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 topics in engineering and the geological sciences.

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/prospects/geninfo.htm)

Aerospace and Mechanical Engineering

Chair:

Stephen M. Batill

Director of Graduate Studies:

John E. Renaud

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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, master of engineering in mechanical engineering, and 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 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 robotics 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, biocompatability, 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 and Biomolecular Engineering, and Computer Science and Engineering.

Mechanical Systems and Robotics 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 and Biomolecular 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 aero-elastic problems, flutter analysis under various flow conditions, analytical methods in aeroelasticity demonstrated by selected problems. (As needed)

521. Numerical Methods

(3-0-3) Paolucci, Powers
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. (Yearly)

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. (As needed)

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 other year)

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. (Every other year)

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: AME 302 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. (Every other year)

551. Advanced Vehicle Dynamics

(3-0-3) Nelson
Prerequisites: AME 444 or AME 302 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. (Every other year)

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. (As needed)

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. (Every other year)

554. Analytical Dynamics

(3-0-3) Skaar
Fundamental principles and analytical methods in dynamics with applications to machine design, robot analysis, and spacecraft control. (Yearly)

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 other year)

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. (Yearly)

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. (Every other year)

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)

598F. 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. (Yearly)

598I. 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 other year)

598J. 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 robtoic manipulators are considered with an emphasis on kinematic design and control. (As needed)

598M. Advanced Design Project
(V-V-V) Staff
Individual or small group product or system design project. (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)

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. (Every other year)

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. (Every other year)

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. (As needed)

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. (As needed)

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. (Yearly)

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. (As needed)

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. (As needed)

641. Spatial Kinematics
(3-0-3) Stanisic
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. (Every other year)

652. Mechanics of Irreversible Deformation
(3-0-3) Corona
Prerequisite: Consent of instructor. Introduction to inelastic deformation of solids. Basic concepts and applications of classical plasticity, viscoelasticity, and viscoplasticity. (As needed)

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. (As needed)

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. (Every other year)

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. (Every other year)

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. (As needed)

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, selected 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 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, *Associate 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 Emeritus.* 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)

Lisa A. Pruitt, *the Viola D. Hank Professor*. B.S., Univ. of Rhode Island, 1988; M.S., Brown Univ., 1990; Ph.D., ibid., 1993. (2004)

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 and Director of Graduate Studies.* 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, *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 and Biomolecular Engineering* (available from the department office).

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; microscale sensor arrays; 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 at the departmental website.

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) Wolf
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)

561. Structure of Solids
(3-0-3) McGinn
This class seeks to provide students with an understanding of the structure of solids, primarily as found in metals, alloys and ceramics applied in technological applications. The structure of crystalline solids on the atomic level as well as the microstructural level will be discussed. Imperfections in the arrangements of atoms will be described, especially as regards their impact on properties. The study of structure through X-ray diffraction will be a recurring theme. A sequence of powder diffraction laboratory experiments (4-5 class periods) will also be included.

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.

572. Topics-Ecology and Environment
(3-0-3) Stadtherr
Prerequisites: CBE 443, 445. This course covers various topics pertaining to Earth's natural (ecological and biogeochemical) systems and the effects of disturbances or imbalances, particularly those caused by human/industrial activities. Based on chemical engineering fundamentals embodied in chemical reaction engineering, process dynamics, and transport phenomena, the principal topics center on population and ecosystem dynamics, and on the fate and transport of chemicals in the environment. Examples and applications are drawn from such subjects as the endangerment or extinction of species, atmospheric greenhouse gases, pollutant dispersion, ozone pollution in the troposphere and depletion in the stratosphere, acid rain, and so on. The course makes extensive use of methods of mathematical modeling, nonlinear dynamics, and computer simulations. In major course assignments, students work in small groups on modeling/simulation projects.

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.

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.

598P. Biological Dynamics and Diagnostics
(3-0-3) Staff
This course will examine physiology phenomena such as cardiac rhythms, bacterial detection/diagnostics, neuron signal transmission, blood circulation, pulmonary airflow, and more general biological topics such as ion channels, actin motors, genomic sequences from the viewpoint of mathematical analysis. Explicit and implicit patterns and organized dynamics will be elucidated and used to provide insight into the underlying physiology or biology.

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, *Director of the Center for Molecularly Engineered Materials and 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 Macrokinetics, 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)

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

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Yahya C. Kurama

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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.

The programs of study offered by the department lead to the master of science degree and the doctor of philosophy. 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 include a total of 72 credit hours with at least 18 credit hours of formal course work, successful completion of a written qualifier examination, a research proposal, an oral candidacy examination, and completion and defense of a dissertation.

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
- Prerequisite
- 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)

532. Environmental Biotechnology
(3-0-3) Nerenberg
Prerequisite: CE 443 or consent of instructor. Environmental biotechnology is the application of biological processes to the solution of environmental problems. Applications include municipal and industrial wastewater treatment, drinking water treatment, remediation of soils and groundwaters, remediation of surface waters and sediments, and control of air contaminants. (Fall)

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)

541. Numerical Methods in Engineering
(3-0-3) Westerink
Prerequisite: MATH 325 or consent of instructor. Finite difference and finite element methods for the solution of ordinary and partial differential equations encountered in engineering. (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. (Spring)

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.

561. Structural Systems
(3-0-3) Kijewski-Correa
Prerequisite: CE 356 or consent of instructor. Overview of common structural systems used in design, with specific focus on the hierarchy of lateral load resisting systems. Course will also highlight innovative structural systems for high rise buildings, collapse mechanisms, and concepts of serviceability and habitability. Codes and commercial software common to practice will be heavily utilized.

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)

565. Foundations and Earth Structures
(3-0-3) Salvati
Prerequisites: CE 445, CE 351 or consent of instructor. The course will cover topics in foundation engineering, including earth pressure theories, design of retaining structures, bearing capacity, and the analysis and design of shallow and deep foundations. (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)

570. Behavior and Design of EQ Resistant Structures
(3-0-3) Kurama
Prerequisite: CE 569 or consent of instructor. Characteristics of earthquakes. Effect of earthquakes on structures. Response of linear-elastic structures under earthquakes. Response of nonlinear-inelastic structures under earthquakes. Behavior of structural members under seismic loading. Principles of earthquake resistant design. Aseismic design procedures: Code implementation. (Spring)

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)

574. Environmental Microbiology
(3-0-3) Woertz
Prerequisite: Consent of instructor. Fundamentals of microbiology as needed to understand environmental systems and microbial treatment processes. Emphasis will be placed on kinetics and energetics of microorganisms, fate of environmental pollutants, biotechnology applications, and laboratory techniques used to cultivate organisms and analyze biological systems. (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) Kijewski-Correa
Prerequisite: CE 569 or consent of instructor. Overview of experimental techniques for analyzing and modeling the behavior of structures under dynamic loads, including stochastic concepts and spectral/time-frequency transform techniques. Course includes vibration measurement through experiments, signal processing and system identification. Experimental modules on acceleration-based system identification, strain/displacement measurement, modal testing and remote data acquisition systems are provided. (Alternate spring)

585. Advanced Topics in Reinforced Concrete Design
(3-0-3) Kurama
Prerequisite: CE 486 or consent of instructor. Behavior of reinforced concrete structures under earthquakes. Seismic design and detailing of RC structures. Nonlinear-inelastic modeling and analysis of RC structures. Seismic evaluation and retrofit of existing structures. (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.

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.

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.

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

443. Wastewater Disposal
444. Groundwater Hydrology
445. Introduction to Geotechnical Engineering
446. Hydraulics
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: ENVG 347 and CHEM 321, or consent of instructor. An introduction to the use of chemical thermodynamics and chemical kinetics in modeling geochemical processes. Special emphasis is placed on water-rock interactions of environmental interest.

519. Surface and Subsurface Geophysics
(3-0-3) Staff
Prerequisite: ENVG 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. ICP Analytical Techniques
(2-1-3) 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
(3-0-3) Staff
Prerequisite: ENVG 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.

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.

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.

574. Water-Rock Interactions
(3-0-3) Maurice
Prerequisite: ENVG 423 or consent of instructor. Fundamental properties of mineral surfaces and of the mineral-water interface. Methods of surface and interface analysis. The electric double layer. Interface reactions including adsorption, mineral growth, and dissolution, photoredox phenomena, and controls on bacterial adhesion.

586. Geomicrobiology
(3-0-3) Fein
Prerequisite: ENVG 403, ENVG 503, or consent of instructor. 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.

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: ENVG 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 and ENVG 403 or ENVG 503, or consent of instructor. 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 graduate geological sciences courses listed above, the following courses offered within the department for advanced undergraduates may be taken for graduate credit (up to a total of 10 credit hours).

415. Environmental Impact of Resource Utilization
458. Geophysics
459. Paleontology
462. Environmental Mineralogy

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 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, *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.* 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., Bogazici 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)

Lynn Ann Salvati, *Clare Boothe Luce Assistant Professor*. B.S., Brown Univ., 1995; M.S., Univ. of California, Berkeley, 1996; Ph.D., ibid., 2002. (2002)

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)

Wilasa Vichit-Vadakan, *Clare Booth Luce Assistant Professor*. B.S., Cornell Univ., 1995; M.S., Massachusetts Institute of Technology, 1997; M.A., Princeton Univ., 1999; Ph.D., ibid., 2002. (2003)

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:

Kevin W. Bowyer

Director of Graduate Studies:

Gregory Madey

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The Program of Studies

Current research emphasizes several distinct areas: computing systems in emergent technologies, algorithms and the theory of computing, prototyping computationally demanding applications, systems and networks, e-technology, computer vision/pattern recognition and artificial intelligence.

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.

Students who show potential for the doctoral level work may be admitted to the Ph.D. program but are expected to complete the master's degree requirements first. The master's degree 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. Doctoral students are normally required to accumulate a minimum of 12 credit hours of satisfactory course work beyond the master'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 110 PC workstations running Windows and Linux, as well as a cluster of 20 Sun Microsystems Blade 1000 workstations with 3D graphics display capability. Also in the cluster are a multimedia laboratory containing Apple and PC systems with Video Recorders, Television tuners, scanners, digital still and video cameras, computer audio systems, and six Xerox line printers which are available to faculty, staff, and students. The College also maintains a teaching lab/classroom with Sun Microsystems Inc., and Linux desktop workstations.

The University's Office of Information Technology provides an AFS file service with 18 Sun UltraSparc fileservers. These fileservers provide over 5 Terabyte of RAID (0+1) mirrorred striped file storage for the campus community. In addition the OIT provides 9 Terabytes of file space as a CIFS filesystem via two Network Appliance File Servers.

The University's High Performance Computer Center provides a wide variety of computer nodes for use by the campus research community. The HPCC also contains several support systems which provide file space, and other services to the HPCC computer cluster systems. The hardware base of the HPCC includes:

Multi-processor Systems:

Eight Sun Enterprise 420R - 4 x 450 MHz processors, 4 GB RAM, 35 GB /scratch space,
Six - Sun V880 - 8 x 900 MHz Cu processors, 16 GB RAM
Sixteen - Sun UltraSparc Enterprise 2400 - 2 x 400 MHz processors, 512 MB RAM.

Beowulf Computer Clusters:

One - Sun Microsystems V60 Beowulf cluster - 128 node Dual 3.0Ghz Xeon CPU, 2Gb RAM.
One - Sun Microsystems Beowulf cluster with Myrinet - 16 Dual 3Ghz Opteron CPU 8GB RAM
One - IBM 1300 (x330) Linux Cluster, 32 Node 2 x 1.4 GHz Pentium III, and 1GB RAM.

The BoB cluster in Chemistry also reserves cycles for use by campus researchers. Bob is the 445th fastest computer in the world. BoB is built out of 106 commodity dual-processor desktop computers. Each computer has 2x 1.7 GHz Xeon processors, 1 GB RDRAM, 40 GB HD and a Gigabit Ethernet card.

The campus is connected to the VbNS Internet-II backbone via a Gigabit connection that is shared with several local industrial partners. Two hundred megabits of this connection is reserved to use for Notre Dame commodity and research traffic. The residence hall network (RESNET) has a separate 45 megabit OC-3 connection via a local service provider. All desktop network ports in the College of Engineering are provided by 10/100 megabit Ethernet switches, and the College is connected to the campus backbone network via dual Gigabit Ethernet connections.

The Department of Computer Science and Engineering maintains an 8-node 16-processor Sun Microsystems Inc., UltraSparc array, and over 100 Dual-CPU Beowulf computer nodes housed in five clusters. In addition, the department provides 85 UltraSparc workstations, 25 Windows workstations, 25 Linux systems and 12 Apple Macintosh G4/G5 systems. The department also contains a research Asynchronous Transfer Mode (ATM) network, a research Myrinet gigabit network, a scanner, color printer, 20 laser printers, and a large-bed plotter.

The System and Network Administration lab contains multiple HP Linux fileservers which provide a total of 2TB of RAID disk storage, a Sun Microsystems Inc., Blade 1000 fileserver, and 24 seats of Solaris, Linux, and Windows systems. The lab also contains a Cisco 4500 router, two Cisco 2924 Ethernet switches, several HP Procurve Gigabit Ethernet switches, , A HP Internet Advisor network analysis system, and various other pieces of network equipment. Software in the lab includes HP Network Node Manager, SNMP, Cisco IOS, Linux, Solaris, Windows (Xp, 2000, Server 2003). The servers in the lab provide access to Oracle, dB2, mysql, and Microsoft SQL databases, and associated web servers (Apache and IIS) to access the databases. This lab is used by several undergraduate courses and research projects within the department.

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, 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/VLSI 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 the 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 _ 0:18_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

Graduate students may also take one upper-level undergraduate course from the following list as credit toward their degree. Full descriptions of these courses are available in the *Bulletin of Information, Undergraduate Programs*.

411. Automata
413. Algorithms
422. Computer System Design
439. Computer Simulation
443. Compilers
444. Introduction to System Administration
456. Data Networks
458. Network Management
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, *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)

Peter M. Kogge, *the Ted H. McCourtney Professor of Computer Science and Engineering and Concurrent Professor of Electrical Engineering.* 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 L. 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)

Douglas Thain, *Assistant Professor*. M.S., Univ. of Wisconsin, 1999; Ph.D., ibid., 2004.

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

Chair:
Yih-Fang Huang

Director of Graduate Studies:
Thomas E. Fuja

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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, including combined source and channel coding and restoration techniques for robust transmission of video/audio; statistical signal processing, including 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 multidimensional 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; nanospectroscopy-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 algorithms.

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 3He 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)

502. Solid State Seminar

(1-0-1) Seabaugh
Prerequisite: Graduate standing. This course consists of lectures by faculty, senior graduate students, and visiting lecturers covering a broad range of topics in electronic materials, devices and circuits. Students read papers in preparation for the weekly talks and are given a comprehensive examination. (Spring)

532 . Advanced Instrumention and Measurement

(3-0-3) Orlov
Prerequisite: EE 342 or equivalent. This course provides a broad introduction to electronic instrumentation as well as an in-depth coverage of modern instrumentation systems used in research and applications. Significant attention is paid to noise, interference reduction, and signal conditioning. Practical applications are explained in detail. (Fall)

542. Analog Integrated Circuit Design

(3-0-3) Seabaugh
Prerequisite: EE 342 or equivalent. 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. (Spring)

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 polysilicon 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. (Fall)

548. Electromagnetic Theory
(3-0-3) Merz
Prerequisite: EE 358 or equivalent. Electromagnetic waves in dielectric and conductive media, guided waves, resonators, radiation, scattering, interference and diffraction. (Spring)

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
Constrained optimization with emphasis on linear optimization. Theory of optimization and convexity. Convergence of algorithms. Simplex and Interior point methods in linear programming. Applications of semi-definite programming. Linear Matrix Inequality (LMI) formulation of engineering problems. (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)

554. Communication Networks
(3-0-3) Haenggi
Review of OSI model and TCP/IP. Introduction to queueing systems and network calculus. Routing flow control, and media access. Traffic modeling. Packet radio networks. Design philosophy of wireless networking standards and protocols. Emerging wireless technologies. (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, H2/H-infinity optimal control, algebraic Riccati equation, and balanced model reductions. (Spring)

556. Fundamentals of Semiconductor Physics
(3-0-3) Seabaugh
Prerequisite: EE 357 or equivalent. An introduction to the physics of semiconductors including crystal structure, energy bands, carrier statistics, Fermi level, equilibrium and nonequilibrium phenomena, current flow, 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. (Fall)

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. Random Vectors, Detection, and Estimation
(3-0-3) Laneman
Prerequisites: Math 323 and EE 354. Fundamentals of probability, random variables, and detection and estimation theory for signal processing, communications, and control. Vector spaces of random variables. Bayesian and Neyman-Pearson hypothesis testing. Bayesian and nonrandom parameter estimation. Minimum-variance unbiased estimators and the Cramer-Rao bounds. (Fall)

565. Optimal Control
(3-0-3) Lemmon
Optimal control is concerned with the synthesis of feedback control laws that minimize some specified measure of control system performance. This course is a rigorous introduction to the theory of optimal control. The topics covered by this course include: calculus of variations, Pontryagins principle, dynamic programming, and other methods. (Fall)

566. Solid-State Devices
(3-0-3) Jena
Prerequisite: EE 556 or equivalent. In-depth analysis of electronic devices with an emphasis on both homojunction and heterojunction devices. Operation of p-n junctions is analyzed, along with BJTs, MOSFETs, and heterojunction devices such as HBTs and MODFETs. (Spring)

568. Photonics
(3-0-3) Hall
Prerequisites: introductory course in semiconductors such as EE 347, EE 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, optical signal processing, holography, optoelectronic devices and optical modulators. A survey of the properties of light, its interaction with matter, and techniques for generating, guiding, modulating and detecting coherent laser light. (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)

573. Random Processes, Detection, and Estimation
(3-0-3) Huang
Prerequisite: EE 563. Fundamentals of random processes, including characterization, convergence issues, covariance and power spectral density. Representations for stochastic processes using Karhunen-Loeve, Fourier, and sampling expansions. Detection and estimation from waveform observations. Advanced topics: linear prediction and spectral estimation; Wiener and Kalman filters. (Spring)

576. Microelectronic Materials
(3-0-3) Kosel
Prerequisite: EE 486 or equivalent. Principles of materials science applied to materials issues in fabrication, operation, and reliability of microelectronic devices. (Spring)

580. Nonlinear Control Systems
(3-0-3) Tabuada
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)

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)

603. Transmission Electron Microscopy
(3-0-3) Kosel
Introduction to transmission electron microscopy (TEM) applied to metals, ceramics and semiconductors. TEM optics, electron diffraction, image formation modes and mechanisms, specimen preparation and practical TEM operation. Analytical techniques for chemical analysis, including energy dispersive x-ray spectroscopy and electron energy loss spectroscopy. (Fall)

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
Co-rerequisite: 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) Fuja
Co-rerequisite: 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)

656. Advanced Semiconductor Physics
(3-0-3) Jena
Prerequisite: EE 566 or equivalent. Starting from electronic bandstructure, the course will cover topics such as electron-phonon interactions, charge scattering and transport, and optical properties of semiconductors. The effects of quantum confinement in nanoscale electronic and optical devices will be covered in detail. The course will bridge between physics and engineering; any of the physical concepts covered will be shown to be the basis of practical semiconductor devices. Students will be required to choose a topic of research, make presentations, and write term papers. (Fall)

660. Optical Characterization of Nanostructures
3-0-3 Merz
Prerequisites: EE 566, EE 587 or equivalent (or approval of 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 such as reflectance and modulation spectroscopy, photoluminescense, time-resolved spectroscopy, infrared absorption, Raman and Brillouin scattering. These fundamentals will be illustrated by examples in current semiconductor research and technology. Optical processes in semiconductors like inter- and intra-band absorption, impurity effects, electro-optical and polarization effects, excitons and their dynamics will be addressed. Emphasis will be given to the use of these techniques to investigate low dimensional nanostructures such as quantum wells, wires, and dots. (Spring)

663. Information and Complexity
(3-0-3) Collins
This course extends the techniques of Information Theory to the non-statistical world. It introduces the basic concepts of undecided ability, Kolmogorov complexity, and NP-Completeness and explains how these circumscribe the performance of communications, storage, and other signal processing systems. (Fall)

664. Wireless Communications
(3-0-3) Fuja
Prerequisite: EE 553. This course will address the physical layer of wireless communication channels. Topics will include: modeling of the wireless channel (e.g. propagation loss, fading), interference models and cell planning, multiple access, and modulation and equalization techniques, well-suited to wireless communications. Standards for cellular systems and wireless LANs will be used to motivate and illustrate. (Fall)

665. Noncooperative Optimal Control: Dynamic Games
(3-0-3) Sain
Prerequisite: EE 555 or consent of instructor.
Review of the history of optimal control: methods of Lagrange, Hamilton, Jacobi, and Bellman. Finite, zero-sum games. Comparison of differing controllers in the presence of different types of disturbances. Finite, nonzero-sum games. Design of controllers to meet different and multiple goals. Infinite games. Noncooperative optimal control of plants satisfying dynamical equations. Notions of saddle points, Nash equilibria, and Stackelberg or hierarchical methods. Worst-case control design. Relation to robust control techniques. (Fall)

666. Advanced Solid State Devices
(3-0-3) Snider
Prerequisite: EE 566. This course provides in-depth coverage of electronic devices, ranging from conventional devices to innovative devices. Topics include MOSFETs, resonant tunnel diodes, single-electron devices, power devices, and heterojunction devices. Particular attention is paid to recent developments in device research. (Spring)

673. Advanced Stochastic Processes
(3-0-3) Stevenson
Prerequisite: EE 573. Stochastic processes are found in probabilistic systems that evolve with time. This course introduces the fundamentals of stochastic processes and the application of stochastic theory to problems in engineering and science. Bernoulli processes, renewal theory, and Markov chains will be covered. (Spring)

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 ten 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:

453. Communication Systems
455. Control Systems
456. Data Networks
462. VLSI Circuit Design
464. Introduction to Neural Networks
466. Topics in Electronic Transport Theory
471. Digital and Digital Signal Processing
472. Analysis of A-C Power Systems
486. Digital and Analog Integrated Circuit Design

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 of Electrical Engineering.* 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, *Associate Professor.* B.S.E.E., Univ. of Notre Dame, 1991; M.Eng., 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; B.S.Comp.E., ibid., 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*. B.Tech, Indian Institute of Technology, Kanpur, 1998; Ph.D., Univ. of California, Santa Barbara, 2003. (2003)

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*. B.S.E.E., Washington Univ., St. Louis, 1995; B.S.C.S., ibid., 1995; S.M.E.E., Massachusetts Institute of Technology, 1997; Ph.D., ibid., 2002. (2002)

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

Craig S. Lent, *the Frank M. Freimann Professor of Electrical Engineering.* A.B., Univ. of California, Berkeley, 1978; Ph.D., Univ. of Minnesota, 1984. (1986)

Christine M. Maziar, *Vice President and Associate Provost of the University and Professor of Electrical Engineering*. B.S.E.E., Purdue Univ., 1981; M.S.E.E., ibid., 1984; Ph.D., ibid., 1986. (2004)

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*. B.S., Univ. Tecnica de Lisboa, Lisbon, Portugal, 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)

Grace Xing, *Assistant Professor*. B.S., Peking Univ., 1996; M.S.E.E., Lehigh Univ., 1998; Ph.D., Univ. of California, Santa Barbara, 2003. (2004)

Engineering and Law Dual Degree Program

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 have a B.S. in an A.B.E.T. accreditted engineering or computer science program and 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.

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 by telephone at (574) 631-7706 or by email at gradad.1@nd.edu.