502. From Biomedical Science to the Marketplace. (C) Prerequisite(s): Graduate students or Senior standing in Bioengineering, or permission of the instructor.
This course explores the transition from discovery of fundamental knowledge to its ultimate application in a clinical device or drug. Emphasis is placed upon factors that influence this transition and upon the integrative requirements across many fields necessary to achieve commercial success. Special emphasis is placed on entrepreneurial strategies, intellectual property, financing and the FDA process of proving safety and efficacy. Current public companies in the medical device and drug industry are studies in detail and critiqued against principles developed in class.

505. Quantitative Human Physiology. (C) Prerequisite(s): BE 305.
Introduction to human physiology using the quantitative methods of engineering and physical science. Emphasis is on the operation of the major organ systems at both the macroscopic and cellular level.

510. Biomechanics and Biotransport. (C) Prerequisite(s): Math through 241; BE 350, BE 324 as pre-or corequisites.
The course is intended as an introduction to continuum mechanics in both solid and fluid media, with special emphasis on the application to biomedical engineering. Once basic principles are established, the course will cover more advanced concepts in biosolid mechanics that include computational mechanics and bio-constitutive theory. Applications of these advanced concepts to current research problems will be emphasized.

L/R 512. Bioengineering III: Biomaterials. (C) Prerequisite(s): General Chemistry, basic biomechanics.
This course provides a comprehensive background in biomaterials. It covers surface properties, mechanical behavior and tissue response of ceramics, polymers and metals used in the body. It also builds on this knowledge to address aspects of tissue engineering, particularly the substrate component of engineering tissue and organs.

513. Cell Biology. (A) Prerequisite(s): Graduate Standing or permission of the instructor.
Introduction to cell and molecular biology with emphasis on quantitative concepts and applications to multicellular systems.

515. Bioengineering Case Studies. (C) Prerequisite(s): Graduate standing. Undergraduates can enroll with approval of the instructor.
This course introduces students to bioengineering research and development as related to meeting clinical needs. The course is broadly organized about the question of "what makes medical technology work". It introduces students to the assessment of medical technology including studies to evaluate safety and effectiveness of new devices. Introduction to regulatory, ethical, legal, and economic issues as they relate to the success of new medical technologies. The course will be taught through examination of case studies, which may vary from year to year. Recent case studies included mammography, heart assist devices and the artificial heart, hyperthermia, safety of radiofrequency energy. The course is taught partly as a seminar, with lectures by departmental and invited outside experts and student presentations in addition to lectures by the instructor.

517. (ESE 517) Optical Imaging. (C) Prerequisite(s): ESE 310 and ESE 325 or equivalent.
A modern introduction to the physical principles of optical imaging with biomedical applications. Propagation and interference of electromagnetic waves. Geometrical optics and the eikonal. Plane-wave expansions, diffraction and the Rayleigh criterion. Scattering theory and the Born

approximation. Introduction to inverse problems. Multiple scattering and radiative transport. Diffusion approximation and physical optics of diffusing waves. Imaging in turbid media. Introduction to coherence theory and coherence imaging. Applications will be chosen from the recent literature in biomedical optics.

520. Computational Neuroscience and Neuroengineering. (M) Finkel.
Computational modeling and simulation of the structure and function of brain circuits. A short survey of the major ideas and techniques in the neural network literature. Particular emphasis on models of hippocampus, basal ganglia and visual cortex. A series of lab exercises introduces techniques of neural simulation.

521. (NGG 521) Brain-Computer Interfaces. (C) Prerequisite(s): BE 301 (Signals and Systems) or equivalent, computer programming experience, preferably MATLAB (e.g., as used the BE labs, BE 209/210/310). Some basic neuroscience background (e.g. BIOL 215, BE 305, BE 520, INSC core course), or independent study in neuroscience, is required. This requirement may be waived based upon practical experience on a case by case basis by the instructor.
The course is geared to advanced undergraduate and graduate students interested in understanding the basics ofimplantable neuro-devices, their design, practical implementation, approval, and use. Reading will cover the basics of neuro signals, recording, analysis, classification, modulation, and fundamental principels of Brain-Machine Interfaces. The course will be based upon twic weekly lectures and "hands-on" weekly assignments that teach basic signal recording, feature extraction, classification and practical implementation in clinical systems. Assignments will build incrementally toward constructing a complete, functional BMI system. Fundamental concepts in neurosignals, hardware and software will be reinforced by practical examples and in-depth study. Guest lecturers and demonstrations will supplement regular lectures.

530. (PHYS585) Theoretical Neuroscience. (C) Prerequisite(s): Knowledge of multivariable calculus, linear algebra and differential equations is required (except by permission of the instructor). Prior exposure to neuroscience and/or Matlab programming will be helpful.
This course will develop theoretical and computational approaches to structural and functional organization in the brain. The course will cover: (i) the basic biophysics of neural responses, (ii) neural coding and decoding with an emphasis on sensory systems, (iii) approaches to t he study of networks of neurons, (iv) models of adaptation, learning and memory, (v) models of decision making, and (vi) ideas that address why the brain is organized the way that it is. The course will be appropriate for advanced undergraduates and beginning graduate students.

537. (CIS 537) Biomedical Image Analysis. (C) Prerequisite(s): Math through multivariate calculus (MATH 241), programming experience, as well as some familiarity with linear algebra, basic physics, and statistics.
This course covers the fundamentals of advanced quantitative image analysis that apply to all of the major and emerging modalities in biological/biomaterials imaging and in vivo biomedical imaging. While traditional image processing techniques

will be discussed to provide context, the emphasis will be on cutting edge aspects of all areas of image analysis (including registration, segmentation, and high-dimensional statistical analysis). Significant coverage of state-of-the-art biomedical research and clinical applications will be incorporated to reinforce the theoretical basis of the analysis methods.

539. (ESE 539) Neural Networks, Chaos, and Dynamics: Theory and Application. (C)
Physiology and anatomy of living neurons and neural networks; Brain organization; Elements of nonlinear dynamics, the driven pendulum as paradigm for complexity, synchronicity, bifurcation, self-organization and chaos; Iterative maps on the interval, period-doubling route to chaos, universality and the Feigenbaum constant, Lyapunov exponents, entropy and information; Geometric characterization of attractors; Fractals and the Mandelbrot set; Neuron dynamics: from Hudgkin-Huxley to integrate and fire, bifurcation neuron; Artificial neural networks and connectionist models, Hopfield (attractor-type) networks,energy functions, convergence theorems, storage capacity, associative memory, pattern classification, pattern completion and error correction, the Morita network; Stochastic networks, simulated annealing and the Boltzmann machine, solution of optimization problems, hardware implementations of neural networks; the problem of learning, algorithmic approaches: Perception learning, back-propagation, Kohonnen's self-organizing maps and other networks; Coupled-map lattices; Selected applications including financial markets.

L/R 540. (BE 440, CBE 540) Biomolecular and Cellular Engineering. (C)
This course provides an introduction to the quantitative methods used in characterizing and engineering biomolecular properties and cellular behavior, focusing primarily on receptor-mediated phenomena. The thermodynamics and kinetics of protein/ligand binding are covered, with an emphasis on experimental techniques for measuring molecular parameters such as equilibrium affinities, kinetic rate constants, and diffusion coefficients. Approaches for probing and altering these molecular properties of proteins are also described, including site-directed mutagenesis, directed evolution, rational design, and covalent modification. Equilibrium, kinetic, and transport models are used to elucidate the relationships between the aforementioned molecular parameters and cellular processes such as ligand/receptor binding and trafficking, cell adhesion and motility, signal transduction, and gene regulation.

546. Fundamental Techniques of Imaging I. (C)
This course covers the fundamentals of modern techniques in biological and in vivo biomedical imaging. This practical course consists of a series of hands-on lab exercises, covering major imaging modalities, but also extends to non-radiology modalities of interest in biological, pathological or animal imaging (e.g., optical imaging). Topics include x-ray, mammography, MRS, MRI, PET, and ultrasound. The emphasis will be on hands-on aspects of all areas of imaging and imaging analysis. Small groups of students will be led by a faculty member with technical assistance as appropriate.

547. Fundamental Techniques of Imaging 2. (C)
This course is a continuation of the course Fundamental Techniques of Imaging 1 (BE546). It builds upon the fall course instruction and continues to expose students to the fundamentals of modern techniques in biological and in vivo biomedical imaging. This course consists of a series of hands-on lab exercises, covering major imaging modalities, but also extends to non-radiology modalities of interest in biological, pathological or animal imaging (e.g., optical imaging). Topics include SPECT, Micro-CT, diffuse optical spectroscopy, in vivo fluorescence imaging, and computed tomography. The course will continue to emphasize the hands-on aspects of all areas of

imaging and imaging analysis. Small groups of students will be led by a faculty member with technical assistance as appropriate.

550. (BE 450) Hemodynamics. (A) Prerequisite(s): BE 350 or equivalent, or permission of the instructor.

Development of concepts about the operation of themammalian cardiovascular system as conceived in the years 198 (by Galenus), 1628 (by Harvey), and 1998 (at Penn by A. Noordergraaf). Example topics include muscle structure and mechanical properties; the singel band structure of the two ventricles; electrical stimulation; Frank's mechanism; and mathematical desription of the heart as a pump.

L/R 552. (CBE 552) Cellular Engineering. (C) Prerequisite(s): Math through 241; BE 350, BE 324 as pre- or corequisites. Molecular & cellular biology.

The goal of this course is to introduce students quantitative concepts in understanding and manipulating the behavior of biological cells. We will try to understand the interplay between molecules in cells and cell function. A particular focus is on receptors - cell surface molecules that mediate cell responses. We will also try to understand processes such as adhesion, motility, cytoskeleton, signal transduction, differentiation, and gene regulation.

553. Principles, Methods, and Applications of Tissue Engineering. (C) Prerequisite(s): Graduate Standing or instructor's permission.

Tissue engineering demonstrates enormous potential for improving human health. While there is an extensive body of literature discussing the state of the art of tissue engineering, the majority of this literature is descriptive and does little to address the principles that govern the success or failure of an engineering tissue. This course explores principles of tissue engineering, drawing upon diverse fields such as developmental biology, immunology, cell biology, physiology, transport phenomena, material science, and polymer chemistry. Current and developing methods of tissue engineering as well as specific applications will be discussed in the context of these principles.

554. (CBE 554) Engineering Biotechnology. (M)
Advanced study of re DNA techniques; bioreactor design for bacteria, mammalian and insect culture; separation methods; chromatography; drug and cell delivery systems; gene therapy; and diagnostics.

L/R 555. (BE 444, CBE 555, MEAM555) Nanoscale Systems Biology. (C) Prerequisite(s): Background in Biology, Chemistry or Engineering with coursework in thermodynamics or permission of the instructor.
From single molecule studies to single cell manipulations, the broad field of cell and molecular biology is becoming increasingly quantitative and increasingly a matter of systems simplification and analysis. The elaboration of various stresses on cellular structures, influences of interaction pathways and convolutions of incessant thermal motions will be discussed via lectures and laboratory demonstration. Topics will range from, but are not limited to, protein folding/forced unfolding to biomolecule associations, cell and membrane mechanics, and cell motility, drawing from very recent examples in the literature. Frequent hands-on exposure to modern methods in the field will be a significant element of the course in the laboratory. Skills in analytical and professional presentations, papers and laboratory work will be developed.

556. Mechanical Forces: Cells/Tissue. (M)
This course will explore the biological effects of mechanical forces at the molecular, cellular and tissue level in specific tissues (blood vessels, cartilage, bone, brain, lung, and skeletal and cardiac muscle). The importance of physical forces in the health, disease, development, remodeling and injury of these tissues will be highlighted. An understanding of these specific systems will provide a foundation for discussions of the molecular basis of mechanotransduction, mechanically induced trauma, as well as the manipulation of the mechanical environment in biotechnology and tissue engineering applications. Throughout the course, the use of engineering principles and methods to understand and model mechanically induced biological phenomena will be stressed.

L/R 557. (CBE 582) From Cells to Tissue: Engineering Structure and Function. (C) Faculty. Prerequisite(s): Math through 241; BE350, BE324 as pre- or corequisites; Molecular & cellular biology.
The goal of this course is to introduce students to quantitative concepts in understanding and manipulating the behavior of biological cells. We will try to understand the interplay between molecules in cells and cell function. A particular focus is on receptors - cell surface molecules that mediate cell responses. We will also try to understand processes such as adhesion, motility, cytoskeleton, signal transduction, differentiation, and gene regulation.

L/R 559. Multiscale Modeling of Biological Systems. (C) Prerequisite(s): Undergraduates who have taken BE 324 or equivalent courses in Quantum Mechanics and/or Statistical Physics need no permission. Others, email instructor for permission.
This course aims to provide theoretical, conceptual, and hands-on modeling experience on three different length and time scales that are crucial to biochemical phenomena in cells and to nanotechnology applications. Special Emphasis will be on cellular signal transduction. 60% lectures, 40% computational laboratory. No programming skills required.

L/R 562. (CBE 562) Drug Discovery & Development. (C)
This course covers topics such as drug discovery targets, drug development, high throughput screening, solid phase synthesis, instrumentation, Lab-on-a-chip, pharmacokinetics, and drug delivery.

L/R 567. (AMCS567, BMB 580) Mathematical Computation Methods for Modeling Biological Systems. (C) Prerequisite(s): BE 324 and BE 350.
This is an introductory course in mathematical biology. The emphasis will be on the use of mathematical and computational tools for modeling physical phenomena which arise in the study biological systems. Possible topics include random walk models of polymers, membrane elasticity, electrodiffusion and excitable systems, single-molecule kinetics, and stochastic models of biochemical networks.

575. Injury Biomechanics. (C) Prerequisite(s): ENM 500 or 510, BE 510 or MEAM 519 or equivalent. A background in physiology and anatomy is also recommended.
This course is intended as an introduction to investigating the mechanics of injury, from the organism to the tissue level. The students will be exposed to both formal didactic instruction and selected field work. The course will cover principles in continuum and analytical mechanics, and will use application in injury research to illustrate these concepts. The course will be divided into three major units. The first unit will be an introduction to variational principles of mechanics and calculus of variations, and will apply these concepts to injury problems (e.g., occupant kinematics during a collision, vehicle kinematics, impact to padded surfaces). Special emphasis will be placed on converting a system input into a body response. The second unit of the course will be used to discuss the effect of gross body motion on tissue and organ mechanical response. Material models of biological tissue will be discussed, and examples relating body motion to tissue response will be reviewed. In the final unit of this course, students are required to research and review a problem of their choice and present a report detailing an engineering based solution to the problem.

580. (PHYS582) Medical Radiation Engineering. (C) Prerequisite(s): Junior standing.
This course in medical radiatioin physics investigates electromagnetic and particulate radiation and its interaction with matter. The theory of radiation transport and the basic concept of dosimetry will be presented. The principles of radiation detectors and radiation protection will be discussed.

581. (BMB 581) Techniques of Magnetic Resonance Imaging. (M)
Detailed survey of the physics and engineering of magnetic resonance imaging as applied to medical diagnosis. Covered are: history of MRI, fundamentals of electromagnetism, spin and magnetic moment, Bloch equations, spin relaxation, image contrast mechanisms, spatial encoding principles, Fourier reconstruction,imaging pulse sequences and pulse design, high-speeding imaging techniques, effects of motion, non-Cartesian sampling strategies, chemical shift encoding, flow encoding, susceptibility boundary effects, diffusion and perfusion imaging.

583. (BE 483) Molecular Imaging. (C) Prerequisite(s): BIOL 215 or BE 305 or permission of the instructor.
This course will provide a comprehensive survey of modern medical imaging modalities with an emphasis on the emerging field of molecular imaging. The basic principles of X-ray, computed tomography, nuclear imaging, magnetic resonance imaging, and optical tomography will be reviewed. The emphasis of the course, however, will focus on the concept of contrast media and targeted molecular imaging. Topics to be covered include the chemistry and mechanisms of various contrast agents, approaches to identifying molecular markers of disease, ligand screening strategies, and the basic principles of toxicology and pharmacology relevant to imaging agents.

584. (MATH584) Mathematics of Medical Imaging and Measurements. (M) Prerequisite(s): Math through 241 as well as some familiarity with linear algebra and basic physics.
In the last 25 years there as has been a revolution in image reconstruction techniques in fields from astrophysics to electron microscopy and most notably in medical imaging. In each of these fields one would like to have a precise picture of a 2 or 3 dimensional object, which cannot be obtained directly. The data that is accessible is typically some collection of weighted averages. The problem of image reconstruction is to build an object out of the averaged data and then estimate how close the reconstruction is to the actual object. In this course we introduce the mathematical techniques used to model measurements and reconstruct images. As a simple representative case we study transmission X-ray tomography (CT). In this contest we cover the basic principles of mathematical analysis, the Fourier transform, interpolation and approximation of functions, sampling theory, digital filtering and noise analysis.

597. Master's Thesis Research. (C)
For students working on an advanced research program leading to the completion of master's thesis.

599. Master's Independent Study. (C)
The purpose of BE 599 is to allow a student to create a customized curriculum to study material beyond or outside the scope of our standard BE course offerings. Independent study is NOT a research or design project, it is a one-on-one or small-group course with a professor. The course should require an effort comparable to that of a regular course, about 10-12 hours per week. A paper or presentation is required

608. (MTR 608) TRANSLATIONAL THERAPEUTI. (B)

612. Materials Affecting Cell and Molecular Function. (M)

This course provides advanced knowledge regarding the effect of the various classes of materials on tissues, cells and molecules, with the emphasis on musculoskeletal tissues. Topics include the effect of particulate matter, controlled release carriers and scaffolds for tissue repair. Emphasis is placed on recent developments in tissue engineering of bone and cartilage. The course discusses the use of materials science techniques in the study of tissue-engineered constructs. Data in the literature related to the subject matter will be extensively discussed and the students will write two articles on selected topics.

619. (BMB 604) Statistical Mechanics. (M) Prerequisite(s): CBE 618 or equivalent.
A modern introduction to statistical mechanics with biophysical applications. Theory of ensembles. Noninteracting systems. Liquid theory. Phase transitions and critical phenomena Nonequilibrium systems. Applications to reaction kinetics, polymers and membranes.

630. (EE 630) Elements of Neural Computation, Complexity and Learning. (M)
Prerequisite(s): A semester course in probability or equivalent exposure to probability (e.g. ESE 530).
Non-linear elements and networks: linear and polynomial threshold elements, sigmoidal units, radial basis functions. Finite (Boolean) problems: acyclic networks; Fourier analysis and efficient computation; projection pursuit; low frequency functions. Network capacity: Feedforward networks; Vapnik-Chervnenkis dimension. Learning theory: Valiant's learning model; the sample complexity of learning. Learning algorithms: Perception training, gradient descent algorithms, stochastic approximation. Learning complexity: the intractability of learning; model selection.

645. Biological Elasticity. (M) Prerequisite(s): BE 510 or equivalent.
Large deformation mechanics of biological materials. Nonlinear elasticity theory, strain energy functions, constitutive laws of hyperelastic and viscoelastic biological materials. Applications to heart, lung, and arteries.

650. Adv Biomed Imag Applic. (M)

655. (MSE 655) Advanced Topics in Biomaterials. (M) Prerequisite(s): BE 512 and MSE 506 or permission of instructor.
The effect of nearly inert and bioactive materials on surrounding tissues. Mechanisms of bone tissue growth enhancement with bioactive ceramics. Elasticity and strength of porous coated and ceramic coated implants. Tissue remodeling around coated implants.

L/R 662. (CBE 618, MEAM662) Advanced Molecular Thermodynamics. (C)
Review of classical thermodynamics. Phase and chemical equilibrium for multicomponent systems. Prediction of thermodynamic functions from molecular properties. Concepts in applied statistical mechanics. Modern theories of liquid mixtures.

SM 699. Bioengineering Seminar. (C)

700. Special Topics in Bioengineering. (M)
The research areas discussed will be those of the participating BE faculty who will direct the discussions and present background material. The purpose of the course is to present current research being done in the bioengineering Graduate Group and study relevant literature. The grade will be based on class participation and a final paper or presentation. Course content and staffing varies from year to year.

799. Research Rotation. (C) Prerequisite(s): PhD Students only.
For students who are fulfilling the Bioengineering research rotation requirements

895. (BIOM895) Methods in Bioengineering Education. (M) PHD students only.
This course provides training in the practical aspects of teaching. The students will attend seminars emphasizing basic pedagogical skills. Depending on the course setting for the practicum portion, student will obtain handson experience developing and delivering lectures, leading recitations, developing and supervising instructional laboratories, preparing and grading homework, grading laboratory reports, and preparing and grading examinations. Practicum experiences will be supervised by a faculty mentor. Students will meet during the practicum portion of the course to discuss difficult situations encountered in the classroom/laboratory and to constructively review each other. Final evaluations will be based on mentor, peer, and student feedback.

899. Independent Study. (C) Graduate Students Only.
The purpose of BE 899 is to allow a student to create a customized curriculum to study material beyond or outside the scope of our standard BE course offerings. Rather than a research or design project, BE 899 is a one-on-one or small-group course with a professor. Students must submit a proposal outlining the study area along with the professor's approval. A paper or presentation is required.

990. Masters Thesis. (C)
For Master's students who have completed the course requirements for the Master's degree and are strictly working to complete the Master's Thesis leading to the completion of a Master's degree. Permission Required.

995. Doctoral Dissertation Status. (C) Prerequisite(s): For Ph.D. Candidates only.
Ph.D. Students register for Doctoral Dissertation Status after they have advanced to Ph.D. candidacy by completing the Candidacy Exam which consists of the Dissertation Proposal Defense.. Permission required

999. Thesis/Dissertation Research. (C)
For students working on an advanced research program leading to the completion of master's thesis or Ph.D. dissertation requirements.