

STAT W4240x Data mining
3 pts. Professors Mazumder, Motta, and Rabinowitz.
Prerequisite: COMS W1003, W1004, W1005, W1007, or the equivalent. Corequisites: Either STAT W3105 or W4105, and either STAT W3107 or W4107. Data Mining is a dynamic and fast growing field at the interface of Statistics and Computer Science. The emergence of massive datasets containing millions or even billions of observations provides the primary impetus for the field. Such datasets arise, for instance, in large-scale retailing, telecommunications, astronomy, computational and statistical challenges. This course will provide an overview of current research in data mining and will be suitable for graduate students from many disciplines. Specific topics covered with include databases and data warehousing, exploratory data analysis and visualization, descriptive modeling, predictive modeling, pattern and rule discovery, text mining, Bayesian data mining, and causal inference.

STAT W4290y Statistical methods in finance
3 pts. Professors ElBarmi, Wang, and Ying.
Prerequisite: STAT W3107 or W4107. A fast-paced introduction to statistical methods used in quantitative finance. Financial applications and statistical methodologies are intertwined in all lectures. Topics include regression analysis and applications to the Capital Asset Pricing Model and multifactor pricing models, principal components and multivariate analysis, smoothing techniques and estimation of yield curves statistical methods for financial time series, value at risk, term structure models and fixed income research, and estimation and modeling of volatilities. Hands-on experience with financial data.

STAT W4315x and y Linear regression models
3 pts. Members of faculty.
Prerequisites: STAT W3107 or equivalent, MATH V1101, V1102, V2010 or permission of program adviser. Theory and practice regression analysis, simple and multiple regression, including testing, estimation and confidence procedures, modeling, regression diagnostics and plots, polynomial regression, colinearity and confounding, model selection, geometry of least squares. Extensive use of the computer to analyze data.

STAT W4325y Generalized linear models
3 pts. Professor Sobel.
Prerequisite: STAT W4315. Statistical methods for rates and proportions, ordered and nominal categorical responses, contingency tables, odds-ratios, exact inference, logistic regression, Poisson regression, generalized linear models.

STAT W4330x Multilevel models
3 pts. Instructor to be announced.
Prerequisites: STAT W4315. Theory and practice, including model-checking, for random and mixed-effects models (also called hierarchical, multi-level models). Extensive use of the computer to analyze data.

STAT W4335x Sample surveys
3 pts. Professors Ben-David and Wu.
Prerequisite: STAT W3107 or W4107. Introductory course on the design and analysis of sample surveys. How sample surveys are conducted, why the designs are used, how to analyze survey results, and how to derive from first principles the standard results and their generalizations. Examples from public health, social work, opinion polling, and other topics of interest.

STAT W4413y Nonparametric statistics
3 pts. Professors Maleki and Sen.
Prerequisite: STAT W3107 or W4107. Statistical inference without parametric model assumption. Hypothesis testing using ranks, permutations, and order statistics. Nonparametric analogs of analysis of variance. Nonparametric regression, smoothing and model selection.

STAT W4437x and y Time series analysis
3 pts. Professors Motta and Wu.
Prerequisite: STAT W4315 or equivalent. Least squares smoothing and prediction, linear systems, Fourier analysis, and spectral estimation. Impulse response and transfer function. Fourier series, the fast Fourier transform, autocorrelation function, and spectral density. Univariate Box-Jenkins modeling and forecasting. Emphasis on applications. Examples from the physical sciences, social sciences, and business. Computing is an integral part of the course.

STAT W4543y Survival analysis
Professor Shnaidman.
Prerequisite: STAT W4315. Survival distributions, types of censored data, estimation for various survival models, nonparametric estimation of survival distributions, the proportional hazard and accelerated lifetime models for regression analysis with failure-time data. Extensive use of the computer.

STAT W4606x and y Elementary stochastic processes
3 pts. Professors Brown and Wang.
Prerequisite: STAT W3105, W4105, or equivalent. Review of elements of probability theory. Poisson processes. Renewal theory. Wald's equation. Introduction to discrete and continuous time Markov chains. Applications to queueing theory, inventory models, branching processes.

STAT W4635y Stochastic processes for finance
3 pts. Professor Zhang.
Prerequisite: STAT W3105, W4105, or equivalent. This course covers theory of stochastic processes applied to finance. It covers concepts of Martingales, Markov chain models, Brownian motion. Stochastic Integration, Ito's formula as a theoretical foundation of processes used in financial modeling. It also introduces basic discrete and continuous time models of asset price evolutions in the context of the following problems in finance: portfolio optimization, option pricing, spot rate interest modeling.

STAT W4702x Statistical inference and modeling
3 pts. Professors Motta.
Prerequisites: Working knowledge of calculus and linear algebra (vectors and matrics), and STAT W4105 or equivalent. Fundamentals of statistical inference and testing, and introduction of statistical modeling. Focuses on inference and testing, covering topics such as maximum likelihood estimates, hypothesis testing, likelihood ratio test, Bayesian inference, etc. Introduction to statistical modeling via introductory lectures on linear regression models, generalized linear regression models, nonparametric regression, and statistical computing. Real-data examples used in lecture discussion and homework problems. Provides foundation for other courses in machine learning, data mining, and visualization.

STAT W4840x Theory of interest
3 pts. Professor Qadir, Szeto, and Xu.
Prerequisite: MATH V1101 or equivalent. Introduction to the mathematical theory of interest as well as the elements of economic and financial theory of interest. Topics include rates of interest and discount; simple, compound, real, nominal, effective, dollar (time)-weighted; present, current, future value; discount function; annuities; stocks and other instruments; definitions of key terms of modern financial analysis; yield curves; spot (forward) rates; duration; immunization; and short sales. The course will cover determining equivalent measures of interest; discounting; accumulating; determining yield rates; and amortization.

Campus and Student Life

The Fu Foundation School of Engineering and Applied Science attracts and admits an exceptionally interesting, diverse, and multicultural group of students, and it takes steps to provide a campus environment that promotes the continued expansion of each student's ideas and perspectives.

This begins within the residence halls, in which nearly all first-year undergraduate students live. The University assigns rooms to both Engineering and Columbia College undergraduate students, ensuring that all students will live either with or near a student attending the other program. Once students have moved into their new campus home, they will find themselves part of a residential system that offers undergraduates a network of social and academic support (more information about the residence halls can be found in the chapter "Housing and Residence Life" in this bulletin).

In addition to robust residential offerings, a blend of academic, educational, social, and cocurricular activities enhances the Columbia experience through integrated efforts of numerous units including the Center for Student Advising, Undergraduate Student Life, Parent and Family Programs, and the Office of Student Conduct and Community Standards.

While the School is large enough to support a wide variety of programs, it is also small enough to promote the close interaction among students, faculty, and administration that has created a strong sense of community on campus.

JAMES H. AND CHRISTINE TURK BERICK CENTER FOR STUDENT ADVISING

403 Lerner Hall, MC 1201
Phone: 212-854-6378
E-mail: csa@columbia.edu
cc-seas.columbia.edu/csa

The James H. and Christine Turk Berick Center for Student Advising (CSA) reflects the mission of the University in striving to support and challenge the intellectual and personal growth of its undergraduate students and by creating a developmental, diverse, and open learning environment. Individually and collaboratively, each advising dean:

- provides individual and group academic advisement, exploration, and counseling
- provides information on preprofessional studies, major declaration and completion, as well as various leadership, career, graduate school, and research opportunities
- designs and facilitates programming to meet the unique developmental needs of each class and to enhance community among students, faculty, and administrators
- interprets and disseminates information regarding University polices, procedures, resources, and programs
- educates and empowers students to take responsibility in making informed decisions
- refers students to additional campus resources

Every undergraduate is assigned an adviser from the Center for Student Advising for the duration of their undergraduate career. When each student matriculates, they are assigned to an advising dean, who specializes in the engineering field the student indicated as his or her first interest on the Columbia application. When a student declares a major, a faculty member is also appointed to advise him or her for the next two years. Depending on their chosen major, students may be assigned to a new advising dean who is a CSA liaison to their department. Advising deans regularly refer students to their academic departments to receive expert advice about their engineering course selections.

Preprofessional Advising

Preprofessional Advising works closely with other staff members of the Center for Student Advising, with faculty in the Arts and Sciences and in SEAS, as well as with the Center for Career Education to provide information for students who plan a career in law or the health professions. The office advises and assists students throughout their four years, but works most closely with students during their application year and with alumni who apply for admission after graduation. Information sheets, forms, and helpful resources are available from the Preprofessional Advising website. Students will still work with their advising deans as their primary advisers; these advisers will be instrumental in writing committee evaluations for some professional schools.

UNDERGRADUATE STUDENT LIFE

The Student Life team works to foster a vibrant and welcoming undergraduate community through organizational advising, leadership development, advocacy, diversity education, civic engagement, and community programming. The team includes Student Engagement, Multicultural Affairs, and Residential Life. Knowing that students' learning continues beyond the classroom, Columbia University strongly encourages students to become involved in programs and activities to enhance their educational experience and personal growth. A wide array of student organizations addresses both student interests and professional concerns, including the arts, politics, identity, culture, and religion. Joining such groups offers an exciting and dynamic opportunity to develop leadership skills that will serve students well throughout their lives.

Student Engagement

Student Engagement is committed to building a strong sense of campus community by helping students enhance their leadership skills, engage in their communities, and explore the cocurricular opportunities available at Columbia University.

This unit supports many of the student organizations on campus and aids them in meeting the objectives of their student group or organization. Staff will assist students who are looking for advisement on running an organization, planning an event, sorting their organization's financial records, or starting a student group. They are there to guide students through formal University processes, help them navigate Columbia's resources, or simply brainstorm new ideas with students.

Here are just a few ways to get involved with campus life through the programs of Student Engagement: tackle a civic engagement project during your time away from campus through the Alternative Break Program and make a difference in a community that matters to you; explore and enjoy New York City's performing arts scene over spring break with the Alternative Spring Break: NYC Performing Arts program or throughout the spring semester with Urban New York; take a break from your classes and studies with Live at Lerner's educational, cultural, and entertainment events that take place in the student center—all offer you opportunities to learn about campus traditions, understand how to access campus resources and support services, and meet the Columbia community through the New Student Orientation Program (NSOP).

Undergraduate Orientation

All new students are required to participate in an orientation program that is designed to acquaint them with the University and its traditions, the administration and faculty of The Fu Foundation School of Engineering and Applied Science, upperclass students, and New York City. The New Student Orientation Program (NSOP) for new undergraduate students begins the week prior to the start of the fall semester. NSOP is intended to assist all new students with the transition to college life.

Orientation is busy, exciting, and a lot of fun, but it is also a week in which important academic decisions are made. Scheduled into the program are information sessions and opportunities to meet with academic advisers. Through large group programs and small group activities, students will be introduced to faculty members, deans, resident advisers, and other students. NSOP includes walking tours of New York City, social events, and information sessions on University services and cocurricular opportunities. During NSOP, new students have the campus to themselves. This provides students with a unique opportunity to make friends and settle into life at Columbia before classes begin.

Undergraduate students may visit cc-seas.columbia.edu/orientation for additional information on NSOP.

Multicultural Affairs

Multicultural Affairs is devoted to promoting a just society and explores issues of interculturalism and diversity within and beyond the Columbia University community. By promoting forums that address diversity issues, self-discovery takes place along with a greater awareness and appreciation of cultural history within and between communities on campus. Multicultural Affairs endeavors to empower students, faculty, and staff with the tools to be able to successfully navigate their environments and thus be able to positively change and impact the community at large.

Programs and services provided by Multicultural Affairs include the Columbia Mentoring Initiative, a program connecting incoming undergraduate students with returning students, and returning students with alumni; Respecting Ourselves and Others Through Education (ROOTEd), a peer diversity facilitation program; Under1Roof, a program during orientation that explores how to create an inclusive community at Columbia University; and the Intercultural House (ICH), a unique residential experience that is supportive of Multicultural Affairs' social justice goals.

Residential Life

Residential Life strives to enhance the quality of the residential experience by cultivating an atmosphere conducive to educational pursuits and the development of community within the student body. These contributions form an integral part of a Columbia education by stimulating mutual understanding and by fostering an atmosphere based on the appreciation of the differences and similarities characterizing such a diverse community.

Working alongside a team of professional staff and Graduate Hall Directors (GHDs), undergraduate Resident Advisers (RAs) live on the floor of every residence hall and serve as role models for their residents. They facilitate discussions about community standards, provide community building programs, and serve as a resource for the residents. RAs serve as the front line of a layered on-call system and are trained to respond to the variety of issues that emerge in community life.

The Faculty-in-Residence Program allows students, alumni, and faculty to meet formally and informally throughout the year. Faculty members who reside in three residence halls invite students to dine in their apartments; organize special programs around issues of interest; provide opportunities for academic growth and challenges within the residence halls; and help students establish links with major cultural, political, and professional institutions in New York City. In addition, the faculty member in residence partners with the Engineering alumni office to provide opportunities for students to network and gain exposure to a variety of careers.

Begun in fall 2006, Res. Inc. allows Engineering and College first-years, sophomores, juniors, and seniors to live together clustered in the Living Learning Center (LLC) housed in Hartley and Wallach Halls. This initiative seeks to bridge the academic and cocurricular experience for students and encourages and supports engineers with entrepreneurial ideas. Mentorship between students, connection among the class years, and alumni interaction are the foundations for the success of the program.

Fraternities and sororities are an active and vibrant community, adding diversity to the residential experience. Some fraternities and sororities have brownstones near campus, and some of the organizations without brownstones have a suite within the residence halls. Residential Life provides guidance and support to the Greek community, advising the four student-governing Greek councils: the InterGreek Council (IGC), InterFraternity Council (IFC), Panhellenic Council, and Multicultural Greek Council (MGC). Fraternity and sorority members share in service, scholastic, philanthropic, cultural, and leadership experiences.

Student Organizations

Programs and activities at Columbia are shaped primarily by students who assume leadership and volunteer positions in hundreds of organizations across the campus. The Engineering Student Council and its associated class councils are the elected representative body of undergraduates at Columbia Engineering. Its members represent student interests on committees and projects addressing a wide range of issues facing the Columbia community and help shape the quality of life for Columbia students.

Working in conjunction with the Student Council, the Activities Board at Columbia (ABC), Student Governing Board (SGB), InterGreek Council (IGC), Community Impact (CI), Club Sports, and Interschool Governing Board (IGB) oversee the management and funding of more than 500 student organizations.

The ABC provides governance for recognized student organizations, including cultural organizations, performance-based and theatrical groups, media and publications groups, competition and special interests groups and preprofessional organizations and societies. The preprofessional organizations and societies are of special interest to engineering students. These societies reflect the range of academic disciplines and interests to be found among students and include the National Society of Black Engineers, the Society of Women Engineers, the American Institute of Aeronautics and Astronautics, and the Biomedical Engineering Society, just to name a few.

The SGB provides governance for recognized student organizations that are faith-based, spiritual, political, activist, and humanitarian and that encourage open interreligious and political dialogue at Columbia University's Morningside campus. The IGB recognizes student organizations whose membership spans across the various undergraduate and graduate schools.

For more information on the IGC, see Residential Life. For more information on Club Sports, see Intercollegiate Athletics Program (page 219), and for more information on Community Impact see Office of the University Chaplain (page 219). All the governing groups provide networking, leadership, and professional development opportunities for students.

OFFICE OF GRADUATE STUDENT AFFAIRS

The Office of Graduate Student Affairs at The Fu Foundation School of Engineering and Applied Science is integral to the School's teaching, research, and service mission and works to enhance the educational opportunities available to students. This office provides leadership for the integration of educational programs and services that enhance recruitment, retention, and quality of campus life for graduate students at Columbia Engineering. It strives to demonstrate sensitivity and concern in addressing the needs of the School's population. The office is dedicated to providing service to prospective, new, and continuing students pursuing a graduate education in engineering or applied science.

Graduate Orientation

All new graduate students participate in the New Graduate Student Orientation program. During this weeklong program, new graduate students learn about various School and University resources, policies and procedures, and other essential information to assist them with their transition to the graduate program. Orientation for new graduate students begins in late August.

In addition to providing information on university resources and policies, students engage in cultural, social, and professional networking activities. Through these activities graduate students are encouraged to connect with their peers, acclimate to the campus and New York City as well as develop their professional portfolios. The Office of Graduate Student Affairs strongly believes that orientation serves as a vehicle in onboarding our graduate students into an active and engaging student life experience at Columbia.

Graduate Student Organizations

Columbia University graduate students can participate in and enjoy hundreds of diverse, University-affiliated social, religious, cultural, academic, athletic, political, literary, professional, public service, and other organizations. At SEAS, graduate students are encouraged to become active members of the Engineering Graduate Student Council (EGSC). The EGSC is a recognized group that consists of representatives from each of the nine academic departments at SEAS. The objectives of the EGSC are to foster interaction among graduate engineering students, to serve as a voice for graduate engineering students, and to sponsor social and educational events of interest to the graduate engineering community.

Graduate Judicial Affairs

The Office of Graduate Student Affairs is responsible for assisting graduate students with upholding academic and community standards. The office provides mandatory academic integrity training for graduate students and is responsible for the Dean's Discipline process.

THE OFFICE OF STUDENT CONDUCT AND COMMUNITY STANDARDS

The Office of Student Conduct and Community Standards was created to assist students in the maintenance of a safe, honest, and responsible campus community. To achieve this goal, Student Conduct and Community Standards partners with administrators and faculty to create programs designed to educate students regarding the potential impact of their actions on both their individual lives and the community at large. In addition, the Office of Student Conduct and Community Standards works with student groups to facilitate the development of skills and processes students can use to hold each other accountable when they encounter inappropriate behavior. The Office of Student Conduct and Community Standards also holds students accountable for inappropriate behavior through the Dean's Discipline process when necessary.

OFFICE OF THE UNIVERSITY CHAPLAIN

Columbia is home to a community of scholars, students, and staff from many different religious backgrounds. The Office of the University Chaplain ministers to their individual faiths and supports individual spirituality, while promoting interreligious understanding. The University Chaplain oversees the work of the United Campus Ministries—a fellowship of more than twenty religious life advisers representing specific faith traditions. The University Chaplain also fosters learning through spiritual, ethical, religious, political, and cultural exchanges and hosts programs on matters of justice, faith, and spirituality. Through these and other means, the Office of the University Chaplain cultivates interfaith and intercultural awareness.

The University Chaplain is available for confidential pastoral counseling to individuals, couples, and families in the Columbia University community. The Office of the University Chaplain may also assist with private ceremonies such as weddings, christenings, and memorial services. We warmly welcome your interest, questions, and participation.

For more information, please call the Earl Hall Center at 212-854-1474 or 212-854-6242 or visit columbia.edu /cu/earl.

LERNER HALL

Lerner Hall is dedicated to student life at Columbia University. A 225,000-square-foot facility located on the southwest corner of campus, Lerner Hall was designed by Bernard Tschumi, the former Dean of Columbia's Graduate School of Architecture, Planning and Preservation. The building features a glass facade and ramps to offer those within Lerner scenic views of campus and to allow those on campus to clearly view the activities within the building.

Opened in 1999, Lerner Hall contains an auditorium that seats up to 1,100, a fully operational cinema, a party space, plus a diverse offering of meeting, rehearsal, and performance spaces, computer labs and kiosks, and 7,000 student mailboxes.

The building also features the University Bookstore, two dining facilities, a banking center and ATM, Package Center, and the Ticket and Information Center. Lerner Hall is home to many critical University resources such as Undergraduate Student Life, the James H. and Christine Turk Berik Center for Student Advising, University Chaplain, University Event Management, and Health Services.

Lerner Hall is much more than a building for performances and events—it is the center of student and campus activity at Columbia.

For more information, visit lernerhall .columbia.edu.

INTERCOLLEGIATE ATHLETICS PROGRAM

Columbia has a long tradition of success in intercollegiate athletics, and The Fu Foundation School of Engineering and Applied Science has always been an active participant in these programs. While Columbia's intercollegiate athletics program is governed by Ivy League regulations, Columbia is also a member of the National Collegiate Athletic Association. Columbia sponsors men's varsity teams in baseball, basketball, cross-country, fencing, football, golf, rowing (heavyweight and lightweight), soccer, squash, swimming and diving, tennis, track and field (indoor and outdoor), and wrestling.

Women in all undergraduate divisions of Columbia and in Barnard College compete together as members of University-wide athletic teams. The arrangement, called a consortium under NCAA rules, is one of only three in the nation and the only one on a Division I level. Currently, there are women's varsity teams in archery, basketball, cross-country, fencing, field hockey, golf, lacrosse, rowing, soccer, softball, squash, swimming and diving, tennis, track and field (indoor and outdoor), and volleyball.

Columbia's commitment to success in intercollegiate athletics competition has been matched by the determination of alumni and administrators to upgrade the University's athletic facilities. The Baker Field Athletics Complex, a few miles up the Hudson River on the northern tip of Manhattan, has been completely rebuilt and expanded. The complex features Robert K. Kraft Field at Lawrence A. Wien Stadium, a 17,000-seat football and lacrosse facility; Robertson Field at Satow Stadium, home of the baseball program; softball and field hockey venues; and an Olympic-quality synthetic track. At Columbia's Dick Savitt Tennis Center at the Baker Athletics Complex there are six cushioned hard tennis courts, all of which are covered by a state-of-the-art air dome for winter use. The Remmer and 1929 Boathouse includes a three-bay shell house, complete with an upper level that includes an erg and weight room. The Campbell Sports Center, the newest athletics building at the Baker Athletics Complex, features coaches, offices, a strength and conditioning center, a theatre-style meeting room, as well as a student-athlete lounge and study space.

Columbia's Dodge Physical Fitness Center draws thousands of students each day for recreation, physical education classes, intramural play, club competition, and varsity sport contests and practices. The Center houses most indoor sports and is available to all registered students. Major athletic facilities on campus include two full-size gymnasiums for basketball, volleyball, and badminton; eight squash and handball courts; the eight-lane Uris pool with three diving boards; a fully equipped three-level exercise and weight room facility; two aerobic dance/martial arts rooms; a fencing room; a wrestling room; an indoor running track; and two fully equipped saunas.

Eligibility for Intercollegiate Athletics

Any student in the Engineering School who is pursuing the undergraduate program or an approved combined program toward a first degree is eligible for intercollegiate athletics. To be eligible for athletic activities, the student must:

- Be a candidate for a bachelor's degree
- Be registered for at least 12 points of credit
- Make appropriate progress toward the degree as defined by the NCAA, the Ivy League, and Columbia University. These criteria are monitored by the Director of Compliance and certified by the Office of the Registrar.
- Have attended the University for not more than eight terms
- Not have completed the requirements for the bachelor's degree

Questions about athletic eligibility should be referred to the appropriate academic adviser or the Director of Compliance in the Department of Intercollegiate Athletics and Physical Education.

Recreational Programs

In addition to the required physical education courses (see page 13), the Department of Intercollegiate Athletics and Physical Education offers a comprehensive Intramural and Club Sports Program. Through intramurals, students have the opportunity to participate in both individual and team sports. Individual activities function through tournaments, while team activities feature both league and tournament competition. Club sports are designed to allow groups of individuals who share a common athletics interest to organize and collectively pursue this activity. Clubs are organized on recreational, instructional, and competitive levels. Activities range from organized instruction to intercollegiate and tournament competition. A list of the intramural activities and sports clubs as well as all information regarding the program can be obtained in the Office of Intramurals and Club Sports, 331 Dodge Fitness Center or on the website at gocolumbialions.com.

CAMPUS SAFETY AND SECURITY

Columbia University prepares an annual security report, which is available to all current and prospective employees and students. The report includes statistics for the three previous years concerning reported crimes that occurred on campus, in certain off campus buildings or property owned or controlled by Columbia University, and on public property within, or immediately adjacent to and accessible from, the campus. The report also includes institutional policies concerning campus security, such as policies concerning sexual assault, and other matters. You can obtain a copy of this report by contacting the Director of Administration and Planning, Public Safety at 212-854-3815 or by accessing the following website: columbia.edu/cu/publicsafety/SecurityReport.pdf.

UNIVERSITY HOUSING

Undergraduate Housing

The residence halls are an important focal point of campus life outside the classroom, with the University housing more than 95 percent of the undergraduate population in residence halls on or near the campus. A trained Residential Life staff lives with the students in the halls. They work to create an atmosphere conducive to educational pursuits and the development of community among the diverse student body. Throughout the year the Residential Life staff presents programs in the residence halls and off campus that are both social and educational.

Columbia guarantees housing for all undergraduate students (except Combined Plan students and visiting students) who have filed their intent to reside on campus by the stated deadline and who have continuously registered as full-time students. Each spring, continuing students participate in a room selection process to select their accommodations for the next academic year. Students who take an unauthorized leave of absence are placed on the nonguaranteed wait list upon their return and are on the wait list for each subsequent year.

A variety of residence hall accommodations are available to Columbia students. Carman, John Jay, Wallach, Wien, Furnald, McBain, Schapiro, Harmony and Broadway Residence Halls are traditional corridor-style residence halls. Of these, all but Wien, John Jay, and Carman have kitchens on each floor. East Campus, 47 Claremont, Hartley (which, together with Wallach, comprises the Living-Learning Center), Hogan, River, Ruggles, 600 West 113th Street, Watt, and Woodbridge offer suite-style living, and all have kitchens. All residence hall rooms are either single or double. Both single and double rooms are available in all halls except Carman, which has only doubles, and Hogan, which is all singles.

The residence halls are also home to a variety of Special Interest Communities. These communities provide an opportunity for students with a common interest to live together and develop programs in their area of interest. The themes may vary from year to year. First-year students are not eligible to live in Special Interest Communities but are welcome to attend events.

Upperclass Columbia students also have the option of living in brownstones, a limited number of fraternity and sorority organizations, and certain Barnard College halls. These rooms are also chosen through a room selection process, which takes place each spring.

For more information, please visit the Housing website at housing.columbia.edu.

Graduate Housing

Graduate students have a number of housing opportunities in the Morningside Heights neighborhood. The three main sources are University Apartment Housing (UAH), International House, and Off-Campus Housing Assistance (OCHA). UAH operates Columbia-owned apartments and dormitory-style suites in the Morningside Heights and Manhattan Valley areas within walking distance of the campus, as well as in Riverdale, in the Bronx. For further information, see UAH's website at columbia.edu/uah. International House, a privately owned student residence near the campus, has accommodations for about five hundred graduate students, both international and American, who attend various area colleges and universities. It provides a supportive and cross-cultural environment with many activities and resources, and it is conveniently located two blocks from the Engineering building. For more information, write or call: International House, 500 Riverside Drive, New York, NY 10027; 212-316-8400; or check their website at www.ihouse-nyc.org.

There are also a number of resources available for searching for off-campus housing opportunities. Columbia's Off-Campus Housing Assistance (OCHA) office assists Columbia students and affiliates in their search for rental housing in the metropolitan area. OCHA manages a database known as the Housing Registry at ocha.facilities.columbia.edu that contains listings of available rooms and apartments in non-Columbia-owned buildings in NYC. The Registry also contains listings of sublets of rooms and apartments in Columbia-managed housing. Prospective roommates can post and search profiles on the Roommates section of the Registry. OCHA offers one-on-one counseling

and is supported in these efforts by a cooperative relationship with two New York City real estate/relocation agencies, Citihabitats and Douglas Elliman, which also offer a discounted broker fee. Only students/affiliates with a UNI or admission acceptance letter are permitted to use the Registry. Office hours and instructions are posted on the website at columbia .edu/ocha.

UAH application information is sent along with acceptance packets from the Office of Graduate Student Affairs. Information on applying for housing is also available in the Office of Graduate Student Affairs and the UAH Office. You can also seek additional information on the Columbia Students Page: columbia. edu/cu/students.

Due to the growing demand for housing, graduate housing is no longer guaranteed, but every effort is made to accommodate you. It is critical that you follow the instructions in your acceptance packet. Housing applications received after the set dates are not guaranteed housing. The order of priority for selection is: graduate fellowship recipients, Zone 1 students (those who live further than 250 miles from campus), and then Zone 2 students (those who live between 50 and 250 miles from campus). All continuing students and applications from Zone 3 areas (within 50 miles) are automatically placed on a waiting list. Depending on availability, students placed on the UAH waitlist receive housing assignments between late December and January for the spring term, and between early August and late September for the fall term.

UAH-approved students can begin moving in during the last week of August for the fall term, and early January for the spring term. Students will be properly notified of Graduate Orientation and Registration, which are generally held the week before the first day of class. If a student needs to move in earlier, proper documentation from the department in support of the request is necessary.

COLUMBIA DINING

First-Year Students

All first-year students in residence are required to enroll in one of three dining plans, each of which is comprised of a varying number of meals served in John Jay Dining Hall, Ferris Booth Commons, or JJ's Place, and Dining Dollars, which can be used at the 12 dining locations on campus. Plan 3 is the only first-year plan that also includes Off Campus Flex. This plan is designed for students who are on campus during breaks (fall, Thanksgiving, and spring), when the dining halls are closed.

First-Year Dining Plans

1. 19 meals per week and 75 Dining Dollars per term, plus 15 floating meals and 6 faculty meals
2. 15 meals per week and 125 Dining Dollars per term, plus 10 floating meals and 6 faculty meals
3. 19 meals per week, $50 Flex and 25 Dining Dollars per term, plus 15 floating meals and 6 faculty meals

The dining plans are transacted through Columbia's ID Card, called the Columbia Card, which serves as a convenient way to enjoy dining all over campus without carrying cash.

Meals

The meals portion of the dining plan enables students to help themselves to unlimited servings of food served in John Jay Dining Hall, Ferris Booth Commons, or JJ's Place. The hours of operations for these locations offer dining options for breakfast, lunch, dinner, and late-night, with continuous dining from 8:00 a.m. to 1:00 a.m.

Dining Dollars

In addition to meals, Dining Dollars comprise the other portion of the first-year dining plan. Each Dining Dollar is equal to one dollar and operates as a declining balance account, much like a debit card.

Columbia Dining maintains 12 dining facilities conveniently located on campus. Each of the locations accepts Dining Dollars, an alternative to cash payment that is accessed by the Columbia Card (student ID card).

With Dining Dollars, students will enjoy the ease and flexibility of cashless transactions as well as the savings of sales tax on all food purchases. Dining Dollars will roll over from year to year until graduation.

Upperclass and Graduate Students

Many upperclass and graduate students who dine on campus open a Dining Dollars account; however, some choose to enroll in an upperclass/graduate student dining plan.

Columbia Dining offers four plans—all are accessed by the Columbia Card and can be used for meals in John Jay Dining Hall, Ferris Booth Commons, or JJ's Place. The hours of operations for these locations offers dining options for breakfast, lunch, dinner, and late-night, with continuous dining from 7:30 a.m. to 1:00 a.m.

Upperclass, GS, and Graduate Dining Plans

A. 14 meals per week and 200 Dining dollars per term, plus 15 floating meals and 6 faculty meals
A Choice. 210 meals per term and 200 Dining Dollars per term, plus 6 guest meals
B. 175 meals and 200 Dining Dollars per term, plus 6 guest meals
C. 100 meals and 125 Dining Dollars per term, plus 4 guest meals
D. 75 meals and 75 Dining Dollars per term, plus 2 guest meals

Kosher Dining Plan

All students who participate in a dining plan, including first-year, upperclass, General Studies, or graduate students, are eligible for the Columbia Kosher Dining Plan. Signing up for this dining plan allows access to a restricted kosher area within John Jay Dining Hall as well as Express Meals to go. CU kosher meals can also, for an additional charge, be exchanged for a kosher meal at Barnard's Hewitt Hall (kosher to kosher only). To sign up, the student selects a plan from either the First Year Dining Plan or the Upperclass Dining Plan options, according to the student's status, then elects to enroll in the Kosher Dining Plan. The addition of the Kosher Dining Plan adds 10 percent to the cost of the selected plan. For more details, a dining plan comparison, and additional tools, visit the Columbia Dining website at dining.columbia.edu.

Locations/Menus/Hours

Locations, menus, and hours of all campus dining facilities can be found at dining.columbia.edu. You can also view photos and take a virtual tour of some of our facilities. Menus and hours are also available on the Dine@CU iPhone app.

Nutrition, Food Allergies, and Special Diets

Registered Dietitian Christina Lee is available on site as well as online to address individual questions and concerns related to food allergies, intolerances, and dietary preferences. Christina can be contacted via e-mail at cl3368@columbia.edu or by phone at 212-854-3353 with questions, to schedule a consultation, or to discuss personal meal planning. For more information and a nutrition calculator, visit the Columbia Dining website. Nutrition data can also be accessed on the Dine@CU iPhone app.

COLUMBIA HEALTH

Phone: 212-854-2284
After-hours Urgent Health Concerns: 212-854-9797
health.columbia.edu

Columbia Health is an integrated program that provides extensive on- and off-campus health care and services for you while you are enrolled at the University. The Columbia Health Program and an accepted medical insurance plan work together to meet your health care needs. Columbia requires all full-time students to enroll in both. To meet the insurance requirement, you must either confirm your enrollment in the Columbia Student Medical Insurance Plan (Columbia Plan) or provide proof of alternate coverage that meets the established criteria listed on the Columbia Health website. Part-time students may also enroll in the Columbia Health Program and Columbia Plan.

Benefits and Services of the Columbia Health Program

The Columbia Health Program compromises five departments and more than 130 individuals to meet your health needs on campus.

Medical Services

John Jay Hall, 3rd and 4th Floors
Phone: 212-854-7426
health.columbia.edu/pcms

Medical Services provides routine and urgent medical care, travel medicine, and immunizations, as well as sexual health services, reproductive and gynecological services, LGBTQ health care, and confidential HIV testing. Students can make appointments online with their health care provider and are encouraged to do so (bios and photos are available online).

Counseling and Psychological Services

Lerner Hall, 8th Floor
Phone: 212-854-2878
health.columbia.edu/cps

Counseling and Psychological Services offers short-term individual counseling, referrals for longer-term therapy, consultations for couples, student-life support groups, medication consultation, and emergency consultation. Students are welcome to select a mental-health clinician (bios and photos are available online).

Disability Services

Lerner Hall, 7th Floor
Phone: 212-854-2388
health.columbia.edu/ods

Disability Services facilitates equal access for students with disabilities by coordinating accommodations and support services, including assistive technology, networking groups, academic skills workshops, and learning specialists. Disability documentation and registration guidelines are available online.

Alice! Health Promotion

Wien Hall, 1st Floor
Phone: 212-854-5453
health.columbia.edu/alice

Alice! Health Promotion connects individuals and groups with information and resources, cultivates healthy attitudes and behaviors, promotes health-supporting policy, and fosters a culture that values and supports individual and community health.

Sexual Violence Response

Lerner Hall, 7th Floor
Phone: 212-854-HELP (4357)
health.columbia.edu/svprp

Sexual Violence Response works to promote behaviors that support positive, healthy, and consensual relationships, and supports survivors and co-survivors of violence through advocacy, connection to resources, community education, training, and engagement.

Student Health Insurance

Wien Hall, 1st Floor
Phone: 212-854-3286

All full-time students are automatically enrolled in the Basic level of the Columbia Plan. To request a waiver from automatic enrollment, you must submit a request at health.columbia.edu before September 30 (February 1 for new spring term enrollment, or June 14 for newly arrived full-time summer trimester students). All waiver requests are considered but approval is not guaranteed.

Optional coverage for early arrival students or eligible dependents of insured students and a separate dental plan are available through Aetna Student Health. For more up-to-date information, visit the Columbia Health website at health.columbia.edu or www.aetnastudenthealth.com/columbiadirect.html.

Immunization Compliance

Wien Hall, 1st Floor
Phone: 212-854-7210

There are two immunization requirements that all new students must meet before arrival on campus:

Meningococcal Meningitis Vaccination
New York State public health law requires that students receive information from their institutions about meningococcal meningitis and the vaccine that protects against most strains of the disease that can occur on university campuses. Columbia students must make an informed decision about being vaccinated and certify their decision online. Full instructions are given at health.columbia.edu and the process takes two to three minutes to complete. You must formally indicate your decision about being vaccinated before you will be permitted to register for classes.

Deadline: Decisions must be recorded online before classes begin. Students will not be permitted to register until a decision is recorded.

Documentation of Immunity to Measles, Mumps, and Rubella (MMR)
New York State public health law requires all Columbia students taking six or more credits must document their immunity to measles, mumps, and rubella. Instructions and the Columbia University MMR Form are available at health.columbia.edu.

Deadline: Completed forms must be mailed or faxed 30 days before registering for classes.

Please visit us at health.columbia.edu or contact us for questions.

Scholarships, Fellowships, Awards, and Prizes

ENDOWED SCHOLARSHIPS AND GRANTS

All endowed scholarships are awarded annually to undergraduate students as part of Columbia's financial aid program. We are unable to accept applications for these awards independent of this process.

Leslie Abbot Scholarship
For an undergraduate student pursuing course of study in mechanical engineering.

Cvi Abel Memorial Scholarship (2003)
Gift of Jack Abel '71.

Aigrain Family Scholarship (2008)
Gift of Jacques and Nicolleta Aigrain P'08. Preference is given to international students studying civil or mechanical engineering.

Walter H. Aldridge (1936)
Gift of Walter H. Aldridge.

Alvey-Ferguson Company Scholarship (1948)
Gift of the Alvey-Ferguson Company.

Erwin H. Amick Memorial Scholarship (1970)
Gift of various donors for students in chemical engineering and applied chemistry.

Nathaniel Arbiter Scholarship (1985)
Gift of various donors in honor of Professor Nathaniel Arbiter for students in the following specializations in order of preference: mineral beneficiation, mines, and physical metallurgy.

Attardo Scholarship (1999)
Gift of Michael J. Attardo '63.

Jee Yin and Choi Heung Au Scholarship Fund (2002)
Gift of Michael M. Au '90. Preference is given to students who have graduated from Stuyvesant High School in New York City.

Frank and Harriet Ayer Scholarship (1977)
Bequest of Frank A. Ayer. Graduates of Deerfield Academy are given first preference.

Cesare Barbieri Scholarship (1953)
Gift of Cesare Barbieri Fund.

William S. Barstow Scholarship (1935)
Gift of William S. Barstow.

Edwin D. Becker Scholarship Fund (1993)
Gift of Edwin D. Becker '56. Preference is given to students from the Rocky Mountain states.

John E. Bertram Memorial Scholarship (1990)
Gift of Mrs. Lucy Bertram and friends in honor of John E. Bertram. Awarded to students in electrical engineering or computer science.

Jerry and Evelyn Bishop Scholarship (1984)
Gift of Jerry '42 and Evelyn Bishop for students in the Combined Plan Program. Preference is given to students in the program who attended Columbia College.

Paul H. Blaustein Scholarship (1994)
Gift of Barbara Blaustein, Stacey Blaustein Divack, and Joshua Divack.

Philip P. Bonanno Scholarship (1999)
Donated by Philip P. Bonanno '55.

Cecil Ane and Tullio J. Borri Family Scholarship
Gift of Tullio J. '51 and Cecil Ane Borri. Preference for students who are majoring in or studying civil engineering.

Cornelius A. Boyle Scholarship (1962)
Bequest of Cornelius A. Boyle.

Lauren Breakiron Scholarships (1999)
Gift of Lauren P. Breakiron '56.

Edwin W. and Mary Elizabeth Bright Scholarship in Mechanical Engineering (1985)
Gift of Edwin W. '42 and Mary Elizabeth Bright to support students studying mechanical engineering.

Lewis G. Burnell Memorial Scholarship (2001)
Gift of Roger W. Burnell in memory of his father, Lewis G. Burnell '32.

Burns and Roe, Arthur J. Fiehn Scholarship (1989)
Gifts from various donors in memory of Arthur J. Fiehn '46.

Samuel J. Clarke Scholarship (1960)
Bequest of Agnes Robertson Clarke.

Class of 1885 (1910)
Gift of the Class of 1885 School of Mines in commemoration of the twenty-fifth anniversary of their graduation.

Class of 1889 (1939)
Gift of the Class of 1889 College and Engineering.

Class of 1900 (1940)
Gift of the Class of 1900 College and Engineering.

Class of 1902 (1952)
Gift of the Class of 1902 College and Engineering.

Class of 1906 (1940)
Gift of the Class of 1906 in honor of Frank D. Fackenthal 1906.

Class of 1907 (1937)
Gift of the Class of 1907. Preference is given to sons and descendants of class members.

Class of 1909 (1959)
Gift of the Class of 1909 in honor of John J. Ryan.

Class of 1913 (1963)
Gift of the Class of 1913 in commemoration of the fiftieth anniversary of their graduation.

Class of 1914 (1937)
Gift of the Class of 1914 College and Engineering for a pre-engineering or pre-architecture student.

Class of 1945 50th Reunion Scholarship
Gift of the Class of 1945.

Class of 1950 Endowed Scholarship (2000)
Gift of members of the Class of 1950 in commemoration of the fiftieth anniversary of their graduation.

Class of 1951 Endowed Scholarship (2001)
Gift of members of the Class of 1951 in commemoration of the fiftieth anniversary of their graduation.

Class of 1952 Endowed Scholarship (2002)
Established by Alexander Feiner ’52.

Class of 1964 Scholarship (2014)
Gift of members of the Class of 1964 in honor of their 50th class reunion.

Hugo Cohn Scholarship (1984)
Gift of Hugo Cohn 1909. Preference is given to electrical engineering students.

Herbert J. Cooper Scholarship (1999)
Gift of Mrs. Deborah Cooper and the Estate of Herbert J. Cooper ’46.

Milton L. Cornell Scholarship (1958)
Gift of various donors in memory of Milton L. Cornell.

Paul and Lillian Costallat Scholarship (1972)
Gift of Paul and Lillian Costallat.

Frederick Van Dyke Cruser Scholarship (1980)
Bequest of Maude Adelaide Cruser to support students in chemical engineering with financial need.

Cytryn Family Scholarship (2002)
Gift from Allan ’72, ’79 and Carol Cytryn.

Peter del Valle Scholarship (2015)
Established by Peter del Valle ’54CC, ’55, ’56.

Frank W. Demuth Scholarship (1965)
Bequest of Frank W. Demuth 1914.

Freda Imber Dicker Endowed Scholarship Fund (2000)
Gift of Dr. Stanley Dicker ’61 in honor of the hundredth anniversary of his mother’s birth (March 5, 1900). Preference is given to juniors and seniors in the Department of Biomedical Engineering.

Jack Dicker Endowed Scholarship (2003)
Gift of Dr. Stanley Dicker ’61 in honor of his father. Preference is given to juniors and seniors in the Department of Biomedical Engineering.

James and Donna Down Scholarship (1997)
Gift of James ’73 and Donna Down to support a deserving minority undergraduate who has demonstrated academic achievement.

Stancliffe Bazen Downes Scholarship (1945)
Bequest of Bezena Treat Downes Merriman in honor of her brother, for a student in civil engineering.

Brooke Lynn Elzweig Scholarship (2002)
Gift of Gary Elzweig ’77. Preference is given to students with high financial need.

John L. Erikson Memorial Scholarship
Gift from Betty Erikson in memory of her husband, John L. Erikson ’50.

Jack B. Freeman Scholarship (1994)
Gift of Jack B. Freeman ’55. Designated to support students who are members of the varsity baseball team.

Pier-Luigi Focardi Scholarship (1964)
Bequest of Clara G. Focardi.

Ford/EEOC Scholarship
Designated for minorities and women. Preference is given to Ford employees, their spouses, or children.

Z. Y. Fu Scholarship (1993)
Gift of The Fu Foundation for undergraduate scholarship support.

Jewell M. Garrelts Scholarship
Gift of Jewell Garrelts; preference for a junior or senior in the Department of Civil Engineering and Engineering Mechanics.

General Motors Scholarship
Designated for minorities and women. Preference is given to General Motors employees, their spouses, or children.

Ben and Ethelyn Geschwind Endowed Scholarship (2004)
Gift of Benjamin and Ethelyn ’84 Geschwind.

Alger C. Gildersleeve Scholarship (1955)
Bequest of Josephine M. Gildersleeve, in honor of Alger G. Gildersleeve 1889.

Frederick A. Goetze Scholarship (1960)
Gift of William A. Baum, in honor of the former Dean of Columbia Engineering.

Sarah E. Grant Memorial Scholarship (1997)
Gift of Geoffrey T. ’82 and Annette M. Grant in memory of their daughter, Sarah. Designated to support students who have demonstrated academic achievement and are student athletes.

Adam R. Greenbaum Memorial Scholarship Fund
Established in memory of Adam R. Greenbaum by his parents, relatives, and friends following his death in February 2001, when he was a sophomore. The scholarship is given to a SEAS sophomore who was named to the Dean’s List as a first-year, as Adam was, with a preference to students from New Jersey and New York.

Luther E. Gregory Scholarship (1963)
Bequest of Luther E. Gregory 1893.

Robert Gross Fund (1999)
Gifts of friends of Robert Gross to support a student in applied physics.

Wallace K. Grubman-Graham Scholarship (1998)
Gift of Wallace Grubman ’50 and the Grubman Graham Foundation to support a student in chemical engineering.

Lawrence A. Gussman Scholarship (1987)
Gift of Lawrence Gussman ’38. Awarded annually to students studying computer science.

Haight Family Scholarship (2004)
Gift of Deborah E. Haight ’00.

Ralph W. Haines Scholarship (2002)
Gift of Ralph W. Haines ’69 for needy and deserving students in Columbia Engineering.

A. A. Halden Scholarship (1962)
Established by bequests from Dorothy C. Halden and Barbara Schwartz in memory of Alfred A. Halden.

Albert M. Hall Scholarship
Preference for students in metallurgy or materials science.

The Hamann Scholarship (1970)
Bequest of Adolf M. Hamann 1910.

Alfred M. and Cornelia H. Haring Scholarship (1965)
Gift of the Aeroflex.

H. Field Haviland Scholarship Fund (1988)
Bequest of Henry F. Haviland 1902. Scholarships are awarded equally between Columbia Engineering and Columbia College.

Harold T. Helmer Scholarship (1965)
Bequest of Harold T. Helmer.

David Bendel Hertz College/ Engineering Interschool Scholarship (1989)
Gift of David B. Hertz '39. Awarded in alternate years to the College and to the Engineering School to a student electing to receive a B.A. from Columbia College and a B.S. from Columbia Engineering.

Edward Gurnee Hewitt Scholarship (1980)
Bequest of Mary Louise Cromwell.

Prentice Hiam Memorial Scholarship (2007)
Gift of Atul Khanna '83. Preference given to international students.

James T. Horn Scholarship (1938)
Gift of Sarah L. and Mary T. Horn, in memory of their brother, James T. Horn 1884.

Richard and Janet Hunter Scholarship (2000)
Gift of Richard '67 and Janet Hunter. Scholarship awarded to 3-2 program participants entering Columbia Engineering with preference given to graduates of Whitman College.

Jonathan Lewis Isaacs Memorial Scholarship (2001)
This scholarship was endowed in 2001 by Gary F. Jonas '66 and Jonathan L. Isaacs '66 as the Future Entrepreneurs Scholarship to acknowledge the thirty-fifth anniversary of their graduation from Columbia Engineering. On April 30, 2003, Mr. Isaacs died at the young age of fifty-seven, and the scholarship was then renamed in his memory by Gary F. Jonas, with the support of Jon's wife, Charlotte Isaacs.

Sheldon E. Isakoff Endowed Scholarship Fund (2000)
Gift of Sheldon E. '45 and Anita Isakoff to support chemical engineering student.

Alfred L. Jaros Memorial Scholarship (1967)
Gift of various donors, in memory of Alfred L. Jaros 1911.

Cavalier Hargrave Jouet Scholarship (1941)
Bequest of Belinda Hearn Jouet, in memory of C. H. Jouet 1882.

Alfred E. Kadell Scholarship (1995)
Bequest of the Estate of Alfred E. Kadell 1921.

Wayne Kao Scholarship (1988)
Gift of Mabel C. Kao in memory of Wayne Kao '49.

Ruth Katzman Scholarship (2011)
Bequest from Ruth Katzman in loving memory of her parents, Max and Lilian Katzman.

Stanley A. and Minna Kroll Scholarship for Engineering and Computer Science (1987)
Gift of Stanley A. Kroll '28 to support students who are studying electrical engineering or computer science.

Henry Krumb Scholarship (1945)
Gift of Henry Krumb for annual scholarships in mining engineering, metallurgy, and ore dressing.

Jacob Kurtz Memorial Scholarship (1982)
Gift of Kulite Semiconductor Products, Inc., and Kulite Tungsten, for undergraduates, preferably studying in the fields of metallurgy or solid-state physics. In memory of Jacob Kurtz 1917.

Ronald A. Kurtz Scholarship Fund (1990)
Gift of Kulite Tungsten.

Lahey Scholarship (1932)
Bequest of Richard Lahey.

Charles and Sarah Lapple Scholarship (2004)
Bequest from the Estate of Charles E. Lapple and Sarah V. Lapple to be used to provide scholarships to deserving undergraduate students.

Frank H. Lee Memorial Scholarships (1986)
Awarded to a student in the Combined Plan Program in honor of Professor Frank H. Lee.

Leung Endowed Scholarship (2006)
Gift of Lawrence Leung P'10, P'15.

James F. Levens Scholarship (1973)
Bequest of Ola Levens Poole for students in chemical engineering and applied chemistry.

George J. Lewin Scholarship (1965)
Gift of George J. Lewin 1917 and family. Preference given to hearing-impaired students.

Alvin and Richard H. Lewis Scholarship
Gift of Alvin and Helen S. Lewis in memory of their son, Richard Lewis '63.

James M. and Elizabeth S. Li Endowed Scholarship (2006)
Gift of James '68, '70, '76 and Elizabeth Li. Awarded to students majoring in industrial engineering and operations.

Robert D. Lilley Memorial Scholarship (1988)
For students who are in their final year of the 3-2 Combined Plan Program and who have a commitment to community service.

Bruce and Doris Lister Endowed Scholarship (2000)
Gift of Bruce A. Lister '43, '47 to support a needy and deserving undergraduate student.

Lu Lo Family Scholarship
Gift of Lu Lo. Established to provide scholarships to undergraduate students, with a preference for students from China.

Anna Kazanjian and Guy Longobardo Scholarship (2007)
Gift of Anna Kazanjian '49, '52 and Guy Longobardo '49, '50, '62. Preference given to students studying mechanical engineering who have demonstrated academic excellence.

Donald D. MacLaren Scholarship (1995)
Established by Donald D. MacLaren '45 to support a student who is studying biochemical engineering.

Manelski Family Scholarship (2004)
Gift of Darren E. Manelski '91.

Ernest Marquardt Scholarship (1968)
Bequest of Ernest Marquardt 1912.

Louis F. Massa Scholarship (1952)
Bequest of Louis F. Massa 1890.

Ralph Edward Mayer Scholarship (1924)
Contributed by friends in memory of Professor Ralph Edward Mayer.

Henry Michel Scholarship (2005)
Gift of Mrs. Mary-Elizabeth Michel in memory of Henry Michel '49 to support civil engineering majors.

Stuart Miller Endowed Scholarship in Engineering (2003)
Gift of Stuart Miller.

John K. Mladinov Scholarship (1994)
Gift of Barbara P. Mladinov in honor of her husband, John K. Mladinov '43. Awarded to a deserving undergraduate with a minor in liberal arts.

Frank C. Mock and Family Scholarship (1987)
Bequest of Frank C. Mock 1913. For students in electrical engineering with financial need.

New Hope Foundation Scholarship (2006)
Gift of Lee and Margaret Lau P'09 P'10CC. Preference is given to students from Ontario, Canada, or mainland China.

A. Peers Montgomery Memorial Scholarship (1990)
Gift of the family of A. Peers Montgomery '26.

John J. Morch Scholarship (1963)
Bequest of John J. Morch.

Seeley W. Mudd Scholarship (1958)
Gift of the Seeley W. Mudd Foundation.

Mary Y. Nee Endowed Scholarship (2008)
Gift of Mary Yuet-So Nee '84.

Frederick Noel Nye Scholarship (1971)
Bequest of Frederick Noel Nye '27.

David Novick Scholarship (2011)
Bequest of David Novick '48, '54 to support civil engineering students.

Parker Family Endowed Scholarship (2001)
Gift of Peter D. Parker '72, '74.

Robert I. Pearlman Scholarship (1989)
Gift of Robert I. Pearlman '55. Preference is given to students from single-parent households.

Robert Peele Scholarship (1925)
Gift of E. E. Olcott 1874.

Brainerd F. Phillipson Scholarship (1936)
Gift of an anonymous donor in memory of Brainerd F. Phillipson.

Andre Planiol Scholarship (1967)
Bequest of Andre Planiol for a student from France.

Roy Howard Pollack Scholarship (1998)
Bequest of Roy Howard Pollack to be used for scholarships for junior or senior students.

Polychrome-Gregory Halpern Scholarship
For students in chemical engineering and applied chemistry.

Rodman K. Reef Scholarship (1999)
Gift of Rodman Reef '69, '78.

Professor William H. Reinmuth Scholarship (1988)
Gift of Curtis Instruments, Inc., awarded in alternate years to Columbia College and Columbia Engineering. Preference will be given to college students studying chemistry and to engineering students studying electrochemistry. Established in honor of Professor William H. Reinmuth.

Patricia Remmer Scholarship (2004)
Bequest of Patricia Cady Remmer '45BC.

Brenda and Dave Rickey Endowed Scholarship Fund (2008)
Gift of David '79 and Brenda Rickey P'08 to benefit undergraduate students from California.

Kevin T. Roach Endowed Scholarship (2003)
Gift of Kevin T. Roach '77.

The Frederick Roeser Fund for Student Aid (1934)
An annual loan to help pay educational expenses, which is awarded to students chosen by the Committee on Scholarships. The amount is individually determined and is to be repaid only if and when the student can do so without personal sacrifice. Repayments go into the Frederick Roeser Research Fund for research in physics and chemistry.

Edgar Lewisohn Rossin Scholarship (1949)
Bequest of Edgar L. Rossin, to provide a scholarship for students in mining engineering.

Harry B. Ryker (1947)
Bequest of Miss Helen L. Ryker in memory of her brother, Harry Benson Ryker 1900.

Thomas J. Sands Endowed Scholarship Fund (2001)
Gift of Thomas J. Sands '86.

Peter K. Scaturro Scholarship Fund (1997)
Gift of Peter K. Scaturro '82, '85 to support students at Columbia Engineering or Columbia College, with preference given to scholar-athletes from Archbishop Molloy H.S. in Briarwood, Queens, NY.

Norman A. Schefer Scholarship (1999)
Gift of Norman A. Schefer '50 and Fay J. Lindner Foundation.

Mark Schlowsky-Fischer Scholarship (2005)
Gift of George Schlowsky '65 in memory

of Mark Schlowsky-Fischer '97 to support students studying computer science.

Ralph J. Schwarz Scholarship (1993)
Gift of the Class of 1943 and other donors in memory of Ralph J. Schwarz '43. To be awarded to academically outstanding students who require financial aid.

David C. and Gilbert M. Serber Memorial Scholarship (1950)
Gift of the Serber family in honor of David Serber 1896. Designated to support a student in civil engineering.

Varsha H. Shah Scholarship (2003)
Gift of Hemant and Varsha Shah to support undergraduate female minority students.

Jared K. Shaper Scholarship
For deserving and qualified candidates for degrees in engineering.

Samuel Y. Sheng Scholarship (2007)
Gift of Samuel Y. Sheng '51, Lauren Wong Sheng '76, Kent Sheng, and Jean Sheng. Awarded to students who demonstrate academic excellence.

Edith Shih Interschool Scholarship Fund (2008)
Gift of Edith Shih, Esq. '77TC, '78TC. Preference is given to international students.

Silent Hoist and Crane Company (1950)
Gift of the Silent Hoist and Crane Company.

David W. Smyth Scholarship (1957)
Bequest of Mrs. Millicent W. Smyth, in memory of her husband, David W. Smyth 1902.

Fritz and Emma Spengler Memorial Scholarship (2005)
Gift of Manfred Spengler '56, '55CC to support student athletes in the 3-2 Combined Plan Program.

Gene F. Straube Fund (2007)
Gift of Gene F. Straube '50, '49 CC. Preference is given to students who graduated from a high school or prep school in northern California, and who are pursing studies in electrical engineering, computer engineering, or computer science.

Steve Tai and Kin-Ching Wu Endowed Scholarship Fund (2001)
Gift of Steve Tai '80.

Tai Family Scholarship (2003)
Gift of Timothy Tai P'06 to be used to support Asian students demonstrating financial need and outstanding academic potential, with preference given to Hong Kong, Taiwanese, mainland Chinese, and Chinese-American applicants for admission. A T. Tai Family Scholar will be named in a first-year class, and with suitable academic achievement and continuing need, would retain that honor until graduation.

Grace C. Townsend Scholarship (1941)
Bequest of Miss Grace C. Townsend.

Theodosios and Ekaterine Typaldos Endowed Scholarship Fund (2000)
Gift of Andreas '69 and Renee Typaldos and the Community Foundation of New Jersey. Preference is given to Greek-American students.

Upton Scholarship
For the children of employees of D. C. Heath and Company of Lexington, Massachusetts.

Valeiras Family Scholarship (2009)
Gift of Horacio and Amy Valeiras P'09 and Peter Valeiras '09.

Kenneth Valentine Memorial Scholarship (1986)
Bequest of Julia H. Valentine, in memory of Kenneth Valentine 1914. Preference is given to students in chemical engineering.

Frank Vanderpoel Scholarship (1936)
Bequest of Frank Vanderpoel.

William E. Verplanck Scholarship (1957)
Gift of Mrs. T. Bache Bleecker and Edward F. Verplanck 1912 in memory of their father, William E. Verplanck 1876.

Arnold Von Schrenk Scholarship (1943)
Bequest of Mrs. Helen von Schrenk in memory of her husband, Arnold von Schrenk.

George Wascheck Scholarship
Bequest of George Wascheck '26.

J. Watumull Scholarship (1989)
For students in the Graduate School of Arts and Sciences and in the Engineering School who are of East Indian ancestry.

Wells and Greene Scholarship
Bequest of Josephine Wells Greene.

Herbert A. Wheeler Scholarship (1923)
Gift of Herbert A. Wheeler.

Frederick C. Winter Scholarship (1966)
Gift of various donors in memory of Frederick C. Winter '43.

William F. Wurster Scholarship (1974)
Gifts of William F. Wurster 1913. Awarded to a student of chemical engineering and applied chemistry.

Robert H. and Margaret H. Wyld Scholarship
Gift of Robert H. 1904 and Margaret H. Wyld.

Max Yablick Memorial Scholarship (1986)
Bequest of Max Yablick 1914. Preference is given to graduates of Hebrew day schools and to students in the Combined Plan Program with Yeshiva University.

Theresa Ann Yeager Memorial Scholarship (1983)
Gift of the family of Theresa Ann Yeager '81 to support a woman who is enrolled Columbia Engineering.

Yu Family Scholarship
Gift of Richard '82 and Jean Yu.

ENDOWED FELLOWSHIPS

All endowed fellowships are awarded annually to graduate students. Preference is given to students who serve as teaching assistants. Graduate students who qualify for these awards will be contacted directly for application materials.

H. Dean Baker Fellowship (1982)
Awarded to support deserving graduate students in mechanical engineering.

Boris A. Bakhmeteff Research Fellowship in Fluid Mechanics
Provides a stipend for the academic year with tuition exemption to be arranged by the recipient's department, to a candidate for a doctoral degree in any department at Columbia University whose research is in fluid mechanics.

Quincy Ward Boese Fellowships
Pre-doctoral fellowships for students studying under the Faculty of Engineering and Applied Science.

Roy S. Bonsib Memorial Fellowship (1957)
Awarded to worthy students for advanced study or research in engineering.

Arthur Brant Fellowship (1997)
Gift of Arthur Brant. Awarded to students of the Henry Krumb School of Mines in the field of applied geophysics.

Samuel Willard Bridgham-William Petit Trowbridge Fellowship
A combined fellowship awarded annually for research.

Byron Fellowship (1980)
Bequest of Verna and Oscar Byron 1914.

William Campbell Fellowships for Encouraging Scientific Research
Four or five fellowships for research in the general field of metals.

Robert A.W. and Christine S. Carleton Fellowships in Civil Engineering
Fellowships awarded to students in the Department of Civil Engineering and Engineering Mechanics.

Chiang Chen Fellowship (2004)
Gift of the Chiang Chen Industrial Charity Foundation. Awarded to students in mechanical engineering.

Professor Bergen Davis Fellowship
Gift of Dr. Samuel Ruben. To be awarded to a student in chemical engineering and applied chemistry upon the recommendation of the senior professor in chemical engineering active in electrochemistry research.

George W. Ellis Fellowships
Awarded annually for graduate study in any division of the University. Open to students who are residents of the state of Vermont or who have been graduated from a Vermont college or university.

Herbert French Fellowship (2010)
Bequest of Ralph S. French '42CC.

Michael Frydman Endowed Fellowship (2000)
Established in 2000, a generous gift of a SEAS alumnus, Michael Frydman. Fellowship is designed to support academically gifted graduate students in the Department of Industrial Engineering and Operations Research, particularly in the Management Science program. Students are awarded a certificate and monetary prize.

Robert F. Gartland Fellowship
Gift of Robert Gartland, an IEOR alumnus. The fellowship is designated to support students in the Master of Science in Financial Engineering program who have demonstrated academic excellence and professional promise. Students are awarded a certificate and monetary prize.

GEM Fellowship
The GEM fellowship provides African-Americans, Hispanic Americans, and Native Americans access to graduate education. The fellowship includes tuition, fees, a stipend, and a paid summer internship. Applicants for this fellowship must be engineering or applied science majors.

Governor's Committee on Scholarship Achievement
One year awards based on financial need. Renewal is based on academic progress, financial need, and availability of funds. The student applies directly to the GCSA; the awards are matched by the School and are not in supplement to initial School awards.

Carl Gryte Fellowship (2007)
Gift from friends of Professor Carl Campbell Gryte. Awarded to students who are studying chemical engineering.

Daniel and Florence Guggenheim Fellowships
Two Ph.D. fellowships for the study of engineering mechanics in the Institute of Flight Structures in the Department of Civil Engineering and Engineering Mechanics. U.S. citizenship or permanent residence required.

M. D. Hassialis Memorial Fellowship (2002)
Gift of former students of the late Krumb Professor Emeritus Hassialis. Awarded to students of the Henry Krumb School of Mines in the field of Earth resources economics and management.

Higgins Fellowships
Designated to support first-year graduate students.

Leta Stetter Hollingworth Fellowship
Gift of Harry L. Hollingworth in memory of his wife to support women who are graduates of the University of Nebraska, with preference given to those who were born in Nebraska or received their earlier education there.

Edward J. Ignall Research Fellowship
Gift of family, friends, and former students in memory of Professor Edward J. Ignall. Awarded to encourage and help support the research activities of a graduate student in the Department of Industrial Engineering and Operations Research.

George M. Jaffin Fellowship
Awarded for graduate study and research leading to the Ph.D. degree in orthopedic biomechanics by the Department of Bioengineering of the Hospital for Joint Diseases, Orthopedic Institute, and the Department of Mechanical Engineering.

Herbert H. Kellogg Fellowship (1988)
Funded by former students and friends of Professor Emeritus H. H. Kellogg and the generous contribution of Professor Kellogg. Awarded to students of mineral engineering and chemical metallurgy.

Otto Kress Fellowship (1990)
Bequest of Mrs. Florence T. Kress in memory of her husband, Otto Kress. Awarded to postgraduate students.

Henry Krumb Fellowships
Annual fellowships in mining engineering, metallurgy, and ore dressing.

John F. T. Kuo Fellowship (1992)

Established by Dr. I. J. Won and other students of Professor Emeritus Kuo for the support of graduate students in applied geophysics.

Charles and Sarah Lapple Fellowship (2004)

Bequest of Charles '36, '37 and Sarah Lapple. Awarded to support deserving students in the Department of Chemical Engineering.

Kuo and Grace Li Memorial Fellowship (1993)

Gift from the Li Foundation Inc. Awarded to students interested in mining, mineral resources, metallurgy, and materials science.

Ralph H. McKee Fellowship (1979)

Bequest of Ralph H. Mckee to support fellowships in the fields of mathematics or chemical engineering.

Walter Mielziner Fellowship (2011)

Bequest of Walter Mielziner '49 to support fellowships for students studying computer science, automatic controls or communications.

Benjamin Miller Memorial Fellowship

Awarded to a student in the Department of Industrial Engineering and Operations Research. Preference is given to students concerned with work in government-industry regulatory policy, procurement procedures and trade regulations.

Nickolaus Fellowship

Gift of Nicholas Nickolaus '50.

Anthony Pesco Fellowship (2006)

Gift of Dr. Anthony Pesco '82, '83, '87 to support students in the Chemical Engineering Department who wish to pursue careers in academia.

Presidential Distinguished Fellowships

These fellowships are awarded annually to selected incoming Ph.D., Eng. Sc.D., and master's/Ph.D. students. Fellowships include tuition plus an annual stipend of $24,000 for up to four years, including three months of summer research. All applications for admission are considered for these new fellowships.

Bernard R. Queneau Fellowship

Gift of Bernard R. Queneau '32CC, '33. Awarded to a student in the Department of Earth and Environmental Engineering.

David M. Rickey Endowed Fellowship (2000)

Gift of David M. Rickey '79. Awarded to students studying electrical engineering under the holder of the David M. Rickey Professorship.

Lydia C. Roberts Graduate Fellowships

Open to persons born in Iowa who have been graduated from an Iowa college or university. In addition to the stipend, the fellow is reimbursed the cost of traveling once from Iowa to New York City and back. Special provisions: holders may not concentrate their studies in law, medicine, dentistry, veterinary medicine, or theology, and each holder must, when accepting the award, state that it is his or her purpose to return to Iowa for at least two years after completing studies at Columbia; holders are eligible for reappointment.

Samuel N. Rubinstein Endowed Fellowship (2005)

Bequest of Leo Rubinstein '63 and gift of Frederick Rubinstein. Awarded to students studying applied mathematics or industrial design.

Frank E. Stinchfield Fellowship in Orthopedic Biomechanics

Awarded for graduate study and research in the Department of Mechanical Engineering through the Orthopedic Research Laboratory of the Department of Orthopedic Surgery, College of Physicians and Surgeons, it carries tuition exemption and a twelve-month stipend of up to $15,000.

Nickolas and Liliana Themelis Fellowship in Earth and Environmental Engineering (2000)

Gift of Nickolas and Liliana Themelis to support students in the Department of Earth and Environmental Engineering.

Erwin S. and Rose F. Wolfson Memorial Engineering Fellowship (1979)

Gift of Erwin S. and Rose F. Wolfson.

OUTSIDE FELLOWSHIP

Wei Family Private Foundation Fellowship

The Wei Family Private Foundation is a 501(c)(3) nonprofit organization established to honor the memory of Dr. Chung Kwai Lui Wei and Mr. Hsin Hsu Wei. The purpose of the foundation is to award scholarship grants to students of Chinese heritage with high academic credentials who are pursuing a graduate degree in Electrical Engineering. Visit www.wfpf888.org for more information.

MEDALS AND PRIZES

American Society of Civil Engineers—The Robert Ridgway Award

Awarded to the senior showing the most promise for a professional career in civil engineering.

American Society of Civil Engineers—Student Chapter Service Award

Established in 2008 to reward one or more students who have been particularly active in the Student Steel Bridge Competition.

American Society of Civil Engineers—Younger Member Forum Award

Awarded annually to that member of the graduating class in civil engineering who has been most active in promoting the aims of the Society.

American Society of Mechanical Engineers

In recognition of outstanding efforts and accomplishments on behalf of the American Society of Mechanical Engineers Student Section at Columbia University.

Applied Mathematics Faculty Award

Awarded to an outstanding senior in the applied mathematics program.

Applied Physics Faculty Award

Awarded to an outstanding graduating senior in the applied physics program.

The Edwin Howard Armstrong Memorial Award

Awarded by the Faculty of Electrical Engineering to one outstanding graduating senior and one outstanding candidate for the M.S. degree, to honor the late Edwin Howard Armstrong,

professor of electrical engineering and noted inventor of wideband FM broadcasting, the regenerative circuit, and other basic circuits of communications and electronics.

The Theodore R. Bashkow Award
A cash award presented to a computer science senior who has excelled in independent projects. This is awarded in honor of Professor Theodore R. Bashkow, whose contributions as a researcher, teacher, and consultant have significantly advanced the art of computer science.

The Charles F. Bonilla Medal
The Bonilla Medal is an award for outstanding academic merit. It is presented annually to that student in the graduating class in the Department of Chemical Engineering who best exemplifies the qualities of Professor Charles F. Bonilla.

The Tullio J. Borri ’51 Award in Civil Engineering
A certificate and cash prize presented annually by the Department of Civil Engineering and Engineering Mechanics to a senior for outstanding promise of scholarly and professional achievement in civil engineering. This award has been made possible by gifts from the stockholder/employees and the board of directors of the Damon G. Douglas Company, a New Jersey-based general contractor, in appreciation of Mr. Borri’s many years of dedicated service and visionary leadership as chairman and president.

Computer Engineering Award of Excellence
Awarded each year by vote of the computer engineering faculty to an outstanding senior in the computer engineering program.

Computer Science Department Award of Excellence
A $512 cash prize to a student who has demonstrated outstanding ability in the field of computer science.

The Edward A. Darling Prize in Industrial Engineering and Operations Research
Established in 1903 by a gift from the late Edward A. Darling, formerly superintendent of Buildings and Grounds; a certificate and prize awarded annually to the most faithful and deserving student of the graduating class in industrial engineering and operations research.

The Edward A. Darling Prize in Mechanical Engineering
Established in 1903 by a gift from the late Edward A. Darling, formerly superintendent of Buildings and Grounds; a certificate and $100 cash prize awarded annually to the most faithful and deserving student of the graduating class in mechanical engineering.

The Adam J. Derman Memorial Award
Established in 1989 by family and friends in memory of Adam J. Derman ’89 and graduate student in the Department of Industrial Engineering and Operations Research. A certificate and cash prize awarded annually by the Department of Industrial Engineering and Operations Research to a member of the graduating class who has demonstrated exceptional ability to make computer-oriented contributions to the fields of industrial engineering and operations research.

Electrical Engineering Department Research Award
Awarded by the faculty of Electrical Engineering to one outstanding graduating senior who has demonstrated outstanding passion and accomplishment in research.

Electrical Engineering Department Service Award
Awarded by the faculty of Electrical Engineering to one outstanding

graduating senior who has made significant contributions to the department and community at large.

Morton B. Friedman Memorial Prize for Excellence
Morton B. Friedman was a visionary in the vanguard of engineering education through his lifelong service as professor, department chair, and senior vice dean. Awarded periodically to an undergraduate or graduate student who best exhibits Dean's Friedman's characteristics of academic excellence, visionary leadership, and outstanding promise for the future.

Zvi Galil Award for Improvement in Engineering Student Life
Given annually to the student group that most improves engineering student life during the academic year. Established in honor of Zvi Galil, Dean of the School from 1995 to 2007.

The Jewell M. Garrelts Award
Awarded to an outstanding graduating senior who will pursue graduate study in the department that was so long and successfully shepherded by Professor Jewell M. Garrelts. This award is made possible by gifts from alumni and friends of Professor Garrelts and from the Garrelts family in honor of an outstanding engineer, educator, and administrator.

The Carl Gryte Prize
Awarded annually to an undergraduate student for service to the Department of Chemical Engineering.

The Stephen D. Guarino Memorial Award in Industrial Engineering and Operations Research
A certificate and cash prize established by a gift from Roger Guarino (1951) in memory of his son. To be awarded to one outstanding senior in the Industrial Engineering and Operations Research Department who, in the opinion of the faculty and Board of Managers of the Columbia Engineering School Alumni Association, has been active in undergraduate activities and has displayed leadership, school spirit, and scholarship achievement.

The Wlliam A. Hadley Award in Mechanical Engineering
Established in 1973 by Lucy Hadley in memory of her husband. The award is made annually in the form of a certificate and cash to that student in the graduating class in mechanical engineering who has best exemplified the ideals of character, scholarship, and service of Professor William A. Hadley.

The Thomas "Pop" Harrington Medal
Presented annually to the student who best exemplifies the qualities of character that Professor Harrington exhibited during his forty years of teaching. The medal is made possible by Dr. Myron A. Coler.

The Yuen-huo Hung and Chao-chin Huang Award in Biomedical Engineering
This award has been endowed to honor the grandfathers of Professor Clark T. Hung in the Department of Biomedical Engineering. His paternal grandfather,Yuen-huo Hung, was a surgeon in Taipei who was renowned for his practice of medicine and for his compassion toward patients. Professor Hung's maternal grandfather, Chao-chin Huang, was a famous politician in Taiwan who dedicated his life to the citizens of his country, serving as mayor of Taipei, speaker ofthe Taiwan Provincial Assembly, and consul general to the United States. This award is given to a graduating doctoral student in the Department of Biomedical Engineering who embodies

the collective attributes of these distinguished individuals.This student will have demonstrated great potential for making significant contributions to the fields of biomedical engineering and public health, and for serving as an ambassador of biomedical engineering.

The Illig Medal
Established in 1898 by a bequest from William C. Illig, E.M., 1882, and awarded by the faculty to a member of the graduating class for commendable proficiency in his or her regular studies.

Industrial Engineering and Operations Research Academic Excellence Award
Given to exceptional students who completed both B.S. and M.S. in the IEOR Department consecutively. Students are awarded a certificate and monetary prize.

Industrial Engineering and Operations Research Graduate Fellowship
Gift from the IEOR Department, nominated by the faculty. This fellowship is designated to support graduate students pursuing degrees in operations research or industrial engineering. Recipients have demonstrated academic excellence and professional promise in the fields. Students are awarded a certificate and monetary prize.

Industrial Engineering and Operations Research Academic Outstanding Service Award
In recognition of significant contributions to the IEOR Department, this award goes to graduate students who have represented the department with grace and intelligence through their work as ambassadors, student leaders, etc. Students are awarded a certificate and monetary prize.

The Bernard Jaffe Prize for the Encouragement of Inventiveness in Engineering
Gift of Fern Jaffe in honor of her late husband, Bernard Jaffe '38, '39. Given annually to an undergraduate and graduate engineering and applied science student who exhibits exceptional qualities of curiosity toward the engineered world and a predisposition toward inventiveness and novel problem solving in both theoretical and physical contexts. Preference is given to students whose endeavors are directed toward the betterment of the human condition.

Eliahu I. Jury Award
Established 1991 for outstanding achievement by a graduate student or recent graduate in the areas of systems, communications, signal processing, or circuits.

Charles Kandel Award
Medal and cash prize presented annually by the Columbia Engineering School Alumni Association to that member of the graduating class who has best promoted the interests of the School through participation in extracurricular activities and student-alumni affairs.

Andrew P. Kosoresow Memorial Award for Excellence in Teaching, TA-ing, and Service
Awarded each year by the Department of Computer Science to up to three computer science students for outstanding contributions to teaching in the department and exemplary service to the department and its mission.

Dongju Lee Memorial Award
Established in 2005 by family and friends in memory of Dongju Lee (DJ), graduate student in the Department of Civil Engineering and Engineering Mechanics, 1999–2003. A certificate and cash prize awarded annually by the department to a doctoral student specializing in geotechnical/ geoenvironmental engineering and of outstanding promise for a career in research and academia.

The Sebastian B. Littauer Award
Established in 1979 in honor of Professor Littauer, a certificate and cash prize presented annually by the Department of Industrial Engineering and Operations Research to a senior for outstanding promise of scholarly and professional achievement in operations research.

Robert D. Lilley Award for Socially Responsible Engineering
Established in 2013 by a gift from Helen M. Lilley, this award supports the activities of student clubs at the School that have as their primary focus socially responsible engineering.

Mechanical Engineering Certificate of Merit
In recognition of excellence in undergraduate studies.

The Henry L. Michel Award in Civil Engineering
Established by the Columbia Engineering School Alumni Association in memory of Henry M. Michel '49, who built Parsons Brinkerhoff into one of the world's leading engineering companies. A certificate and cash prize is presented annually by the Department of Civil Engineering and Engineering Mechanics to a student or group of students in the Civil Engineering Department who demonstrate outstanding promise of leadership and professional achievement in civil and construction engineering. The award is in support of a project with emphasis on the construction industry in which the students participate.

Paul Michelman Award for Exemplary Service to the Computer Science Department
This award is given to a Ph.D. student in computer science who has performed exemplary service to the department, devoting time and effort beyond the call to further the department's goals. It is given in memory of Dr. Paul Michelman '93, who devoted himself to improving our department through service while excelling as a researcher.

Millman Award
A certificate and prize, in honor of Jacob Millman, awarded to two of the most outstanding teaching assistants for the academic year.

The Russell C. Mills Award
Presented to a computer science major for excellence in computer science in memory of Russell C. Mills, a Ph.D. candidate in computer science who exemplified academic excellence by his boundless energy and intellectual curiosity.

The Mindlin Scholar in Civil Engineering and Engineering Mechanics
This award will be made each year to a graduate student in the Department of Civil Engineering and Engineering Mechanics in recognition of outstanding promise of a creative career in research

and/or practice. This award is made possible by gifts of friends, colleagues, and former students of Professor Raymond D. Mindlin, and, above all, by the Mindlin family. It is intended to honor the Mindlin brothers, Raymond, Eugene, and Rowland, who excelled in their respective scientific fields of engineering research, engineering practice, and medical practice.

The Moles' Student Award in Civil Engineering
Awarded to the student in engineering whose academic achievement and enthusiastic application show outstanding promise of personal development leading to a career in construction engineering and management.

The James F. Parker Memorial Award (Mechanical Engineering Design Award)
James F. Parker served and represented Columbia engineering students as their Dean from 1975 to 1984. He also distinguished himself in the pursuit and analysis of two-dimensional art. In recognition of his special combination of talents and their integration, the School of Engineering and Applied Science salutes the graduate student who has distinguished her- or himself as a designer. A person of creative and innovative inclination receives the James Parker Medal, as evidenced by outstanding performance in courses integrating engineering analysis and design.

The Robert Peele Prize
A prize of $500 awarded from time to time to that member of the graduating class in mining engineering who has shown the greatest proficiency in his or her course of studies.

The Claire S. and Robert E. Reiss Award in Biomedical Engineering
This award is given by Robert E. Reiss, B.S.'66, and his wife, Claire S., to the graduating senior(s) in biomedical engineering judged by faculty of the program as most likely to contribute substantially to the field.

The Robert Edward Reiss Award in Chemical Engineering
Awarded annually to the student in the Department of Chemical Engineering who shows the greatest promise of success in applying the discipline of chemical engineering to the improvement of biological products and medical devices.

The Francis B. F. Rhodes Prize
Established in 1926 by Eben Erskine Olcott 1874, in memory of his classmate, Francis Bell Forsyth Rhodes, School of Mines, 1874, and awarded from time to time to the member of the graduating class in materials science and metallurgical engineering who has shown the greatest proficiency in his or her course of study.

School of Engineering and Applied Science Scholar Athlete Award
Presented from time to time by the Office of the Dean to that graduating student who has distinguished himself or herself as a varsity athlete and scholar.

School of Engineering and Applied Science Student Activities Award
This award is presented to an undergraduate degree candidate in Columbia Engineering who by virtue of his or her willingness, energy, and leadership has significantly contributed to the cocurricular life of the School.

Robert Simon Memorial Prize
The Robert Simon Memorial Prize was established in 2001 to honor Robert Simon, a Columbia alumnus who spent a lifetime making valuable contributions to computational and mathematical sciences, and is awarded annually by the Department of Applied Physics and Applied Mathematics to the doctoral student who has completed the most outstanding dissertation. Should no dissertation qualify in a given year, the prize may be awarded to either the most outstanding student who has completed a Master of Science degree in the department or to the most outstanding graduating senior in the department.

The Richard Skalak Memorial Prize
The Richard Skalak Memorial Prize was founded in recognition of the pioneering contributions of Richard Skalak to the development of the biomedical engineering program at Columbia University. Dr. Skalak was an inspirational teacher and scholar who taught students and colleagues to appreciate the value of broad interactions between engineering and medicine, particularly in the fields of cardiovascular mechanics, tissue engineering, and orthopedics. The Richard Skalak Memorial Prize is awarded annually to a senior biomedical engineering student who exemplifies the qualities of outstanding engineering scholarship and breadth of scientific curiosity that form the basis for lifelong learning and discovery.

Professor Rene B. Testa Award
A prize that will be given to graduate and undergraduate students who have achieved excellence in their academic program and have actively participated in the research and testing mission of the Carleton Laboratory.

The George Vincent Wendell Memorial Medal
Established in 1924 by the friends in the alumni and faculty of the late Professor George Vincent Wendell to honor and perpetuate his memory; a certificate and medal awarded annually by choice of the class and the faculty to that member of the graduating class who best exemplifies his ideals of character, scholarship, and service.

RESIDENCE HALL SCHOLARSHIPS

Class of 1887 Mines Residence Scholarship
Awarded annually to a third-year degree candidate, with preference given to descendants of members of the Class of 1887 Mines.

Class of 1896 Arts and Mines Scholarship
Awarded annually to a degree candidate in Columbia College, Columbia Engineering, or the Graduate School of Architecture and Planning, with preference given to descendants of members of the Class of 1896 Arts and Mines.

Class of 1916 College and Engineering Fund
Gift of the Class of 1916 College and Engineering.

University and School Policies, Procedures, and Regulations

REGISTRATION AND ENROLLMENT

Registration is the process that reserves seats in particular classes for eligible students. It is accomplished by following the procedures announced in advance of each term's registration period.

Enrollment is the completion of the registration process and affords the full rights and privileges of student status. Enrollment is accomplished by the payment or other satisfaction of tuition and fees and by the satisfaction of other obligations to the University.

Registration alone does not guarantee enrollment; nor does registration alone guarantee the right to participate in class. In some cases, students will need to obtain the approval of the instructor or of a representative of the department that offers a course. Students should check this bulletin, their registration instructions, the Directory of Classes, and also with an adviser for all approvals that may be required.

To comply with current and anticipated Internal Revenue Service mandates, the University requires all students who will be receiving financial aid or payment through the University payroll system to report their Social Security number at the time of admission. Newly admitted students who do not have a Social Security number should obtain one well in advance of their first registration. International students should consult the International Students and Scholars Office, located at 524 Riverside Drive (212-854-3587), for further information.

Special billing authorization is required of all students whose bills are to be sent to a third party for payment. Students who are not citizens of the United States and who need authorization for special billing of tuition and/or fees to foreign institutions, agencies, or sponsors should go to the International Students and Scholars Office with two copies of the sponsorship letter.

University Regulations

Each person whose enrollment has been completed is considered a student of the University during the term for which he or she is enrolled unless his or her connection with the University is officially severed by withdrawal or for other reasons. No student enrolled in any school or college of the University shall at the same time be enrolled in any other school or college, either of Columbia University or of any other institution, without the specific authorization of the dean or director of the school or college of the University in which he or she is first enrolled.

The privileges of the University are not available to any student until enrollment has been completed. Students are not permitted to attend any University course for which they are not officially enrolled or for which they have not officially filed a program unless they have been granted auditing privileges.

The University reserves the right to withhold the privileges of registration and enrollment or any other University privilege from any person who has outstanding financial, academic, or administrative obligations to the University.

Continuous registration until completion of all requirements is obligatory for each degree. Students are exempted from the requirement to register continuously only when granted a voluntary or medical leave of absence by their Committee on Academic Standing (for undergraduate students) or the Office of Graduate Student Affairs (for graduate students).

Registration Instructions

Registration instructions are announced in advance of each registration period. Students should consult these instructions for the exact dates and times of registration activities. Students must be sure to obtain all necessary written course approvals and advisers' signatures before registering. Undergraduate students who have not registered for a full-time course load by the end of the change of program period will be withdrawn from the School, as will graduate students who have not registered for any course work by the end of the change of program period. International students enrolled in graduate degree programs must maintain full-time status until degree completion.

DEGREE REQUIREMENTS AND SATISFACTORY PROGRESS

Undergraduate

Undergraduate students are required to complete the School's degree requirements and graduate in eight academic terms. Full-time undergraduate registration is defined as at least 12 semester credits per term. However, in order to complete the degree, students must be averaging 16 points per term. Students may not register for point loads greater than 21 points per term without approval from the Committee on Academic Standing.

To be eligible to receive the Bachelor of Science degree, a student must complete the courses prescribed in a faculty-approved major/program (or faculty-authorized substitutions) and achieve a minimum cumulative grade-point average (GPA) of 2.0. Although the minimum number of academic credits is 128 for the B.S. degree, some programs of the School require a greater number of credits in order to complete all the requirements. Undergraduate engineering degrees are awarded only to students who have completed at least 60 points of course work at Columbia. No credit is earned for duplicate courses, including courses that are taken pass/fail the first time and the final grade is a P.

Undergraduates in the programs accredited by the Engineering Accreditation Commission of ABET (biomedical engineering, chemical engineering, civil engineering, Earth and environmental engineering, electrical engineering, and mechanical engineering) satisfy ABET requirements by taking the courses in prescribed programs, which have been designed by the departments so as to meet the ABET criteria.

Attendance

Students are expected to attend their classes and laboratory periods. Instructors may consider attendance in assessing a student's performance and may require a certain level of attendance for passing a course.

Graduate

Graduate students are required to complete the School's degree requirements as outlined on page 26 (The Graduate Programs). Full-time graduate registration is defined as at least 12 credits per term. Students may not register for point loads greater than 21 credits per term.

A graduate student who has matriculated in an M.S. program or is a special student is considered to be making normal progress if at the completion of 9 credits, he or she has earned a cumulative GPA of 2.5. Candidates in the Doctor of Engineering Science (Eng.Sc.D.) program are expected to achieve a 3.0 grade-point average at the completion of 9 points of course work.

Thereafter, graduate students are considered to be making minimum satisfactory progress if they successfully complete at least 75 percent of all courses they have registered for as candidates for the degree with grades of C– or better. Students placed on academic probation because of their grades are nonetheless considered to be making minimum satisfactory progress for their first term on probation (see chapter "Academic Standing," following). Degree requirements for master's degrees must be completed within five years; those for the doctoral degrees must be completed within seven years. A minimum cumulative grade-point average of 2.5 (in all courses taken as a degree candidate) is required for the M.S. degree; a minimum GPA of 3.0 is required for the Doctor of Engineering Science (Eng.Sc.D.) degree. The minimum residence requirement for each Columbia degree is 30 points of course work completed at Columbia.

Changes in Registration

A student who wishes to drop or add courses or to make other changes in his or her program of study after the change of program period must obtain the signature of his or her adviser. A student who wishes to drop or add a course in his or her major must obtain department approval. The deadline for making program changes in each term is shown in the Academic Calendar. After this date, undergraduate students must petition their Committee on Academic Standing; graduate students must petition the Office of Graduate Student Affairs. For courses dropped after these dates, no adjustment of fees will be made. Failure to attend a class without officially dropping the class will result in a grade indicating permanent unofficial withdrawal (UW).

Transfer Credits

Undergraduate students may obtain academic credit toward the B.S. degree by completing course work at other accredited four-year institutions. Normally, this credit is earned during the summer. To count as credit toward the degree, a course taken elsewhere must have an equivalent at Columbia University and the student must achieve a grade of at least B. An exception to this policy is made for students enrolled in an approved study abroad program. Students in an approved study abroad program will receive transfer credit if they earn a grade of C or higher. To transfer credit, a student must obtain prior approval from his or her adviser and the department before taking such courses. A course description and syllabus should be furnished as a part of the approval process. Courses taken before the receipt of the high school diploma may not be credited toward the B.S. degree. A maximum of 6 credits may be applied toward the degree for college courses taken following the receipt of a high school diploma and initial enrollment at Columbia University.

Master degree students are not eligible for transfer credits.

Students possessing a conferred M.S. degree may be awarded 2 residence units toward their Ph.D., as well as 30 points of advanced standing toward their Ph.D. or Eng.Sc.D. with departmental approval.

Examinations

Midterm examinations: Instructors generally schedule these in late October and mid-March.

Final examinations: These are given at the end of each term. The Master University Examination Schedule is available online and is confirmed by November 1 for the fall term and April 1 for the spring term. This schedule is sent to all academic departments and is available for viewing on the Columbia website. Students should consult with their instructors for any changes to the exam schedule. Examinations will not be rescheduled to accommodate travel plans.

Note: If a student has three final examinations scheduled during one calendar day, as certified by the Registrar, an arrangement may be made with one of the student's instructors to take that examination at another, mutually convenient time during the final examination period. This refers to a calendar day, not a 24-hour time period. Undergraduate students unable to make suitable arrangements on their own should contact their adviser. Graduate students should contact the Office of Graduate Student Affairs.

Transcripts and Certifications

For information on the Federal Family Education Rights and Privacy Act (FERPA) of 1974, please visit http://facets.columbia.edu—*Essential Policies for the Columbia Community*. Information on obtaining University transcripts and certifications will be found as a subhead under Essential Resources.

Report of Grades

Grades can be viewed by using the Student Services Online feature located on the Student Services home page at columbia.edu/students. If you need an official printed report, you must request a transcript (please see Transcripts and Certifications above).

All graduate students must have a current mailing address on file with the Registrar's Office.

Transcript Notations

The grading system is as follows: A, excellent; B, good; C, satisfactory; D, poor but passing; F, failure (a final grade not subject to re-examination). Occasionally, P (Pass) is the only passing option available. The grade-point average is computed on the basis of the following index: A=4, B=3, C=2, D=1, F=0. Designations of + or – (used only with A, B, C) are equivalent to 0.33 (i.e., B+=3.33; B–=2.67). Grades of P, INC, UW, and MU will not be included in the computation of the grade-point average.

The mark of R (registration credit; no qualitative grade earned): not accepted for degree credit in any program. R credit is not available to undergraduate students for academic classes. In some divisions of the University, the instructor may stipulate conditions for the grade and report a failure if those conditions are not satisfied. The R notation will be given only to those students who indicate, upon registration and to the instructor, their intention to take the course for R, or who, with the approval of the instructor, file written notice of change of intention with the registrar not later than the last day for change of program. Students wishing to change to R credit after this date are required to submit the dean's written approval to the registrar. A course which has been taken for R credit may not be repeated later for examination credit. The mark of R is automatically given in Doctoral Research Instruction courses.

The mark of UW (unofficial withdrawal): given to students who discontinue attendance in a course but are still officially registered for it, or who fail to take a final examination without an authorized excuse.

The mark of IN (incomplete): granted only in the case of incapacitating illness as certified by the Health Services at Columbia, serious family emergency, or circumstances of comparable gravity. Undergraduate students request an IN by filling out the Incomplete Request Form with their advising dean prior to the final exam for the course in the semester of enrollment. Students requesting an IN must gain permission from both the Committee on Academic Standing (CAS) and the instructor. Graduate students should contact their instructor. If granted an IN, students must complete the required work within a period of time stipulated by the instructor but not to exceed one year. After a year, the IN will be automatically changed into an F or the contingency grade.

The mark of YC (year course): a mark given at the end of the first term of a course in which the full year of work must be completed before a qualitative grade is assigned. The grade given at the end of the second term is the grade for the entire course.

The mark of CP (credit pending): given only in graduate research courses in which student research projects regularly extend beyond the end of the term. Upon completion, a final qualitative grade is then assigned and credit allowed. The mark of CP implies satisfactory progress.

The mark of MU (make-up examination): given to a student who has failed the final examination in a course but who has been granted the privilege of taking a second examination in an effort to improve his or her final grade. The privilege is granted only when there is a wide discrepancy between the quality of the student's work during the term and his or her performance on the final examination, and when, in the instructor's judgment, the reasons justify a make-up examination. A student may be granted the mark of MU in only two courses in one term, or, alternatively, in three or more courses in one term if their total point value is not more than 7 credits. The student must remove MU by taking a special examination administered as soon as the instructor can schedule it.

The mark of P/F (pass/fail): Undergraduate students may take up to 6 credits of the 9-11 nontechnical elective credit on a P/F basis. These courses must be at the 3000-level or higher and must be courses that can be taken P/F by students attending Columbia College (e.g. instruction classes in foreign language and core curriculum classes are not eligible). These courses may not count toward the minor, and cannot be uncovered under any circumstances. Students may take only one class P/F per semester to count toward the 128 points, exclusive of physical education credit and any other course that is taught only on a P/F basis. Please note that physical education classes are the only courses taught solely on a P/F basis that may apply toward the 128 credits for the degree. The P/F option does not count toward degree requirements for graduate students.

The mark of W (official withdrawal): a mark given to students who are granted a leave of absence after the drop deadline for the semester. The grade of W, meaning "official withdrawal," will be recorded as the official grade for the course in lieu of a letter grade. The grade of W will zero out the credits for the class so the student's GPA will not be affected.

Name Changes

Students may change their name of record by submitting a name change affidavit to the Student Service Center. Affidavits are available from this office or online at registrar.columbia.edu.

GRADUATION

Columbia University awards degrees three times during the year: in February, May, and October. There is one commencement ceremony in May.

Application or Renewal of Application for the Degree

In general, students pick up and file an application for a degree at their schools or departments, but there are several exceptions. Candidates for Master of Science degree may pick up and file their application for the degree with the Diploma Division, 210 Kent Hall, or through the registrar's website: registrar.columbia.edu/registrar-forms/application-degree-or-certificate.

Candidates for doctoral and Master of Philosophy degrees should inquire at their departments but must also follow the instructions of the Dissertation Office, 107 Low Library.

General deadlines for applying for graduation are November 1 for February, December 1 for May, and August 1 for October. (When a deadline falls on a weekend or holiday, the deadline moves to the next business day.) Doctoral students must deposit their dissertations two days before the above conferral dates in order to graduate.

Students who fail to earn the degree by the conferral date for which they applied must file another application for a later conferral date.

Diplomas

There is no charge for the preparation and conferral of an original diploma. If your diploma is lost or damaged, there will be a charge of $100 for a replacement diploma. Note that replacement diplomas carry the signatures of current University officials. Applications for replacement diplomas are available on our website: registrar.columbia.edu/registrar-forms/application-replacement-diploma. Any questions regarding graduation or diploma processing should be addressed to diplomas@columbia.edu.

ACADEMIC HONORS

Dean's List

To be eligible for Dean's List honors, an undergraduate student must achieve a grade-point average of 3.5 or better and complete at least 15 graded credits with no unauthorized incompletes, UWs, or grades lower than C.

Honors Awarded with the Degree

At the end of the academic year, a select portion of the candidates for the Bachelor of Science degree who have achieved the highest academic cumulative grade-point average are accorded Latin honors. Latin honors are awarded in three categories (cum laude, magna cum laude, and summa cum laude) to no more than 25 percent of the graduating class, with no more than 5 percent summa cum laude, 10 percent magna cum laude, and 10 percent cum laude. Honors are awarded on the overall record of graduating seniors who have completed a minimum of four semesters at Columbia. Students may not apply for honors.

ACADEMIC MONITORING

The Undergraduate Committee on Academic Standing determines academic policies and regulations for the School except in certain instances when decisions are made by the faculty as a whole. The Undergraduate Committee on Academic Standing is expected to uphold the policies and regulations of the Committee on Instruction and determine when circumstances warrant exceptions to them.

Academic performance is reviewed by advisers at the end of each semester. The Undergraduate Committee on Academic Standing, in consultation with the departments, meets to review undergraduate grades and progress toward the degree. Indicators of academic well-being are grades that average above 2.0 each term, in a coordinated program of study, with no incomplete grades.

Possible academic sanctions include:

- *Warning:* C– or below in any core science course or in a required course for their major; low points toward degree completion
- *Academic Probation:* Students will be placed on academic probation if they meet any of the conditions below:
  - fall below a 2.0 GPA in a given semester
  - have not completed 12 points successfully in a given semester
  - have not completed chemistry, physics, University Writing, The Art of Engineering, and calculus during the first year
  - receive a D, F, UW, or unauthorized Incomplete in any first-year/sophomore required courses
  - receive a D, F, UW, or unauthorized Incomplete in any course required for the major
  - receive straight C's in the core science courses (chemistry, calculus, physics)
  - not making significant progress toward the degree
- *Continued Probation:* Students who are already on probation and fail to meet the minimum requirements as stated in their sanction letter
- *Strict Probation:* Students who are already on probation, fail to meet the minimum requirements as stated in their sanction letter, and are far below minimum expectations. This action is typically made when there are signs of severe academic difficulty.
- *Suspension and Dismissal:* Students who have been placed on academic probation and who fail to be restored to good academic standing in the following semester can be considered either for suspension or dismissal by the Undergraduate Committee on Academic Standing. The decision to suspend or dismiss a student will be made by the Committee on Academic Standing in the Center for Student Advising and the Dean's Office in close consultation with the student's departmental adviser when the student has declared a major. In cases of suspension, the student will be required to make up the deficiencies in their academic record by taking appropriate courses at a four-year accredited institution in North America. Students must be able to complete their degree requirements in their eighth semester at Columbia after readmission. If this is not achievable, then students should be considered for dismissal instead.

The courses that the student must take will be determined by the Undergraduate Committee of Academic Standing and by the student's departmental adviser when the student has declared a major. All proposed courses will be reviewed by the appropriate faculty who teach the equivalent classes at Columbia University. All courses that are being taken to fulfill a major requirement or as a technical elective must be approved by the student's departmental adviser. Courses being taken to count as a nontech elective or to count as general credit would only require the approval of the Undergraduate Committee on Academic Standing. The existing procedures for the approval of outside credit will be followed in these cases. Students must receive a grade of B or better for the credit to be transferred.

The Office of Graduate Student Affairs monitors the academic progress of graduate students in consultation with the departments.

MEDICAL LEAVE OF ABSENCE

A medical leave of absence for an undergraduate student is granted by the James H. and Christine Turk Berick Center for Student Advising to a student whose health prevents him or her from successfully pursuing full-time study. Undergraduates who take a medical leave of absence are guaranteed housing upon their return.

A medical leave of absence for a graduate student is granted by the Office of Graduate Student Affairs, so please consult with this office for more information.

Documentation from a physician or counselor must be provided before such a leave is granted. In order to apply for readmission following a medical leave, a student must submit proof of recovery from a physician or counselor. A medical leave is for a minimum of one year and cannot be longer than two years. If the student does not return within the two-year time frame, he or she will be permanently withdrawn from the School. Students may only return in the fall or spring term, not in summer sessions.

When a medical leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be W (official withdrawal) in all courses. In certain circumstances a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted.

In exceptional cases, an undergraduate student may apply for readmission following a one-term medical leave of absence. In addition to providing a personal statement and supporting medical documentation for the medical leave readmission committee to review, the student will also need to provide a well-developed academic plan that has been approved by the departmental adviser and the Center for Student Advising as part of the readmission process. This plan must demonstrate that his or her return to Columbia Engineering following a one-semester leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eighth semester. The final decision regarding whether or not a student will be allowed to be readmitted after a one-semester leave will be made by the Medical Leave Readmission Committee. The deadlines for petitioning a readmission after a one-semester leave are June 1 for the fall semester and November 1 for the spring semester.

During the course of the leave, students are not permitted to take any courses for the purpose of transferring credit and are not permitted to be on campus. For more information about the medical leave of absence policy, consult your advising dean.

VOLUNTARY LEAVE OF ABSENCE

A voluntary leave of absence (VLOA) may be granted by the Committee on Academic Standing to undergraduate students who request a temporary withdrawal from Columbia Engineering for a nonmedical reason. Students considering a voluntary leave must discuss this option in advance with their advising dean. Voluntary leaves are granted for a period of one academic year only; VLOAs will ordinarily not be granted for one semester, or for more than one year. Students must be in good academic standing at the time of the leave and must be able to complete their major and degree in eight semesters.

A voluntary leave of absence for a graduate student is granted by the Office of Graduate Student Affairs, so please consult with this office for more information.

When a voluntary leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be a W (official withdrawal) in all courses. In certain circumstances a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted.

In exceptional cases, an undergraduate may apply for readmission following a one-term voluntary leave of absence. The student will need to provide to the Committee on Academic Standing a well-developed academic plan that has been approved by the departmental adviser and the Center for Student Advising as part of the admission process. This plan must demonstrate that his or her return to Columbia Engineering following a one-semester leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eighth semester. The Committee on Academic Standing will review the student's academic plan and request for readmission. The deadlines for petitioning for readmission after a one-semester leave are June 1 for the fall semester and November 1 for the spring semester.

Students may not take courses for transferable credit while on leave. Finally, students who choose to take voluntary leaves are not guaranteed housing upon return to the University. International students should contact the International Students and Scholars Office to ensure that a leave will not jeopardize their ability to return to Columbia Engineering.

UNDERGRADUATE EMERGENCY FAMILY LEAVE OF ABSENCE

Students who must leave the University for urgent family reasons that necessitate a semester-long absence (e.g., family death or serious illness in the family) may request an emergency family leave of absence. Documentation of the serious nature of the emergency must be provided. Students must request an emergency family leave of absence from their advising dean in the James H. and Christine Turk Berick Center for Student Advising.

When an emergency family leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be W (official withdrawal) in all courses. In certain circumstances, a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted.

To return, students must notify the Center for Student Advising as soon as possible, ideally by November 1 for the spring semester and June 1 for the fall semester. Students must request readmission in writing and submit a statement describing their readiness to return. Once readmission is granted, housing will be guaranteed. SEAS students may request permission to return after one semester as long as they can demonstrate that they can remain on sequence with their course work and have the prior approval of the departmental adviser.

Students who decide not to return must notify the James H. and Christine Turk Berick Center for Student Advising of their decision. The date of separation for the leave of absence will be the date of separation for withdrawal. Leaves may not extend beyond four semesters. Students who do not notify the Center for Student Advising of their intentions by the end of the two-year period will be permanently withdrawn.

LEAVE FOR MILITARY DUTY

Please refer to Military Leave of Absence Policy in *Essential Policies for the Columbia Community* (facets.columbia.edu) for recent updates regarding leave for military duty.

INVOLUNTARY LEAVE OF ABSENCE POLICY

Please refer to Involuntary Leave of Absence Policy in *Essential Policies for the Columbia Community* (facets.columbia.edu).

REQUIRED MEDICAL LEAVE FOR STUDENTS WITH EATING DISORDERS

Please refer to Required Medical Leave for Students with Eating Disorders in *Essential Policies for the Columbia Community* (facets.columbia.edu).

READMISSION

Students seeking readmission must submit evidence that they have achieved the purposes for which they left. Consequently, specific readmission procedures are determined by the reasons for the withdrawal. Further information for undergraduate students is available in the Center for Student Advising. Graduate students should see the Office of Graduate Student Affairs.

Students applying for readmission should complete all parts of the appropriate readmission procedures by June 1 for the autumn term or November 1 for the spring term.

LIFE IN THE ACADEMIC COMMUNITY

The Fu Foundation School of Engineering and Applied Science within Columbia University is a community. Admitted students, faculty, and administrators come together and work through committees and other representative bodies to pursue and to promote learning, scholarly inquiry, and free discourse. As in any community, principles of civility and reasoned interaction must be maintained. Thus, methods for addressing social as well as academic behaviors exist.

RULES OF UNIVERSITY CONDUCT

Rules of University Conduct are included under University Regulations in *Essential Policies for the Columbia Community* (facets.columbia.edu).

STUDENT CONDUCT

The continuance of each student upon the rolls of the University, the receipt of academic credits, graduation, and the conferring of the degree are strictly subject to the disciplinary powers of the University.

Although ultimate authority on matters of student discipline is vested in the Trustees of the University, the Dean of the School and his staff are given responsibility for establishing certain standards of behavior for Columbia Engineering students beyond the regulations included in the Statutes of the University and for defining procedures by which discipline will be administered.

We expect that in and out of the classroom, on and off campus, each student in the School will act in an honest way and will respect the rights of others. Freedom of expression is an essential part of University life, but it does not include intimidation, threats of violence, or the inducement of others to engage in violence or in conduct which harasses others. We state emphatically that conduct which threatens or harasses others because of their race, sex, religion, disability, sexual orientation, or for any other reason is unacceptable and will be dealt with very severely. If each of us at Columbia can live up to these standards, we can be confident that all in our community will benefit fully from the diversity to be found here. Any undergraduate student who believes he or she has been victimized should speak with an adviser in the James H. and Christine Turk Berick Center for Student Advising, a member of the Residential Life staff, or a member of the Office of Student Conduct and Community Standards; graduate students should speak with an officer in the Office of Graduate Student Affairs.

While every subtlety of proper behavior cannot be detailed here, examples of other actions subject to discipline are:

- dishonesty in dealings with University officials, including members of the faculty
- knowingly or recklessly endangering the health or safety of others
- intentionally or recklessly destroying, damaging, or stealing property
- possession, distribution, or use of illegal drugs
- possession of weapons
- refusal to show identification at the request of a University official; failure to respond to the legitimate request of a University official exercising his or her duty
- threatening, harassing, or abusing others
- violating local, state, or federal laws
- violating the “Rules of University Conduct” (copies of which are available in 406 Low Library and other locations mentioned above)
- violating the rules of the residence halls as outlined in the “Guide to Living”; this also applies to all fraternity and sorority housing
- violating the University’s Alcohol Policy
- violating the University’s Sexual Assault Policy
- violating the rules governing Columbia University Information Technology (CUIT) policies and procedures
- representing any commercial interest on campus or operating any business on campus without authorization from the Associate Dean of Career Services

ACADEMIC INTEGRITY

Academic integrity defines a university and is essential to the mission of education. At Columbia students are expected to participate in an academic community that honors intellectual work and respects its origins. In particular, the abilities to synthesize information and produce original work are key components in the learning process. As such, a violation of academic integrity is one of the most serious offenses a student can commit at Columbia and can result in dismissal.

Students rarely set out with the intent of engaging in violations of academic integrity. But classes are challenging at Columbia, and students will often find themselves pressed for time, unprepared for an assignment or exam, or feeling that the risk of earning a poor grade outweighs the need to be thorough. Such circumstances lead some students to behave in a manner that compromises the integrity of the academic community, disrespects their instructors and classmates, and deprives them of an opportunity to learn. In short, they cheat. Students who find themselves in such circumstances should immediately contact their instructor and adviser for advice.

The easiest way to avoid the temptation to cheat in the first place is to prepare yourself as best you can. Here are some basic suggestions to help you along the way:

- Understand instructor expectations and policies.
- Clarify any questions or concerns about assignments with instructors as early as possible.
- Develop a timeline for drafts and final edits of assignments and begin preparation in advance.
- Avoid plagiarism: acknowledge people's opinions and theories by carefully citing their words and always indicating sources.
- Utilize the campus's resources, such as the advising centers and Counseling and Psychological Services, if feeling overwhelmed, burdened, or pressured.
- Assume that collaboration in the completion of assignments is prohibited unless specified by the instructor.

Plagiarism and Acknowledgment of Sources

Columbia has always believed that writing effectively is one of the most important goals a college student can achieve. Students will be asked to do a great deal of written work while at Columbia: term papers, seminar and laboratory reports, and analytic essays of different lengths. These papers play a major role in course performance, but more important, they play a major role in intellectual development. Plagiarism, the use of words, phrases, or ideas belonging to another, without properly citing or acknowledging the source, is considered one of the most serious violations of academic integrity and is a growing problem on university campuses.

One of the most prevalent forms of plagiarism involves students using information from the Internet without proper citation. While the Internet can provide a wealth of information, sources obtained from the web must be properly cited just like any other source. If you are uncertain how to properly cite a source of information that is not your own, whether from the Internet or elsewhere, it is critical that you do not hand in your work until you have learned the proper way to use in-text references, footnotes, and bibliographies. Faculty members are available to help as questions arise about proper citations, references, and the appropriateness of group work on assignments. You can also check with the Undergraduate Writing Program. Ignorance of proper citation methods does not exonerate one from responsibility.

Personal Responsibility, Finding Support, and More Information

A student's education at Columbia University is comprised of two complementary components: a mastery over intellectual material within a discipline and the overall development of moral character and personal ethics. Participating in forms of academic dishonesty violates the standards of our community at Columbia and severely inhibits a student's chance to grow academically, professionally, and socially. As such, Columbia's approach to academic integrity is informed by its explicit belief that students must take full responsibility for their actions, meaning you will need to make informed choices inside and outside the classroom. Columbia offers a wealth of resources to help students make sound decisions regarding academics, extracurricular activities, and personal issues. If you don't know where to go, see your advising dean.

Academic Integrity Policies and Expectations

Violations of policy may be intentional or unintentional and may include dishonesty in academic assignments or in dealing with University officials, including faculty and staff members. Moreover, dishonesty during the Dean's Discipline hearing process may result in more serious consequences.

Common types of academic integrity violations:

- Plagiarism: the use of words, phrases, or ideas belonging to another, without properly citing or acknowledging the source
- Self-plagiarism: the submission of one piece of work in more than one course without the explicit permission of the instructors involved
- Falsification or misrepresentation of information in course work or lab work; on any application, petition, or forms submitted to the School
- Fabrication of credentials in materials submitted to the University for administrative or academic review
- Violating the limits of acceptable collaboration in course work set by a faculty member or department
- Facilitating academic dishonesty by enabling another to engage in such behavior
- Cheating on examinations, tests, or homework assignments
- Unauthorized collaboration on an assignment
- Receiving unauthorized assistance on an assignment
- Copying computer programs
- Unauthorized distribution of assignments and exams
- Lying to a professor or University officer
- Obtaining advance knowledge of exams or other assignments without permission

DISCIPLINARY PROCEDURES

Many policy violations that occur in the Residence Halls rules are handled by the Associate Directors of Residential Life. Some serious offenses are referred directly to the Office of Student Conduct and Community Standards. Violations in University Apartment Housing are handled by building managers and housing officials. Some incidents are referred directly to the School's housing liaison in the Office of Graduate Student Affairs.

Most violations of rules concerning fraternities or sororities as organizations are handled by the Associate Director of Greek Life and Leadership. Some serious offenses are referred directly to the Office of Student Conduct and Community Standards.

In matters involving rallies, picketing, and other mass demonstrations, the Rules of University Conduct outlines procedures.

The Office of Student Conduct and Community Standards is responsible for all disciplinary affairs concerning undergraduate students that are not reserved to some other body. The Office of Graduate Student Affairs is responsible for all disciplinary affairs concerning graduate students that are not reserved to some other body.

Dean's Discipline Process for Undergraduate and Graduate Students

The purpose of the Dean's Discipline process is twofold. First, it is used to determine the accused student's responsibility for the alleged violation(s) of Columbia Engineering or University policy(ies). In addition, it is an opportunity for the student to engage in a meaningful conversation regarding his or her role as a member of the Columbia community. The Dean's Discipline process is not an adversarial process, nor is it a legalistic one, and therefore the technical rules of evidence applicable to civil and criminal court cases do not apply.

In a situation requiring immediate action, a student may be removed from housing, if applicable, and/or placed on interim suspension if it is determined that the student's behavior makes his or her presence on campus a danger to the normal operations of the institution, or to the safety of himself or herself or others or to the property of the University or others.

When a complaint is received, the Office of Student Conduct and Community Standards or Office of Graduate Student Affairs determines whether Dean's Discipline is an appropriate response or if the complaint should be referred elsewhere. If a Dean's Discipline hearing is to occur, a student is informed in writing of the complaint made against him/her and of the next step in the process. At the hearing, at least two staff members will present the accused student with the information that supports the allegation that he/she has violated Columbia Engineering or other University policy(ies). The student is then asked to respond and will be given an opportunity to present information on his or her behalf.

At the conclusion of the hearing, the hearing officers will make a determination, based on all of the information available to them, regarding whether the accused student is responsible for the violation(s). The standard of proof used to make this determination is the preponderance of the evidence standard. This standard allows for a finding of responsibility if the information provided shows that it is more likely than not that a violation of Columbia policy(ies) occurred. If the student is found responsible, the degree of seriousness of the offense and the student's previous disciplinary record, if any, will determine the severity of the sanction that will be issued. The student will be notified of the outcome of the hearing in writing.

A student found responsible after a hearing has the right to request an appeal of the decision and the resulting sanctions. There are three grounds upon which an appeal of the decision may be made. A student found responsible for the violation of Columbia policy(ies) may request a review of the decision if: (1) the student believes a procedural error occurred, which the student feels may change or affect the outcome of the decision; (2) the student has substantive new evidence that was not available at the time of the hearing and that may change the outcome; or (3) the student feels that the severity of the sanction is inappropriate given the details of the case. The request for review must be made in writing as directed in the hearing outcome letter. For more information about the discipline process for undergraduate students, please visit the Office of Student Conduct and Community Standards website (studentconduct.columbia.edu/). For more information about the discipline process for graduate students, please visit the Office of Graduate Student Affairs website (engineering.columbia.edu/graduate-student-affairs).

Confidentiality

In general, under University policy and federal law, a student's record, including information about Dean's Discipline proceedings, is confidential; however, there are certain exceptions to this rule. One exception to this principle is that the outcome of Dean's Disciplinary proceedings alleging a crime of violence may be disclosed both to the accuser and the accused. To read more about the exceptions that apply to the disclosure of student records information, please visit facets.columbia.edu/policy-access-student-records-ferpa.

Students found responsible for reportable violations of conduct, including academic integrity violations, may face reports of such offenses on future recommendations for law, medical, or graduate school. The parents or guardians of undergraduate students may also be notified.

ESSENTIAL POLICIES FOR THE COLUMBIA COMMUNITY

This bulletin is intended for the guidance of persons applying for or considering application for admission to Columbia University and for the guidance of Columbia students and faculty. The bulletin sets forth in general the manner in which the University intends to proceed with respect to the matters set forth herein, but the University reserves the right to depart without notice from the terms of this bulletin. The bulletin is not intended to be and should not be regarded as a contract between the University and any student or other person.

Valuable information to help students, faculty, and staff understand some of the policies and regulations of the University can be found in *Essential Policies for the Columbia Community* at facets .columbia.edu.

Policies on this website pertain to campus safety (including harassment and discrimination), the confidentiality of student records, drug and alcohol use, student leaves, and political activity, as well as others. This is a useful reference to several important polices the Columbia University maintains including the following:

- Student E-mail Communication Policy
- Information Technology Policies
- Social Security Number Reporting
- Policy on Access to Student Records (FERPA)
- University Regulations
- Policies on Alcohol and Drugs
- Student Policies and Procedures on Discrimination and Harassment
- Gender-Based Misconduct Policies for Students
- Protection of Minors
- University Event Policies
- Policy on Partisan Political Activity
- Campus Safety and Security
- Crime Definitions in Accordance with the Federal Bureau of Investigation's Uniform Crime Reporting Program
- Morningside Campus: Required Medical Leave for Students with Eating Disorders
- Voluntary Leave of Absence Policy
- Involuntary Leave of Absence Policy
- Military Leave of Absence Policy
- Central Administration of the University's Academic Programs
- Non-Retaliation Policy
- Essential Resources
- Student Consumer Information
- Additional Policy Sources
- Directory

RESERVATION OF UNIVERSITY RIGHTS

This bulletin is intended for the guidance of persons applying for or considering application for admission to Columbia University and for the guidance of Columbia students and faculty. The bulletin sets forth in general the manner in which the University intends to proceed with respect to the matters set forth herein, but the University reserves the right to depart without notice from the terms of this bulletin. The bulletin is not intended to be, and should not be regarded as, a contract between the University and any student or other person.

ATTENDANCE

Students are held accountable for absences incurred owing to late enrollment.

RELIGIOUS HOLIDAYS

It is the policy of the University to respect its members' religious beliefs. In compliance with New York State law, each student who is absent from school because of his or her religious beliefs will be given an equivalent opportunity to register for classes or make-up any examination, study, or work requirements that he or she may have missed because of such absence due to religious beliefs, and alternative means will be sought for satisfying the academic requirements involved.

Officers of administration and of instruction responsible for scheduling academic activities or essential services are expected to avoid conflict with religious holidays as much as possible. If a suitable arrangement cannot be worked out between the student and the instructor involved, they should consult the appropriate dean or director. If an additional appeal is needed, it may be taken to the Provost.

ACADEMIC DISCIPLINE

See Policy on Conduct and Discipline.

THE FEDERAL FAMILY EDUCATIONAL RIGHTS AND PRIVACY ACT (FERPA)

See Transcripts and Certifications.

COLUMBIA UNIVERSITY OMBUDS OFFICE

The Ombuds Office is a neutral and confidential resource for informal conflict resolution, serving the entire Columbia University community—students, faculty, and employees.

As an institution, Columbia University is committed to the principles of equity and excellence. It is actively pursues both, adhering to the belief that equity is the partner of excellence. Columbia University's goal is a workforce and student body that reflects the diversity and talent of New York City, the larger metropolitan area, and the nation. In furtherance of this goal, Columbia has implemented policies and programs which seek to ensure that its employment and educational decisions are based on individual merit and not on bias or stereotypes.

The Office of Equal Opportunity and Affirmative Action (EOAA) has overall responsibility for the management of the University's Student Policies and Procedures on Discrimination and Harassment and the Employment Policies and Procedures and local laws and has been designated as the University's Compliance Office for the Title IX, Section 504 of the Rehabilitation Act, and other equal opportunity, nondiscrimination, and affirmative action laws. Students, faculty, and staff may contact the EOAA to inquire about their rights under University policies, request assistance, seek information about filing a complaint, or report conduct or behavior that may violate these policies.

All students and applicants for admission are protected from coercion, intimidation, interference, or retaliation for filing a complaint or assisting in an investigation under any of the applicable policies and laws.

STUDENT POLICIES ON DISCRIMINATION AND HARASSMENT

Columbia University is committed to providing a learning, living, and working environment free from unlawful discrimination and to foster a nurturing and vibrant community founded upon the fundamental dignity and worth of all its members. Consistent with this commitment, and with all applicable laws, it is the policy of the University not to tolerate unlawful discrimination in any form and to provide persons who feel that they are victims of discrimination with mechanisms for seeking redress.

Columbia University prohibits any form of discrimination against any person on the basis of race, color, sex, gender, pregnancy, religion, creed, marital status, partnership status, age, sexual orientation, national origin, disability, military status, or any other legally protected status in the administration of its educational policies, admissions policies, employment, scholarship and loan programs, and athletic and other University-administered programs.

Nothing in this policy shall abridge academic freedom or the University's educational mission. Prohibitions against discrimination and discriminatory harassment do not extend to statements or written materials that are relevant and appropriately related to the subject matter of courses.

All members of the University community are expected to adhere to the applicable policies, to cooperate with the procedures for responding to complaints of discrimination, harassment, and gender-based and sexual misconduct, and to report conduct or behavior they believe to be in violation of these policies to the Office of Equal Opportunity and Affirmative Action, to Student Services for Gender-Based and Sexual Misconduct, or to the Department of Education, Office for Civil Rights (New York Office), 646-428-3800, OCR.NewYork@ed.gov.

CONSENSUAL ROMANTIC AND SEXUAL RELATIONSHIPS

Columbia University maintains policies regarding consensual romantic and sexual relationships between faculty and students, and staff and students. The Faculty-Student Relationship Policy states that no faculty member shall exercise academic or professional authority over any student with whom he or she has or previously has had a consensual romantic or sexual relationship. This policy covers all officers of instruction, research, and the libraries, including student officers of instruction, research, and teaching assistants.

The Staff-Student Relationship Policy states that no staff member at Columbia should participate in the supervision, employment actions, evaluation, advising, or mentoring of any Columbia University student with whom that staff member has or has had a consensual romantic or sexual relationship, except in unusual circumstances, where explicit advance authorization has been obtained.

For additional information on these issues, policies and resources, please visit the Sexual Respect website at titleix.columbia.edu.

DISABILITY ACCOMMODATION

Students seeking access, accommodations or support services for a disability should contact Disability Services at 212-854-2388. Information on the services provided by Disability Services may be found online at health.columbia.edu/docs/services/ods/index.html.

FORMAL COMPLAINT PROCEDURES

Procedure for Complaint Against Another Student

Gender-Based Misconduct Policies for Students

Complaints against students for gender-based misconduct are processed in accord with the Gender-Based Misconduct Policies for Students. Students who attend Barnard College and Teachers College as well as Columbia University are covered by these policies. The use of the term "gender-based misconduct" includes sexual assault, sexual harassment, gender-based harassment, stalking, and intimate partner violence.

Columbia Law School Policy on Gender-Based Misconduct

Reports of alleged gender-based misconduct by a Columbia Law School student should be filed with the Columbia Law School Dean of Students at 212-854-7420. A copy of the policy may be found at eoaa.columbia.edu/resources/documents.

Student Policies and Procedures on Discrimination and Harassment

Complaints against other students for other forms of discrimination and harassment are processed in accord with the Student Policies and Procedures on Discrimination and Harassment and should be filed with the Dean of the school in which the respondent student is enrolled.

Procedure for Complaints Against a Student Organization

Students who wish to file a complaint of discrimination or harassment against a student organization should do so in consultation with the Dean of their own school; the Dean will identify the appropriate procedure and channels and assist the student in pursuing the complaint.

Procedure for Complaint Against a Member of the Faculty or Staff

Office of Equal Opportunity and Affirmative Action

Complaints against employees and third parties affiliated with the University for discrimination and harassment are processed in accord with the Employment Policies and Procedures on Discrimination and Harassment. The use of the term "discrimination and harassment" include discrimination, discriminatory harassment, gender-based harassment, stalking, intimate partner violence, sexual harassment, and sexual assault.

Violations of the University's Employment Policies and Procedures on Discrimination and Harassment and the Student Policies and Procedures on Discrimination and Harassment are prohibited. Appropriate disciplinary action may be taken against any employee or student who violates these policies.

Columbia also offers a number of confidential resources to students who believe they were subjected to discrimination, harassment, or gender-based or sexual misconduct and who do not wish to report to the University.

Counseling Services

Columbia Morningside: 212-854-2878
CUMC: 212-496-8491

Rape Crisis/Anti-Violence Support Center

Phone: 212-854-HELP

Office of the University physics

Phone: 212-854-6242

Health Services*

Columbia Morningside: 212-854-2284
Columbia Morningside Clinician On-Call: 212-854-9797
CUMC: 212-305-3400
CUMC Clinician On-Call: 212-305-3400

*Medical providers are considered confidential resources in the context of providing medical treatment of a patient.

Grievance Procedures

Students should consult SEAS policies on Student Grievances, Academic Concerns and Complaints for the appropriate procedure to complain about a faculty member's conduct in an instructional setting.

Sexual Assault Policy

On February 25, 2000, the University Senate adopted a Sexual Misconduct Policy and Disciplinary Procedure that can be used as an alternative to the Dean's Discipline; the policy and procedure have been renamed the Sexual Assault Policy and the Disciplinary Procedure for Sexual Assault respectively. The policy prohibits sexual assault by any student and is University wide, applying to all students in all schools of the University, including Teacher's College and Barnard College. The Disciplinary Procedure for Sexual Assault is an option that applies to all students with the exception of students within the Law School, Jewish Theological Seminary, and/or Union Theological Seminary. Complaints of sexual assault for these schools are addressed through Dean's Discipline. If the student being accused attends CC/SEAS, the Disciplinary Procedure for Sexual Assault will be the exclusive mechanism for filing a complaint.

Copies of the policy and procedure are available from the Administrative Coordinator of the Disciplinary Procedure for Sexual Assault, 701A Lerner, Mail Code 2617, 2920 Broadway, New York, NY 10027; telephone: 212-854-1717; fax: 212-8542728; columbia.edu/cu/dpsa. The policy and procedure can also be found in the Office of the Dean of Students of every school.

Policy

The University's Policy on Sexual Assault requires that standards of sexual conduct be observed on campus, that violations of these standards are subject to discipline, and that resources and structures be sufficient to meet the physical and emotional needs of individuals who have experienced sexual assault. Columbia University's policy defines sexual assault as nonconsensual, intentional physical contact of a sexual nature, such as unwelcome physical contact with a person's genitals, buttocks, or breasts. Sexual assault occurs when the act is committed either by (a) physical force, violence, threat or intimidation; (b) ignoring the objections of another person; (c) causing another's intoxication or impairment through the use of drugs or alcohol; or (d) taking advantage of another person's incapacitation, state of intimidation, helplessness, or other inability to consent.

Complaint Resolution Options

Three University-based options are available for resolution of complaints of sexual assault against a student:

1. Dean's Discipline within the school of the charged student;

2. the University's Disciplinary Procedure for Sexual Assault; or

3. mediation through an accredited mediator affiliated with the University, such as the Ombuds Officer.

Complaints may also be filed with the New York City Police Department.

Choosing to pursue a disciplinary action can be a difficult and confusing decision. The Manager of the Disciplinary Procedure for Sexual Assault is available to assist you in understanding your options for complaint resolution, as are trained peer advocates from the Rape Crisis/Anti-Violence Support Center.

Helen Arnold, Manager
Disciplinary Procedure for Sexual Assault
hva2002@columbia.edu
701A Lerner, Mail Code 2617
2920 Broadway
New York, NY 10027
phone: 212-854-1717
fax: 212-854-2728
columbia.edu/cu/dpsa

Complaints about nonstudent members of the University community should be directed to the Office of Equal Opportunity and Affirmative Action at Columbia, the Dean of Studies Office at Barnard, or the Office of the Associate Dean at Teachers College.

The following procedures are part of a process to ensure that student concerns about experiences in the classroom or with faculty are addressed in an informed and appropriate manner.

Due to the size and diverse nature of our scholarly community, each school maintains its own processes for addressing issues raised by students, including their concerns about experiences in the classroom or with faculty at their school. Experience has shown that most student concerns are best resolved in a collaborative way at the school level. Columbia Engineering offers several informal paths for students to use, as described in this statement.

If a student's concerns are not satisfied through this process, or if the student believes that a direct complaint to the Dean is more appropriate, formal grievance procedures are available through the Vice Dean of the School. These procedures should be used for complaints about Engineering faculty. For those faculty who are not members of Columbia Engineering, the student should consult the procedures of the school in which they serve.

For academic complaints relating to Engineering faculty, these procedures, like those of other schools, provide for a final appeal to the University Provost.

The procedures under item A do not take the place of the grievance procedures already established to address disputes over grades, academic dishonesty, or issues of behavioral concerns as they relate to student conduct (see item B). They also should not be used when students believe that they have been the victim of sexual harassment or discrimination (see item C) or that faculty have engaged in scholarly or scientific misconduct (see item D).

We welcome students' thoughts on ways to clarify or enhance these procedures. If you are an Engineering student, please e-mail seasdean@columbia.edu.

COMPLAINTS ABOUT FACULTY AND STAFF ACADEMIC MISCONDUCT

In fulfilling their instructional responsibilities, faculty are expected to treat their students with civility and respect. They "should promote an atmosphere of mutual tolerance, respect, and civility. They should allow the free expression of opinions within the classroom that may be different from their own and should not permit any such differences to influence their evaluation of their students' performance. They should confine their classes to the subject matter covered by their courses and not use them to advocate any political or social cause" *(2008 Faculty Handbook)*. A fuller description of faculty rights and obligations may be found in the *Faculty Handbook* (columbia.edu/cu/vpaa/handbook). Students who feel that members of the Engineering faculty have not met those obligations may take the following steps (the procedure below also applies to complaints against instructional and administrative staff):

Students are encouraged to seek a resolution to their complaints about faculty misconduct by talking directly with the faculty member. If they feel uncomfortable handling the situation in this manner, they may ask for help from a departmental faculty mediator, who will assist students with complaints about faculty members, other academic personnel, or administrators.

The name of the faculty mediator is posted in the department office and on the departmental website. Students may also ask the department chair or administrator to direct them to the faculty mediator. The faculty mediator tries to resolve any issue by informal meetings with the student and others, including faculty as seems appropriate. Students who are dissatisfied with the outcome may request a meeting with the department chair. The chair will review the mediator's recommendation and seek informally to resolve the student's complaint.

- Students may bring their concerns to the University's Ombuds Officer, who serves as an informal, confidential resource for assisting members of the University with conflict resolution. The Ombuds Officer provides information, counseling, and referrals to appropriate University offices and will also mediate conflicts if both parties agree. The Ombuds Officer does not have the authority to adjudicate disputes and does not participate in any formal University grievance proceedings. Further information on the Ombuds Office may be found at columbia.edu/cu/ombuds.

- Students may seek a grievance hearing if informal mediation fails. The grievance procedures students should follow will depend upon the school within which the faculty member is appointed and the nature of the alleged misconduct.

If the faculty member holds an appointment in Columbia Engineering, the student may use the procedures described below to address the issues listed below. If the faculty member belongs to another school, students must use the procedure of that school. They may, however, ask for help from the departmental faculty mediator, chair, and the School's deans in identifying and understanding the appropriate procedures.

Conduct that is subject to formal grievance procedure includes:

- failure to show appropriate respect in an instructional setting for the rights of others to hold opinions differing from their own;
- misuse of faculty authority in an instructional setting to pressure students to support a political or social cause; and
- conduct in the classroom or another instructional setting that adversely affects the learning environment.

Formal grievance procedure at Columbia Engineering

If the informal mediation mentioned above failed, the student should compose and submit to the Vice Dean of the School a written statement documenting the grievance and should also include a description of the remedy sought. This should be done no later than 30 working days after the end of the semester in which the grievance occurred.

The Vice Dean will review the complaint to determine if a grievance hearing is warranted. If so, the Vice Dean will convene an ad hoc committee consisting of the Associate Dean for Graduate Student Affairs (graduate students) or the Senior Associate Dean of Student Affairs (undergraduate students), who acts as chair; a faculty member chosen by the Vice Dean; and a student chosen by one of the student councils (an undergraduate or a graduate student to correspond to the status of the student grieving).

The faculty member is given the student's letter of complaint and invited to submit a written response. The Committee reviews both statements and is given access to any other written documents relevant to the complaint. It will normally interview both the grievant and the faculty member and may, at its discretion, ask others to provide testimony. The merits of the grievance are evaluated within the context of University and Engineering school policy.

The investigative committee serves in an advisory capacity to the Dean of the School. It is expected to complete its investigation in a timely manner and submit a written report to the Dean, who may accept or modify its findings and any recommendations it may have made to remedy the student's complaint. The Dean will inform both the student and the faculty member of his decision in writing.

The committee ordinarily convenes within 10 working days of receiving the complaint from the Vice Dean and ordinarily completes its investigation and sends the Dean its report within 30 working days of convening. The Dean normally issues his or her decision within 30 working days of receiving the committee's report.

The Dean may discipline faculty members who are found to have committed professional misconduct. Any sanctions will be imposed in a manner that is consistent with the University's policies and procedures on faculty discipline. In particular, if the Dean believes that the offense is sufficiently serious to merit dismissal, he or she can initiate the procedures in Section 75 of the University Statutes for terminating tenured appointments, and nontenured appointments before the end of their stated term, for cause.

Either the student or the faculty member may appeal the decision of the Dean to the Provost. Findings of fact, remedies given the student, and penalties imposed on the faculty member are all subject to appeal. A written appeal must be submitted to the Provost within 15 working days of the date of the letter informing them of the Dean's decision.

Normally, the Provost will take no longer than 30 working days to evaluate an appeal. The Provost usually confines his or her review to the written record but reserves the right to collect information in any manner that will help to make his or her decision on the appeal.

The Provost will inform both the student and the faculty member of his or her decision in writing. If the Provost decides that the faculty member should be dismissed for cause, the case is subject to further review according to the procedures in Section 75 of the University Statutes, as noted above. Otherwise the decision of the Provost is final and not subject to further appeal.

All aspects of an investigation of a student grievance are confidential. The proceedings of the grievance committee are not open to the public. Only the student grievant and the faculty member accused of misconduct receive copies of the decisions of the Dean and the Provost. Everyone who is involved with the investigation of a grievance is expected to respect the confidentiality of the process.

DISPUTES OVER GRADES OR OTHER ACADEMIC EVALUATIONS

The awarding of grades and all other academic evaluations rests entirely with the faculty. If students have a concern relating to a particular grade or other assessment of their academic work, the student first should speak with the instructor of the class to understand how the grade or other evaluation was derived and to address the student's specific concern.

If the students do not feel comfortable speaking with the class instructor about the matter, they should then bring the issue to the attention of their class dean (undergraduate students) or department chair (graduate students).

If the students are unable thus to resolve the matter to their satisfaction and believe that a procedural issue is involved, they should bring the matter to the attention of the Vice Dean. The Vice Dean will work with the student and the faculty to determine whether there has been a procedural breach and if so, take immediate steps to remedy the matter. If the Vice Dean, together with appropriate faculty other than the instructor, decides that there is no need for further action, the student will be informed and the decision will be final.

DISCRIMINATION, HARASSMENT, AND GENDER-BASED MISCONDUCT

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Columbia University prohibits any form of discrimination against any person on the basis of race, color, sex, gender, pregnancy, religion, creed, marital status, partnership status, age, sexual orientation, national origin, disability, military status, or any other legally protected status in the administration of its educational policies, admissions policies, employment, scholarship and loan programs, and athletic and other University-administered programs.

Nothing in this policy shall abridge academic freedom or the University's educational mission. Prohibitions against discrimination and discriminatory harassment do not extend to statements or written materials that are relevant and appropriately related to the subject matter of courses.

If the alleged misconduct involves discrimination, harassment, gender-based or sexual misconduct, a student should file a complaint with the Associate Provost for Equal Opportunity and Affirmative Action. The procedures for handling such complaints are described in the statements Student Policies and Procedures on Discrimination and Harassment and in Gender-Based Misconduct Policies for Students

SCIENTIFIC OR SCHOLARLY MISCONDUCT

Complaints against the School's faculty that allege scientific or scholarly misconduct are evaluated using other procedures. These are contained in the Columbia University Institutional Policy on Misconduct in Research.

Directory of University Resources

COLUMBIA UNIVERSITY RESOURCE LIST

UNDERGRADUATE ADMISSIONS

Office of Undergraduate Admissions
212 Hamilton, MC 2807
212-854-2522
undergrad.admissions.columbia.edu
ugrad-ask@columbia.edu

Jessica Marinaccio
Dean of Undergraduate Admissions and Financial Aid

Joanna May, jm2638@columbia.edu
Associate Dean of Undergraduate Admissions

Meaghan McCarthy, mm3359@columbia.edu
Director of Programming and Outreach

David Buckwald, db2326@columbia.edu
Director of International Admissions and Strategic Initiatives

Diane McKoy, dm18@columbia.edu
Senior Associate Director

Dana Pavarini, dwp2102@columbia.edu
Associate Director, Director of Engineering Recruitment, and Director of the Undergraduate Recruitment Committee

UNDERGRADUATE ADVISING

James H. and Christine Turk Berick Center for Student Advising
403 Lerner Hall, MC 1201
212-854-6378
cc-seas.columbia.edu/csa
csa@columbia.edu

Monique Rinere, mrinere@columbia.edu
Dean of Advising

Cheryl de Moose, cd2783@columbia.edu
Director

Andrew Plaa, ap50@columbia.edu
Associate Dean of Advising

Angie Carrillo, ac2335@columbia.edu
Associate Dean

A. Alex España, aae2003@columbia.edu
Associate Dean

Megan Rigney, mr2168@columbia.edu
Associate Dean

UNDERGRADUATE STUDENT LIFE

510–515 Lerner, MC 2601
212-854-3612

Cristen Kromm, cs867@columbia.edu
Dean of Undergraduate Student Life

Beth Vanderputten Perlongo, bv2145@columbia.edu
Director of Strategic Planning and Operations

Sallee Spearman, ss4690@columbia.edu
Director of Student Financial Advising

Multicultural Affairs
510 Lerner, MC 2607
212-854-0720

Melinda Aquino, ma2398@columbia.edu
Associate Dean of Multicultural Affairs

Chia-Ying Sophia Pan, cp2804@columbia.edu
Director of Education, Outreach, and International Student Support

Intercultural Resource Center (IRC)
552 West 114th Street, MC 5755
212-854-7461

Marta Esquilin, mee2009@columbia.edu
Director of Intercultural and Social Justice Programming

Residential Life
515 Lerner, MC 4205
212-854-6805

Tara Hanna, tkh2105@columbia.edu
Director of Residential Life

Brad Badgley, bjb2153@columbia.edu
Director of Fraternity and Sorority Life

Student Engagement
515 Lerner, MC 2601
212-854-3611

Joshua Lucas, wjl2119@columbia.edu
Director of Student Community Programs

Philip Masciantonio, pm2811@columbia.edu
Director of Broadcasting and Operations, WKCR 89.9FM

Annie Virkus, av2581@columbia.edu
Director of Leadership and Civic Engagement

COLUMBIA COLLEGE

208 Hamilton, MC 2805
212-854-2441

James J. Valentini
Dean of Columbia College

Kathryn B. Yatrakis, kby1@columbia.edu
Dean of Academic Affairs

CORE CURRICULUM PROGRAM OFFICES

Center for the Core Curriculum
202 Hamilton, MC 2811
212-854-2453

Roosevelt Montás, rm63@columbia.edu
Director of the Center for the Core Curriculum

Art Humanities
826 Schermerhorn, MC 5517
212-854-4505

Branden Joseph, bwj4@columbia.edu
Director of Undergraduate Studies

Music Humanities
621 Dodge, MC 1813
212-854-3825

Susan Boynton, slb184@columbia.edu
Director of Undergraduate Studies

Contemporary Civilization
514 Fayerweather, MC 2811
212-854-5682

James Zetzel, zetzel@columbia.edu
Director of Undergraduate Studies

Literature Humanities
202 Hamilton, 212-854-2453
Mail Code 2811

All inquiries concerning Lit Hum should be directed to the Center for the Core Curriculum (listed above)

Undergraduate Writing Program
310 Philosophy, MC 4995
212-854-3886
uwp@columbia.edu

Nicole Wallack, *Director*

GRADUATE STUDENT AFFAIRS

Office of Graduate Student Affairs
530 S. W. Mudd, MC 4708
212-854-6438

Tiffany M. Simon, tms26@columbia.edu
Associate Dean of Graduate Student Affairs

Ellie Bastani, efb2123@columbia.edu
Assistant Dean of Graduate Student Services and Postdoctoral Affairs

Graduate Admissions
530 S. W. Mudd, MC 4708
212-854-6438

Jocelyn Morales, jm2388@columbia.edu
Associate Director

Clarissa C. Pena, ccp2133@columbia.edu
Student Services Manager

Graduate Student Life
530 S. W. Mudd, MC 4708
212-854-6438

Fred Sanchez, fs2553@columbia.edu
Assistant Director of Graduate Student Services

COLUMBIA VIDEO NETWORK

540 S. W. Mudd, MC 4719
212-854-6447

cvn.columbia.edu
info@cvn.columbia.edu

COMPUTING SUPPORT CENTER

Client Services Help Desk
202 Philosophy, MC 4926
212-854-1919
askcuit@columbia.edu

CENTER FOR CAREER EDUCATION

East Campus, Lower Level, MC 5727
212-854-5609

careereducation.columbia.edu
careereducation@columbia.edu

FINANCIAL AID (UNDERGRADUATE)

Office of Undergraduate Financial Aid and Educational Financing
Office: 618 Lerner
Mailing: 100 Hamilton, MC 2802
212-854-3711
ugrad-finaid@columbia.edu

Kathryn Tuman, kathryn.tuman@columbia.edu
Executive Director of Financial Aid

Pamela Mason, pamela.mason@columbia.edu
Senior Associate Director of Financial Aid

Leah Soman, lb2566@columbia.edu
Associate Director of Financial Aid

Vladimir Pucheck, vap2121@columbia.edu
Associate Director of Financial Aid

Noelle Cavacchioli, nrc2127@columbia.edu
Assistant Director, Graduate Engineering Financial Aid Liaison

FINANCIAL AID (GRADUATE)

Federal Financial Aid (Loans, Work Study)
Financial Aid and Educational Financing
615 Lerner, MC 2802
212-854-3711

Jacqueline Perez, jg363@columbia.edu
Associate Director

Marjorie Ortiz, mo2219@columbia.edu
Senior Assistant Director

Institutional Financial Aid (Grants, Fellowships, Assistantships)
Office of Graduate Student Affairs
530 S. W. Mudd, MC 4708
212-854-6438

PUBLIC SAFETY OFFICE

111 Low Library, MC 4301
212-854-2797 (24 hours a day)
publicsafety@columbia.edu

Campus Emergencies:
212-854-5555 (4-5555)

Escort Service:
212-854-SAFE (4-7233)

James F. McShane
Vice President for Public Safety

COLUMBIA HEALTH

General Info: 212-854-2284
After-hours Urgent Health Concerns: 212-854-9797
health.columbia.edu

CU-EMS (Ambulance)
212-854-5555 or 4-5555 from a campus phone

Insurance and Immunization Compliance Offices
Lerner, 5th Floor, MC 2605
Insurance Office: 212-854-3286
Immunization Compliance Office: 212-854-7210

Student Medical Insurance Plan Administrators: Aetna Student Health
1-800-859-8471
www.aetnastudenthealth.com/columbiadirect.html

Alice! Health Promotion
Lerner, 5th Floor, MC 2605
212-854-5453
health.columbia.edu/alice

Counseling and Psychological Services
Lerner, 8th floor, MC 2606
212-854-2878

Disability Services
108A Wien Hall, MC 3711
Voice/TTY: 212-854-2388

Medical Services
John Jay Hall, 3rd and 4th Floors
212-854-7426 (Appointments)
212-854-6655 (Gay Health Advocacy Project)

Sexual Violence Response Rape Crisis/Anti-Violence Support Center
Lerner, 7th floor
212-854-HELP (4357)

OFFICE OF EQUAL OPPORTUNITY AND AFFIRMATIVE ACTION

103 Low Library, MC 4333
212-854-5511

Melissa Rooker, mrooker@columbia.edu
Associate Provost

Durelle Hill, dh2681@columbia.edu
Interim Assistant Director

Student Services for Gender-Based and Sexual Misconduct
Wien Hall, Suite 108C
212-854-1717

Rosalie Siler, ssgbsm@columbia.edu
Assistant Director

INTERNATIONAL STUDENTS AND SCHOLARS OFFICE

524 Riverside Drive, Suite 200
212-854-3587
Mailing: 2960 Broadway, MC 5724

OFFICE OF STUDENT CONDUCT AND COMMUNITY STANDARDS

800 Watson Hall
612 West 115th Street, MC 2611
212-854-6872

Jeri Henry, jh3079@columbia.edu
Associate Vice President for Student Conduct and Community Standards

OFFICE OF UNIVERSITY LIFE

212-854-0411
UniversityLife@columbia.edu

Suzanne Goldberg, sgoldberg@columbia.edu
Executive Vice President for University Life

HOUSING AND DINING

Columbia Housing
118 Hartley, MC 3003
212-854-2946
housing@columbia.edu

Columbia Dining
125 Wallach, MC 3003
212-854-4076
eats@columbia.edu

LIBRARIES

Butler Library Information
535 West 114th Street
212-854-7309

Science & Engineering Library
401 Northwest Corner
212-851-2950

MATH/SCIENCE DEPARTMENTS

Biological Sciences
600 Fairchild, MC 2402
212-854-4581

Deborah Mowshowitz, dbm2@columbia.edu
Director of Undergraduate Programs

Chemistry
344 Havemeyer, MC 3178
212-854-2202

Vesna Gasperov, vg2231@columbia.edu
Undergraduate Program Coordinator

Earth and Environmental Sciences
106 Geoscience, Lamont-Doherty Earth Observatory, 845-365-8550

Sidney Hemming, sidney@ldeo.columbia.edu
Codirector of Undergraduate Studies

Walter C. Pitman, pitman@ldeo.columbia.edu
Codirector of Undergraduate Studies

Terry Plank, tplank@ldeo.columbia.edu
Codirector of Undergraduate Studies

Mathematics
410 Mathematics, MC 4426
212-854-2432

Panagiota Daskalopoulos, pdaskalo@math.columbia.edu
Director of Undergraduate Studies

Physics
704 Pupin, Mail Code 5255
212-854-3348

Jeremy Dodd, dodd@phys.columbia.edu
Director of Undergraduate Studies

Statistics
1255 Amsterdam Avenue
Room 1005 SSW, MC 4690
212-851-2132

Daniel Rabinowitz, dan@stat.columbia.edu
Director of Undergraduate Studies

OMBUDS OFFICE

660 Schermerhorn Ext., MC 5558
212-854-1234
ombuds@columbia.edu
columbia.edu/cu/ombuds

On Wednesdays the Ombuds Officer is at the Columbia Medical Center office:
101 Bard Hall
50 Haven Avenue
212-304-7026

Joan C. Waters
Ombuds Officer

THE EARL HALL CENTER

Office of the University Chaplain
Office: W710 Lerner
Mailing: 202 Earl Hall, MC 2008
212-854-6242, 212-854-1493

Jewelnel Davis, chaplain@columbia.edu
University Chaplain

INTERCOLLEGIATE ATHLETICS AND PHYSICAL EDUCATION

Dodge Physical Fitness Center
212-854-3439

Abbey Lade, al3524@columbia.edu
Director of Physical Education, Associate in Physical Education

Jessica De Palo, jd2923@columbia.edu
Associate Athletics Director for Enrichment Services

REGISTRAR

210 Kent, MC 9202

Barry Kane, bk2430@columbia.edu
Associate Vice President and University Registrar

Monica Avitsur, ma2685@columbia.edu
Deputy University Registrar

Jennifer Love, jll2212@columbia.edu
Associate Director, Student Service and ID Centers

Jennifer Caplan, jc12@columbia.edu
Associate Registrar

Sheila Serrano, ss1897@columbia.edu
Associate Registrar

Kristabelle Munson, km2137@columbia.edu
Associate Registrar and Director of Client Services

Austin Wanta, aw2768@columbia.edu
Assistant Registrar for IT

James Cunha, jhc4@columbia.edu
Assistant Registrar

Lenore Hubner, lah2@columbia.edu
Assistant Registrar

Jeanelle Folkes, jaf2007@columbia.edu
Operations and Systems Support Specialist

George Voorhis, gfv2@columbia.edu
Technical Specialist for Client Support

Bill Santin, bws1@columbia.edu
Registrar Services Associate

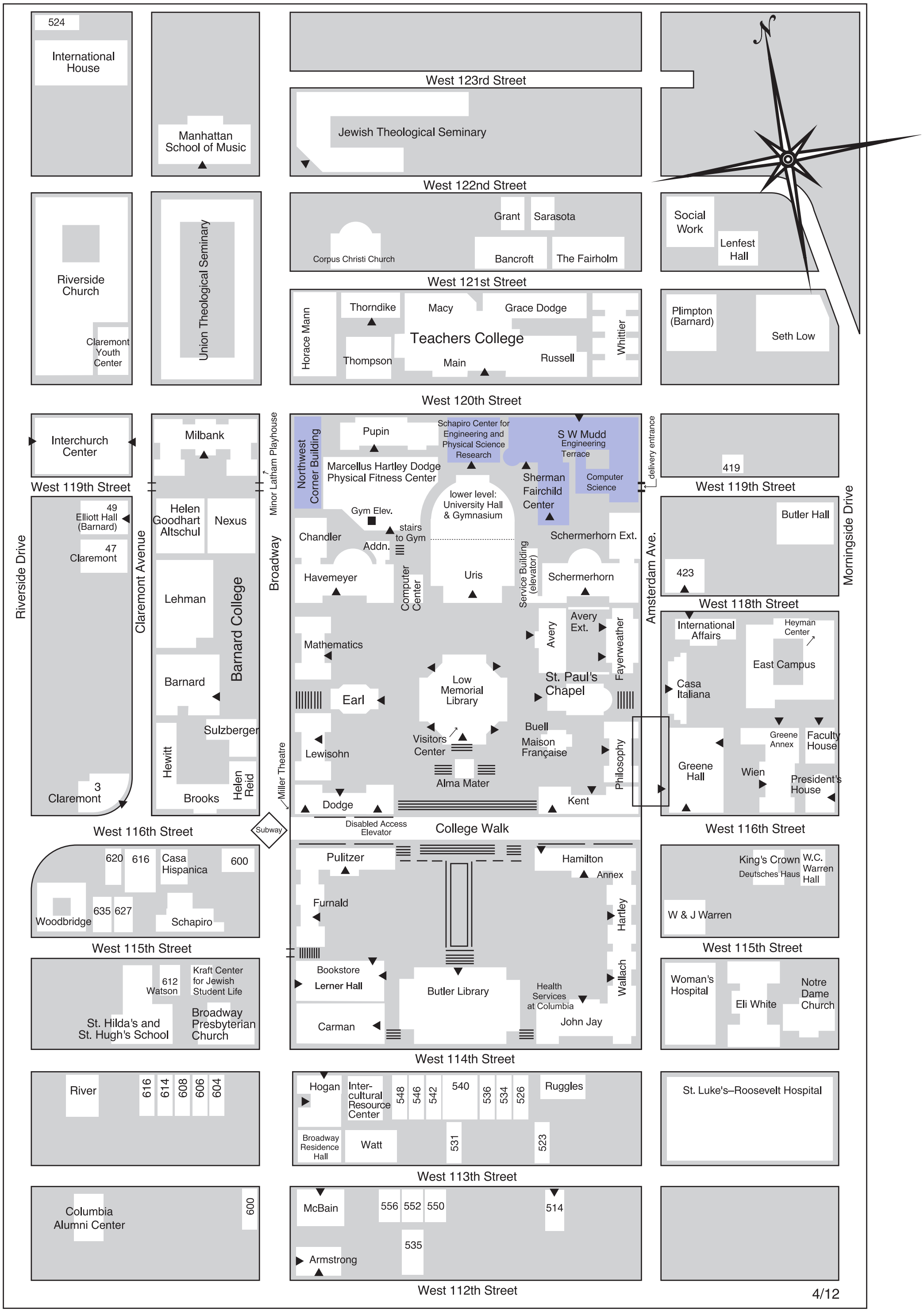
Michael Lam, ml3517@columbia.edu
Reporting Specialist

Justin Merced, jmm2238@columbia.edu
Scheduling Analyst

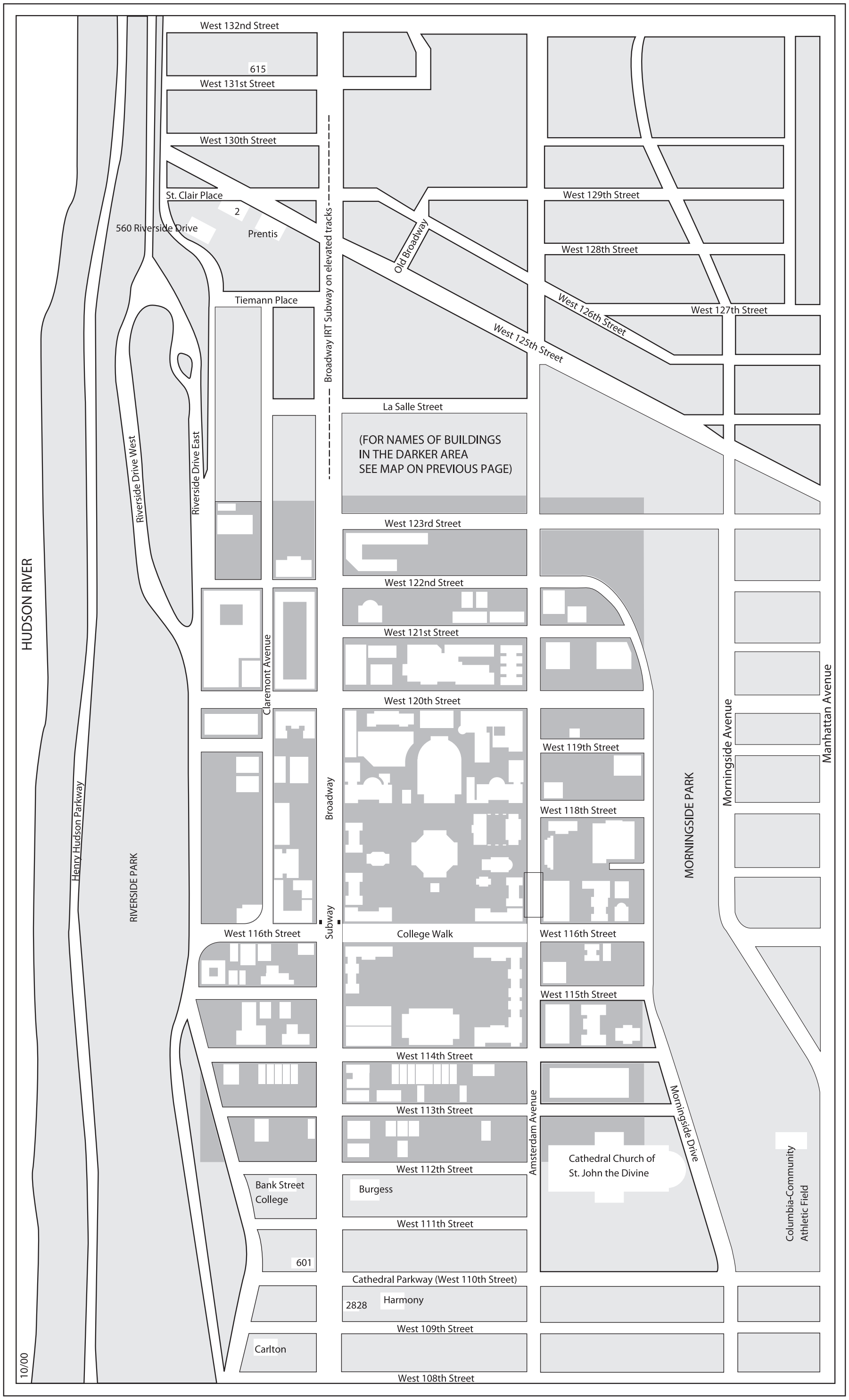
STUDENT SERVICE CENTER

205 Kent, MC 9202
212-854-4400

COLUMBIA UNIVERSITY
THE MORNINGSIDE CAMPUS & ENVIRONS



THE MORNINGSIDE HEIGHTS AREA OF NEW YORK CITY



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Academic Calendar 2015–2016

The following Academic Calendar was correct and complete when compiled; however, the University reserves the right to revise or amend it, in whole or in part, at any time. Information on the current Academic Calendar may be obtained in the Student Service Center, 205 Kent, 212-854-4330, or visit registrar.columbia.edu.

FALL TERM 2015

August

31–Sept. 7	New student orientation program.

September

1	Last Day to apply for October degrees.
3	Registration by appointment for first-year students.
7	Labor Day. University holiday.
8	First day of classes.
8-11, 14-18	Change of program by appointment.
18	Last day to (1) register for academic credit, (2) change course programs, (3) submit written notice of withdrawal from the fall term to the Dean of Student Affairs for full refund of tuition and special fees. No adjustment of fees for individual courses dropped after this date.
18	Last day to confirm, update, or request a waiver from the Student Medical Insurance Plan.

October

21	October degrees conferred.
22	Midterm date.

November

2	Last day to apply for February degrees.
2	Academic holiday.
3	Election Day. University holiday.
16-20	Registration by appointment for spring 2016.
19	Last day to drop Engineering courses without academic penalty. Last day to change a grading option.
26-27	Thanksgiving holiday.

December

1	Last day to apply for May degrees.
14	Last day of classes.
15-16	Study days.
17-23	Final examinations.
24–Jan. 18	Winter holiday.

SPRING TERM 2016

January

11-15	Registration by appointment for all classes.
18	Birthday of Martin Luther King Jr. University holiday.
19	First day of classes.
19-22, 25-29	Change of program by appointment.
29	Last day to (1) register for academic credit, (2) change course programs, (3) submit written notice of withdrawal from the spring term to the Dean of Student Affairs for full refund of tuition and special fees. No adjustment of fees for individual courses dropped after this date. Last day to confirm, update, or request a waiver from the Student Medical Insurance Plan.

February

10	February degrees conferred.

March

7	Midterm date.
14-18	Spring holiday.
24	Last day to drop Engineering courses without academic penalty. Last day to change grading option.

April

18-22	Registration by appointment for fall 2016.

May

2	Last day for continuing students to apply for financial aid for the 2016–2017 academic year.
2	Last day of classes.
3-5	Study days.
6-13	Final examinations.
15	Baccalaureate Service.
16	Engineering Class Day.
18	2016 University Commencement.

Columbia | Engineering
The Fu Foundation School of Engineering and Applied Science

500 West 120th Street
New York, NY 10027