Chemical and Biomolecular Engineering

The Department of Chemical and Biomolecular Engineering offers courses and training culminating in the Bachelor of Science degree in Chemical and Biomolecular Engineering. This discipline is dedicated to solving problems and generating valuable products involving chemical and biological transformations at the molecular scale. The undergraduate program emphasizes the molecular science aspects of biology and chemistry along with the engineering concepts essential to developing commercial products and processes. By selecting an appropriate concentration or by choice of free electives, students can prepare for a professional career path or for further study in chemical, biomolecular, or a related engineering field as well as medical, law, or business school. In the tradition of the Johns Hopkins University, many undergraduates are also involved in research, working closely with faculty and graduate students in research groups.

Students pursuing a BS degree in Chemical and Biomolecular Engineering have the opportunity, if they choose, to take some of their courses in a particular area in order to obtain a concentration. The two concentrations that students may choose to complete, Interfaces and Nanotechnology (IN) and Molecular and Cellular Bioengineering (MCB), are described below.

Interfaces and Nanotechnology (IN) Concentration.

Material properties of nanoparticles depend upon their dimensions; by making particles in the nanometer size range, materials with new optical, electrical and magnetic properties can be created. The ability to fabricate these particles and assemble them into ordered structures is central to exploiting these new materials. As such, engineering at the nanoscale will be dominated by surface science, as surface to volume ratios become large. Furthermore, self-assembly techniques, in which molecules can spontaneously assemble in ordered structures with nanometer length scales are ripe for exploitation to create new materials. In this concentration, students are trained in the fundamental scientific underpinnings of this emerging discipline.

Molecular and Cellular Bioengineering (MCB) Concentration

Many biological transformations of interest in biotechnology and biomedicine involve transformations at molecular and cellular levels. These molecular transformations include the genetic manipulation of cells in order to produce valuable designer protein and vaccines for the biopharmaceutical industry. Alternatively, cellular transformation events can be critical to the onset of diseases such as arteriosclerosis and cancer. Cellular transformations can be critical to the treatment of diseases such as inducing the death of cancer cells or the manipulation of stem cells along desirable pathways. Students wishing to study molecular and cellular events in biological systems and their applications in more detail can pursue an optional concentration in Molecular and Cellular Bioengineering. Students in this concentration will take lecture and laboratory courses in Cell Biology in order to fulfill advanced science requirements and electives in bioengineering subjects such as Cell Engineering, Tissue Engineering, Drug Delivery, Biological Macromolecules, or Molecular Evolution. In addition, students will take Biomolecular Engineering Laboratory in order to equip students with the hands-on skills needed for future careers involving the application of biological systems at the molecular and cellular level.

The mission of the chemical and biomolecular engineering undergraduate program is to provide students with the knowledge and skills required to pursue a professional career or to continue their studies towards an advanced degree. Recent graduates of the Chemical and Biomolecular Engineering program will:

- Become practicing engineers in industries related to chemistry and the life sciences, and/or pursue additional graduate or professional education.
- Solve challenging and diverse problems in the workplace, using their mastery of chemical and biomolecular engineering skills.
- Work effectively independently and in diverse multidisciplinary teams using good communication skills and while adhering to the highest ethical standards.
- Seek out professional challenges and opportunities that demonstrate leadership and a commitment to excellence in all professional endeavors.

The department also offers graduate programs leading to the Master of Science and Ph.D. degrees. These programs emphasize research leading to written thesis.

Undergraduate students strongly involved in research may be interested in our BS/MSE program in Chemical and Biomolecular Engineering that allows students to obtain an Masters in Science in Engineering immediately after the Bachelors of Science by adding an additional year of study.

The Faculty

Gregory Aranovich, Research Professor: molecular thermodynamics, phase equilibria, adsorption phenomena, and separation processes.

Michael J. Betenbaugh, Professor (Chair): genomics, recombinant DNA biotechnology, biopharmaceuticals, metabolic engineering, insect and mammalian cell culture, glycosylation engineering, and cell death processes.

Marc D. Donohue, Professor (Associate Dean for Research, Whiting School of Engineering): phase equilibria, statistical thermodynamics, kinetics of diffusion and phase transitions, adsorption.

German Drazer, Assistant Professor: transport phenomena in micro/nanofluidic systems, mixing, separation and detection in microdevices, multiscale modeling of molecular systems, interfacial phenomena at molecular scales, structure and transport in suspensions of nanoparticles, transport in porous media.

David Gracias, Assistant Professor: micro/nanofabrication, self-assembly, hybrid microelectronics, thin films, polymer and biomaterial surfaces, non-linear optical spectroscopy, probe microscopy.

Jeffrey Gray, Assistant Professor: biomolecular modeling, protein assembly and function, therapeutic antibodies, proteomics, nanoscale structure formation.

Justin Hanes, Associate Professor: biomaterials synthesis, nanosystems for targeted drug/gene delivery, extra- and intracellular barriers to targeted drug/gene delivery, cancer therapeutics, pulmonary drug delivery

Michael J. Karweit, Research Professor: numerical analysis, statistics, fluid mechanics, acoustics.

Joseph L. Katz, Professor: nucleation processes (e.g., condensation of supersaturated vapors, boiling of superheated liquids and its applications e.g., the Ouzo effect, parts per quadrillion detection) formation of nanosized ceramic oxide powders in flames, new proteomics tools.

Konstantinos Konstantopoulos, Associate Professor: cell and molecular engineering; functional genomics; fluid mechanics in medical applications: cancer metastasis, thrombosis, inflammation/bacterial infection.

Marc A. Ostermeier, Assistant Professor: biomolecular engineering, molecular evolution, protein engineering, combinatorial methods, biosensors, protein therapeutics.

Michael E. Paulaitis, Research Professor: high-pressure phase equilibria, supercritical fluids, hydration phenomena, thermodynamic and transport properties of polymeric materials and proteins.

Kathleen J. Stebe, Professor: transport phenomena at interfaces, Marangoni effects, dynamic surface tension, fluid particle behavior, adsorption of surfactants and proteins, electroporation, vesicle mechanics.

Denis Wirtz, Professor: cell adhesion and migration, cell mechanics, cytoskeleton, receptor-ligand interactions, cancer, particle tracking, new proteomics tools.

Joint, Part-Time and Visiting Appointments

Frederick J. Krambeck, Research Professor: chemical reaction engineering, modeling and optimization, biochemical dynamics.

Peter C. Searson, Professor: synthesis and characterization of nanostructured materials, thin films, metallization.

Jonah Earlbacher, Assistant Professor: nanostructured materials, self-organization and pattern formation, computational materials science, kinetics of shape change, ion beam interactions with surfaces, ultra-high vacuum processing.

Jennifer H. Elisseeff, Assistant Professor: tissue engineering, biomaterials, cartilage regeneration.

Kam W. Leong, Professor: protein and gene delivery, tissue engineering, polymeric biomaterials.

Ben Ho Park, Assistant Professor: somatic cell engineering, drug screening, genetics, breast cancer.

Chang-Ho Park, Visiting Professor: Biological removal of indoor/outdoor air pollutants (aromatic, sulfur, and chlorinated compounds). Engineering-based research on herbal medicine and acupuncture. Control of gastrointestinal bacterial growth and animal cell apoptosis using herbal extracts.

Lecturers

Haley Kermis, Lecturer: undergraduate education and outreach, biosensors; biomaterials.

John van Winkle, Lecturer: fuel cells, chlor-alkali manufacture, synthetic fibers, electrochemistry, ultra-pure chemicals, polycarbonates, silicon purification processes.

Facilities

The offices and state-of-the-art laboratories of Chemical and Biomolecular Engineering are located in the New Engineering Building, Maryland Hall, and Krieger Hall on the Homewood campus. The research laboratories are well-equipped for studies in the areas of biochemical engineering, cell and tissue engineering, phase equilibria, membrane science, polymer science, interfacial phenomena, separation processes, fluid mechanics, and nucleation phenomena. The Milton S. Eisenhower Library on the Homewood campus contains over two million volumes and access to more than 325 electronic journals. The university's other libraries located at the School of Medicine and at the Applied Physics Laboratory are also available to students. Through close collaborations with scientists at the National Institutes of Health, and the National Institute of Standards and Technology, the Institute for Genomic Research, Human Genome Sciences, Inc., and the Food and Drug Administration, students and faculty also have access to a variety of world-class facilities and other resources for research.

Financial Aid

Undergraduate scholarships and financial assistance are described in the catalog (see page 19). Part-time work is available in the Chemical and Biomolecular Engineering research laboratories on research projects supported by grants and contracts. There also is a federally sponsored work-study program for qualified students. A program has been established in the School of Engineering to coordinate work projects with local industries.

Financial assistance to graduate students is available in the forms of research assistantships, teaching assistantships, fellowships, and partial or full tuition remission. The financial aid package is specified following acceptance into the graduate program.

Undergraduate Program

The undergraduate program in chemical engineering is accredited by the Accreditation Board for Engineering and Technology (ABET) and by the American Institute of Chemical Engineers. As permitted under the ABET guidelines, we are continually upgrading our undergraduate programs to include the latest advances in chemical engineering. Such modifications will enable us to offer the best possible education experience to our undergraduates. For the latest chemical engineering educational programs, potential applicants are referred to our Web site at www.jhu.edu/chbe.

Requirements for the B.S. Degree

(See also General Requirements for Departmental Majors, page 46.)

The bachelor of science degree requires a minimum of 128 credits. Additional details are given in the *Chemical and Biomolecular Engineering Undergraduate Advising Manual* available from the department. The 128 credits must include:

- *Chemical and Biomolecular Engineering Core Courses.* The following ChemBE courses are required 540.101, 540.102, 540.202, 540.203, 540.204, 540.303, 540.301, 540.490, 540.304, 540.306, 540.311 (or 540.313), 540.314, and 540.409. Entry into any Chemical and Biomolecular Engineering core course is contingent upon receiving a C- or better in all prerequisite courses which are part of the Chemical and Biomolecular Engineering core. Students also must have a grade point average of at least 2.00 in the Chemical and Biomolecular Engineering core courses to graduate.
- *Other Engineering Courses.* A minimum of 48 engineering credits are required for the degree; therefore, in addition to the 42 credits of chemical and biomolecular engineering core courses, students are required to take at least 6 engineering elective credits.
- *Physics Courses and Laboratories.* The following physics courses are required: 171.101, 173.111 and 171.102.
- *Basic Chemistry Courses and Laboratories.* The following chemistry courses are required: 030.101, 030.105, 030.102, and 030.106.
- *Basic Biology Course.* All students are required to take Biochemistry (020.305).
- *Advanced Chemistry and Biology Courses.* The following two advanced chemistry courses are required 030.205, and 030.307. Students are required to take five additional credits (usually two courses) beyond these two required courses. Students that are concentrating in Molecular and Cellular Bioengineering or Interfaces and Nanotechnology have additional and/or alternate requirements (see below).
- *Mathematics Requirement.* The following mathematics courses are required: Calculus I, II and III (110.108, 110.109 and 110.202) and either Differential Equations with Applications (110.302) or Differential Equations (550.303). Calculus is so essential to Chemical Engineering that a grade of C- or better in both Calculus I and Calculus II is required.
- *Humanities and Social Sciences Courses.* Eighteen credits designated as humanities (H) or social science (S) are required. Students are required to take these courses in at least three subject areas. In addition students are required to take at least one concentration consisting of two or

more courses in at least one area of humanities or social sciences.

- *Writing Courses.* Two writing intensive or 'W' courses are required. Except for those students who have achieved a high level of writing capability, we strongly recommend that either Expository Writing (060.113) or Technical Communications (500.211) be one of the courses. The courses that are taken to satisfy the writing requirement must be passed with a grade of C- or better.
- *Undesignated Electives.* A minimum of 128 credits is required for the degree. Therefore, in addition to all the credits taken to fulfill the requirements mentioned in the various sections above (e.g. chemical engineering core courses, engineering electives, advanced chemistry electives, computing requirement, mathematics requirement, and H & S courses) up to 13 additional credits (called undesignated credits) are required.

Example Program for Chemical and Biomolecular Engineering Degree

Freshman Year/Fall

030.101 Intro to Chemistry I	3
030.105 Intro to Chemistry I Lab	1
110.108 Calculus I	4
171.101 General Physics I	4
173.111 General Physics Lab I	1
540.101 Chemical and Biomol. Eng. in Workplace	1
H/S Elective	3
Total	17

Freshman Year/Spring

030.102 Intro to Chemistry II	3
030.106 Intro to Chemistry II Laboratory	1
110.109 Calculus II	4
171.102 General Physics II	4
540.102 Intro. To Chemical and Biomolecular Engineering Problems	1
H/S Elective	3
Total	16

Sophomore Year/Fall

540.202 Intro. Chemical & Biological Process Analysis	4
490.490 Chemical and Biomolecular Lab Safety and Ethics*	1
110.202 Calculus III	4
020.305 Biochemistry	4
030.205 Organic Chemistry I	4
Total	17

Sophomore Year/Spring

540.203 Engineering Thermo	3
540.303 Transport I	4
110.302 Differential Equations with Applications	4
Advanced Chemistry Elective	4
Total	15

Junior Year/Fall

540.204 Applied Physical Chem.	3
540.304 Transport II	4
030.307 Physical Chemistry Instrumentation Lab III	3
Engineering Elective	3
H/S Elective	3
Total	16

Junior Year/Spring

540.301 Kinetic Processes	4
540.306 Chemical & Biological Separations	4
Advanced Chemistry Elective	3
Undesignated Elective	3
H/S Elective	3
Total	17

Senior Year/Fall

540.311 Chemical Engineering Lab	6
540.409 Modeling Dynamics & Control for Chemical and Biological Systems	3
H/S Elective	3
Undesignated Electives	3
Total	15

Senior Year/Spring

314.314 Chemical and Biomolecular Product Design	4
Engineering Elective	3
H/S Elective	3
Undesignated Electives	5
Total	15

Concentrations

Students pursing a degree in Chemical and Biomolecular Engineering have the option of concentrating in specific fields including Interfaces and Nanotechnology and Molecular and Cellular Bioengineering. Students completing a concentration will have this fact designated on their official university transcript. These concentrations have additional and/or alternate requirements, as described.

Molecular and Cellular Bioengineering (MCB) Concentration

Students must fulfill the following requirements:

- 020.306 Cell Biology is required and satisfies four credits of the advanced chemistry or chemistry-related electives.
- The requirement for 030.307 Physical Chemistry Instrumentation Lab III is replaced with a requirement for both 020.315 Biochemistry Lab and 020.316 Cell Biology Lab.
- Six credits of bioengineering electives are required.
- Students take 540.313 Chemical and Biomolecular Engineering Lab instead of 540.311 Chemical Engineering Lab.

Note that the four credits from Cell Biology and the one extra credit arising from taking 020.315 and 020.316 instead of 030.307 satisfy the requirement for 5 credits of advanced chemistry and biology electives.

Interfaces and Nanotechnology (IN) Concentration

- Six credits of interfaces and nanotechnology electives are required. See department for a list of approved electives.

Example Program: Molecular and Cellular Bioengineering Concentration

Freshman Year/Fall

030.101 Intro to Chemistry I	3
030.105 Intro to Chemistry I Lab	1
110.108 Calculus I	4
171.101 General Physics I	4
173.111 General Physics Lab I	1
540.101 Chemical and Biomol. Eng. in Workplace	1
H/S Elective	3
Total	17

Freshman Year/Spring

030.102 Intro to Chemistry II	3
030.106 Intro to Chemistry II Laboratory	1
110.109 Calculus II	4
171.102 General Physics II	4
540.102 Intro. To Chemical and Biomolecular Engineering Problems	1
H/S Elective	3
Total	16

Sophomore Year/Fall

202.202 Intro. Chemical & Biological Process Analysis	4
490.491 Chemical and Biomolecular Lab Safety and Ethics*	1
110.202 Calculus III	4
020.305 Biochemistry	4
030.205 Organic Chemistry I	4
Total	17

Sophomore Year/Spring

540.203 Engineering Thermo	3
540.303 Transport I	4
110.302 Differential Equations with Applications	4
020.306 Cell Biology	4
Total	15

Junior Year/Fall

540.204 Applied Physical Chem.	3
540.304 Transport II	4
020.315 Biochemistry Lab	2
Bioengineering Elective	3
H/S Elective	3
Total	15

Junior Year/Spring

540.301 Kinetic Processes	4
540.306 Chemical & Biological Separations	4
Undesignated Elective	3
020.316 Cell Biology Lab	2
H/S Elective	3
Total	16

Senior Year/Fall

540.313 Biomolecular Engineering Lab	6
540.409 Modeling Dynamics & Control for Chemical and Biological Systems	3
H/S Elective	3
Undesignated Electives	3
Total	15

Senior Year/Spring

314.315 Chemical and Biomolecular Product Design	4
Bioengineering Elective	3
H/S Elective	3
Undesignated Electives	7
Total	17

Example Program: Interfaces and Nanotechnology Concentration

Freshman Year/Fall

030.101	Intro to Chemistry I	3
030.105	Intro to Chemistry I Lab	1
110.108	Calculus I	4
171.101	General Physics I	4
173.111	General Physics Lab I	1
540.101	Chemical and Biomol. Eng. in Workplace	1
H/S Elective		3
	Total	17

Freshman Year/Spring

030.102	Intro to Chemistry II	3
030.106	Intro to Chemistry II Laboratory	1
110.109	Calculus II	4
171.102	General Physics II	4
540.102	Intro. To Chemical and Biomolecular Engineering Problems	1
H/S Elective		3
	Total	16

Sophomore Year/Fall

540.202	Intro. Chemical & Biological Process Analysis	4
490.492	Chemical and Biomolecular Lab Safety and Ethics*	1
110.202	Calculus III	4
020.305	Biochemistry	4
030.205	Organic Chemistry I	4
	Total	17

Sophomore Year/Spring

540.203	Engineering Thermo	3
540.303	Transport I	4
110.302	Differential Equations with Applications	4
Advanced Chemistry Elective		3
	Total	14

Junior Year/Fall

540.204	Applied Physical Chem.	3
540.304	Transport II	4
030.307	Physical Chemistry Instrumentation Lab III	3
Engineering Elective		3
H/S Elective		3
	Total	16

Junior Year/Spring

540.301	Kinetic Processes	4
540.306	Chemical & Biological Separations	4
030.TBA	Surface & Inter. Chem.	3
Undesignated Elective		3
H/S Elective		3
	Total	17

Senior Year/Fall

540.311	Chemical Engineering Lab	6
540.409	Modeling Dynamics & Control for Chemical and Biological Systems	3
H/S Elective		3
Undesignated Electives		3
	Total	15

Senior Year/Spring

314.316	Chemical and Biomolecular Product Design	4
Engineering Elective		3
H/S Elective		3
Undesignated Electives		6
	Total	16

B.S./M.S.E. Program in Chemical and Biomolecular Engineering

The B.S./M.S.E. program in Chemical and Biomolecular Engineering allows students to obtain a master of science in engineering immediately after the bachelor of science degree by adding up to an additional year of study. For students who qualify academically, the Whiting School of Engineering allows a half-tuition waiver after the completion of eight semesters or having received the bachelor of science degree.

Graduate Program

Graduate Degree Requirements

Master of Science in Engineering

The master's degree candidate must complete course work and research requirements. The course work requirements are identical to those for the Ph.D. degree. The student must also perform research that culminates in a master's essay which is approved by the research adviser and accepted by the departmental graduate committee. Master's degree candidates must also present their research results at an open seminar attended by the faculty and students. Students with a strong undergraduate background in chemical engineering usually complete the master's degree program in 12-18 months. A student whose undergraduate background is in another scientific area (such as chemistry, biology, or physics) normally completes the program within 24 months.

Doctor of Philosophy

Students must take six graduate-level courses, and are expected to attend seminars throughout their years in residence in the program. They must enroll in a minimum of two semesters of graduate seminars. There are three required core courses in thermodynamics, transport phenomena, and reaction kinetics. The student selects additional courses with the help of the graduate adviser to design a curriculum suitable for the student's interest. Students must maintain a B average in course work and satisfactory progress in research.

The student must pass a departmental candidacy exam for the Ph.D. program. This oral exam focuses on material covered in an undergraduate chemical engineering curriculum, including transport phenomena, thermodynamics, and reaction kinetics. Graduate students normally take this exam during the first year of graduate study.

The student must also pass the university's Graduate Board Oral (GBO) exam. This exam is administered by a committee of five faculty members consisting of the research adviser, another member of the Department of Chemical and Biomolecular Engineering, and three faculty members from other science or engineering departments. The GBO is a comprehensive examination in the candidate's field of specialization and requires proficiency on the graduate level in areas outside the major field. The exam is usually taken by the fifth semester.

The student must write a thesis based on original research and defend it before three faculty, at least two of whom are from the Department of Chemical and Biomolecular Engineering.

There is no foreign language requirement for the Ph.D. degree. A student with a strong undergraduate background usually earns the Ph.D. degree in four to five years.

Additional details on the graduate program are listed in the Graduate Student Handbook available from the department.

Undergraduate Courses

540.101 Chemical and Biomolecular Engineering in the Workplace: Biotechnology, Nanotechnology, and beyond

A series of lectures will introduce the student to the myriad of different career opportunities available to Chemical and Biomolecular Engineers. Weekly seminars by invited guests in combination with department faculty will introduce students to important real world problems in molecular biotechnology, electronics, law, medicine, biopharmaceuticals, energy, and the environment. Students will learn how chemical and biomolecular engineering concepts can impact these areas and the role of engineers in industry, academics, medicine and the non-profit sector. A variety of different companies and institutions will be profiled on a weekly basis. Prerequisites: none.
1 credit

540.102 Intro to Chemical and Biomolecular Engineering Problems

This course will introduce students to typical problems encountered by chemical and biomolecular engineers, and the tools used to address them. Fundamental concepts in material and energy balances, thermodynamics, transport phenomena and reaction kinetics will be introduced, and will demonstrate the relevance of future chemical and biomolecular core engineering courses. Student will also be exposed to valuable engineering skills such as: problem identification and solving, design of experiments and the analysis and interpretation of data.
Kermis 1 credit

540.202 (E) Introduction to Chemical and Biological Process Analysis

Introduction to chemical and biomolecular engineering and the fundamental principles of chemical process analysis. Formulation and solution of material and energy balances on chemical processes. Reductionist approaches to the solution of complex, multi-unit processes will be emphasized. Introduction to the basic concepts of thermodynamics as well as chemical and biochemical reactions and computer programming. Prerequisites: 030.101, 171.101.
Wirtz 4 credits

540.203 (E) Engineering Thermodynamics

Development of classical thermodynamic relationships and constitutive equations for one and two component systems. Introduction to phase equilibria and chemical reaction equilibria. Applications include the analysis and design of engines, refrigerators, heat pumps, compressors, and turbines. Prerequisites: 540.202, 030.101, 171.101. Corequisite: 110.202.
Staff 3 credits

540.204 (E) Applied Physical Chemistry

Introduction of the methods used to solve thermodynamic problems faced by chemical and biomolecular engineers, including phase and chemical equilibria problems, the thermodynamic properties of interfaces, and the thermodynamics of macromolecules. The basic thermodynamic relationships to describe phase equilibrium of single-component and multicomponent systems are developed.

Thermodynamic models for calculating fugacity are presented. Multicomponent phase equilibrium problems addressed include liquid-vapor, liquid-liquid, and liquid-liquid-vapor equilibrium. Basic thermodynamic relationships to describe chemical equilibria, the physical chemistry of liquid-liquid and liquid-solid interfaces, and the conformation of biological macromolecules are also presented. Prerequisite: 540.203.
Gracias 3 credits

540.301 (E) Kinetic Processes
Review of numerical methods applied to kinetic phenomena and reactor design in chemical and biological processes. Homogeneous kinetics and interpretation of reaction rate data. Batch, plug flow, and stirred tank reactor analyses, including reactors in parallel and in series. Selectivity and optimization considerations in multiple reaction systems. Nonisothermal reactors. Elements of heterogeneous kinetics, including adsorption isotherms and heterogeneous catalysis. Coupled transport and chemical/biological reaction rates. Prerequisites: 540.203, 540.303.
Hanes 4 credits

540.303 (E,N) Transport Phenomena I
Introduction to the field of transport phenomena. Molecular mechanisms of momentum transport (viscous flow), energy transport (heat conduction), and mass transport (diffusion). Isothermal equations of change (continuity, motion, and energy). The development of the Navier Stokes equation. The development of nonisothermal and multicomponent equations of change for heat and mass transfer. Exact solutions to steady state, isothermal unidirectional flow problems, to steady state heat and mass transfer problems. The analogies between heat, mass, and momentum transfer are emphasized throughout the course. Corequisite: 500.303.
Stebe 4 credits

540.304 (E,N) Transport Phenomena II
Dimensional analysis and dimensionless groups. Laminar boundary layers, introduction to turbulent flow. Definition of the friction factor. Macroscopic mass, momentum and mechanical energy balances (Bernouilli's equation). Metering of fluids. Convective heat and mass transfer. Heat and mass transfer in boundary layers. Correlations for convective heat and mass transfer. Boiling and condensation. Interphase mass transfer. Prerequisite: 540.303, 550.303
Konstantopoulos 4 credits

540.306 (E) Chemical and Biological Separations
This course covers staged and continuous-contacting separations processes critical to the chemical and biochemical industries. Processes considered include distillation, liquid-liquid extraction, gas absorption, leaching chromatography, crystallization, precipitation, filtration, and drying. Particular emphasis is placed on the biochemical uses of these processes and consequently on how the treatment of these processes differs from the more traditional approach. Prerequisites: 540.202, 540.303.
Staff 4 credits

540.311 Chemical Engineering Laboratory
Students are challenged with laboratory projects that are not well-defined and learn to develop an effective framework for approaching experimental work by identifying the important operating variables, deciding how best to obtain them, and using measured or calculated values of these operating variables to predict, carryout, analyze, and improve upon experiments. Each student analyzes three of the following four projects: distillation, gas absorption, liquid-liquid extraction and chemical kinetics in a tubular flow reactor and also one of the projects in 540.313. In addition to technical objectives, this course stresses oral and written communication skills and the ability to work effectively in groups. Prerequisites: 540.301, 540.304, 540.306.
Katz 6 credits (W)

540.313 Chemical and Biomolecular Engineering Lab
Students are challenged with laboratory projects that are not well-defined and learn to develop an effective framework for approaching experimental work by identifying the important operating variables, deciding how best to obtain them, and using measured or calculated values of these operating variables to predict, carryout, analyze, and improve upon experiments. Each student analyzes three biomolecular engineering projects and one of the projects in 540.311. In addition to technical objectives, this course stresses oral and written communication skills and the ability to work effectively in groups. Prerequisites; 540.301, 540.304, 540.306.
Ostermeier 6 credits (W)

540.314 (E) Chemical and Biomolecular Product and Process Design
This course guides the student through the contrasting aspects of product design and of process design. Product design concerns the recognition of customer needs, the creation of suitable specifications, and the selection of best products to fulfill the needs. Process design concerns the quantitative description of processes which serve to produce many commodity chemicals, the estimation of process profitability, and the potential for profitability improvement through incremental changes in the process. Students work in small teams to complete a major project demonstrating their understanding of and proficiency in the primary objectives of the course. Students report several times both orally and in writing on their accomplishments. Prerequisites: 540.301, 540.304, 540.306, 540.311
Katz, Van Winkle 4 credits

540.409 (E,Q) Modeling, Dynamics & Control for Chemical & Biological Systems
Introduction to process modeling and simulation. Steady state and unsteady state analysis of chemical process, biomolecular, and cellular control systems. State-space, Laplace transform techniques, block diagram algebra, and transfer functions. Control theory applied to chemical and biological processes including feedback and feedforward control. Frequency response, stability analysis, and introduction to nonlinear dynamics. Corequisites: 500.303 or 110.302 or equivalent differential equations course, 540.203, 540.301, 540.303.
Gray 3 credits

540.426/626 (E) Introduction to Biomacromolecules
This course introduces modern concepts of polymer physics to describe the conformation and dynamics of biological macromolecules such as filamentous actin, microtubule, and nucleic acids. We will introduce scattering techniques, micromanipulation techniques, as well as rheology. Applied to the study of polymers for tissue engineering and drug delivery applications.
Wirtz 3 credits

540.427 (E) Introduction to Polymer Science
Topics include bonding in polymers, polymer morphology, molecular weight characterization, polymer solubility and solutions, transitions in polymers, condensation and free-radical polymerization, copolymerization, rubber elasticity, viscoelasticity, polymer processing. Prerequisite: junior standing in engineering or the physical sciences.
Staff 3 credits

540.430 (E) Protein Solution Thermodynamics
Much of our current understanding of protein interactions has been from observations of bulk thermodynamic behavior, such as solubility, osmotic pressure, and adsorption. More recently, however, intermolecular forces have been measured directly for proteins using techniques such as surface force apparatus, atomic force microscopy, and osmotic pressure. The course will examine the relationship between forces in protein solutions and the macroscopic thermodynamic properties of protein solutions.
Staff 3 credits

540.431 (E, N) Biochemical Engineering/ Biotechnology
Application of engineering principles in biochemistry and microbiology. Topics include a brief review of microbiology, fermentation kinetics, microbial growth models, recombinant DNA technology, cell line development, mass and energy balances, metabolic processes, transport phenomena in biotechnology systems, and recent advances in biotechnology.
Betenbaugh 3 credits

540.433/633 (E) Engineering Aspects of Controlled Drug Delivery
This course addresses the fundamental engineering behind the development and understanding of controlled drug delivery systems. Focus is placed on the encapsulation and delivery of therapeutic proteins and genes from polymeric devices due to their increasing prevalence and importance in pharmaceutical products. Routes of drug delivery to be covered include oral, transdermal, pulmonary, injection, and surgical implantation. Topics include biological barriers to drug delivery, drug pharmacokinetics, particle targeting via receptor-ligand interactions, intracellular transport of colloidal particles and synthetic gene delivery vectors. Prerequisites: Transport Phenomena course (such as 540.303 or 580.461) and Kinetic Processes course (such as 540.301). Otherwise, permission may be given in special cases by instructor.
Hanes 3 credits

540.435 (E) Genome Engineering
The interpretation of cellular functions at the genetic level and the application of this knowledge for technological innovation. Topics include bioinformatics, combinatorial biochemistry, genome shuffling, metabolic engineering, and bioremediation.
Betenbaugh 3 credits

540.437/637 (E,N) Application of Molecular Evolution to Biotechnology
One of the most promising strategies for successfully designing complex biomolecular functions is to exploit nature's principles of evolution. This course provides an overview of the basics of molecular evolution as well as its experimental application to the engineering of proteins, DNA and RNA with functions of therapeutic, scientific, or economic value. The course will cover the generation of diversity (e.g., mutagenesis and DNA shuffling), the coupling of genotype and phenotype (e.g., surface display of proteins and peptides), and methods for screening and selection. Prerequisites: Biochemistry (020.305) or Molecules and Cells (580.221). Otherwise, permission may be given in special cases by instructor.
Ostermeier 3 credits

540.438/638 (E) Interfacial Phenomena in Nanotechnology
Nanotechnology is a new field that is still being defined, with concepts ranging from nanorobotics to nanomaterials. Whatever the outcome, engineering at the nanoscale will be dominated by surface science, as surface to volume ratios become large. Furthermore, self-assembly techniques, with which molecules can spontaneously assemble in ordered structures with nanometer length scales are ripe for exploitation to create new materials. In this class, the fundamentals of interfacial thermo-dynamics, interfacial interactions (e.g., van der Wall's interactions, electostatics, steric interactions), adsorption, self-assembly, and specific interactions will be covered with an emphasis on how to exploit these ideas in application in nanotechnology.
Stebe 3 credits

540.440/640 Micro and Nanotechnology
Micro/Nanotechnology is the field of fabrication, characterization and manipulation of extremely small objects (dimensions on the micron to nanometer length scale). Microscale objects, because of their small size are expected to be at the frontier of technological innovation for the next decade. This course will include a description of the materials used in microtechnology, methods employed to fabricate nanoscale objects, techniques involved in characterizing and exploiting the properties of small structures, and examples of how this technology is revolutionizing the areas of Electronics and Medicine.
Gracias 3 credits

540.441/641 Cellular Engineering
Lectures will provide an overview of molecular biology fundamentals, an extensive review on extracellular matrix and basics of receptors, followed by topics on cell-cell and cell-matrix interactions at both the theoretical and experimental levels. Subsequent lectures will cover the

effects of physical (e.g. shear, stress, strain), chemical (e.g. cytokines, growth factors) and electrical stimuli on cell function, emphasizing topics on gene regulation and signal transduction process. Material on cell-cycle,apoptosis, metabolic engineering, and gene therapy will also be incorporated into the course. Cross-listed with 580.441.
Konstantopoulos, Yarema 3 credits

540.451 Cell Engineering Lab
Course will consist of six experiments and provide students with valuable hands-on experience in cell and tissue engineering. The experiments include the basics of cell culture techniques, gene transfection, and metabolic engineering. Cross-listed with 580.451. Limit: 16
Elisseeff 1 credit

540.473 (E,N) Interfacial Phenomena
Course provides an overview of colloid and surface science. Topics include surface and interfacial tension and surface energies (definitions and methods of measurement), interactions at solid-liquid interfaces, thermodynamics of fluid interfaces, hydrodynamics of interfacial systems, including Marangoni flows, and applications of colloid and surface science in the chemical industry.
Stebe 3 credits

540.490 Chemical and Laboratory Safety
This course is meant to provide the student with a basic knowledge of laboratory safety; hazards, regulations, personal protective equipment, good laboratory practice, elementary toxicology, and engineering controls. It has been developed by the Department of Chemical and Biomolecular Engineering to assist with regulatory compliance, minimize hazards, and reduce the severity of any incidents that may occur in the department's laboratories. The course is a prerequisite of 540.311. It is required of all Chemical and Biomolecular Engineering undergraduates. In addition once per year a three-hour refresher seminar must be taken by all students involved in laboratory research.
Staff 1 credit

540.501-506 Undergraduate Independent Study
Students do a reading course in specialized areas not directly available by lecture courses. Assignments and problems are prescribed by a faculty member.
1-3 credits

540.521-528 Undergraduate Research
Students do individual projects (or in collaboration with faculty and/or graduate students) in areas basic to chemical engineering.
1-3 credits

540.600-601 Chemical and Biomolecular Engineering Seminar
Lectures are presented on current subjects relevant to chemical engineering. Prerequisites: 540.303, 540.306.
1 credit

Cross-Listed

500.101 (E) What is Engineering?
This is a course of lectures, laboratories, and special projects. Its objective is to introduce students not only to different fields of engineering but also to the analytic tools and techniques that the profession uses. Assignments include hands-on and virtual experiments, oral presentations of product design, and design/construction/testing of structures. Open to freshmen only.
Karweit 3 credits

500.111 (E,N) Energy and the Environment
Katz 3 credits

500.150 (H,E) Ethical and Societal Issues in Engineering
Donohue 3 credits

500.200 (E,Q) Computing for Engineers and Scientists
This course emphasizes computer usage for solving problems in engineering and science. Topics include structure and operation of a computer, FORTRAN 77, and elementary computational mathematics and numerical analysis. Prerequisite: 110.109.
Karweit 3 credits

500.301 (E,Q) Computational Techniques in Engineering and Science
Beginning with a review of structured programming languages (C, FORTRAN), this course develops the numerical tools needed to solve basic engineering and science problems. Topics include numerical solutions of equations, interpolation, approximation, numerical differentiation and integration, root finding, and solutions to linear systems. Accuracy and stability are emphasized throughout. Engineering problems requiring the use of algorithms from Press, et al., Numerical Recipes are assigned weekly. Prerequisites: 110.202, 550.291, and a cursory knowledge of C or FORTRAN; or instructor's permission.
Karweit 4 credits

570.429 (E,N) Surface Effects in Technological Processes and Materials
Mechanical properties and stability of disperse systems and materials are considered in dependence on real microheterogeneous structure and physical/chemical surface phenomena determining particles cohesion. Concepts of modern physical/chemical mechanics are applied to achieving two cardinal goals: high stability and durability of materials including natural and living tissues, and low resistance during deformation and treatment, independence upon surrounding media and other environmental conditions. Prerequisites: 570.444 or general physics and chemistry.
Shchukin 3 credits fall

Undergraduate Courses (Part-Time)

545.447 System Safety and Risk Management
Methods, mathematics, and management approaches for evaluating the safety of complex technical systems are presented. Examples of risk assessments pertaining to the design, operation, siting, transportation, and emergency planning of both chemical and nuclear materials are studied. Topics include probability and reliability concepts; failure data analysis; FMEA (Failure Modes and Effects Analysis); fault-tree and event-tree techniques; human factors and human error models; multiobjective risk assessment, optimization, and display of information; safety goals; ethics; perceptual risk; reliability assurance and maintenance; cost-benefit and analysis for safety improvement; accident mitigation; and research priority setting. Also radiological and toxicological aspects of consequence, and modeling for estimating environmental and public health impacts are reviewed.
Marguilies 3 credits

545.449 Statistical Design of Experiments
This course introduces the basic concepts which underlie modern statistically designed experimental programs. These programs typically test many variables simultaneously and are very efficient tools for developing empirical mathematical models which accurately describe physical and chemical processes. They are readily applied to production plant, pilot plant, and laboratory systems, and should be part of every practicing engineer's repertoire. Topics include fundamental statistics; the statistical basis for recognizing real effects in noisy data; statistical tests and reference distributions; analysis of variance; construction, application, and analysis of factorial and fractional factorial designs; screening design; response surface and optimization methods; and application to plant operations.
Staff

545.451 Introduction to Colloids and Surface Science
The course provides an overview of colloid and surface science. Topics include surface and interfacial tension and surface energies (definitions and methods of measurement), interactions at solid-liquid interfaces, thermodynamics of fluid interfaces, phenomenology of colloidal systems (classification, preparation and morphology), sedimentation and diffusion of fine particles in dispersed systems, and rheology of colloidal systems.
Middleton, Stebe

Graduate Courses

540.621 Advanced Chemical Engineering Thermodynamics I
A comprehensive examination of the fundamental laws, principles, and concepts of classical statistical thermodynamics. Detailed discussion of various topics such as the properties of pure fluids, the thermodynamics of flow processed, chemical reaction equilibria, and equations of state, solutions, and phase behavior.
Paulaitis 3 hours

540.623 Phase Equilibria
Equilibrium properties of pure and mixed fluids. Modern methods of applying classical and statistical thermodynamics to calculation of phase behavior of fluid mixtures. Molecular thermodynamics of multicomponent systems with applications to separation operations.
Donohue 3 hours

540.624 Applied Statistical Thermodynamics
A review of introductory course concepts (i.e., the canonical ensemble, other ensembles, the ideal monatomic gas, ideal diatomic and polyatomic gases), imperfect gases, corresponding states, distribution functions, perturbation theories, nucleation. Prerequisite: six weeks or more of introductory level statistical mechanics or statistical thermodynamics.
Katz 3 hours

540.626 (E) Introduction to Biomacromolecules
(For description, see 540.426)
Wirtz 3 credits

540.633 Engineering Aspects of Controlled Drug Delivery
(For description see 540.433)
Hanes 3 hours

540.637 (E,N) Application of Molecular Evolution to Biotechnology
(For description, see 540.437)
Ostermeier 3 credits

540.642 Advanced Chemical Kinetics and Reactor Design
Complex reaction networks;Wei-Prater analysis; the Himmelblau-Jones-Bischoff method. Detailed coverage of Hougen-Watson models for heterogeneous catalytic reaction kinetics; model discrimination and parameter estimation. Other topics include coupled heterogeneous reaction and transport, generalized moduli catalyst deactivation models, batch reactors, CSTRs, and PFRs; fixed bed reactors including stability criteria, and multibed optimization; residence time distributions and non-ideal reactor models; fluidized bed and multiphase reactors. Prerequisite: linear algebra.
Staff 3 hours

540.651 Advanced Transport Phenomena
This course is a one-semester survey of convection and convective transport. The conservation equations of mass, linear momentum, angular momentum, and energy are derived for single component systems. Exact solutions to the Navier-Stokes equations are derived. The behavior of fluid particles in the creeping flow limit is studied in detail. Inertial effects in these systems are then discussed. Scaling arguments for nondimensionalizing governing equations and asymptotic methods are introduced. The lubrication

and boundary layer equations are derived. Weak convective effects in heat and mass transfer are discussed.
Stebe 3 hours

540.725-726 Topics in Molecular Thermodynamics
Lectures are presented on current topics relevant to molecular thermodynamics.
Donohue 2 hours

540.801-810 Graduate Research
1-12 hours

Graduate Courses
(Part-Time)

545.616 Transport Properties
Gas and liquid transport properties determine the flow of mass, momentum and energy, as well as more exotic properties, in gases and liquids not at equilibrium. The prediction and understanding of the processes underlying these fluxes can be important in the design of chemical process plants. The course develops the modern theory of gas and liquid transport properties from a physically convincing, but not mathematically rigorous, perspective to acquaint students with the transport properties of real molecules and the methods of estimating them. Subjects include Boltzmann equations for real molecules, methods of deducing transport properties from them, and methods of estimating transport properties from molecular modes. The course also examines the estimation of transport properties in ionized gases, dense gases and liquids. Applications are made to Brownian motion and to the evaporation of the heat transfer to aerosols.
Hunter

545.642 Advanced Chemical Kinetics and Reactor Design
Cross listed with 540.642

Interdepartmental

360.676 Principles of Bioinformatics
An interdisciplinary course on the computational and statistical issues that arise in the analysis of DNA and protein sequence data. The course is intended to introduce this fast-growing area to students from various backgrounds such as biology, computer science, mathematics, and mathematical sciences. Lecturers from each of these departments will provide background on the relevant issues from their area. Topics include data models and query languages in bioinformatics; sample genomic database resources: GenBank, SwissProt, TIGR Comprehensive Microbial Resource; statistical hypothesis testing; Markov chains; sequence analysis: multiple sequence alignment, fragment assembly, EST assembly, genome annotation, gene finding.

Faculty contacts: Betenbaugh (Chemical and Biomolecular Engineering), Cunningham (Biology), Salzberg (Computer Science), Zelditch (Mathematics), Naiman (Mathematical Sciences).
spring