

# The Division of Engineering

Five departments in the Division of Engineering offer program opportunities to qualified graduate students for advanced instruction and research leading to the degrees of master of science and doctor of philosophy. The graduate program strikes a balance between basic science and engineering application, theory and experiment, and scholarly achievement and professional development. The division has attracted scholars—faculty, postdocs and students—with interests encompassing a wide range of modern computer science, geological sciences, and engineering theory and practice.

Through its program of sponsored research, the division enhances the opportunities available to its faculty and graduate students to conduct research in their areas of interest. Responding to the requirements of an increasingly complex and interrelated social context, the division has developed a number of interdisciplinary programs of advanced teaching and research. Some of these programs are in collaboration with faculty members of other divisions and institutes within the University, while others involve cooperative efforts with professional colleagues from outside organizations. (<http://www.nd.edu/~engineer/graduate/grad.html>)

## Aerospace and Mechanical Engineering

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### *Chair:*

Stephen M. Batill

### *Director of Graduate Studies:*

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### *The Program of Studies*

The Department of Aerospace and Mechanical Engineering offers graduate programs of study and research leading to the degrees of master of science in aerospace engineering, master of science in mechanical engineering, and master of engineering in mechanical engineering, as well as doctor of philosophy. In addition, a combination master of engineering/juris doctor degree program is available only to Notre Dame law students.

For those students seeking a master's degree, the programs aim at proficiency and creative talent in the application of basic and engineering sciences to relevant problems in the two engineering disciplines. The doctoral program strives to prepare students for creative and productive scholarship. It is designed to suit each student's interests and gives students the opportunity to conduct individual theoretical and/or experimental research under the supervision of the department faculty.

Students in either the master's degree or the doctoral degree programs must satisfy departmental and University course requirements along with the residence requirement.

Every degree-seeking student is required to participate in the academic programs of the department by performing a teaching-related assignment.

Current research efforts are within the areas of aerospace sciences, biomechanics and biomaterials, mechanical systems and design, solid mechanics and materials, and thermal and fluid sciences.

### *Aerospace Sciences*

The aerospace sciences area emphasizes both the theoretical and the experimental aspects of aeroacoustics, aero-optics, aerospace systems design, high-lift aerodynamics, low Reynolds-number aerodynamics, low speed aerodynamics, particle dynamics, flow control, transonic, supersonic and hypersonic flows, and vortex aerodynamics.

### *Biomechanics and Biomaterials*

The biomechanics and biomaterials area offers opportunities for both basic and applied research using both experimental and computational techniques. Research focuses on the design and manufacture of next-generation orthopaedic devices, biological material characterization, the design, synthesis, and characterization of novel biomaterials, biocompatibility, tribology, surgical simulation, human body kinematics, and computational modeling of biomechanical systems. Collaborative research efforts are maintained with

industrial partners and the Departments of Biological Sciences, Chemical Engineering, and Computer Science and Engineering.

### *Mechanical Systems and Design*

Research in this area is in both the theoretical and the experimental aspects of computer-aided design and manufacturing, design for manufacturing, design optimization, model-based design, reliability, dynamic and control systems, mechanism and machine theory, robotics, and tribology.

### *Solid Mechanics and Materials*

Research in this area focuses on the theoretical, experimental, and computational aspects of coupled field phenomena in continuum mechanics, cyclic plasticity, damage mechanics, dynamic deformation and fracture, fatigue crack initiation, fracture analysis of aircraft structures, high temperature fatigue of engineering alloys, inelastic buckling, interface fracture mechanics, modeling of composite and fused deposition polymeric materials, and structural stability.

### *Thermal and Fluid Sciences*

Experimental and theoretical research in this area is conducted in boundary layer phenomena, chaos in fluid systems, computational fluid mechanics, detonation theory, droplet sprays, fire research, fluid-structure interaction, flow control, food processing technology, hydronics, hydrodynamic stability, industrial energy conservation, microfluid mechanics, molecular dynamics, multiphase and buoyant flows, reacting flows, turbulent flows, and solidification of liquid metals.

In cooperation with the Department of Civil Engineering and Geological Sciences, the Department of Aerospace and Mechanical Engineering offers an interdisciplinary program of study and research in the areas of solid, continuum, and structural mechanics. Courses in these subject areas listed by each department are cross-listed and are offered jointly. Students pursuing research in the areas of biomaterials and biomechanics may take selected courses offered by the Department of Chemical Engineering.

### Course Descriptions

Each course listing includes:

- Course number
- Title
- (Lecture hours per week—laboratory or tutorial hours per week—credits per semester)
- Instructor
- Course description
- (Semester normally offered)

#### 520. Introduction to Aeroelasticity

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Aerodynamic loadings, steady state aeroelastic problems, flutter analysis under various flow conditions, analytical methods in aeroelasticity demonstrated by selected problems. (As needed)

#### 521. Numerical Methods

(3-0-3) Paolucci

Interpolation, differentiation, integration, initial value and boundary value problems for ordinary differential equations; solution methods for parabolic, hyperbolic, and elliptic partial differential equations; applications to classical and current research problems in engineering and science. (Every fall)

#### 530. Physical Gas Dynamics

(3-0-3) Jumper

An introduction to quantum mechanics, internal structure, and quantum energy states of monatomic and diatomic gases. Application to chemical reactions, dissociating gases, and ionized gases. High temperature properties of air. (Alternate spring semesters)

#### 538. Intermediate Fluid Mechanics

(3-0-3) Staff

*Prerequisites:* Elementary fluid mechanics, differential equations.

Derivation of governing equations of mass, momentum, and energy for a viscous, compressible fluid; general survey of vortex dynamics, potential flow, viscous flow, and compressible flow. (Every fall)

#### 541. Advanced Kinematics

(3-0-3) Stanisic

An in-depth study of the curvature theory of planar one and two degree-of-freedom motions. Applications to synthesis of mechanisms and control of manipulators. Introduction to spatial kinematics and screw theory. (Every spring)

#### 542. Advanced Mechanical Behavior of Materials

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Description of the mechanical behavior of metals, polymers, composites, ceramics, and glass, and characterization of the relationships between macroscopic deformation and fracture behavior of solids and meso/micro- and atomic-level mechanisms and models.

#### 544. Optimum Design of Mechanical Elements

(3-0-3) Renaud

Introduction to basic optimization techniques for mechanical design problems. Current applications. (Every spring)

#### 545. Intermediate Heat Transfer

(3-0-3) Staff

Fundamentals of heat convection and radiation, scaling and heat transfer analysis in external and internal flows, turbulent heat transfer, thermal radiation properties of ideal and real surfaces, radiative transfer in black and gray enclosures, introduction to radiative transfer with participating media. (Every spring)

#### 550. Advanced Control Systems

(3-0-3) Goodwine, Skaar

*Prerequisites:* ME 437 or equivalent.

The application of techniques such as the phase-plane method, Lyapunov method, vector-format method, the z-transform method, and statistical methods to the design of control systems. (Alternate years)

#### 551. Advanced Vehicle Dynamics

(3-0-3) Nelson

*Prerequisites:* AERO 444 or ME 335, ME 437 or equivalent.

The equations of motion of a rigid airplane are developed and analyzed. The relationship between aerodynamic stability derivatives, vehicle motion, and handling qualities is presented. Also classical and modern control theory is applied to the design of automatic flight control systems. (Alternate years)

#### 552. Mathematical Theory of Robotic Manipulation

(3-0-3) Goodwine

*Prerequisite:* AME 469 or equivalent.

Homogeneous representation of rigid motion in  $R^3$ , exponential coordinates for rigid motions, twists and screws, spatial and body velocities, and adjoint representation for coordinate transformations. Manipulator kinematics via the product of exponentials formulation, inverse kinematics, Jacobians, singularities, and manipulability. Multi-fingered hand kinematics including contact models, the grasp map, force closure, grasp planning, grasp constraints, and rolling contact kinematics.

#### 553. Introduction to Acoustics and Noise

(2-2-3) Atassi

*Prerequisite:* Consent of instructor.

A course that treats the fundamentals of sound and noise production, transmission, and measurement. Theoretical, experimental, environmental, and legislative topics. (Alternate years)

#### 554. Analytical Dynamics

(3-0-3) Skaar

Fundamental principles and analytical methods in dynamics with applications to machine design, robot analysis, and spacecraft control. (Every spring)

#### 558. Elasticity

(3-0-3) Mason, Corona

The fundamental theories and techniques in elasticity are covered. Variational methods and complex variable techniques are included, and applications are demonstrated by selected problems. (Every spring)

#### 559. Advanced Mechanics of Solids

(3-0-3) Staff

The course covers fundamental principles and techniques in stress analysis of trusses, beams, rigid frame, and thin-walled structures. Emphasis is placed on energy methods associated with calculus of variations. (Every fall)

#### 560. Finite Element Methods in Structural Mechanics

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Finite element methods for static and dynamic analysis of structural and continuum systems. Displacement approach for two- and three-dimensional solids along with beams, plates, and shells. Material and geometric nonlinearities. (As needed)

*561. Mathematical Methods I*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Multidimensional calculus, linear analysis, linear operators, vector algebra, ordinary differential equations. (Every fall)

*562. Mathematical Methods II*

(3-0-3) Staff

Continuation of AME 561.

Partial differential equations, characteristics, separation of variables, similarity and transform solutions, complex variable theory, singular integral equations, integral transforms. (Every spring)

*563. Finite Elements in Engineering*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Fundamental aspects of the finite element method are developed and applied to the solution of PDEs encountered in science and engineering. Solution strategies for parabolic, elliptic, and hyperbolic equations are explored. (As needed)

*565. Tribology*

(3-0-3) Schmid, Ovaert

Fundamentals of the nature of surface contact. Regimes of fluid film lubrication, friction and wear models, and surface characteristics are analyzed and applied to machine elements and manufacturing processes. (As needed)

*569. Structural Dynamics*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Examines problems in the vibration of continuous linear elastic structures, including strings, rods, beams, membranes, and plates; Hamilton's principle; solution by separation of variables, integral equation and transform methods; variational methods of approximation including the finite element method; computational methods. (As needed)

*570. Advanced Measurements Laboratory*

(2-1-3) Staff

A graduate short course designed to give students laboratory experience in the use of modern measurements and the design of experiments for specific problems. (Every fall)

*598. Special Studies*

(V-V-V) Staff

Individual or small group study under the direction of a faculty member in a graduate subject not currently covered by any University course. (As needed)

*598. F Orthopaedic Biomechanics*

(3-0-3) Niebur

An introduction to the mechanics of the musculoskeletal system. Major topics include kinematics and dynamics of motion, mechanical behavior of musculoskeletal materials, and design considerations for orthopaedic devices. (Every fall)

*598. I Intelligent Systems*

(3-0-3) Sen

An introduction to a unified view of the aerospace and mechanical engineering applications of intelligent systems theory and practice including; systems theory, artificial neural networks, fuzzy logic, genetic algorithms, expert systems, hybrid methods, and applications to mechanical systems and thermofluids. (Every fall)

*598. J Analysis of Spatial Mechanisms*

(3-0-3) Stanisic

A study of modern methods of kinematic analysis of spatial mechanisms and machinery. Conventional machinery as well as robotic manipulators and humanoid systems are considered. New types of highly dextrous robotic manipulators are considered with an emphasis on kinematic design and control. (As needed)

*599. Thesis Direction*

(V-V-V) Staff

This course is reserved for the six-credit-hour thesis requirement of the research master's degree. (Every semester)

*600. Nonresident Thesis Research*

(0-0-1) Staff

For master's degree students. (As needed)

*601. Viscous Flow Theory I*

(3-0-3) Staff

*Prerequisite:* AME 538.

Properties and solutions of the Navier-Stokes equations, high and low Reynolds number approximations for steady and unsteady flows. (Every spring)

*602. Viscous Flow Theory II*

(3-0-3) Staff

*Prerequisite:* AME 601 or consent of instructor.

Approximate methods in solving the boundary layer equations. Properties and solutions of viscous compressible flows. Introduction to equations of motion in turbulent shear flows. (As needed)

*603. Turbulence*

(3-0-3) Thomas

*Prerequisite:* Consent of instructor.

Experimental facts, measurements, theory, correlations, simple approximations. Homogeneous turbulence, spectra, direct interaction, numerical models, theory of Kraichnan, meteorology, diffusion. (Alternate spring semesters)

*604. Hydrodynamic Stability*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Introduction of the major fundamental ideas, methods, and results of the theory of hydrodynamic stability. Examples of major applications are presented. (Alternate fall semesters)

*610. Flow Control*

(3-0-3) Staff

*Prerequisite:* AME 538

Passive, active, and reactive flow management strategies to achieve transition delay/advance, separation control, mixing augmentation, drag reduction, lift enhancement, and noise suppression.

*611. Dynamics of Compressible Fluids*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Theoretical gas dynamics, including properties of compressible real fluids and fundamental relations for subsonic and supersonic flows. (As needed)

*612. Unsteady Aerodynamics and Aeroacoustics*

(3-0-3) Atassi

*Prerequisites:* Fluid mechanics, ideal aerodynamics.

Unsteady flows, unsteady aerodynamics of airfoils, cascades, and finite wings, acoustics in moving media, aerodynamic sound, Lighthill's analogy, far field conditions, Kirchhoff's method, numerical methods in aeroacoustics. (Alternate fall semesters)

*620. Computational Fluid Mechanics*

(3-0-3) Paolucci

*Prerequisite:* AME 521, AME 538

Generalized coordinate transformation, grid generation, and computational methods for inviscid flow, viscous incompressible flow, and viscous compressible flow. (Alternate years)

*621. Thermal Radiation*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Basic concepts and laws of thermal radiation. Radiative properties of gases and surfaces. Radiative exchange between surfaces. Gaseous radiation interaction. (Alternate fall semesters)

**623. Thermal Convection**

(3-0-3) Staff

*Prerequisite:* AME 601.

Forced convection in ducts; Graetz solution and extensions; free or forced flow boundary layer heat transfer; turbulent heat transfer; combined forced and free convection; heat transfer including phase change. (Alternate fall semesters)

**641. Spatial Kinematics**

(3-0-3) Stanisc

*Prerequisite:* Kinematic Synthesis, Linear Algebra and AME 541.

A study of the finite and instantaneous kinematics of rigid body systems including closed and open loop systems with up to five degrees-of-freedom. Position analysis via coordinate transformations. Development of Screw Theory with applications to dimensional synthesis of mechanisms and path tracking control of manipulators.

**650. Advanced Topics in Solid Mechanics**

(3-0-3) Corona, Mason

*Prerequisite:* Consent of instructor.

Topics in solid mechanics normally not covered in elementary graduate courses. Topics covered may vary. (As needed)

**651. Fracture of Materials**

(3-0-3) Staff

*Prerequisite:* AME 559 or equivalent.

Concepts of fracture of brittle and ductile materials. Methods for determination of stress intensity factors, crack open displacements, and energy release rates under static and dynamic conditions. (Alternate years)

**652. Mechanics of Irreversible Deformation**

(3-0-3) Corona

*Prerequisite:* AME 658 and AME 559 or consent of instructor.

Introduction to inelastic deformation of solids. Basic concepts and applications of classical plasticity, viscoelasticity, and viscoplasticity.

**653. Mechanics and Failure of Composites**

(3-0-3) Mason

*Prerequisites:* AME 558, AME 561, and AME 562.

An introduction to the mechanics and failure of composites. Concepts in static and dynamic anisotropic elasticity are covered as are basic concepts in viscoelasticity and hygrothermal behavior. These topics lead into a discussion of laminate theory, failure theories, shear lag theory, and micro-mechanics of composites.

**654. Geometric Nonlinear Control Theory**

(3-0-3) Goodwine

*Prerequisite:* Consent of instructor.

Review of state space linear dynamical control systems, basic Lyapunov theory, and bifurcation theory. Basic concepts and methods from differential geometry including manifolds, tangent spaces, vector fields, distributions, Frobenius' Theorem, and matrix groups and their application to nonlinear control including I/O and full state linearization via state feedback, controllability and observability, trajectory generation for nonlinear systems, and applications to stratified systems such as legged robotic locomotion and robotic manipulation.

**657. Continuum Mechanics**

(3-0-3) Staff

*Prerequisite:* AME 558 or AME 538 or consent of instructor.

Deformation and motion of continua and singular surfaces; general balance equations; stress principle; balance laws for mass, momentum, and energy; thermodynamics of continua; entropy balance; constitutive relationships; material symmetry and invariance theory; linear and nonlinear constitutive models; variational foundations; topics of special interest. (Alternate years)

**666. Stability Theory of Structural Systems**

(3-0-3) Staff

*Prerequisite:* AME 559 or consent of instructor.

The general principle of stability of structural systems. Euler buckling and post-buckling behavior of discrete and continuous systems are presented. (As needed)

**667. Theory of Plates and Shells**

(3-0-3) Staff

*Prerequisite:* AME 559 or consent of instructor.

Differential geometry of surface in tensor form, stress resultants and stress couples, equations of equilibrium, principle of virtual work, Sanders-Koiter nonlinear shell theories, compatibility relations, linear shell theories, static-geometric duality, stability of shells, applications to shells of various geometries.

**697. Directed Readings**

(V-V-V) Staff

Content, credit, and instructor will be announced by the department. (As needed.)

**698. Special Studies**

(V-V-V) Staff

Content, credit, and instructor will be announced by the department. (As needed)

**699. Research and Dissertation**

(V-V-V) Staff

Required for candidates for the advanced degree in the research program. (Every semester)

**700. Nonresident Dissertation Research**

(0-0-1) Staff

This course is reserved to provide the required continuing minimal registration of one credit hour per academic semester for nonresident graduate students who wish to retain their degree status. (As needed)

**701. Graduate Seminar**

(2-0-0) Staff

Required for all aerospace graduate students. Discussion of current topics in research and engineering by guest lecturers and staff members. (Every semester)

In addition to the courses listed above, 400-series courses for advanced undergraduates may be taken for graduate credit, subject to approval of the Department of Aerospace and Mechanical Engineering. For information on these courses, refer to the College of Engineering section of the *Bulletin of Information, Undergraduate Programs*.

**Faculty**

Hafiz Atassi, *the Viola D. Hank Professor*. Engineer, Ecole Centrale de Paris; Licence, Univ. of Paris, 1963; Ph.D., *ibid.*, 1966. (1969)

Stephen M. Batill, *Chair and Professor*. B.S., Univ. of Notre Dame, 1969; M.S., *ibid.*, 1970; Ph.D., *ibid.*, 1972. (1978)

Alan P. Bowling, *Assistant Professor*. B.S., Univ. of Texas, 1983; Ph.D., Stanford Univ., 1998. (2001)

Raymond M. Brach, *Professor Emeritus*. B.S., Illinois Institute of Technology, 1958; M.S., *ibid.*, 1962; Ph.D., Univ. of Wisconsin, 1965. (1965)

Thomas C. Corke, *Director of Hessert Laboratory for Aerospace Research, Director of Graduate Studies, and the Clark Equipment Professor*. B.S., Illinois Institute of Technology, 1974; M.S., *ibid.*, 1976; Ph.D., *ibid.*, 1981. (1999)

Edmundo Corona, *Associate Professor*. B.S.A.E., Univ. of Texas, Austin, 1983; M.S., *ibid.*, 1986; Ph.D., *ibid.*, 1990. (1991)

Patrick F. Dunn, *Professor*. B.S., Purdue Univ., 1970; M.S., *ibid.*, 1971; Ph.D., *ibid.*, 1974. (1985)

J. William Goodwine, *Assistant Professor*. B.S., Univ. of Notre Dame, 1988; J.D., Harvard

Law School, 1991; M.S., California Institute of Technology, 1993; Ph.D., *ibid.*, 1998. (1998)

James E. Houghton, *Assistant Professor Emeritus*. B.S.E.E., Univ. of Notre Dame, 1949; M.S., *ibid.*, 1962. (1952)

Robert A. Howland Jr., *Associate Professor*. B.A., Yale Univ., 1965; M.S., *ibid.*, 1966; Ph.D., North Carolina State Univ., 1974. (1981)

Nai-Chien Huang, *Professor Emeritus*. B.S., National Taiwan Univ., 1953; M.S., Brown Univ., 1958; Ph.D., Harvard Univ., 1963. (1969)

Frank Incropera, *the Matthew H. McCloskey Dean of the College of Engineering and the H. Clifford and Evelyn A. Brosey Professor of Mechanical Engineering*. S.B., Massachusetts Institute of Technology, 1961; M.S., Stanford Univ., 1962; Ph.D., *ibid.*, 1966. (1998)

Edward W. Jerger, *Professor Emeritus*. B.S., Marquette Univ., 1946; M.S., Univ. of Wisconsin, 1947; Ph.D., Iowa State Univ., 1951. (1955)

Eric J. Jumper, *Professor*. B.S.M.E., Univ. of New Mexico, 1968; M.S.M.E., Univ. of Wyoming, 1969; Ph.D., Air Force Institute of Technology, 1975. (1989)

Francis M. Kobayashi, *Professor Emeritus and Assistant Vice President Emeritus for Research*. B.S., Univ. of Notre Dame, 1947; M.S., *ibid.*, 1948; Sc.D., *ibid.*, 1953. (1948)

Lawrence H. N. Lee, *Professor Emeritus*. B.S., Utopia Univ., 1945; M.S., Univ. of Minnesota, 1947; Ph.D., *ibid.*, 1950. (1950)

John W. Lucey, *Associate Professor*. B.S., Univ. of Notre Dame, 1957; S.M., Massachusetts Institute of Technology, 1963; Ph.D., *ibid.*, 1965. (1965)

James J. Mason, *Associate Professor*. B.S., Univ. of California, 1986; M.S., *ibid.*, 1988; Ph.D., California Institute of Technology, 1993. (1993)

Stuart T. McComas, *Professor Emeritus*. B.S.M.E., Marquette Univ., 1956; M.S., Univ. of Minnesota, 1960; Ph.D., *ibid.*, 1964. (1963)

Scott C. Morris, *Assistant Professor*. B.S., Michigan State Univ., 1994; M.S., *ibid.*, 1997; M.S., *ibid.*, 2001 Ph.D., *ibid.*, 2002. (2002)

Thomas J. Mueller, *the Roth-Gibson Professor of Aerospace Engineering*. B.S., Illinois Institute of Technology, 1956; M.S., Univ. of Illinois, 1958; Ph.D., *ibid.*, 1961. (1965)

Victor W. Nee, *Professor Emeritus*. B.S., National Taiwan Univ., 1957; Ph.D., Johns Hopkins Univ., 1967. (1965)

Robert C. Nelson, *Professor*. B.S., Univ. of Notre Dame, 1964; M.S., *ibid.*, 1966; Ph.D., Pennsylvania State Univ., 1974. (1975)

Glen Niebur, *Assistant Professor*. B.S., Univ. of Minnesota, 1986; M.S.M.E., *ibid.*, 1995; Ph.D., Univ. of California at Berkeley, 2000. (2001)

Timothy C. Ovaert, *Professor*. B.S., Univ. of Illinois, 1981; M.S., Northwestern Univ., 1985; Ph.D., *ibid.*, 1989. (2000)

Samuel Paolucci, *Professor*. B.S., Drexel Univ., 1975; Ph.D., Cornell Univ., 1979. (1989)

Joseph M. Powers, *Associate Professor*. B.S., Univ. of Illinois, 1983; M.S., *ibid.*, 1985; Ph.D., *ibid.*, 1988. (1989)

Francis H. Raven, *Professor Emeritus*. B.S., Pennsylvania State Univ., 1950; M.S., *ibid.*, 1951; Ph.D., Cornell Univ., 1958. (1958)

John E. Renaud, *Professor*. B.S., Univ. of Maine, 1982; M.S., Rensselaer Polytechnic Institute, 1989; Ph.D., *ibid.*, 1992. (1992)

Ryan K. Roeder, *Assistant Professor*. B.S., Purdue Univ., 1994; Ph.D., Purdue Univ., 1999. (2001)

Steven R. Schmid, *Associate Professor*. B.S., Illinois Institute of Technology, 1986; M.S., Northwestern Univ., 1989; Ph.D., *ibid.*, 1993. (1993)

Mihir Sen, *Professor*. B.Tech., Indian Institute of Technology, 1968; Sc.D., Massachusetts Institute of Technology, 1975. (1986)

Steven B. Skaar, *Associate Chair and Professor*. A.B., Cornell Univ., 1975; M.S., Virginia Polytechnic Institute and State Univ., 1978; Ph.D., *ibid.*, 1982. (1989)

Michael M. Stanisic, *Associate Professor*. B.S., Purdue Univ., 1980; M.S., *ibid.*, 1982; Ph.D., *ibid.*, 1986. (1988)

Albin A. Szewczyk, *Professor Emeritus*. B.S.M.E., Univ. of Notre Dame, 1956; M.S.M.E., *ibid.*, 1958; Ph.D., Univ. of Maryland, 1961. (1962)

Flint O. Thomas, *Professor*. B.S., Indiana State Univ., 1977; M.S.M.E., Purdue Univ., 1980; Ph.D., *ibid.*, 1983. (1988)

Kwang-Tzu Yang, *the Viola D. Hank Professor Emeritus of Aerospace and Mechanical Engineering*. B.S., Illinois Institute of Technology, 1951; M.S., *ibid.*, 1952; Ph.D., *ibid.*, 1955. (1955)

## Chemical and Biomolecular Engineering

### Chair:

Mark J. McCready

### Director of Graduate Studies:

Mark A. Stadtherr

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### The Program of Studies

The department offers programs leading to the degrees of master of science and doctor of philosophy. The aim of the graduate program is to prepare qualified candidates for research, development, teaching, and other professional careers in chemical engineering. Thus, the Ph.D. program is emphasized.

The objective of the doctoral program is to superimpose upon a broad education the ability to think independently in new fields, to coordinate technical ideas at an advanced level, and to make a systematic approach to the solution of new problems.

The course work is chosen in consultation with department faculty and the dissertation research adviser according to procedures outlined in *A Guide to Graduate Studies in Chemical Engineering*.

The master's degree program consists of at least 15 credit hours of course work, plus 15 credit hours of thesis research and graduate seminar. For the Ph.D. degree, a minimum of 30 credit hours of course work is required, in addition to 42 credit hours of dissertation research and graduate seminar. There are required courses in the areas of thermodynamics, reaction engineering, transport phenomena, and mathematical methods.

After the second semester of residence, each Ph.D. student presents written and oral reports based on thesis research or project work. These reports, along with performance in courses, in research, and in teaching assistantship duties, constitute the comprehensive

evaluation in chemical engineering. This allows the faculty to evaluate the student's grasp of chemical engineering fundamentals and his or her ability to perform original, independent research. Students who pass the comprehensive evaluation may continue to the Ph.D. program.

Ph.D. students generally take the oral candidacy examination before the end of the fifth semester in residence. This examination focuses on the progress achieved in thesis-related work and on the proposed future research.

The departmental faculty believes that all students seeking advanced degrees in chemical engineering should have some experience related to the instruction of others. Therefore, all first- and second-year graduate students are assigned teaching assistant duties. These duties consist of conducting recitation sections for lecture courses, supervising laboratory courses, or grading homework.

Full-time students normally complete the Ph.D. degree requirements in about four-and-a-half years beyond the bachelor's degree. Requirements for the master's degree can normally be completed in two years of full-time study.

A student pursuing the Ph.D. degree will be eligible to receive an M.S. degree after completing five semesters in the Ph.D. program, passing the Ph.D. Candidacy Exam, and preparing and submitting for publication a research paper in collaboration with the student's research advisor(s). This paper shall describe work in which the student has a primary (not supporting) role, be submitted to a research journal or to the proceedings of a technical conference, and be subject to peer review.

New graduate students in chemical engineering select their research area and director during their first semester in residence at Notre Dame. Areas of current research include applied mathematics; biological materials; bioseparations; catalysis and surface science; ceramic materials; chemical reaction engineering; combustion synthesis of materials; drug delivery systems; ecological modeling; environmentally conscious design; fuel cells; gas-liquid flows; ionic liquids; materials science; microfluidic devices; molecular modeling and simulation; molecular theory of transport; nano-structured materials; parallel computing; phase equilibria; pollution prevention; polymer rheology; process dynamics and control; process optimization and design;

process simulation; statistical mechanics; superconducting materials; supercritical fluids; suspension rheology; and transport in porous media.

More detailed descriptions of the research interests of individual faculty members may be found in the brochure, *Chemical Engineering, University of Notre Dame*, and at the departmental Web site.

In addition to graduate assistantships and Peter C. Reilly Fellowships, several industrial fellowships also are available for highly qualified students.

#### Course Descriptions

Each course listing includes:

- Course number
- Title
- (Lecture hours per week—laboratory or tutorial hours per week—credits per semester)
- Instructor
- Course description
- (Semester normally offered)

#### 510. *Advanced Thermodynamics* (3-0-3) Strieder

*Prerequisite:* CHEG 327 or equivalent.

An advanced treatment of physical and chemical thermodynamics for engineers.

#### 538. *Introduction to Statistical Thermodynamics for Engineers* (3-0-3) Strieder

*Prerequisite:* CHEG 327 or equivalent.

Development of the fundamentals of statistical mechanics and thermodynamics. Applications to monatomic gases and solids, diatomic and polyatomic gases, chemical equilibrium, dense gases, solids, and liquids.

#### 542. *Mathematical Methods in Engineering I* (3-0-3) Hill

*Prerequisite:* Consent of instructor.

Rigorous development of tools of mathematical analysis and application of these to solve engineering problems. Topics include matrices, linear and nonlinear ordinary differential equations, special functions, and modeling. (Fall)

#### 544. *Transport Phenomena I* (3-0-3) Chang

Differential balance equations that govern transport processes are derived and used to solve problems that demonstrate the physical insight necessary to apply these equations to original situations. The emphasis in this course is on fluid mechanics. (Every year)

#### 545. *Transport Phenomena II* (3-0-3) Leighton

The differential equations that govern transport phenomena are applied to the solution of various heat and mass transfer problems.

#### 546. *Advanced Chemical Reaction Engineering* (3-0-3) Varma

*Prerequisite:* Undergraduate course in chemical reaction engineering.

Analyses and mathematical modeling of chemical reactors with emphasis on heterogeneous reaction systems. (Every year)

#### 552. *Mathematical Methods in Engineering II* (3-0-3) Chang

*Prerequisite:* CHEG 542 or consent of instructor.

Continuation of 542, which covers treatment of partial differential equations, transform methods, perturbation methods, and approximation methods, including methods of weighted residuals and variational method. (Spring)

#### 553. *Advanced Chemical Engineering Thermodynamics* (3-0-3) Maginn

*Prerequisite:* Consent of instructor.

This course is focused on an advanced treatment of thermodynamic concepts. An introduction to molecular thermodynamics is given, followed by detailed treatments of phase equilibrium, equation-of-state development and activity coefficient models.

#### 556. *Polymer Engineering* (3-0-3) Hill

*Prerequisite:* Senior or graduate student standing in science or engineering.

A course for seniors and graduate students in science and engineering who are interested in applications of engineering to polymer science and technology. Topics include polymerization reactions and the structure, properties, processing, and production of polymers. (Every year)

#### 567. *Heterogeneous Catalysis* (3-0-3) Wolf

*Prerequisite:* Consent of instructor.

Introduction to solid state and surface chemistry, adsorption, reaction of gases on solid surfaces, experimental techniques in catalysis, catalyst preparation, and industrial catalytic processes.

*598. Special Studies*

(V-V-V) Staff

*Prerequisite:* Consent of instructor.

Individual or small group study under the direction of a faculty member in a graduate subject not concurrently covered by any University course. (Every semester)

*598A. Phase Transformations in Solids*

(3-0-3) McGinn

This course covers a range of common phase transformations found in a wide range of materials. Topics covered include phase diagrams, diffusion, interfaces in solids, solidification phenomena, and diffusional and diffusionless phase transformations. Nucleation, precipitate growth, ordering, and martensitic transformations are all discussed. The level is aimed at advanced undergraduate and first-year graduate students.

*598C. Electrochemistry and Corrosion*

(3-0-3) Miller

A study of some of the major concepts of electrochemistry and materials science that provides the student with a foundation for understanding, at a conceptual level, some of the important corrosion processes, as well as the methods of their control as practiced today in various industrial environments.

*598D. Structure of Solids*

(3-0-3) McGinn

This class will deal with the crystallographic structure of solids, primarily as found in metals, alloys, and ceramics. Imperfections in the arrangements of atoms will be emphasized, especially as regards their impact on properties. The study of structure through x-ray diffraction will be a recurring theme.

*598E. Ceramic Materials*

(3-0-3) Miller

An introduction to the principles that govern the synthesis, processing, structure, and performance of modern ceramic materials. Emphasis is on the use of these principles to understand and solve engineering problems with ceramics.

*598F. Chemical Process Simulation and Optimization*

(3-0-3) Stadtherr

This course will provide an overview of the computational methodologies used for chemical process simulation and optimization. Topics will include: (1) how to formulate process models; (2) how to solve process models (linear and nonlinear equation solving, etc.); and (3) how to optimize using process models (linear and nonlinear programming, global optimization, etc.).

*598G. Principles of Materials Selection*

(3-0-3) Miller

One of the most important tasks that an engineer may be called upon to perform is that of materials selection with regard to component design. It is essential that the engineering student become familiar with and versed in the procedures and protocols that are normally employed in this process. This course will discuss materials selection issues in several contexts and from various perspectives. A case study method will be used to frame real-life engineering problems so that they can be carefully analyzed in detail so that the student may observe the procedures and rationale that are involved in the materials selection decision-making process. Mechanical, IC packaging, and corrosion case studies, in addition to others, will be used.

*598J. Selected Topic/Materials Processing*

(3-0-3) McGinn

This course covers a limited number of materials processing techniques used by materials researchers as well as industrial manufacturers. The primary areas to be covered include thin film processing, fine ("nanoscale") particle processing, crystal growth, and a few selected ceramics processing techniques. Within each of these areas various techniques will be discussed, with both the theoretical and practical aspects being described.

*598M. Macromolecular Bioengineering*

(3-0-3) Ostafin

Recent advances in molecular biology have made it possible to thoroughly study biological macromolecules. These macromolecules can perform many important functions, such as information transfer, catalysis, energy acquisition, transport regulation, and energy generation. This course focuses on the unique characteristics of macromolecules and how they can contribute in the area of engineering, such as in developing nanoscale devices, innovative materials, information storage devices, energy capture and storage, and many other applications.

*598N. Biomedical Engineering Transport Phenomena*

(3-0-3) Palmer

This course brings together fundamental engineering and life science principles, and provides a focused coverage of key concepts in biomedical engineering transport phenomena. The emphasis is on chemical and physical transport processes with applications toward the development of drug delivery systems, artificial organs, bioartificial organs, and tissue engineering.

*598R. BioProcess Engineering*

(3-0-3) Ostafin

BioProcess Engineering is the application of engineering principles to design, develop, and analyze processes that use biocatalysts. These may be in the form of a living cell, its substructures, or their chemical components. In this course you learn concepts of cellular biology, and are introduced to mathematical-based engineering analysis of complex biological systems. By the end of this course you should be able to understand basic structure and function of cells, homogeneous and heterogeneous enzyme kinetics, the regulation of cell growth, the design and operation of bioreactors, recovery and characterization of products, and methods in genetic engineering and molecular cloning.

*599. Thesis Direction*

(V-V-V) Staff

Research to satisfy the six credit hours required for the master's degree.

*600. Nonresident Thesis Research*

(0-0-1) Staff

Required of nonresident graduate students who are completing their theses in absentia and who wish to retain their degree status.

*669, 679. Graduate Seminar*

(1-0-1) (1-0-1) Staff

Staff members, guest speakers, and doctoral students discuss current research problems. (Every semester)

*698. Special Studies in Chemical Engineering*

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by department. (Every year)

*698A. Ceramics*

(3-0-3) Miller

The theoretical and empirical principles of ceramic materials.

*698B. Nonlinear Dynamics and Pattern Formation*

(3-0-3) Chang

This course reviews some classical pattern formation dynamics in extended domains. Specific topics include Rayleigh-Benard convection, Hamiltonian dynamics, wave phenomena, solidification, Turing patterns, etc. Analytical and numerical tools will be introduced to reduce the model dimension and to classify the pattern dynamics.

*698D. Molecular Theory*

(3-0-3) Maginn

*Prerequisite:* Consent of instructor.

An introduction to statistical mechanical theories and molecular simulation techniques used to calculate properties of interest to chemical engineers.

*699. Research and Dissertation*

(V-V-V) Staff

Research and dissertation for resident doctoral students.

*700. Nonresident Dissertation Research*

(0-0-1) Staff

Required of nonresident graduate students who are completing their dissertations in absentia and who wish to retain their degree status.

*Faculty*

Sudhir Aki, *Assistant Research Professor*. B.S., Andhra Univ., 1991; Ph.D., Univ. of Toledo, 1998. (2001)

Joan F. Brennecke, *the Keating-Crawford Professor of Chemical Engineering*. B.S., Univ. of Texas, 1984; M.S., Univ. of Illinois, 1987; Ph.D., *ibid.*, 1989. (1989)

Hsueh-Chia Chang, *the Bayer Corporation Professor of Chemical Engineering*. B.S., California Institute of Technology, 1976; Ph.D., Princeton Univ., 1980. (1987)

Evgeny Demekhin, *Research Professor*. Ph.D., Moscow State Univ., 1981. (2002)

Daniel E. E. Hayes, *Visiting Research Professor*. B.S.M.E., Oklahoma State Univ., 1968; M.S., Air Force Institute of Technology, 1971; M.S., Univ. of Dayton, 1981. (2001)

Davide A. Hill, *Associate Professor*. Dottore in Ingegneria Chimica, Univ. di Napoli, Italy, 1983; Ph.D., Univ. of California, Berkeley, 1989. (1990)

Jeffrey C. Kantor, *Vice President for Graduate Studies and Research, Dean of the Graduate School, and Professor of Chemical and Biomolecular Engineering*. B.S., Univ. of Minnesota, 1976; M.A., Princeton Univ., 1977; Ph.D., *ibid.*, 1980. (1981)

David T. Leighton Jr., *Professor*. B.S.E., Princeton Univ., 1980; M.S., Stanford Univ., 1981; Ph.D., *ibid.*, 1985. (1985)

Edward J. Maginn, *Associate Professor*. B.S., Iowa State Univ., 1987; Ph.D., Univ. of California, Berkeley, 1995. (1995)

Mark J. McCready, *Chair and Professor*.

B.Ch.E., Univ. of Delaware, 1979; M.S., Univ. of Illinois, 1981; Ph.D., *ibid.*, 1984. (1984)

Paul J. McGinn, *Professor*. B.S., Univ. of Notre Dame, 1980; M.S., *ibid.*, 1983; Ph.D., *ibid.*, 1984. (1987)

Albert E. Miller, *Professor*. B.S., Colorado School of Mines, 1960; Ph.D., Iowa State Univ., 1964. (1967)

Alex S. Mukasyan, *Research Professor*. M.S., Moscow Physical Engineering Institute, 1980; Ph.D., Institute of Chemical Physics, USSR Academy of Sciences, 1986; D.Sc., Institute of Structural Macrokines, Russian Academy of Sciences, 1994. (1997)

Kenneth R. Olson, *Adjunct Professor of Biological Sciences (South Bend Center for Medical Education) and Concurrent Professor*. B.S., Univ. of Wisconsin-LaCrosse, 1969; M.S., Michigan State Univ., 1970; Ph.D., *ibid.*, 1972. (1975)

Agnes E. Ostafin, *Assistant Professor*. B.S., Wayne State Univ., 1989; Ph.D., Univ. of Minnesota, 1994. (1999)

Andre F. Palmer, *Assistant Professor*. B.S., Harvard Univ., 1995; Ph.D., The Johns Hopkins Univ., 1998. (2001)

Roger A. Schmitz, *the Keating-Crawford Professor of Chemical Engineering*. B.S., Univ. of Illinois, 1959; Ph.D., Univ. of Minnesota, 1962. (1979)

Mark A. Stadtherr, *Director of Graduate Studies and Professor*. B.Ch.E., Univ. of Minnesota, 1972; Ph.D., Univ. of Wisconsin, 1976. (1996)

William C. Strieder, *Professor*. B.S., Pennsylvania State Univ., 1959; Ph.D., Case Institute of Technology, 1963. (1966)

Arvind Varma, *Director of the Center for Molecularly Engineered Materials and the Arthur J. Schmitt Professor*. B.S., Punjab Univ., 1966; M.S., Univ. of New Brunswick, 1968; Ph.D., Univ. of Minnesota, 1972. (1975)

Eduardo E. Wolf, *Professor*. B.S., Univ. of Chile, 1969; M.S., Univ. of California, Davis, 1972; Ph.D., Univ. of California, Berkeley, 1975. (1975)

**Civil Engineering and Geological Sciences***Chair:*

Peter C. Burns

*Director of Graduate Studies:*

Yahya C. Kurama

Telephone: (574) 631-5380

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Location: 156 Fitzpatrick Hall

E-mail: cegeos@nd.edu

Web: <http://www.nd.edu/~cegeos>*The Program of Studies*

The graduate program in civil engineering and geological sciences provides an interdisciplinary atmosphere conducive to preparation of qualified candidates for careers in structural/geotechnical engineering, environmental engineering, bioengineering, and geological sciences.

Advanced study in civil engineering and geological sciences includes research and professional specialization in the following fields: biological treatment of hazardous wastes; earthquake/wind/offshore engineering; environmental chemistry; groundwater hydrology; hydraulics and water resources; structural mechanics and design; structural reliability; mantle petrology and planetary differentiation; sedimentology; environmental mineralogy; paleontology; low-temperature geochemistry; and biogeochemistry.

Many synergies exist among the respective research programs: structural engineers and geotechnical engineers, water chemists and geochemists, groundwater hydrologists, and hydrogeologists all work together to develop unique new insights in their respective research endeavors. Moreover, the department's analytical strength is complemented by the Center for Environmental Science and Technology, which involves faculty from seven science and engineering departments in basic scientific research in pollution control.

The department is home to the Environmental Molecular Science Institute, which institute blends the environmental science and engineering expertise and facilities of the University with those at Argonne, Sandia, and Oak Ridge National Laboratories. The scientific mission of the institute is to determine the effects of nano- and micro-particles (e.g., bacteria, natural organic matter, and mineral aggregates) on heavy metal and actinide transport in geologic systems. Students in the institute experience a highly interdisciplinary

research environment and are encouraged to participate in the internship program, which enables graduate students to conduct research with our national laboratory and industry partners.

The bioengineering program integrates principles of engineering, microbiology, chemistry, and biochemistry to address problems of fermentation engineering, biological treatment of hazardous wastes, and naturally induced genetic changes in mixed culture systems. An emphasis of study is the use of forcing functions to select for appropriate population distributions in industrial and municipal treatment facilities.

The environmental engineering program emphasizes water chemistry, hydrology, water supply, wastewater treatment, and water pollution control. Research topics include numerical modeling in surface and subsurface hydrology, experimental methods in surface and subsurface hydrology, and development of water and wastewater systems appropriate for rural U.S. areas and developing countries.

The structural/geotechnical engineering program provides a modern, progressive curriculum that emphasizes theory and application along with classical and modern numerical solution procedures. Areas of research emphasis include civil infrastructure development, wind/offshore/earthquake engineering, structural design, structural behavior, soil-structure interaction, soil dynamics, and material characterization and durability. Course offerings represent a cooperative interdisciplinary effort among the Departments of Aerospace and Mechanical Engineering, Electrical Engineering, and Civil Engineering and Geological Sciences.

The geological sciences program integrates classical geology with an interdisciplinary view of global evolution and the environment. Research topics include planetary differentiation, mantle petrology, biogeochemistry, environmental geochemistry and mineralogy, analytical geochemistry, and mass extinctions. Students are encouraged to explore related courses in other departments in order to foster interdisciplinary thinking in their research and beyond.

The programs of study offered by the department lead to the master of science degree and the doctor of philosophy degree. The department requires a minimum cumulative grade point average of 3.0 for graduation from its degree programs.

Although both research and nonresearch options are available to students seeking the master's degree, the research option is the preferred and normal route. The nonresearch option is allowed only in exceptional circumstances. In the research option, 30 credit hours are required with six to 12 of these credits devoted to thesis research, depending on the program of study developed in conjunction with the department. The research option requires a completed thesis and an oral defense of that thesis. The master's research is commonly completed by the end of the fourth semester of enrollment.

Requirements for the doctor of philosophy degree include approximately one academic year of course work (24 credits) beyond the master's degree, approximately one year of doctoral research, and successful completion of the candidacy and dissertation examinations.

Programs of study and research are arranged to suit the specific background and interests of the individual student, with guidance and approval of the faculty of the department and in conformity with the general requirements of the Graduate School.

Regardless of funding source, all students participate in the educational mission of the department by serving as teaching assistants for eight hours per week during their first year, four hours per week during their second year, and four hours per week during one additional semester.

Students in all the graduate programs are encouraged to include courses from other departments and colleges within the University to expand their understanding of today's complex technological-social-economic problems. In the past, students have shown particular interest in extradepartmental courses in biological sciences, chemical engineering, chemistry, economics, electrical engineering, mathematics, and mechanical engineering.

Admission to graduate study in civil engineering and geological sciences is not limited to undergraduate majors in civil engineering and/or geology. Those with undergraduate majors in other fields of engineering or the physical sciences are encouraged to apply.

Financial aid is available to qualified candidates in the form of tuition scholarships and competitive stipends. Additional fellowships are available for students from underrepresented groups.

### *Course Descriptions*

Each course listing includes:

- Course Number
- Title
- (Lecture hours per week–laboratory or tutorial hours per week–credits per semester)
- Instructor
- Course Description

### *Civil Engineering*

#### *525. Advanced Geostatistics*

(3-0-3) Silliman

*Prerequisite:* CE 331 or consent of instructor.

Introduction to modern geostatistical techniques, including principal component analysis, factor analysis, kriging, and 3-D simulation. The focus is on application to field data and analysis. Substantial computer programming required. (Every other year)

#### *530. Environmental Chemistry*

(3-0-3) Maurice

*Prerequisite:* Consent of instructor.

Applications of acid-base, solubility, complex formation, and oxidation reduction equilibria to water supply, wastewater treatment, and natural environmental systems. (Fall)

#### *531. Introduction to Bioengineering*

(3-0-3)

*Prerequisite:* Consent of instructor.

Biological systems, including those involved in the fermentation industry and biological wastewater treatment, are discussed. An introduction to microbiology and biochemistry is provided. (Fall)

#### *534. Design of Biological Waste Treatment Systems*

(3-0-3)

*Prerequisite:* CE 531 or consent of instructor.

In-depth discussion of biological waste treatment. Review of pilot and full-scale treatment systems from bench scale studies for both domestic and industrial wastes. Heavy emphasis on literature reviews, designs, and discussions. (Alternate spring)

#### *539. Advanced Hydraulics*

(3-0-3) Westerink

Application of the basic principles of fluid mechanics. Study of laminar flow, turbulent flow, and dispersion processes with emphasis on conduit and open channel flow. (Fall)

#### *544. Advanced Groundwater*

(3-0-3) Silliman

*Prerequisite:* CE 444 or consent of instructor.

The equations of flow and transport are derived for porous media and fractured rocks.

Additional topics include well test analysis, advanced transport theory, and state-of-the-art field methods. (Fall)

*550. Advanced Control Systems*

(3-0-3) Staff

*Prerequisite:* EE 337.

The application of techniques such as the phase-plane method, Lyapunov method, vector-format method, the z-transform method, and statistical methods to the design of control systems.

*554. Analytical Mechanics*

(3-0-3) Staff

*Prerequisite:* ME 356.

Introduction to advanced methods in analytical mechanics. A study of nonholonomic systems, stability of motion, and variation principles in classical and continuum mechanics.

*557. Continuum Mechanics*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Tensor analysis, general kinematics, equilibrium conditions and thermodynamics of continuous media, constitutive equations. Extensions and applications in the theory of elasticity, fluid dynamics, thermoelasticity, viscoelasticity, and thermoviscoelasticity.

*558. Elasticity*

(3-0-3) Staff

The fundamental theories and techniques in elasticity are covered. Variational methods and complex variable techniques are included, and applications are demonstrated by selected problems.

*559. Advanced Mechanics of Solids*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

Advanced topics in mechanics of solids including elasticity, torsion, stability, energy principles, and inelastic materials.

*560. Finite Elements in Structural Mechanics*

(3-0-3) Kirkner

*Prerequisite:* CE 356 or consent of instructor.

Finite-element methods for static and dynamic analysis of structural and continuum systems. Analysis of two- and three-dimensional solids as well as plates and shells. Introduction to nonlinear analysis.

*563. Finite Elements in Engineering*

(3-0-3) Westerink

*Prerequisite:* CE 441 or consent of instructor.

Fundamental aspects of the finite-element method are developed and applied to the

solution of PDEs encountered in science and engineering. Solution strategies for parabolic, elliptic, and hyperbolic equations are explored. (Spring)

*569. Structural Dynamics*

(3-0-3) Kirkner

*Prerequisite:* Consent of instructor.

Vibration of single-degree, multi-degree, and continuous linear viscoelastic systems. Dynamic analysis of structural systems in both frequency and time-domain. Also study of nonlinear and nonclassical damped systems with applications to earthquake/wind engineering. (Fall)

*571. Structural Reliability and Probabilistic Bases of Design*

(3-0-3) Staff

*Prerequisite:* CE 331 or consent of instructor. Identification and modeling of nondeterministic problems in the context of engineering design and decision making; stochastic concepts and simulation models. (Fall)

*573. Environmental Engineering Design*

(3-0-3) Ketchum

*Prerequisite:* Consent of instructor.

Application of physical, chemical, and biological unit operations and processes to the functional designs of municipal water pollution control facilities. (Fall)

*576. Design of Structures to Resist Natural Hazards*

(3-0-3) Kareem

*Prerequisite:* CE 486 or consent of instructor. Natural hazards and associated load effects on structures. Analysis of damage caused by wind storms, earthquakes, and ocean waves. Design provisions to resist damage from natural hazards. (Spring)

*581. Experimental Methods in Structural Dynamics*

(3-0-3) Staff

*Prerequisite:* CE 569 or consent of instructor. Experimental methods in the behavior of structures under dynamic loading. Principles of vibration measurement and digital signal processing. Modal analysis, system identification, and control. (Alternate spring)

*598. Special Studies*

(V-V-V) Staff

Individual or small-group study under the direction of a faculty member in a graduate subject not concurrently covered by any University course.

*598B. Behavior and Design of Building Structural Systems*

(V-V-V) Staff

Behavior and design of gravity load and lateral load-resisting systems. Force distribution and elastic drift calculations. Development of ductile structures for seismic-resistant design. Moment frames, braced frames, wall systems, hybrid structures. Introduction to tall building concepts.

*598C. Environmental and Technological Aspects of Minerals*

(3-0-3) Burns

*Prerequisite:* Consent of instructor.

This course explores the chemistry and structures of minerals with emphasis on environmental and technological issues. Topics of environmental significance include the disposal of spent nuclear fuel, contamination of soils with heavy metals, and the remediation of mine tailings. Emphasis will be on the mineralogy of uranium, lead, mercury, iodine, selenium, and tellurium. Technological aspects of minerals, such as the use of zeolites and clay minerals as molecular sieves and as waste containment vessels, will be addressed.

*598D. Advanced Structural Stability*

(V-V-V) Staff

Development of classical elastic stability relationships. Inelastic buckling, torsional buckling, and load-deflection behavior of thin-walled metal members. Frame stability. Development of design equations.

*598E. Advanced Topics in Reinforced Concrete Design*

(V-V-V) Kurama

Behavior of reinforced concrete structures under earthquakes. Seismic design and detailing of RC structures. Nonlinear-elastic modeling and analysis of RC structures. Seismic evaluation and retrofit of existing structures.

*598J. Multiphase Flow/Porous Media*

(3-0-3) Staff

Thermodynamically Constrained Averaging Theory Approach to multiphase flow in porous media is developed. Averaged conservation equations are developed that model phases, interfaces, and common lines in multiphase flow. Closure conditions are developed using the constrained entropy inequality.

*599. Thesis Direction*

(V-V-V) Staff

Research to satisfy the six credit hours required for the research master's degree.

**600. Nonresident Thesis Research**

(0-0-1) Staff

Required of nonresident graduate students who are completing their theses in absentia and who wish to retain their degree status.

**661. Random Vibration of Mechanical and Structural Systems**

(3-0-3) Staff

*Prerequisite:* CE 569 or consent of instructor. Random vibration analysis of linear and nonlinear systems. Analytical and simulation methods are used to determine system performance and reliability. Applications are emphasized. (Alternate spring)

**663. Advanced Finite-Element Methods in Structural Mechanics**

(3-0-3) Kirkner

*Prerequisite:* CE 563 or equivalent.

Finite-element methods for static and dynamic analysis of structural and continuum systems. Displacement approach for two- and three-dimensional solids along with beams, plates, and shells. Material and geometric nonlinearities.

**669. Earthquake Engineering**

(3-0-3) Staff

*Prerequisite:* CE 569 or consent of instructor. Analysis of structures and other constructed facilities under earthquake loads. Modeling of earthquake-induced ground motion and seismic design input. Principles of earthquake resistant design. (Alternate spring)

**671. Wind Engineering**

(3-0-3) Kareem

*Prerequisite:* CE 569 or consent of instructor. Analysis of structural response due to wind loading. Modeling of wind-induced forces. Principles of design to resist damage due to high wind loads. (Alternate fall)

**680. Civil Engineering Graduate Seminar**

(V-V-V) Staff

Presentation of technical papers, topics of current research interest, research methodology, professional ethics, and registration.

**698. Special Studies**

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by the department.

**699. Research and Dissertation**

(V-V-V) Staff

Research and dissertation for resident doctoral students.

**700. Nonresident Dissertation Research**

(0-0-1) Staff

Required of nonresident graduate students who are completing their dissertations in absentia and who wish to retain their degree status.

**Upper-level Undergraduate Courses**

In addition to the CE courses listed above, the following courses offered within the department for advanced undergraduates may be taken for graduate credit (to a total of 10 credit hours).

441. *Numerical Methods in Engineering*442. *Water Distribution and Wastewater Collection*443. *Wastewater Disposal*444. *Groundwater Hydrology*445. *Introduction to Geotechnical Engineering*452. *Introduction to Water Chemistry and Treatment*453. *Waste Disposal Management*466. *Structural Steel Design*470. *Construction Management*486. *Reinforced Concrete Design***Geological Sciences**503. *Geochemistry*

(3-0-3) Fein

*Prerequisites:* GEOS 347 and CHEM 321 or consent of instructor.

An introduction to chemical processes in igneous, metamorphic, sedimentary, and aqueous systems. Topics include thermodynamics, kinetics, organic and environmental geochemistry, and geomicrobiology.

519. *Surface and Subsurface Geophysics*

(3-0-3) Staff

*Prerequisite:* GEOS 458 or equivalent.

Study of seismic waves, magnetic and electromagnetic probes, and gravitational and heat flow quantization. Special attention is given to exploration with shear waves, heat flow due to climatic fluctuations, and induced polarization for detection of contaminated soils.

528. *CP Analytical Techniques*

(2.5-0-3) Jain

Students are introduced to the analytical techniques of inductively coupled plasma-mass spectroscopy (ICP-MS) and -atomic emission spectrometry (ICP-AES). The first half of the course covers the theory of ICP-MS and ICP-AES as well as specialized sample introduction techniques. Three weeks are spent in the lab learning machine tuning/setup techniques, ICP-MS and ICP-AES software, and sample preparation/calibration protocols. The last third of the course is spent conducting independent projects. Graduate students are strongly advised to make this project related

to their research and senior undergraduates are encouraged to choose a project which will help in the workplace or in graduate school.

542. *Surficial Processes*

(2-3-3) Staff

*Prerequisite:* GEOS 342 or consent of instructor.

A quantitative study of natural chemical and physical processes (e.g., weathering) that produce both erosional and depositional landforms. One-day field trip is required.

545. *Microbes in Fluid-Rock Systems*

(3-0-3) Fein

*Prerequisite:* CE 430/530, GEOS 403/503, or equivalent.

This course explores current research involving the interaction between microbes and geologic systems, focusing on the ability of microbes to affect mass transport in fluid-rock systems. Readings concentrate on laboratory, field, and modeling studies of environmental and/or geologic interest.

547. *Geodynamics*

(3-0-3) Staff

*Prerequisite:* Consent of instructor.

This course applies continuum physics to geological problems, beginning with plate tectonics, progressing into the study of stress and strain in geologic strata from earth processes. Large-scale problems (frictional heating on faults, flow through volcanic pipes, mantle convection) are examined by applying principles from heat transfer, faulting, and fluid mechanics.

562. *ICP-MS Analytical Techniques*

(2-1-3) Neal

*Prerequisite:* Consent of instructor.

Introduction to the analytical technique of inductively coupled plasma-mass spectrometry (ICP-MS). The first half of the course covers the theory of ICP-MS as well as specialized sample introduction techniques. Three weeks are spent in the lab learning machine tuning/setup techniques, ICP-MS software, and sample preparation/calibration protocols. The last third of the course is spent conducting independent projects. Graduate students are strongly advised to relate this project to their research.

568. *Environmental Isotope Chemistry*

(3-0-3) Neal

*Prerequisite:* Consent of instructor.

The course focuses on radioactive and stable isotopes, both natural and manmade, in the environment. Specific topics include: age dating, identification of geological reservoirs, and radioactive waste disposal.

598. *Special Studies*

(V-V-V) Staff

Individual or small-group study under the direction of a faculty member in a graduate subject not concurrently covered by any University course.

598C. *Environmental and Technological Aspects of Minerals*

(3-0-3) Burns

*Prerequisite:* Consent of instructor.

This course explores the chemistry and structures of minerals with emphasis on environmental and technological issues. Topics of environmental significance include the disposal of spent nuclear fuel, contamination of soils with heavy metals, and the remediation of mine tailings. Emphasis will be on the mineralogy of uranium, lead, mercury, iodine, selenium, and tellurium. Technological aspects of minerals, such as the use of zeolites and clay minerals as molecular sieves and as waste containment vessels, will be addressed.

599. *Thesis Direction*

(V-V-V) Staff

Research to satisfy the six credit hours required for a research master's degree.

600. *Nonresident Thesis Research*

(0-0-1) Staff

Required of nonresident graduate students who are completing their theses in absentia and who wish to retain their degree status.

634. *Paleoecology*

(3-0-3) Rigby

*Prerequisite:* GEOS 459 or equivalent.

This course covers pre- and postmortem ecology of ancient organisms, their depositional environments, behavior, and relationship to environmental conditions as interpreted from the rock record.

635. *High-Temperature Geochemistry*

(3-0-3) Neal

*Prerequisite:* CHEM 321, GEOS 403/503, or equivalent.

Study of magma generations and evolution from a geochemical and thermodynamic standpoint. Recognition of igneous processes will result in the formulation of petrogenetic models using actual data sets. These models will be tested using thermodynamic approaches.

698. *Special Studies*

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by the department.

699. *Research and Dissertation*

(V-V-V) Staff

Research and dissertation for resident doctoral students.

700. *Nonresident Dissertation Research*

(0-0-1) Staff

Required of nonresident graduate students who are completing their dissertations in absentia and who wish to retain their degree status.

*Upper-level Undergraduate Courses*

In addition to the geological sciences courses listed above, the following courses offered within the department for advanced undergraduates may be taken for graduate credit (to a total of 10 credit hours).

454. *Marine Geology*458. *Geophysics*459. *Paleontology**Faculty*

Peter C. Burns, *Chair and the Henry J. Massman Jr. Professor of Civil Engineering and Geological Sciences*. B.Sc., Univ. of New Brunswick, 1988; M.Sc., Univ. of Western Ontario, 1990; Ph.D., Univ. of Manitoba, 1994. (1997)

Jeremy B. Fein, *Director of the Environmental Molecular Science Institute and Associate Professor*. B.A., Univ. of Chicago, 1983; M.Sc., Northwestern Univ., 1986; Ph.D., *ibid.*, 1989. (1996)

Robert L. Irvine, *Professor Emeritus*. B.S., Tufts Univ., 1964; M.S., *ibid.*, 1965; Ph.D., Rice Univ., 1969. (1974)

Ahsan Kareem, Ph.D., *the Robert M. Moran Professor of Civil Engineering and Geological Sciences*. B.S., W. Pakistan Univ. of Engineering and Technology, 1968; M.S., Univ. of Hawaii, 1975; Ph.D., Colorado State Univ., 1978. (1990)

Sydney Kelsey, *Professor Emeritus*. B.Sc., Univ. of Leeds, 1946. (1967)

Lloyd H. Ketchum Jr., *Associate Professor and Fellow of the Helen Kellogg Institute for International Studies*. B.S.C.E., Michigan State Univ., 1960; M.S.E., Univ. of Michigan, 1964; M.Ph., *ibid.*, 1964; Ph.D., *ibid.*, 1972. (1973)

Tracy Kijewski-Correa, *the Rooney Family Assistant Professor*. B.S., Univ. of Notre Dame, 1997; M.S., *ibid.*, 2000; Ph.D. *ibid.*, 2003. (2003)

David J. Kirkner, *Associate Professor*. B.S., Youngstown State Univ., 1971; Ph.D., Case Western Reserve Univ., 1979. (1979)

Yahya C. Kurama, *Director of Graduate Studies and Associate Professor*. B.S., Bogazinci Univ., 1990; M.S., Lehigh Univ., 1993; Ph.D., *ibid.*, 1997. (1998)

Kenneth R. Lauer, *Professor Emeritus*. B.S., Univ. of Alberta, 1947; M.Sc., *ibid.*, 1948; M.C.E., Cornell Univ., 1952; Ph.D., Purdue Univ., 1960. (1956)

Jerry J. Marley, *Associate Professor Emeritus*. B.S., Univ. of Notre Dame, 1957; M.S., Iowa State Univ., 1962; Ph.D., *ibid.*, 1969. (1969)

Patricia A. Maurice, *Director of the Center for Environmental Science and Technology and Professor*. B.A., Johns Hopkins, 1982; M.S., Dartmouth, 1985; Ph.D., Stanford, 1994. (2000)

Clive R. Neal, *Associate Professor*. B.Sc., Univ. of Leicester, 1982; Ph.D., Univ. of Leeds, 1985. (1990)

Robert Nerenberg, *Assistant Professor*. M.S., Wayne State Univ., 1992; Ph.D., Northwestern Univ., 2003. (2003)

J. Keith Rigby Jr., *Associate Professor*. B.S., Brigham Young Univ., 1971; M.Phil., Columbia Univ., 1974; Ph.D., *ibid.*, 1976. (1982)

Rev. James A. Rigert, C.S.C., *Associate Professor Emeritus*. B.S., Univ. of Portland, 1957; M.S., Cornell Univ., 1960; Ph.D., Univ. of Illinois, 1971; Ph.D., Texas A&M Univ., 1980. (1973)

Stephen E. Silliman, *Professor and Fellow of the Center for Social Concerns*. B.S.E., Princeton Univ., 1979; M.S., Univ. of Arizona, 1981; Ph.D., *ibid.*, 1986. (1986)

Jeffrey W. Talley, *Assistant Professor*. B.S.F., Louisiana State Univ., 1981; M.A., Assumption College, 1985; M.L.A., Washington Univ. in St. Louis, 1988; M.S.E., Johns Hopkins Univ., 1995; Ph.D., Carnegie Mellon Univ., 2000. (2001)

James I. Taylor, *Professor Emeritus*. B.S.C.E., Case Institute of Technology, 1956; M.S.C.E., *ibid.*, 1962; Ph.D., Ohio State Univ., 1965. (1976)

Joannes J. Westerink, *Associate Professor*. B.S., State Univ. of New York, 1979; M.S., *ibid.*, 1981; Ph.D., Massachusetts Institute of Technology, 1984. (1990)

Jennifer R. Woertz, *Assistant Professor*. B.S., Univ. of Illinois, 1996; M.S., Univ. of Texas, 1998; Ph.D.; Univ. of Texas, 2003. (2003)

## Computer Science and Engineering

### Chair:

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### Director of Graduate Studies:

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### The Program of Studies

The graduate program in the Department of Computer Science and Engineering covers the major disciplines of computer science and computer engineering. The program is designed to prepare students for careers in these high technology areas, including university teaching and research as well as industrial or governmental research and advanced development.

To achieve this goal, the department offers programs of study and research leading to the degrees of master of science in computer science and engineering and the doctor of philosophy. Current research emphasizes six distinct areas: computing systems in emergent technologies, algorithms and the theory of computation, prototyping computationally demanding applications, systems and networks software, e-technology, and computer vision and pattern recognition. New investigative thrusts highlighting nontraditional and interdisciplinary projects, such as bioinformatics and cognitive science are in the planning stages.

Some graduate students are admitted to the master's program. This program requires a minimum of 24 credit hours of course work beyond the bachelor's degree and a master's thesis. A full-time student can complete these requirements in three regular academic semesters plus the summer, although the majority of students take four semesters. The student must, upon the acceptance of the thesis, successfully pass an oral thesis defense examination.

Those students who show potential for the doctoral level work may be admitted to the Ph.D. program directly but are expected to complete the master's degree requirements first. Students who complete the master's program may also apply for admission to the doctoral program during their final semester of master's work. Doctoral students are normally required to accumulate a minimum of

36 credit hours of satisfactory course work beyond the bachelor's degree, plus a dissertation.

The doctoral program normally requires four years of full-time work. The requirements include successful completion of the Ph.D. qualifying and candidacy examinations, a dissertation, and the oral dissertation defense examination. Students are encouraged to pursue course work outside the department whenever such studies support their program in the major field.

The Ph.D. qualifying examination is written and is normally taken in the second spring semester after entering the program with a bachelor's degree. Those admitted with a master's degree are required to take the Ph.D. qualifying examination the first spring after entering the program. The Ph.D. candidacy requirement, which consists of a written and an oral part, is administered to determine if the student has identified a viable dissertation topic. The candidacy consists of a written topic proposal followed by an oral examination. After passing the Ph.D. candidacy, which typically takes place after the completion of the formal course work, the student devotes essentially all efforts to completing his or her dissertation research. At the dissertation defense, the student defends the dissertation before an oral examining board. In recent years, students have completed the Ph.D. degree requirements in about four to five years.

Finally, both M.S. and Ph.D. candidates are required to complete a teaching apprenticeship that involves teaching duties of one semester for M.S. candidates and two semesters for Ph.D. candidates.

### Research Facilities

Notre Dame's College of Engineering maintains a cluster of 99 Sun Microsystems Inc. UltraSPARC 30 workstations with 3D graphics display capability. The cluster also contains 15 iMacs, several Dell Optiplex GXPRO 180 workstations, six Hewlett-Packard 5SiMX laser printers, and a Hewlett-Packard 4500N color printer, which are available to students and researchers.

The University's computing center supports AFS file service with 20 UltraSPARC Enterprise file servers. These file servers provide over four Terabytes of RAID (0+1) mirrored/striped file storage space for the campus community. The computing center also supports a cluster of IBM RS/6000s, a 16-processor IBM SP-1, an eight-processor IBM SP-2

array and two Silicon Graphics computer/servers. The campus is currently connected to the VbNS Internet-II back-bone via a 155 million bit-per-second connection.

In addition to the cluster sponsored by the College of Engineering, the department maintains a 32-node, 64 processor Sun UltraSPARC array, three eight-node UltraSPARC 1 arrays, a 10-node 20-CPU Linux cluster, a two node 4 processor IBM SP-2 array, and three Compaq NT file servers. The department also provides 85 UltraSPARC workstations, 25 Windows workstations, 25 Linux systems, and 12 Apple Macintosh G3/G4 systems. A research ATM network, a research Myrinet gigabit network, a wireless 802.11 network, a scanner, color printer, 20 laser printers, and a large-bed plotter are also available to students.

The System and Network Administration lab contains two Compaq DL380 NT file servers, each containing 50 GB of RAID disk storage, a Sun UltraSPARC 60 file server, eight Compaq Windows 2000 workstations and eight Sun UltraSPARC 5 workstations. In addition, the lab contains a Cisco 4500 router, two Cisco 2924 Ethernet switches, an IBM 8285 ATM network, an IBM 8271 ATM to Ethernet bridge, a Hewlett Packard Internet Advisor network analysis system, and various other pieces of network equipment.

The Artificial Intelligence and Robotics laboratory currently hosts five robots, one ActivMedia Pioneer Peoplebot, three ActivMedia Pioneer P2Dxe robots, and one Arrick Robotics Trilobot. All ActivMedia robots have an onboard Linux PC, Sony pan-tilt-zoom cameras and are equipped with wireless Ethernet links. They are operated using AGES, a distributed agent development environment under development in the lab. Additional computing equipment comprises four Dell Linux PC desktops, one Dell laptop, and one SUN UltraSPARC workstation.

Additional equipment is available by individual research group to support specific research projects. Specialized laboratories that include this equipment are the Distributed Computer Lab, the Laboratory of Computational Life Sciences, the Lab for VLSI, the Robotics Lab, and the Computer Vision Research Lab.

A specialized College of Engineering research library holds more than 50,000 volumes. The Engineering Library augments the University's Theodore M. Hesburgh Library, which contains more than three million volumes

and receives 625 journals related to engineering. The Hesburgh Library also provides database searches and bibliographic instruction.

### Course Descriptions

Each course listing includes:

- Course number
- Title
- (Lecture hours per week—laboratory or tutorial hours per week—credits per semester)
- Instructor
- Course description
- (Semester normally offered)

#### 511. *Complexity and Algorithms*

(3-0-3) Chen

A study of theoretical foundations of computer science and a selection of important algorithm techniques. Topics include the classes of P and NP, the theory of NP-completeness, linear programming, advanced graph algorithms, parallel algorithms, approximation algorithms, and randomized algorithms. (Spring)

#### 513. *Numerical Methods and Computation*

(3-0-3) Izaguirre

Introduction to analysis and implementation of numerical methods for scientific computation. Topics include computer arithmetic, solution of linear and nonlinear equations, approximation, numerical integration and differentiation, numerical solution of ordinary and partial differential equations, and applications of all of these. (Fall)

#### 521. *Computer Architecture*

(3-0-3) Uhran

Classic computer architectures are considered along with standard parameters for their evaluation. Characteristics that improve performance are introduced. Various forms of parallel processing with specific implementation examples are given. More recent architectural approaches to improve performance are discussed, such as RISC, Fault Tolerance, and others. (Spring)

#### 531. *Programming Languages*

(3-0-3) Kogge

An introduction to modern programming concepts and computational models as embodied in a number of different classes of languages. These include (1) function-based languages such as Lisp, Scheme, SASL, ML; (2) logic-based languages such as Prolog, Parlog, Strand, OPS; and (3) object-oriented languages such as Smalltalk and C++. (Fall, even-numbered years)

#### 532. *Software Engineering*

(3-0-3) Schaelicke

A comprehensive course about the methodologies required to control the complexity involved in the development of large software systems. Students are given the opportunity to practically apply software engineering techniques taught in this course through several medium-sized programming problems and one large-scale development project. Emphasis is on the use of requirements and prototyping for design and software reliability, reuse, and development management. (Fall, odd-numbered years)

#### 533. *Object-Oriented Computing*

(3-0-3) Staff

Introduction to object-oriented computing and its application. Topics include: abstract data types, encapsulation, inheritance, classes and instances, C++ programming language, object implementation technologies, and example systems. (Spring, odd-numbered years)

#### 542. *Operating System Design*

(3-0-3) Chandra, Striegel

Computer operating system design for resource management, communication, and security in a multiprogramming environment. Students will create modules for an existing operating system. (Fall)

#### 554. *Computer Communication Networks*

(3-0-3) Staff

The analysis of computer communication protocols. The course focuses on existing communications protocols; local area networks; routing; queuing analysis; congestion control mechanisms; analysis of high-level applications. (Spring, odd-numbered years)

#### 562. *VLSI Computer Design*

(3-0-3) Brockman

CMOS devices and circuits, scaling and design rules, floor planning, data and control flow, synchronization and timing. Individual design projects. (Fall)

#### 566. *Computer Graphics*

(3-0-3) Flynn

Two-and-three dimensional geometric algorithms and transformations; curve and surface representation; visible surface determination; illumination and shading; advanced modeling; animation; generation and sensing of light. (Spring)

#### 571. *Artificial Intelligence*

(3-0-3) Scheutz, Madey, Flynn

This course is intended as a base for further study in the fields encompassed by artificial intelligence. The focus is on representations, strategies, and mathematical formulation with some applications. (Fall, odd-numbered years)

#### 597. *Directed Readings*

(V-V-V) Staff

Topics will vary from semester to semester and will be announced in advance. Possible topics might include: computer-aided design, numerical analysis and computation, distributed computing, computational geometry, special VLSI architectures, and others of interest to students and faculty.

#### 598. *Special Studies*

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by department. (Offered if necessary)

#### 598E. *Introduction to E-Technology*

(3-0-3) Madey

Introduction to concepts, theories and techniques of Internet and WWW programming. The goal of this course is to prepare the student to design and develop Web-based applications, e-Commerce applications, e-Science applications and Internet-based services. Students will be expected to design a large system (course project) requiring integration with other student projects.

#### 598F. *Behavior-Based Robotics*

(3-0-3) Scheutz

This course is designed to provide a forum for applying and testing artificial intelligence methods and models, especially behavior-based techniques, on a robot. While models will be evaluated with respect to their theoretical tenability, most emphasis will be given to issues of practicality. These practical considerations will be extensively studied in simulations as well as real-world implementations on a variety of robots. Implementations might also comprise new ideas, hopefully giving rise to original research results.

#### 598M. *Digital Systems Testing*

(3-0-3) Michael

A comprehensive and detailed treatment of digital systems testing and testable design. Fundamental concepts as well as the latest advances and challenges in the field of ULSI/VLIS testing are examined. Topics covered include fault modeling and simulation, combinational and sequential circuit

test generation, memory and delay test, and design-for-testability methods such as scan and built-in self-test. Testing of embedded cores in systems-on-chip environments is also considered. A major outcome of this course is the analysis, design, and implementation of CAD tools that give solutions to test-related problems.

*598N. Computer Networks*

(3-0-3) Chandra

Course projects will be chosen allowing the opportunity to explore research ideas of interest with a goal to produce conference-quality publications. Good research potential is preferred over a system that just works. Projects will be evaluated on the demonstration of the lessons learned as well as the coherent presentation of the results. A public mini-symposium will be organized at the end of the semester with groups presenting their experiences.

*598Q. Computer Vision*

(3-0-3) Flynn

Course is designed to give broad coverage of computer vision fundamentals and in-depth coverage of the research literature in a topic of interest to the student. Lectures introducing the fundamentals of each topic area will be followed by discussions.

*598U. Computer Security*

(3-0-3) Striegel

This course is a survey of topics in realm of computer security. This course will introduce the students to many contemporary topics in computer security ranging from PKI's (Public Key Infrastructures) to cyber-warfare to security ethics. Students will learn fundamental concepts of security that can be applied to many; traditional aspects of computer programming and computer systems design. The course will culminate in a research project where the student will have an opportunity to more fully investigate a topic related to the course.

*598V. CAD of Digital Systems*

(3-0-3) Hu

This is a senior/entry graduate level course intended to expose students to the fundamentals of CAD tools for the design and analysis of digital systems. With the most advanced CAD tools it is possible to design Systems On a Chip (SOCs) featuring more than 100 million gates with device feature sizes of  $\sim 0.18\ \mu\text{m}$ . However, these tools are not "push-button" tools. In order to obtain optimum results it is crucial for a designer to understand

the underlying algorithms. The course aims at introducing to students the theory and implementation behind commercial CAD tools so that they will be able to contribute to the development of such tools as well as be productive users of such tools. The main topics include basic algorithms for CAD, digital system modeling, timing and power analysis, logic/architectural synthesis, physical level design, and system-level design.

*599. Thesis Direction*

(V-V-V) Staff

Research to satisfy the six credit hours required for the master's degree. (Every semester)

*600. Nonresident Thesis Research*

(0-0-1) Staff

Required of nonresident master's degree students who are completing their theses in absentia and who wish to retain their degree status. (Every semester)

*611. Parallel Algorithms*

(3-0-3) Chen

Introduction to parallel computational models (e.g., PRAM, fine-grain networks, and coarse-grain networks); relationship and simulation between different models. Parallel algorithm techniques and their implementation in various models for sorting, searching, message routing, data structures, graph problems, geometric problems, the FFT and matrix operations. Layout techniques and their relationship to VLSI layout systems. Lower bound results on communication complexity. Inherently sequential problems and P-completeness. (Spring, odd-numbered years)

*643. Principles of Parallel Computing*

(3-0-3) Schaelicke

A comprehensive study of the fundamentals and research frontiers of parallel computing. Topics include new computing paradigm of shared-memory, distributed-memory, data-parallel and data-flow models; techniques to improve parallelism, scheduling theory, algorithms for parallel machines, and interconnection networks. (Fall, odd-numbered years)

*644. Distributed Systems*

(3-0-3) Chandra

Study of recent trends in the design of distributed operating systems. It examines the role of network operating systems as distinct from distributed operating systems communication, interprocess communication issues, and questions of synchronization. Distributed

naming, process management, and migration and resource allocation are also covered. Communication and security are reviewed and important experimental systems are explored. (Spring, even-numbered years)

*655. Specialized Parallel Architectures*

(3-0-3) Staff

A comprehensive study of the fundamental issues and recent developments of designing parallel and pipelined array processors and control/data path in the algorithmic and architectural levels. Topics include methodologies of mapping algorithms onto processor arrays, partitioning, scheduling, resource binding, algorithm transformations, and fault tolerance. (Fall, even-numbered years)

*697. Directed Readings*

(V-V-V) Staff

Topics will vary from semester to semester and will be announced in advance. Possible topics might include: computer-aided design, numerical analysis and computation, distributed computing, computational geometry, special VLSI architectures, and others of interest to students and faculty.

*698. Special Studies*

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by department. (Offered if necessary)

*698E. Advanced Embedded Systems Design*

(3-0-3) Hu

This is an advanced graduate level course intended to expose students to the state-of-the-art design and analysis techniques for embedded systems. The main topics include system modeling, performance and power/energy analysis and estimation, system-level partitioning, synthesis and interfacing, co-simulation and emulation, and re-configurable computing platforms.

*699. Research and Dissertation*

(V-V-V) Staff

Research and dissertation for resident doctoral students. (Every semester)

*700. Nonresident Dissertation Research*

(0-0-1) Staff

Required of nonresident doctoral students who are completing their dissertations in absentia and who wish to retain their degree status. (Every semester)

### Upper-level Undergraduate Courses

The following undergraduate courses, described in the *Bulletin of Information, Undergraduate Programs*, may be taken for graduate credit:

- 411. Automata
- 413. Algorithms
- 422. Computer System Design
- 439. Computer Simulation
- 443. Compilers
- 444. Introduction to System Administration
- 456. Data Networks
- 458. Network Management
- 471. Introduction to Artificial Intelligence
- 472. Introduction to Neural Networks

### Faculty

Panos J. Antsaklis, *Director of the Center for Applied Mathematics, the H. C. and E. A. Brosey Professor of Electrical Engineering, and Concurrent Professor of Computer Science and Engineering*. Dipl., National Technical Univ. of Athens, 1972; M.S., Brown Univ., 1974; Ph.D., *ibid.*, 1977. (1980)

Kevin W. Bowyer, *Chair, the Schubmehl-Prein Professor, and Concurrent Professor of Electrical Engineering*. B.S., George Mason Univ., 1976; Ph.D., Duke Univ., 1980. (2001)

Jay B. Brockman, *Associate Professor and Concurrent Associate Professor of Electrical Engineering*. Sc.B., Brown Univ., 1982; M.S.E.E., Carnegie Mellon Univ., 1988; Ph.D., *ibid.*, 1992. (1992)

Ramzi K. Bualuan, *Associate Professional Specialist*. B.S.E.E., American Univ. Beirut, 1983; M.S., Univ. of Notre Dame, 1985. (1993)

Surendar Chandra, *Assistant Professor*. B.E., Anna Univ., Madras, 1988; M.S., Worcester Polytechnic Institute, 1993; Ph.D., Duke Univ., 2000. (2002)

Danny Z. Chen, *Professor*. B.S., Univ. San Francisco, 1985; M.S., Purdue Univ., 1988; Ph.D., *ibid.*, 1992. (1992)

Patrick J. Flynn, *Associate Professor*. B.S.E.C.E., Michigan State Univ., 1985; M.S.C.S., *ibid.*, 1986; Ph.D., *ibid.*, 1990. (2001)

Joseph C. Freeland, *Associate Professional Specialist*. B.S.E., Purdue Univ., 1985. (1995)

Eugene W. Henry, *Professor Emeritus*. B.S.E.E., Univ. Notre Dame, 1954; M.S.E.E., *ibid.*, 1955; Ph.D., Stanford Univ., 1960. (1960)

Xiaobo (Sharon) Hu, *Associate Professor*. B.S., Tianjin Univ., 1982; M.S., Polytechnic Institute New York, 1984; Ph.D., Purdue Univ., 1989. (1996)

Yih-Fang Huang, *Chair and Professor of Electrical Engineering and Concurrent Professor of Computer Science and Engineering*. B.S.E.E., National Taiwan Univ., 1976; M.S.E.E., Univ. of Notre Dame, 1980; M.A., Princeton Univ., 1981; Ph.D., *ibid.*, 1982. (2003)

Jesús A. Izaguirre, *Assistant Professor*. B.A., ITESM-Mexico, 1991; M.S., Univ. of Illinois Urbana-Champaign, 1996; Ph.D., *ibid.*, 1999. (1999)

Meneloas Karavelas, *Assistant Professor*. Dipl., National Technical Univ. of Athens, 1995; M.S., Stanford Univ., 1997; Ph.D., *ibid.*, 2001. (2003)

Peter M. Kogge, *the Ted H. McCourtney Professor*. B.S., Univ. of Notre Dame, 1968; M.S., Syracuse Univ., 1970; Ph.D., Stanford Univ., 1973. (1994)

Gregory R. Madey, *Director of Graduate Studies, Professional Specialist, and Concurrent Associate Professor*. B.S., Cleveland State Univ., 1974; M.S., *ibid.*, 1975; M.S., Case Western Reserve Univ., 1979; Ph.D., *ibid.*, 1984. (2000)

Maria K. Michael, *Visiting Assistant Professor*. B.S., Southern Illinois Univ., 1996; M.S., *ibid.*, 1998; Ph.D., *ibid.*, 2002. (2002)

Lambert Schaelicke, *Assistant Professor*. Dipl., Tech. Univ. Berlin, 1995; Ph.D., Univ. Utah, 2001. (2001)

Matthias Scheutz, *Assistant Professor*. M.A., Univ. of Vienna, 1989; M.S., *ibid.*, 1993; M.S.E.E., Vienna Univ. of Technology, 1993; Ph.D., Univ. Vienna, 1995; M.S., Indiana Univ., 1996; Ph.D., *ibid.*, 1999. (1999)

Robert Stevenson, *Professor of Electrical Engineering and Concurrent Professor of Computer Science and Engineering*. B.E.E.E., Univ. Delaware, 1986; Ph.D., Purdue Univ., 1990. (2003)

Aaron Striegel, *Assistant Professor*. B.S., Iowa State Univ., 1998; Ph.D., *ibid.*, 2002. (2003)

John J. Uhran Jr., *Senior Associate Dean for Academic Affairs in the College of Engineering, Professor of Computer Science and Engineering, and Professor of Electrical Engineering*. B.S., Manhattan College, 1957; M.S., Purdue Univ., 1963; Ph.D., *ibid.*, 1966. (1966)

## Electrical Engineering

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### The Program of Studies

The department offers programs leading to the M.S. and Ph.D. degrees in electrical engineering. Research areas include communications systems; control systems; signal and image processing; solid-state nanoelectronics, microwave electronics, optoelectronic materials and devices, and ultrahigh-speed and microwave-integrated circuits.

A research M.S. degree requires a total of 30 credit hours beyond the B.S., with at least 6 credit hours coming from thesis research. A research M.S. also requires the completion and defense of an M.S. thesis. A nonresearch M.S. degree requires 30 credit hours of course work. All students must take a written qualifying examination at the end of their second semester of graduate study; successful completion of the exam is required to receive an M.S. degree and to continue to the Ph.D. program. Doctoral students must accumulate a minimum of 36 course credits beyond the B.S. degree, pass the qualifying and candidacy examinations at the Ph.D. level, spend at least two years in resident study, and write and defend a Ph.D. dissertation.

### Research Areas

*Electronic Circuits and Systems.* Approximately half of the faculty members have research interests in this area, which includes systems and control, signal and image processing, and communications. Projects are conducted in the following areas: turbo coding and iterative decoding; bandwidth efficient coding and modulation; radio architecture and codes for deep space and satellite communications; multimedia communication-combined source and channel coding and restoration techniques for robust transmission of video/audio; statistical signal processing-array signal processing (radar, sonar) and adaptive interference mitigation in wireless communications; identification and estimation-blind identification, set membership estimation, adaptive equalization, and spectral analysis;

digital filtering-analysis and design of multi-dimensional filters, floating point realizations, robust stability of discrete-time systems, and nonlinear discrete-time systems; digital image processing-data compression for image sequences, video data processing, tomographic image reconstruction, and image restoration/enhancement; control systems-investigations of stability, robust control, restructurable control, zero dynamics, modeling, and nonlinear servomechanism design; control of communication networks; autonomous control systems-theoretical developments for realization of control systems with enhanced operational capabilities; hybrid and discrete event systems; and large-scale dynamic systems-qualitative properties of large-scale dynamical systems addressing Lyapunov stability, input-output properties, and decomposition problems.

*Electronic Materials and Devices.* The other half of the faculty members have research interests in this area, which includes solid-state, nanoelectronics, and optoelectronic materials and devices. Current research projects include quantum device phenomena-optical properties, localization, universal conductance fluctuations, transport, interference, and resonant tunneling; nanoelectronic systems-novel circuits-and-systems architectures for the nanoelectronic regime; experimental nanoelectronics-nanofabrication of quantum dots, cryogenic characterization of single-electron effects, and ultra-small resonant tunneling diodes for ultrahigh-speed digital ICs; nano-spectroscopy-high-spatial, spectral, and temporal resolution investigations of quantum dots via atomic force microscopy and near-field scanning optical microscopy; device degradation-studies of the electromigration behavior of ultrasmall metal interconnects and hot carrier effects in MOS oxide breakdown phenomena; optoelectronic materials-studies of the optical and material properties of compound semiconductor native oxides; optoelectronic devices-fabrication and characterization of waveguides and optical components for integrated photonic ICs, semiconductor lasers, and optical amplifiers; micromachining-fabrication of microelectromechanical devices utilizing Si processing, particularly reactive ion etching; and ultrahigh-speed circuits and devices for digital and microwave circuit applications.

#### *Research Facilities*

Several major research laboratories in the department support the study of electronic and photonic materials and devices and the

analysis and design of communication systems, control systems, and signal and image processing.

The Nanofabrication Facility allows fabrication of ICs and devices with geometries as small as 0.02 microns. The 3600-square-foot cleanroom contains a photomask generator, four contact mask aligners, a wafer stepper, nine furnace tubes, a plasma etcher, PECVD, APCVD, LPCVD, RIE, ICP Deep RIE, five evaporators, and a sputtering system. Inspection systems include an ISI SEM, Hitachi FESEM, a prism coupler, an interferometer, an ellipsometer, a variable-angle spectroscopic ellipsometer, two surface profilers, a four-point probe, and two Zeiss optical microscopes. A 50-kV SEM/EML system is available for nanolithography. Postprocessing equipment includes a wafer-dicing saw, and two wire bonders.

Advanced measurement facilities include low-temperature equipment such as a <sup>3</sup>He cryostat capable of 300 mK and magnetic fields of 11T and a dilution refrigerator capable of 10mK, with fields up to 11T. A UHV-STM with atomic resolution is available for sample characterizations, along with two AFMs.

The High-Speed Circuits and Devices Laboratory houses a state-of-the-art microwave and high-speed digital device and circuits characterization facility. Full on-wafer testing capability, including analog characterization to 50 GHz and digital testing to 12.5 Gb/s, allow for comprehensive characterization of both analog and digital high-speed microelectronic circuits. In addition, facilities for high-speed optoelectronic characterization of detectors and photoreceiver subsystems for fiber-optic telecommunications are available. State-of-the-art microwave CAD, data collection, and data analysis facilities are also in place for rapid circuit design and characterization. The Semiconductor Optics Lab includes a 15-watt Argon-ion laser, a tunablemode-locked Ti:sapphire laser delivering femtosecond pulses, an He-Cd laser, and He cryostats with high spatial resolution and magnetic fields up to 12 Tesla.

The Laboratory for Image and Signal Analysis (LISA) features a dozen state-of-the-art workstations for development and analysis of digital signal, image, and video processing algorithms; equipment for the acquisition, processing, and real-time display of HDTV sequences; cameras; frame grabbers; a flat-bed scanner; several high-definition, 24-bit color monitors; and specialized printers.

The Control Systems Research Laboratory contains several workstations networked to a set of dSpace miniboxes (microcontrollers) and a network of personal computers (PCs) running QNX (a real-time version of UNIX).

The Communication Systems Research Laboratory and the Wireless at Notre Dame (WAND) lab have a full complement of RF measurement equipment, wide-band digitizers, and connections to roof antennas as well as a full complement of supporting workstations.

The department has its own electronics shop run by a full-time technician, and the Solid-State Laboratories are overseen by a full-time professional specialist and a full-time technician. Another full-time professional specialist manages the department's undergraduate laboratories.

#### *Application*

GRE General Test scores, TOEFL scores for international students, two transcripts showing academic credits and degrees, letters of recommendation from 3 or 4 college faculty members and a statement of intent should be sent to the Graduate Admissions Office, University of Notre Dame, 502 Main Building, Notre Dame, Indiana 46556.

The GRE should be taken no later than January preceding the academic year of enrollment, particularly if financial aid is desired.

The application deadlines are November 1 for the spring semester and February 1 for fall admission.

#### *Course Descriptions*

Each course listing includes:

- Course number
- Title
- (Lecture hours per week—laboratory or tutorial hours per week—credits per semester)
- Instructor
- Course description
- (Semester normally offered)

#### *546, 546L. IC Fabrication and Laboratory (3-0-3) Snider*

This course introduces students to the principles of integrated circuit fabrication. Topics covered in the lectures include photolithography, impurity deposition and diffusion, oxidation, thin-film deposition, and dry etching, as well as advanced fabrication techniques such as chemical-mechanical polishing (CMP) and dual-damascene. In the

laboratory, students will apply these methods to fabricate a poly-silicon gate CMOS integrated circuit. The circuits fabricated, such as a sound chip playing the Notre Dame fight song, typically contain more than 5,000 transistors.

### 550. *Linear Systems*

(3-0-3) Bauer

*Prerequisite:* EE 354 or equivalent.

State variable descriptions of linear dynamical systems. Solution of state equations for continuous-time and discrete-time systems. Input-output descriptions: impulse response and transfer function. Controllability, observability, canonical forms, stability. Realizations of input-output descriptions. State feedback and state observers. Polynomial matrix and matrix fraction descriptions of linear, time-invariant systems. (Fall)

### 551. *Mathematical Programming*

(3-0-3) Antsaklis

Theory of constrained optimization complemented by comprehensive computing exercises. Linear programming and convexity. Simplex algorithm. Optimality conditions for nonlinear optimization. Convergence of algorithms. Interior point methods in linear programming. (Alternate spring)

### 553. *Advanced Digital Communications*

(3-0-3) Costello

*Prerequisite:* EE 563 or equivalent.

Review of the signal space approach to communication theory and the derivation of optimum receiver principles. Intersymbol interference and equalization. Modulation and coding for fading and wireless channels. Introduction to spread spectrum communication and digital cellular systems. (Spring)

### 555. *Multivariable Control*

(3-0-3) Lemmon

*Prerequisite:* EE 550 or equivalent.

This course studies the design of robust optimal controllers for linear continuous-time systems. Topics include: normal linear signal/system spaces, matrix fraction descriptions, internal stability, uncertain systems, robust stability, robust performance, SISO/MIMO loopshaping, linear fractional transformations and the generalized regulator problem, H<sub>2</sub>/H<sub>∞</sub> optimal control, algebraic Riccati equation, and balanced model reductions. (Spring)

### 556. *Fundamentals of Semiconductor Physics*

(3-0-3) Seabaugh

*Prerequisite:* EE 357, EE 476 or equivalent.

Treatment of the basic principles of solids. Topics include periodic structures, lattice waves, electron states, static and dynamic properties of solids, electron-electron interaction transport, and optical properties. (Fall)

### 558, 558L. *Microwave Circuit Design and Measurement*

(3-0-3) Fay

An introduction to microwave circuit design, analysis, and measurement techniques, with emphasis on computer-aided design and application to modern microwave communication and sensing systems. (Spring)

### 561. *Multi-Dimensional Signal Processing*

(3-0-3) Bauer

An introduction to the analysis and design of systems that process multidimensional signals. Emphasis is placed on the study of m-D digital filters and m-D signals. Specific topics include m-D sampling, m-D transforms, analysis and design of FIR and IIR m-D filters, stability, quantization effects, inverse problems, etc. (Alternate spring)

### 563. *Stochastic Processes*

(3-0-3) Laneman

*Prerequisites:* MATH 323 and EE 354.

This course provides a graduate-level introduction to probability, random variables, and distribution functions, including random sequences and probabilistic convergence. It also covers fundamental concepts of stochastic processes such as stationarity, second-order statistics, Gaussian processes, Markov processes, and linear system responses to stochastic processes. More advanced topics include abstract vector space concepts and the vector space of random variables, random sequence representations of random processes, and time averages and ergodicity. (Fall)

### 566. *Solid-State Devices*

(3-0-3) Snider

*Prerequisite:* EE 556 or equivalent.

In-depth analysis of electronic devices with an emphasis on both homojunction and hetero-junction devices. Operation of p-n junctions is analyzed, along with BJTs, MOSFETs, and hetero-junction devices such as HBTs and MODFETs. (Spring)

### 571. *Statistical Signal Processing*

(3-0-3) Huang

*Prerequisite:* EE 563 or equivalent.

This course covers essential statistical concepts for signal and image processing. The

topics include Bayesian estimation methods such as MMSE and MAP as well as MLE; optimality theory of estimation that includes concepts of sufficiency, consistency, and efficiency; Fisher's information; confidence intervals and basic hypothesis testing; classical Fourier-analysis based spectral analysis methods and modern eigen-decomposition based methods such as MUSIC and ESPRIT; interference suppression for emerging communication technologies such as wireless multiuser communications. (Spring)

### 576. *Microelectronic Materials*

(3-0-3) Kosel

*Prerequisite:* EE 486 or equivalent.

*Prerequisite:* 476 or equivalent introduction to electronic properties of materials. Principles of materials science applied to materials issues in fabrication, operation, and reliability of microelectronic devices. (Spring)

### 580. *Nonlinear Control Systems*

(3-0-3) Lemmon

*Prerequisite:* EE 450 or equivalent.

This course studies the analysis and design of nonlinear feedback control systems. Topics include: Lyapunov stability, Input-Output Stability of Perturbed Systems, Model-reference adaptive control, sliding mode control, Lyapunov redesign methods, back stepping, and feedback linearization. (Alternate fall)

### 581. *Digital Image Processing*

(3-0-3) Stevenson

*Prerequisite:* EE 563.

An introduction to the manipulation and analysis of digital images, intended as a foundation for research in such fields as visual communications, medical imaging, and image analysis. Specific topics include human visual effects, filtering, compression, restoration, and reconstruction. (Alternate fall)

### 587. *Quantum Mechanics for Electrical Engineers*

(3-0-3) Lent

The course focuses on those aspects of quantum theory that are of particular relevance to electrical engineering. It is intended to give seniors and first-year graduate students a working knowledge of quantum mechanics at a level sufficient to illuminate the operation of standard and advanced quantum devices. Topics include classical mechanics versus quantum mechanics, early quantum theory, Schrödinger formulation, time-dependent and time-independent Schrödinger equation, Dirac formulation, Bloch theorem, magnetic effects, open quantum systems, and density matrices.

*598. Special Studies*

(V-V-V) Staff

Individual or small-group study under the direction of a faculty member in a graduate subject not currently covered by any University course. (Fall and spring)

*598A. Modern Photonics*

(3-0-3) Hall

*Prerequisite:* EE 347, 556 or equivalent.

A hands-on overview of the important role of photons alongside electrons in modern electrical engineering. Photonics technologies studied include lasers, optical fibers, integrated optics, optoelectronic devices, and optical modulators. A survey of the properties of light, its interactions with matter, and techniques for generating, guiding, modulating and detecting coherent laser light.

*598E. Optical Characterization of**Nanostructures*

(3-0-3) Merz

*Prerequisites:* Undergraduate quantum mechanics, electricity and magnetism, and solid state physics. Graduate students of chemistry, engineering, materials science, and physics are welcome *with approval of the instructor*.

This course treats the optical characterization techniques that are employed to investigate the physical properties of modern semiconducting materials. A brief overview will first be given of the basic science and growth of these materials, and the theory for their optical characterization. A detailed description will then be provided of measurement techniques, illustrated by examples of the application of these techniques to current semiconductor research and technology. Emphasis will be given to the use of these techniques to investigate low dimensional nanostructures such as quantum wells, wires, and dots.

*598F. Analog Integrated Circuit Design*

(3-0-3) Seabaugh

This course covers bipolar and complementary metal oxide semiconductor (CMOS) amplifier design, including frequency response, noise, feedback, stability, and compensation. Operational amplifiers, bandgap reference circuits, oscillators, and phase lock loops are analyzed. Both analytic and SPICE circuit design methods are developed.

*598G. Robust Stability of Linear Systems*

(3-0-3) Bauer

*Prerequisite:* A good background in linear systems.

This course provides a graduate-level coverage of recent results in robust stability of dynamical systems under structured uncer-

tainties. Since the content is based on various recent publications, there is no textbook required. Topics will include stability of continuous and discrete domain polynomials, continuous and discrete state space systems, and time-variant/nonlinear systems. Fundamental tools such as the principle of argument and the Hermite-Biehler Theorem will be covered early in the course.

*598H. Instrumentation for Nanoelectronics*

(3-0-3) Orlov

*Prerequisite:* EE 342.

This lab course is intended to give students hands-on practice on measurements and applications of nanoelectronics devices combined with development and implementation of interfacing instrumentation. Single-Electron and Nanomagnetic devices are the primary subjects of the course.

*598I. Advanced Instrumentation and Measurement*

(3-0-3) Orlov

*Prerequisite:* EE 342.

This course covers the general information on instrumentation and measurements. It aims to give the broad introduction to electronic instrumentation as well as provide in depth coverage of modern instrumentation systems used in cutting-edge research and applications in microelectronics. Significant attention is paid to cover noise and interference reduction and signal conditioning. Various examples of practical applications are explained in detail.

*598X. Principles of Vacuum Systems for Microelectronics*

(1-0-1) Bernstein

*Prerequisite:* EE 446, EE 546 or consent of instructor.

Fundamentals of vacuum environments and systems for microelectronics applications. A survey of vacuum pumps, gauges, and practices will be presented.

*598Y. SEM and Nanofabrication*

(1-0-1) Bernstein

*Prerequisite:* EE 446, EE 546 or consent of instructor.

A short introduction to fundamentals of scanning electron microscopy and electron beam lithography. SEM fundamentals will be used to illustrate issues in nanofabrication by EBL.

*598Z. Advanced Nanolithography*

(1-0-1) Bernstein

*Prerequisite:* EE 446, EE 546 and EE 598X or consent of instructor.

A short introduction to the wide array of technologies used for performing lithography below 0.1 micron.

*599R. Thesis Direction*

(V-V-V) Staff

Research to satisfy the six credit hours required for the master's degree. (Fall and spring)

*600. Nonresident Thesis Research*

(0-0-1) Staff

Required of nonresident master's students who are completing their theses in absentia and who wish to retain their degree status. (Fall and spring)

*650. Advanced Linear Systems Design*

(3-0-3) Sain

*Prerequisite:* EE 550 or consent of instructor.

Applications of modern algebra to problems of complicated linear system design. Quotients and state variable design; freedom and system-matrix design; tensors and multilinear design. (Alternate fall)

*653. Information Theory*

(3-0-3) Costello

*Prerequisite:* EE 563 or equivalent.

A study of Shannon's measure of information to include: mutual information, entropy, and channel capacity; the noiseless source coding theorem; the noisy channel coding theorem; rate distortion theory and data compression; channel coding and random coding bounds. (Alternate fall)

*654. Coding Theory*

(3-0-3) Costello

*Prerequisite:* EE 563 or equivalent.

Error control coding techniques for digital transmission and storage systems. Linear block codes, cyclic codes, BCH codes, and Reed-Solomon codes. Syndrome decoding. Convolutional codes, maximum likelihood decoding, maximum a posteriori probability decoding, and sequential decoding. Block and trellis coded modulation. Low density parity check codes and turbo codes. Applications to computer memories, data networks, space and satellite transmission, data modems. (Alternate fall)

*655. Digital Control Systems*

(3-0-3) Antsaklis

*Prerequisite:* EE 455 and EE 550 or equivalent.

Analysis and design of discrete-time and sampled-data control systems. State space descriptions and transfer function descriptions using the z-transform. Control design using classical (root-locus, Bode, Nyquist), state space, and polynomial techniques. (Alternate spring)

665. *Control Systems Optimization*

(3-0-3) Sain

*Prerequisite:* EE 555 or consent of instructor. History of the Optimal Control Problem. Ideas of Jacobi, of Lagrange, of Hamilton, and of Pontryagin. Necessary conditions for solutions; sufficient conditions for solutions. Solution settings in terms of partial differential equations and in terms of two-point boundary value problems. Extensions to the case of competing control players. Introduction to the theory of dynamic games. Two-player, zero-sum games. Stochastic games. Game value as a random variable. Cumulants as a random variable description. Cumulant games. (Alternate fall)

675. *Stochastic Control Theory*

(3-0-3) Sain

*Prerequisite:* EE 555 or consent of instructor. Optimal control in the presence of process noise. Cost as a random variable. Minimizing average cost over many realizations of a process. Optimal control when the system will operate only a small number of times. Distribution of the cost. Description of stochastic cost by moments or by cumulants. Optimal stochastic control of cost cumulants. Application to the protection of buildings from earthquakes. (Alternate fall)

698. *Special Studies*

(V-V-V) Staff

This number is reserved for specialized and/or experimental graduate courses. Content, credit, and instructor will be announced by department. (Offered as necessary)

699. *Research and Dissertation*

(V-V-V) Staff

Research and dissertation for resident doctoral students. (Fall and spring)

700. *Nonresident Dissertation Research*

(0-0-1) Staff

Required of nonresident doctoral students who are completing their dissertations in absentia and who wish to retain their degree status. (Fall and spring)

*Upper-level Undergraduate Courses*

Up to six credits at the 400-499 level may be applied toward the M.S. degree, and up to twelve credits at the 400-499 level may be applied to the Ph.D. The following undergraduate courses, described in the *Bulletin of Information, Undergraduate Programs*, are available for graduate credit:

446. *IC Fabrication Laboratory*453. *Communication Systems*455. *Control Systems*456. *Data Networks*458. *Engineering Electromagnetics*464. *Introduction to Neural Networks*466. *Topics in Electronic Transport Theory*468. *Modern Photonics*471. *Digital Signal Processing*472. *Analysis of A-C Power Systems*476. *Electronic Properties of Materials*477. *Photovoltaics*486. *Analog Integrated Circuit Design*496. *Digital Integrated Circuits**Faculty*

Panos J. Antsaklis, *Director of the Center for Applied Mathematics, the H. C. and E. A. Brosey Professor of Electrical Engineering, and Concurrent Professor of Computer Science and Engineering*. Dipl., National Technical Univ. of Athens, 1972; Sc.M., Brown Univ., 1974; Ph.D., *ibid.*, 1977. (1980)

Peter H. Bauer, *Professor*. Diplom. Engineer in Electrical Engineering, Technische Universitaet Muenchen, 1984; Ph.D., Univ. of Miami, 1987. (1988)

Gary H. Bernstein, *Associate Chair and Professor*. B.S.E.E., Univ. of Connecticut, 1979; M.S.E.E., Purdue Univ., 1981; Ph.D., Arizona State Univ., 1987. (1988)

William B. Berry, *Professor Emeritus*. B.S.E.E., Univ. of Notre Dame, 1953; M.S.E.E., *ibid.*, 1957; Ph.D., Purdue Univ., 1963. (1964)

Kevin Bowyer, *Chair and the Schubmehl-Prein Professor of Computer Science and Engineering and Concurrent Professor of Electrical Engineering*. B.S., George Mason Univ., 1976; Ph.D., Duke Univ., 1980. (2001)

Jay B. Brockman, *Associate Professor of Computer Science and Engineering and Concurrent Associate Professor*. Sc.B., Brown Univ., 1982; M.S.E.E., Carnegie Mellon Univ., 1988; Ph.D., *ibid.*, 1992. (2002)

Oliver M. Collins, *Professor*. B.S., California Institute of Technology, 1986; M.S.E.E., *ibid.*, 1987; Ph.D., *ibid.*, 1989. (1995)

Daniel J. Costello, *the Leonard Bettex Professor of Electrical Engineering*. B.S.E.E., Seattle Univ., 1964; M.S.E.E., Univ. of Notre Dame, 1966; Ph.D., *ibid.*, 1969. (1985)

Patrick J. Fay, *Assistant Professor*. B.S.E.E., Univ. of Notre Dame, 1991; M.S.E.E., Univ. of Illinois at Urbana-Champaign, 1993; Ph.D., *ibid.*, 1996. (1997)

Thomas E. Fuja, *Director of Graduate Studies and Professor*. B.S.E.E., Univ. of Michigan, 1981; M.S.E.E., Cornell Univ., 1983; Ph.D., *ibid.*, 1987. (1998)

Martin Haenggi, *Assistant Professor*. Dipl. El.-Ing. ETH, ETH Zurich, 1995; Dipl. NDS ETH, *ibid.*, 1998; Ph.D., *ibid.*, 1999 (2000)

Douglas C. Hall, *Associate Professor*. B.S., Miami Univ., 1985; M.S., Univ. of Illinois at Urbana-Champaign, 1988; Ph.D., *ibid.*, 1991. (1994)

Yih-Fang Huang, *Chair and Professor of Electrical Engineering and Concurrent Professor of Computer Science and Engineering*. B.S.E.E., National Taiwan Univ., 1976; M.S.E.E., Univ. of Notre Dame, 1979; Ph.D., Princeton Univ., 1982. (1982)

Debdeep Jena, *Assistant Professor*. Ph.D., Univ. of California, Santa Barbara, 2002.

Thomas H. Kosel, *Associate Professor*. B.S., Univ. of California, 1967; M.S., *ibid.*, 1970; Ph.D., *ibid.*, 1975. (1978)

J. Nicholas Laneman, *Assistant Professor*. Ph.D., Massachusetts Institute of Technology, 2002. (2002)

Michael D. Lemmon, *Associate Professor*. B.S.E.E., Stanford Univ., 1979; M.S.E.E., Carnegie Mellon Univ., 1987; Ph.D., *ibid.*, 1990. (1990)

Craig S. Lent, *Professor*. A.B., Univ. of California, Berkeley, 1978; Ph.D., Univ. of Minnesota, 1984. (1986)

James L. Merz, *the Frank M. Freimann Professor of Electrical Engineering*. B.S., Univ. of Notre Dame, 1959; M.A., Harvard Univ., 1961; Ph.D., *ibid.*, 1967. (1994)

Anthony N. Michel, *the Frank M. Freimann Professor Emeritus of Engineering*. B.S.E.E., Marquette Univ., 1958; M.S., *ibid.*, 1964; Ph.D., *ibid.*, 1968; D.Sc., Tech. Univ., Graz, 1973. (1984)

Alexander Mintairov, *Research Associate Professor*. Ph.D., Ioffe Physical Technical Institute, Russia, 1987. (2003)

Alexei Orlov, *Research Associate Professor*. Ph.D., Russian Academy of Science, 1990.

John Ott, *Assistant Professional Specialist*. M.S.E.E., Univ. of Notre Dame, 1998.

Wolfgang Porod, *Director of the Center for Nano Science and Technology and the Frank M. Freimann Professor of Electrical Engineering*. M.S., Univ. of Graz, 1979; Ph.D., *ibid.*, 1981. (1986)

Joachim J. Rosenthal, *Professor of Mathematics and Concurrent Professor of Electrical Engineering*. Vordiplom, Univ. Basel, 1983; Diplom, *ibid.*, 1986; Ph.D., Arizona State Univ., 1990. (1990)

Michael K. Sain, *the Frank M. Freimann Professor of Electrical Engineering*. B.S., St. Louis Univ., 1959; M.S., *ibid.*, 1962; Ph.D., Univ. Illinois, 1965. (1965)

Ken D. Sauer, *Associate Professor*. B.S.E.E., Purdue Univ., 1984; M.S.E.E., *ibid.*, 1985; M.A., Princeton Univ., 1987; Ph.D., *ibid.*, 1989. (1989)

R. Michael Schafer, *Professional Specialist*. B.S.E.E., Univ. of Notre Dame, 1975; M.S.E.E., *ibid.*, 1977; Ph.D., *ibid.*, 1980. (1996)

Alan C. Seabaugh, *Professor*. B.S.E.E., Univ. of Virginia, 1977; M.S.E.E., *ibid.*, 1979; Ph.D., *ibid.*, 1985. (1999)

Gregory Snider, *Associate Professor*. B.S.E.E., California State Polytechnic Univ., 1983; M.S.E.E., Univ. of California, Santa Barbara, 1987; Ph.D., *ibid.*, 1991. (1994)

Robert L. Stevenson, *Professor of Electrical Engineering and Concurrent Professor of Computer Science and Engineering*. B.E.E., Univ. of Delaware, 1986; Ph.D., Purdue Univ., 1990. (1990)

Paulo Tabuada, *Assistant Professor*. Ph.D., Univ. Tecnica de Lisboa, Lisbon, Portugal, 2002. (2003)

John J. Uhran Jr., *Senior Associate Dean for Academic Affairs in the College of Engineering, Professor of Computer Science and Engineering, and Professor of Electrical Engineering*. B.S., Manhattan College, 1957; M.S., Purdue Univ., 1963; Ph.D., *ibid.*, 1966. (1966)

To be awarded both degrees, the candidate must complete a minimum of 99 credit hours, 75 in law and 24 in the engineering program. The engineering degree awarded will be the master of engineering with a concentration in one of the engineering disciplines offered in Notre Dame's Division of Engineering. The course work-only master's program requires the completion of 24 credit hours of engineering, mathematics, or science courses acceptable to the appropriate engineering department; six credit hours of appropriate law courses; and a master's examination. Courses for the M.Eng. will be chosen in consultation with an adviser in the student's engineering department. The recommended distribution of engineering courses in the Law School curriculum is one each semester during the first and third years of study and two each semester during the second year.

#### *Admission*

Admission to the program requires a separate application to each school. Admissions decisions will be made independently by the Law School and by the Graduate School.

Law School applications may be obtained from the Director of Admissions, P.O. Box 959, University of Notre Dame, Notre Dame, IN 46556-0959, telephone (574) 631-6626.

For further information about the engineering program, contact the Office of Graduate Admissions.

## **Engineering and Law Dual Degree Program**

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The dual degree program in engineering and law is designed for law students who are interested in pursuing careers in areas such as patent, environmental, telecommunications, or similar law specialties. To be eligible for the master of engineering degree, the candidate must also be a candidate for the juris doctor degree in the Notre Dame Law School. The master's of engineering program is not available as an individual degree program.