

# Chemical and Biochemical Engineering

## Chair

- C. Allan Guymon

**Undergraduate major:** chemical engineering (B.S.E.)

**Graduate degrees:** M.S. in chemical and biochemical engineering; Ph.D. in chemical and biochemical engineering

**Faculty:** <https://cbe.engineering.uiowa.edu/people>

**Website:** <https://cbe.engineering.uiowa.edu/>

Chemical and biochemical engineers combine engineering principles with knowledge of mathematics and specific sciences—chemistry, the biological sciences, and physics—to develop and operate processes that convert raw materials into products that benefit society. For example, biochemical engineers might develop and operate processes to convert switchgrass into biofuels or to mass produce an antibiotic.

Chemical and biochemical engineers engage in a wide variety of activities that benefit the global community. Fuel cells, solar energy, and biorenewable fuels (e.g., biodiesel or ethanol) fall within the realm of chemical engineering. Chemical engineering distinguishes itself from other engineering professions with its reliance on chemical reactions and physicochemical transformations to produce a wide variety of important materials and products. Biochemical engineers are involved in a wide variety of industrial biocatalytic, fermentation, and cell culture processes that generate products ranging from the high fructose corn syrup in soft drinks to recombinant human insulin.

As part of their training, chemical and biochemical engineers learn ethical design and a respect for the larger issues in any design, such as community health, employee safety, and the global implications of the design. The University of Iowa's curriculum emphasizes chemical process safety and environmentally conscious chemical engineering design.

## Programs

### Undergraduate Program of Study

#### Major

- Major in Chemical Engineering (Bachelor of Science in Engineering)

### Graduate Programs of Study

#### Majors

- Master of Science in Chemical and Biochemical Engineering
- Doctor of Philosophy in Chemical and Biochemical Engineering

## Facilities

### Undergraduate Core

#### Materials Science Laboratory

The Materials Science Laboratory is equipped with optical microscopes and facilities for metallographic preparation. Mechanical tensile testing instruments, heat treatment and sintering furnaces, and hardness testing machines also are available. Teaching aids include metallography specimen kits and crystallography packages.

### Required Undergraduate Laboratories

#### Chemical Engineering Laboratory

The Chemical Engineering Laboratory provides instruction for undergraduate students in CBE:3150 Thermodynamics/Transport Laboratory and CBE:3155 Chemical Reaction Engineering/Separations Laboratory. It is equipped for experimentation in thermodynamics, fluid flow, heat transfer, mass transfer, chemical reaction engineering, and separations. The lab includes pilot plant equipment, such as a distillation column, wiped film evaporator, shell-and-tube heat exchanger, jacketed kettle, and agitated extractor. Other equipment includes a concentric tube heat exchanger, reciprocating plate extractor, membrane gas separator, fluid friction apparatus, and heat conduction apparatus. Analytical equipment includes gas chromatographs, UV/visible spectrophotometers, polarimeters, and refractometers.

The lab is continuously updated to reflect advances at the forefront of chemical engineering technology. Additionally, a wide array of small equipment is available to support laboratory projects and demonstrations in chemical engineering courses and for use by students performing independent investigations.

#### Chemical Process Safety Laboratory

The Chemical Process Safety Laboratory is an integral part of CBE:3125 Chemical Process Safety. It is equipped with two Miniflash automatic flash point tester (closed cap), an advanced reactive system screening tool (ARSST), a minimum ignition energy (MIE) apparatus, a flammability chamber, a modified Hartmann tube, a Hartmann bomb, a liquid conductivity apparatus, a powder changeability apparatus, a powder volume resistivity apparatus, a Van de Graaff generator, two high impedance electrometers, a field meter, a Faraday cage, and relief sizing software. This equipment is used in a series of experiments to demonstrate the principles of flammability, reactivity, explosions, relief valve sizing, and electrostatics relevant to industry.

#### Biochemical Engineering Laboratory

The Biochemical Engineering Laboratory is an integral part of CBE:5205 Introduction to Biochemical Engineering. It is equipped with two controlled New Brunswick BioFlo/CelliGen 115 bioreactors, three New Brunswick C76 Water Bath Shakers, a UV/visible spectrometer, a Thermo Scientific Nanodrop 3300 fluorospectrometer, and a YSI 2700 Select Biochemistry Analyzer. This equipment is used to study the growth and metabolism of microorganisms and recombinant protein production.

## Process Control Laboratory

The Process Control Laboratory is a modern, computer-based instructional laboratory that is integral to CBE:4105 Process Dynamics and Control in Design. The lab consists of computer control of a shell-and-tube heat exchanger and a level-and-flow control process rig with state-of-the-art industrial control interfaces.

The Computer Control Laboratory offers an ensemble of learning experiences with the same equipment. Additional laboratories provide instruction in the use of process simulators that provide analogies and better insight into the control process. Topics include determination of the gain and time constants for single-capacitance systems; determination of gain, time constant, and damping factor of second-order processes; determination of open-loop and closed-loop response to step-and-ramp changes in input for single-capacitance and multicapacitance processes; approximations of multicapacitance systems as first-order and second-order processes with dead time; analysis of instrumentation characteristics and transfer functions; tuning and optimization of feedback control parameters (P, PI, PID); system identification through frequency response methods; and determination of system stability.

Experimental arrangements in the lab are simple enough in design to be easily understood, yet complicated enough to help students appreciate system characteristics inherent in industrial processes (e.g., large time lags, error in parameter estimation).

## Graduate Facilities and Laboratories

The department offers a wide variety of facilities to support and develop research activities.

### Air Pollution Computational, Field, and Laboratory Studies

The department maintains extensive facilities for computational, field, and laboratory studies of air pollution, carbon cycle gases, aerosols, and nanoparticles at the Center for Global and Regional Environmental Research (CGRER). The center occupies 5,000 square feet of lab and office space on the fourth floor of the Iowa Advanced Technology Laboratories.

CGRER houses one R2 ImmersaDesk Portable Large Scale Visualization System and is linked on campus to two more R2 ImmersaDesk units.

The center's computer laboratory for environmental and spatial data analysis provides numerous Windows and UNIX workstations, sophisticated software packages, and workstations and a file server necessary to run intensive visualization programs. The network backbone is University supported with high-speed wireless throughout. A variety of digital environmental databases and an extensive library of documentation and related references are available. There are 4 Beowulf Linux clusters on site and Linux clusters of 4, 16, 18, and 20 nodes for large computations and data assimilation. CGRER retains 15 TB of redundant storage and 50 TB of total storage; local storage space is scalable and expandable. A variety of software packages and programming languages are available for data analysis and display, including Arc/Info, Arcview, NCAR Graphics, Matlab, S-Plus, and Vis5d, as well as geographical information software. The ESRI software suite is part of a University-wide site license.

Laboratory and field equipment includes aerosol samplers, including scanning mobility particle sizers for aerosols from 3 nm to 1 micron with time resolution to 30 seconds; aerosol particle sizers for aerodynamic measurements of in situ particles with time resolution to 1 second; and varied condensation particle counters for measuring total particle counts. Several hygroscopic tandem differential mobility analyzers are used, as well as varied aerosol generation devices and unique aerosol inlets for RH and temperature modification and control. Cloud droplet number can be measured in the lab or in the field using a Droplet Measurement Technologies cloud condensation nuclei detector. Advanced computer control of instruments is available through Labview.

Selected instruments are field deployable in a custom air-conditioned trailer. Through collaboration with the IIHR—Hydroscience & Engineering, access to micrometeorology sensors, 1-D and 2-D elastic and Raman LIDAR, and gas sensors is available, including multichannel ammonia monitors.

## Biochemical Engineering

Biochemical engineering laboratories provide facilities for preparation of biological media and cultivation of organisms as well as for separation and analysis of biomolecules. This equipment includes biological incubators and floor incubator shakers, agitated and airlift bioreactors, light microscopes, autoclaves, Vi-Cell cell counter, thermocycler for PCR amplification of DNA, high- and low-speed centrifuges, UV-Vis spectrophotometers, a lyophilizer, biological safety cabinets, and an anaerobic glove box. Phase-contrast and epifluorescence microscopes, gel electrophoresis systems, gas chromatography units with flame ionization and electron capture detectors, and several high-performance liquid chromatography systems with refractive index and photodiode array detectors are available for characterization of microorganisms and constituent biomolecules. In addition, the lab has multiple extremophile cultivation systems including a high-pressure (0.1-100 MPa) cell cultivation system, several continuous cultivation systems, and high-temperature oil bath shakers for physiological studies of extremophilic microbes.

Through collaborative research agreements, graduate students also have access to specialized facilities for electron microscopy, large-scale fermentation, protein structure, recombinant DNA research, and tissue culture/hybridoma; the Flow Cytometry Facility; and the High Resolution Mass Spectrometry Facility.

## Biomedical Engineering

The biomedical engineering laboratories house particle technology equipment including microemulsion equipment for drug encapsulation, sonicators, benchtop scale spray dryers, laser diffraction particle sizer, zetapotentiometer; DNA preparation equipment, gel electrophoresis apparatus; interfacial stress rheometer, surface tensiometer, UV-Vis/fluorescent plate reader, high-performance liquid chromatograph, luminometer, lyophilizer, custom-built simulated cough machine, microscopes, incubators, wet chemistry equipment, rotary shakers, incubated plate shakers, autoclave, centrifuges, and laboratory computers. Cell culture and bacterial culture facilities are housed adjacent to the laboratories.

Graduate students also have access to core research facilities including the Central Microscopy Research Facility, Flow Cytometry Facility, Iowa Institute of Human Genetics, Electron Spin Resonance Facility, Nuclear Magnetic Resonance Facility,

High Resolution Mass Spectrometry Facility, and the Center for Gene Therapy.

## Computer Facilities

The departmental computer facilities contain a variety of graphics workstations, printers, and microcomputers. The department is supported by the college's Engineering Technology Center, which maintains a large network of high performance UNIX and Windows XP workstations along with extensive commercial and public domain software. The department also has access to the University's central research facility in high-speed vector computation. This facility has SGI Power Challenger minisupercomputers and provides nodes for external links for access to supercomputers.

## Fundamentals and Applications of Photopolymerization

The Photopolymerization Center was established to advance fundamental understanding of the kinetics and mechanisms of photopolymerizations. To this end, the center provides unique opportunities for collaborations by industrial and academic investigators to explore photopolymerization processes and develop novel applications based on photopolymerizations.

The center provides equipment and instrumentation for the characterization of photopolymerization systems on the molecular, microscopic, and macroscopic levels. Center researchers pursue understanding of fundamental photophysical and photochemical processes involved in the photoinitiation reaction; characterization of high-speed propagation and termination kinetics that lead to the polymer structure; and evaluation of material properties through the course of the photopolymerization reaction. Both radical and cationic photopolymerizations are studied with state-of-the-art experimental techniques to elucidate the complex chemical and physical mechanisms that control the initiation, propagation, and termination of the active centers.

## Courses

## Chemical and Biochemical Engineering Courses

**CBE:0000 Chemical Engineering Internship/Co-op 0 s.h.**  
Chemical engineering students participating in the Cooperative Education Program register for this course during work assignment periods; registration provides a record of participation in the program on the student's permanent record. Requirements: admission to Cooperative Education Program.

**CBE:1000 CBE Departmental Seminar 1 s.h.**  
Introduction to the profession and the department; presentations by guest speakers, visits to laboratories and industries.

**CBE:1180 First-Year Seminar 1 s.h.**  
Small discussion class taught by a faculty member; topics chosen by instructor; may include outside activities (e.g., films, lectures, performances, readings, visits to research facilities, field trips). Requirements: first- or second-semester standing.

**CBE:2030 Energy and Society 3 s.h.**  
History of energy development and use throughout the world; how energy has affected the development of human societies; societal impact of engineering advances; current state of energy consumption worldwide, including distribution of energy sources, global variations in consumption, advantages and disadvantages of current energy sources; role of fossil fuel consumption in global climate change, potential scenarios for the future of energy.

**CBE:2040 Environment, Energy, and Climate Change 3 s.h.**  
Covers traditional concerns (e.g., pollution and conservation of energy resources) with clear, scientific explanations; Earth's dynamic processes and response to natural and human-induced stresses; the link between energy and climate; reasons why we need to support reducing emissions and build a clean and sustainable environment.

**CBE:2050 Severe and Unusual Weather 3 s.h.**  
Basic weather concepts behind severe weather phenomena and essential safety information; how weather events cause billions of dollars in damage and thousands of casualties; winter storms can impact half of the nation, paralyzing the transportation network with icy roads and wind driven snow; tornadoes can strike within minutes tearing apart homes; hurricanes can destroy entire communities with strong winds, heavy rain, and deadly storm surge; understanding severe weather and knowing what to do before, during, and after an event can significantly reduce injury, deaths, and property damage. Same as CEE:2050.

**CBE:2105 Process Calculations 3 s.h.**  
Fundamental principles of chemical process analysis, including material and energy balances for single-unit and multiple-unit processes, analysis of reactive and nonreactive systems, introduction to equations of state, thermodynamics of multiphase systems. Prerequisites: MATH:1550.

**CBE:3000 Professional Seminar: Chemical Engineering 1 s.h.**  
Professional aspects of chemical engineering presented through lectures and discussions by guest speakers, field trips, films, panel discussions. Prerequisites: CBE:2105. Requirements: sophomore standing.

**CBE:3105 Chemical Engineering Thermodynamics 3 s.h.**  
Applications of thermodynamic principles to chemical and physical processes; prediction of material properties; phase and chemical equilibria applied to mixtures and reacting systems. Prerequisites: ENGR:2130. Corequisites: CBE:2105.

**CBE:3109 Fluid Flow 2 s.h.**  
Fundamentals of fluid flow, including fluid statics, fluid rheology, laminar and turbulent flow in pipes, external flow, flow through packed beds, fluidized beds, pumps and compressors, boundary layer theory, potential flow, dimensional analysis, and Navier Stokes Equations. Corequisites: CBE:2105.

**CBE:3110 Engineering Flow and Heat Exchange 3 s.h.**  
Fundamentals of fluid flow and heat transfer; fluid rheology, boundary layer theory, potential flow, dimensional analysis, laminar and turbulent flow in pipes, flow through packed beds, fluidized beds, pumps, flow measurement, filtration, heat exchanger design, and conductive, convective, and radiative heat transfer. Corequisites: CBE:2105.

- CBE:3113 Heat and Mass Transfer** 3 s.h.  
Fundamentals of heat and mass transfer including heat exchanger design; conductive, convective, and radiative heat transfer; mechanisms of diffusional and convective mass transfer. Prerequisites: MATH:2560 and CBE:2105. Recommendations: CBE:3109.
- CBE:3115 Mass Transfer and Separations** 3 s.h.  
Mechanisms of diffusional mass transfer; solution of industrial problems, including the design of distillation, extraction, absorption, adsorption, drying, membrane processes; mechanical separations. Prerequisites: CBE:3110 and CBE:3105.
- CBE:3117 Separations** 3 s.h.  
Solution of industrial problems including design of distillation, extraction, absorption, adsorption, drying, membrane processes, and mechanical separations. Prerequisites: CBE:2105 and CBE:3105. Corequisites: CBE:3113.
- CBE:3120 Chemical Reaction Engineering** 3 s.h.  
Application of chemical reaction kinetics to design of chemical reactors: batch reactors, mixed flow reactors, plug flow reactors; reversible and irreversible single reactions; parallel, series, and mixed reactions; temperature and pressure effects on reactor design; heterogeneous catalysis; transport in porous catalysts. Prerequisites: MATH:2560. Corequisites: CBE:3105. Recommendations: CBE:3113.
- CBE:3125 Chemical Process Safety** 3 s.h.  
Application of transport phenomena, thermodynamics, chemical kinetics to study of safety, health, loss prevention; government regulations, toxicology/industrial hygiene, relief sizing, runaway reactions, toxic release and dispersion models, source models, fires and explosions, risk assessment, hazard identification, case studies and accident investigation, incorporation of safety into design; laboratory experiments. Prerequisites: CBE:3105 and CBE:3109. Corequisites: CBE:3113.
- CBE:3150 Thermodynamics/Transport Laboratory** 3 s.h.  
Error analysis, propagation of errors, experimental design, data collection techniques, report writing, oral presentations, laboratory safety; laboratory investigations of thermodynamics, fluid flow, heat transfer, fluid rheology. Prerequisites: CBE:3105 and CBE:3113. Recommendations: statistics course.
- CBE:3155 Chemical Reaction Engineering/Separations Laboratory** 2 s.h.  
Experimental design, data collection techniques, report writing, oral presentations; laboratory investigations of chemical reaction engineering and separations; experiments with plug flow and batch reactors, distillation, evaporation, membrane separation. Prerequisites: CBE:3117. Corequisites: CBE:3120. Recommendations: STAT:2020.
- CBE:3160 Engineering Analysis of Alternative Energy Systems** 3 s.h.  
Engineering and sustainability analyses of conventional and emerging energy technologies; alternative energy sources, including biomass, wind, solar, geothermal; alternative energy carriers (transportation fuels), including varied biofuels, hydrogen, natural gas, ammonia. Prerequisites: ENGR:2130.
- CBE:3205 Introduction to Biochemical Engineering** 3 s.h.  
Biochemistry, cellular biology, recombinant DNA and hybridoma technologies; emphasis on engineering aspects of biotechnology, including enzyme kinetics, cell growth kinetics, transport phenomena in bioreactors, bioreactor design, bioseparations, formulation and sterilization of growth media, commercial applications of biotechnology. Prerequisites: CBE:2105. Corequisites: CBE:3109. Recommendations: CBE:3120.
- CBE:3415 Statistical and Computational Analysis of Weather and Climate Data** 3 s.h.  
Statistical and computational (Python programming) analysis of weather and climate data, univariate and multivariate statistics, hypothesis testing, statistical forecasting, forecast verification, time-series analysis, principal component analysis, trend analysis, and cluster analysis. Requirements: senior or graduate standing.
- CBE:3998 Individual Investigations: Chemical Engineering** arr.  
Individual projects for chemical engineering undergraduate students, such as laboratory study, engineering design project, analysis and simulation of an engineering system, computer software development, research.
- CBE:4105 Process Dynamics and Control in Design** 3 s.h.  
Theory and application of process dynamics to the design of chemical process control systems; mathematical models of unit operations, transfer functions, feedback and feed-forward control, stability, instrumentation, digital control systems; computer methods, including simulation and commercial software use; laboratory focus on process analysis and design. Prerequisites: MATH:2560 and CBE:2105 and (CBE:3109 or CBE:3110). Corequisites: CBE:3120.
- CBE:4109 Chemical Engineering Process Design I** 2 s.h.  
Engineering economics of process evaluation, including time value of money and bases for cost estimation; preliminary design of chemical process plants using computer-aided engineering. Prerequisites: (CBE:3110 and CBE:3115) or (CBE:3109 and CBE:3113 and CBE:3117). Corequisites: CBE:3120 and CBE:3125.
- CBE:4110 Chemical Engineering Process Design II** 3 s.h.  
Capstone chemical engineering course; design and optimization of chemical process plants; application of process calculations, thermodynamics, kinetics, process synthesis, energy efficiency in separations, heat-exchanger network synthesis, physical property estimation, safety, computer-aided design, unit operations theory, process control, and economics. Prerequisites: CBE:4109. Recommendations: CBE:4105 and CBE:5205.
- CBE:4156 Scanning Electron Microscopy and X-Ray Microanalysis** arr.  
Microscopy methods for research; all aspects of research, from sample preparation to imaging to data analysis; when to use a particular microscopy procedure; theory, operation, and application of scanning electron microscopy, scanning probe microscopy, laser scanning microscopy, X-ray microanalysis. Requirements: a physical science course. Same as ACB:4156, EES:4156.
- CBE:4195 Senior Enriching Activities Seminar** 0 s.h.  
Aspects of chemical engineering education, including multidisciplinary team skills, understanding the impact of engineering practice locally and globally. Corequisites: CBE:4110. Requirements: completion of enriching activity.

- CBE:4410 Sustainable Systems** 3 s.h.  
New and emerging concepts in sustainable systems design and assessment. Same as CEE:4107.
- CBE:4420 Environmental Chemistry** 3 s.h.  
Principles of general, physical, organic chemistry applied in water and air systems; emphasis on qualitative and quantitative understanding of chemical kinetics and equilibrium; acid-base reactions, complex formation, precipitation, dissolution, and oxidation-reduction reactions; organic nomenclature. Prerequisites: CHEM:1120. Same as CEE:4150.
- CBE:4459 Air Pollution Control Technology** 3 s.h.  
Sources, environmental and health impacts, regulations, modeling of air pollution; processes and alternative strategies for control; global climate considerations. Same as CEE:4159, IGPI:4159.
- CBE:5000 Seminar in Chemical and Biochemical Engineering** 1 s.h.  
Presentation and discussion of recent advances and research in chemical and biochemical engineering by guest lecturers, faculty, students. Requirements: graduate standing.
- CBE:5100 Graduate Professional Development Seminar** 1 s.h.  
Seminar participants work with a faculty member to select and attend eight hours of approved seminars and professional development trainings at the University of Iowa; final meeting of participants is held to share notable seminars; typical seminar series include College of Engineering lectures, departmental and research center graduate seminars, the CBE professional seminar series, offerings of the Center for Teaching and Learning. Requirements: CBE masters standing.
- CBE:5104 Introduction to Literature Review and Technical Writing** 3 s.h.  
Review of technical literature, how to contribute to it; produce and present orally a peer-reviewed-journal-quality review article; brainstorming, group writing, research ethics, plagiarism. Recommendations: nonthesis track graduate standing.
- CBE:5105 Introduction to Literature Review and Proposal Writing** 3 s.h.  
Tools for reviewing literature, skills for critical reading of publications, training in successful proposal writing; experience drafting a proposal that can be used as a starting point for the Ph.D. comprehensive.
- CBE:5110 Intermediate Thermodynamics** 3 s.h.  
Fundamental principles of thermodynamics as applied to phase equilibrium; properties of fluids, first and second law, variable composition systems, behavior of real fluids, mathematical techniques for solution thermodynamics. Requirements: CBE:3105 or ME:3040 or graduate standing. Same as ME:5210.
- CBE:5115 Transport Phenomena I** 3 s.h.  
Unified treatment of momentum, mass, energy transport in chemical engineering problems; use of vector and tensor notations in expressing equations of continuity, motion, energy.
- CBE:5140 Mathematical Methods in Engineering** 3 s.h.  
Linear ordinary differential equations, series solutions of differential equations, special functions, Laplace transforms, Fourier series, matrices, linear systems, eigenvalue problems, second-order partial differential equations. Prerequisites: MATH:2550 and MATH:2560. Same as CEE:5513, ME:5113.
- CBE:5199 Contemporary Topics: Chemical and Biochemical Engineering** arr.  
Research techniques for graduate students in chemical and biochemical engineering.
- CBE:5205 Introduction to Biochemical Engineering** 3 s.h.  
Biochemistry, cellular biology, recombinant DNA and hybridoma technologies; emphasis on engineering aspects of biotechnology, including enzyme kinetics, cell growth kinetics, transport phenomena in bioreactors, bioreactor design, bioseparations, formulation and sterilization of growth media, commercial applications of biotechnology. Prerequisites: CBE:2105. Corequisites: CBE:3109. Recommendations: CBE:3120.
- CBE:5210 Bioseparations** 3 s.h.  
Unit operations used to isolate and purify biologically derived chemicals, including flocculation, filtration, centrifugation, extraction, adsorption, chromatography, precipitation, crystallization, electrophoresis and cell disruption for intracellular product recovery.
- CBE:5250 Introduction to Biocatalysis** 3 s.h.  
Applications of biological catalysis in varied industries; potential of biological catalysis to address future challenges in science and engineering.
- CBE:5300 Drug Delivery Devices** 3 s.h.  
Why drug delivery devices are needed and how they are regulated; review of several clinical device categories (inhalation, transdermal, implantable) and preclinical technologies on the horizon.
- CBE:5309 Polymer Fundamentals** 1 s.h.  
Basic knowledge of polymers required as a foundation for other UI courses on polymers: basic polymer terminology, polymer groups, polymerization mechanisms, molecular weight determination. Five weeks. Same as BME:5415.
- CBE:5310 Polymer Science and Technology** 3 s.h.  
Uses, properties of industrially important polymeric materials; polymer chemistry, polymer structure, characterization, polymer processing. Prerequisites: CHEM:2220. Corequisites: CBE:3120.
- CBE:5315 Polymer Chemistry** 3 s.h.  
Monomer reactivity and polymerization reactions; step, radical, ionic, and ring-opening polymerizations. Prerequisites: CHEM:2220.
- CBE:5390 Photopolymerization Topics** 1 s.h.  
Seminars presented by faculty members, research assistants, students.
- CBE:5405 Green Chemical and Energy Technologies** 3 s.h.  
Strategies for pollution prevention for chemical processes studied at the macroscale (industrial sector), the mesoscale (unit operations), and the microscale (molecular level); case studies. Prerequisites: CBE:2105.
- CBE:5415 Satellite Image Processing and Remote Sensing of Atmosphere** 3 s.h.  
Introduction to principles of atmospheric radiation and techniques for satellite image processing; hands-on experience with data calibration, image registration and enhancement, noise filtering and (supervised and unsupervised) multi-spectral classification of satellite imageries; various satellite sensors used for monitoring of different atmospheric processes and constituents. Same as IGPI:5415.

**CBE:5417 Physical Meteorology and Atmospheric Radiative Transfer** 3 s.h.

Physical processes for weather and climate including radiative transfer, cloud and precipitation formation, and atmospheric electricity; theory of scattering by atmospheric particles (e.g., clouds, aerosols, molecules), atmospheric radiative transfer equations, and numerical techniques and tools to solve these equations. Requirements: senior or graduate standing. Same as IGPI:5417.

**CBE:5425 Atmospheric Chemistry and Physics** 3 s.h.

Principal chemical and physical processes affecting atmospheric trace gas and pollutant cycles; emphasis on atmospheric photochemistry, aerosol science, major sources and removal processes. Corequisites: CBE:3120. Same as CEE:5115.

**CBE:5875 Perspectives in Biocatalysis** 1-3 s.h.

Applied enzymology, protein design, structure-activity relationships, biosensor technology, microbial transformations, biodegradation of environmental pollutants. Requirements: graduate standing in a participating department supported by the Predoctoral Training Program in Biotechnology. Same as BIOC:5875, CEE:5875, CHEM:5875, MICR:5875, PHAR:5875.

**CBE:5998 Individual Investigations: Chemical and Biochemical Engineering** arr.

Individual projects for chemical and biochemical engineering graduate students; may include laboratory study, engineering design project, analysis and simulation of an engineering system, computer software development, research. Requirements: graduate standing.

**CBE:5999 M.S. Thesis Research: Chemical and Biochemical Engineering** arr.

Experimental and/or analytical investigation of an approved topic for partial fulfillment of requirements for M.S. with thesis in chemical and biochemical engineering. Requirements: graduate standing.

**CBE:6145 Diffusive Transport** 3 s.h.

Diffusive transport of heat, mass, and momentum; phenomenological laws and analogies; analytical and numerical solution techniques; inverse heat conduction; multiphase and multicomponent systems. Prerequisites: ME:5145. Same as ME:6245.

**CBE:6415 Advanced Satellite and Remote Sensing of Atmosphere** 3 s.h.

Cloud masking and retrieval of cloud properties from satellites, aerosol detection and retrievals, Earth radiation energy budget, land and/or ocean remote sensing, microwave remote sensing, wind retrieval, multi-sensor intercomparison and validation, optimization and inversion theory; hands-on projects.

**CBE:7999 Research: Chemical and Biochemical Engineering Ph.D. Dissertation** arr.

Experimental and/or analytical investigation of an approved topic for Ph.D. in chemical and biochemical engineering.