Cornell University Announcements

Graduate Study in Engineering and Applied Science

Cornell University Announcements
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Graduate Study in Engineering and Applied Science

Cornell University
Ithaca, New York

Contents

The courses and curricula described in this Announcement, and the teaching personnel listed herein, are subject to change at any time by official action of Cornell University.

The Programs at Cornell

At Cornell, graduate study in engineering and applied science is conducted within the context of a large and diverse university with an international reputation. The faculty and facilities of the College of Engineering provide a foundation for graduate education in these areas, but the resources of the entire University are available to each graduate student in accordance with his or her particular needs and interests.

Individual graduate programs are organized according to fields of instruction. So, too, is this Announcement. In each of the following sections the advanced-degree programs of a particular field are described in terms of research and educational opportunities, the professors who are involved in them, and the facilities that are available—the kind of information that is often not found in course catalogs but is very important to individual students seeking the best place to pursue their particular course of study.

The degrees offered in each area include the research-oriented Master of Science (M.S.) and Doctor of Philosophy (Ph.D.) degrees and, in many cases, the professional Master of Engineering (M.Eng.) degree. Prospective students should understand the general nature of the programs leading to each of these advanced degrees, as well as the specific requirements.

In planning an M.S. or Ph.D. program, for example, the prospective student must first decide which graduate field offers the course work and research opportunities best suited to his or her plans and interests, since admission to the programs is determined by the faculty of the individual fields. The separation of graduate programs into fields is necessarily somewhat arbitrary; some areas of research are interdisciplinary in nature, and some of the fields draw on faculty members in related departments or areas. The M.S. or Ph.D. candidate also selects a special committee, headed by the professor who will supervise the student's work. The information in this booklet may be helpful in making the selections of field and major professor.

M.Eng. degrees are offered in a number of professional engineering fields: aerospace, agricultural, chemical, civil, electrical, materials, mechanical, and nuclear engineering; computer science; and operations research and industrial engineering. These degrees are described under the particular subject areas.

Additional information about degree requirements and admission procedures is included in the section on general information.

Aerospace Engineering

Aerospace engineering, traditionally concerned with the flight of aircraft, guided missiles, and space vehicles, is constantly expanding the frontiers of its technology and encountering new, often interdisciplinary, problems. The objective of graduate programs in aerospace engineering at Cornell is to educate selected engineering and science graduates for research and advanced development in this science and technology. About twenty students are currently enrolled in the graduate Field of Aerospace Engineering and in the Master of Engineering (Aerospace) program. Students who plan to work for the Ph.D. degree are encouraged to matriculate first in the M.Eng. program.

In the curriculum, emphasis is placed on the aerospace and associated sciences as well as on current design practice. Students are encouraged to take courses in physics, mathematics, chemistry, astronomy, and allied engineering subjects, as well as those offered by the Field of Aerospace Engineering, in order to strengthen their understanding of fundamentals.

Also of interest to aerospace engineering students are graduate courses offered by the closely related Field of Mechanical Engineering. The two fields conduct a joint weekly colloquium and a joint weekly research conference at which students and faculty members discuss their progress and the audience makes comments and suggestions. Graduate students find this conference particularly helpful in the early phases of their research. Direct contact between faculty members and students is emphasized, and students are also encouraged to interact with one another in solving research problems. The entire field operates as a research group, and a friendly, informal atmosphere prevails.

Facilities

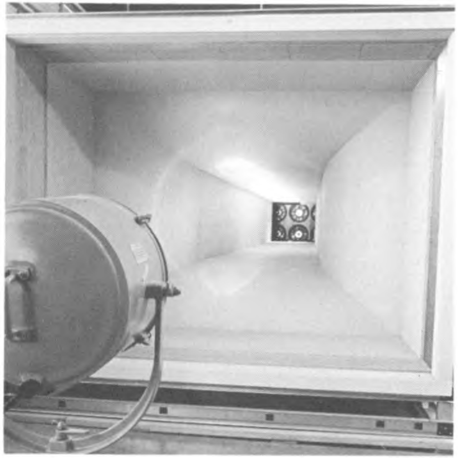
Experimental facilities are available for laboratory studies in basic fluid mechanics, aerodynamics, turbulence, gasdynamics, magnetohydrodynamics, plasmadynamics, combustion, laser chemistry, geophysical fluid dynamics, ferrofluidics, and general acoustics. The College of Engineering maintains a diversified machine shop to support sponsored research projects; equipment needed to facilitate original investigations can be fabricated.

The field has a long history of pioneering work in the development of the shock tube as a research tool for the study of chemical kinetics and electrically conducting gases and for supporting studies in fusion plasmadynamics and laser chemistry.

A facility recently constructed in cooperation with the College of Architecture, Art, and Planning is a wind tunnel for the study of peculiarities of flow around tall buildings. Other wind tunnels are being used for investigations of turbulence; of automobile, bicycle, airplane, and windmill models; and of collisionless plasmas.

Areas of Research

The Field of Aerospace Engineering maintains an emphasis on research in basic fluid



mechanics, aerodynamics, magnetohydrodynamics, turbulence, transonic flow, geophysical flow problems, and related aspects of studies in pollution control and atmospheric dynamics. Current projects include several involving aerodynamic noise associated with compressors, turbines, and helicopters. Also under way are sound propagation studies designed to find methods for controlling the noise of aircraft, particularly around airports.

Various fundamental and applied aerodynamic problems characterized by unsteady effects are subjects of another research project. Also, attempts are being made to understand, from the viewpoint of fluid mechanics, convection cells driven by radioactivity inside the earth and the moon, and their geophysical consequences. In other areas of research the possibilities of fusion power are being explored, and pollution control is being studied. The development of computing techniques, including both finite-element and finite-difference methods for the solution of fluid mechanical problems, is being actively pursued. As part of an interdisciplinary project on the injection molding process, the fluid motion and heat transfer of highly non-Newtonian polymer melts are being investigated.

Active research topics are indicated by the following examples of recent theses (listed with the name of the supervising professor) and publications. A more complete list of publications is available upon request.

Auer, P. L. 1976. Energy self-sufficiency. *Annual Review of Energy* 1:685.

Caughey, D. A., and Jameson, A. 1979. Numerical calculation of transonic potential flow about wing-body combinations. *AIAA Journal* 17:175.

Dulikravich, D. S. 1979. Numerical calculation of inviscid transonic flow through rotors and fans. Ph.D. thesis (D. A. Caughey).

George, A. R. 1978. Helicopter noise — state of the art. *Journal of Aircraft* 15:707.

George, A. R., and Kim, Y. N. 1979. High-altitude, long-range sonic boom propagation. *Journal of Aircraft* 9:637.

Homan, H. S. 1978. An experimental study of reciprocating internal combustion engines operated on hydrogen. Ph.D. thesis (P. C. T. de Boer).

Kilgore, T. R. 1978. The primordial nebula of Mars as suggested by a capture scheme involving gas drag. M.S. thesis (D. A. Caughey).

Kim, Y. N. 1979. High frequency broadband rotor noise. Ph.D. thesis (A. R. George).

Leibovich, S. 1978. The structure of vortex breakdown. *Annual Review of Fluid Mechanics* 10:221.

Lottey, J. M. 1980. The turbulent transport of atmospheric aerosols. M.S. thesis (J. L. Lumley).

Lumley, J. L. 1977. The return to isotropy of homogeneous turbulence. *Journal of Fluid Mechanics* 82:161.

———. 1980. Second order modeling of turbulent flows. In *Prediction methods for turbulent flows,* ed. W. Kollman, p. 1. Washington, D.C.: Hemisphere Publishing Corp.

Matalon, M. 1977. Diffusion flames in a chamber for large activation energy. Ph.D. thesis (G. S. S. Ludford).

Mengle, V. G. 1979. Non-synchronous whirling in axial turbomachinery rotors due to fluid-dynamic excitation. M.S. thesis (S.-F. Shen).

Morjaria, M. A. 1978. Finite element methods of Newtonian and non-Newtonian creeping flows. M.S. thesis (S.-F. Shen).

Nordmann, J. C. 1980. Two problems pertaining to the dynamics of the origin of the moon, and its subsequent orbital evolution. Ph.D. thesis (D. L. Turcotte).

Obikane, Y. 1979. Turbulence modeling in homogeneous flows: determination of the rapid terms. Ph.D. thesis (J. L. Lumley).

Shen, S.-F. 1977. Finite element methods in fluid mechanics. *Annual Review of Fluid Mechanics* 9:421.

Shen, S.-F. 1978. Unsteady separation according to the boundary layer equations. *Advances in Applied Mechanics* 18:177.

Shepherd, D. G. 1978. Wind power. In

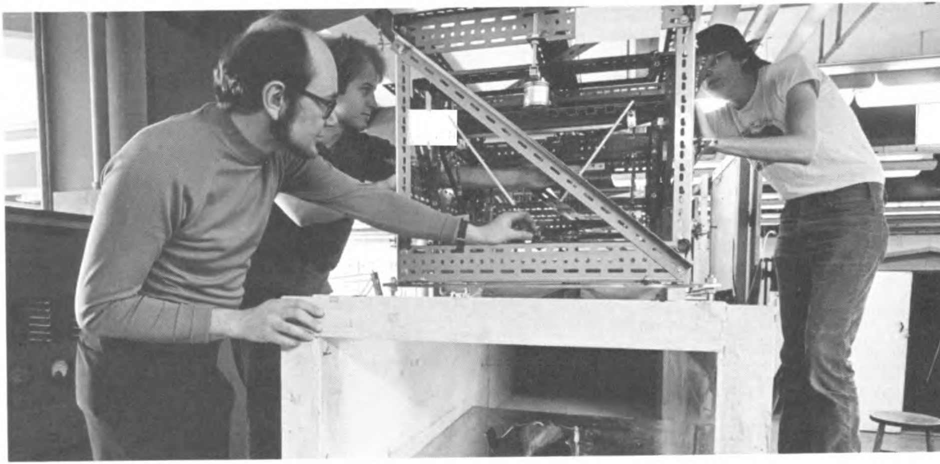
Advances in energy systems and technology, vol. 1, ed. P. L. Auer, p. 1. New York: Academic Press.
Smith, K. O., and Gouldin, F. C. 1979. Turbulence Effects on Flame Speed and Flame Structure. Paper 79–0016, read at 17th AIAA Aerospace Sciences Meeting, January 15–17, 1979, New Orleans, Louisiana.
Theocleous, I. C. 1978. Incompressible unsteady pressure distribution on an airfoil in moving gusts. M.S. thesis (A. R. George).
Upadhyay, R. K. 1978. Slow viscous flow in a channel with sharp corners. M.S. thesis (S.-F. Shen).
Wadia, A. R. 1978. The finite element technique for transonic flows with shocks. M.S. thesis (S.-F. Shen).
Warhaft, Z., and Lumley, J. L. 1978. An experimental study of the decay of temperature fluctuations in grid-generated turbulence. *Journal of Fluid Mechanics* 88:659.

M.Eng.(Aerospace) Degree Program

The Master of Engineering (Aerospace) program is designed to increase the student's facility in the application of the basic sciences to engineering problems of importance in this field. Because aerospace engineering is continually engaged in new areas, an essential guideline for the program is to reach beyond present-day practices and techniques; this is achieved by supplying the student with the fundamental background and the analytical techniques that will remain useful in all modern engineering developments.

The program is intended primarily for baccalaureate degree holders who are interested in extending their education in the aerospace field. Candidates for the Ph.D. program in this area who do not already hold a master's degree are also encouraged to matriculate as candidates for the M.Eng. (Aerospace) degree. A candidate normally has a background equivalent to an accredited four-year bachelor's degree program in aerospace or mechanical engineering or in engineering physics; a student with a different background may be required to take supplemental courses.

Requirements for the degree include the completion of four three-hour core courses in fluid mechanics, theoretical aerodynamics, or high-temperature gasdynamics, all areas in which active research is being carried out.



The drag of racing vehicles was studied in a Master of Engineering degree project supervised by Professor Albert R. George *(left)*. The students are measuring drag forces on a model *(below)* of a competition race car.

Available core courses are Physics of Fluids I, Combustion Processes, Dynamics of Flight Vehicles, Fluid Mechanics I and II, Incompressible and Compressible Aerodynamics, and Energy and Fluid Systems Laboratory. The faculty may modify the core course requirement to suit individual needs, interests, and background. For example, course sequences leading to specialization in energy conversion, aerophysics, or chemical kinetics can be arranged.

Also required are six hours of elective subjects such as Theory of Viscous Flows, Special Topics in Aerospace Engineering, Numerical Methods in Fluid Flow and Heat Transfer, Physics of Fluids II, and Plasmadynamics. Many other electives are available in aerospace engineering and related fields. Also required are six hours of mathematics, attendance at the weekly colloquium and an advanced seminar, and a project.

Subject areas available for M.Eng.(Aerospace) projects (and the professors who are working in these areas) include pollution control in automobile engines designed so as not to compromise efficiency or performance (E. L. Resler, Jr.); hydrogen and methanol internal combustion engines, solar energy collectors, and electric probes as combustion analyzers (P. C. T. de Boer); combustion studies (F. C. Gouldin); wind tunnel experimentation, atmospheric flow, and vehicle aerodynamics (A. R. George); unsteady flow experimentation (S.-F. Shen); controlled fusion (P. L. Auer); and fundamental properties of turbulence (J. L. Lumley, Z. Warhaft).

Some recent M.Eng.(Aerospace) projects and the faculty advisers are:

Evaporation Time of Water Droplets from a Hot Plate (P. C. T. de Boer)
Dynamical Effects of Radiation Pressure (E. L. Resler, Jr.)
Simulation of Two-Dimensional Filling of a Cavity with Variable Thickness (S.-F. Shen)
Transonic Nacelle Inlet Design (D. A. Caughey)
Visualization of Velocity Profiles in Unsteady Boundary Layers (S.-F. Shen)
Wind Tunnel Design and Calibration (A. R. George)
Design and Testing of an Electrostatic Ion-Energy Analyzer in a Plasma Wind Tunnel (P. L. Auer and P. C. T. de Boer)

Faculty Members and Their Research Interests

Peter L. Auer, A.B. (Cornell), Ph.D. (California Institute of Technology): *plasma physics, fusion power, energy policy analysis*
David A. Caughey, B.S.E. (Michigan), A.M., Ph.D. (Princeton): *fluid dynamics, transonic flow, computational aerodynamics*
P. C. Tobias de Boer, Ir.(M.E.) (Delft), Ph.D. (Maryland): *combustion processes, alternative fuels for combustion engines, high-temperature gasdynamics*
Albert R. George (Director of the School of Mechanical and Aerospace Engineering), B.S.E., A.M., Ph.D. (Princeton): *aerodynamics, fluid dynamics, aeroacoustics, sonic boom, turbulence*
Frederick C. Gouldin, B.S.E., Ph.D. (Princeton): *fluid dynamics, combustion, propulsion*
Sidney Leibovich, B.S. (California Institute of Technology), Ph.D. (Cornell): *fluid dynamics, wave propagation, air-sea interactions, dynamics of vortex flows*
Geoffrey S. S. Ludford, B.A., M.A., Ph.D., ScD. (Cambridge): *fluid mechanics, magnetohydrodynamics, combustion and related applied mathematics*
John L. Lumley, B.A. (Harvard), M.S.E., Ph.D. (Johns Hopkins): *fluid dynamics, turbulence and turbulence modeling, geophysical turbulence, stochastic processes*
Edwin L. Resler, Jr., B.S. (Notre Dame), Ph.D. (Cornell): *high-temperature gasdynamics, pollution control, ferrofluid mechanics*
Shan-Fu Shen, B.S. (National Central, China), Sc.D. (M.I.T.): *aerodynamics, computational fluid mechanics, polymer processing*
Dennis G. Shepherd, B.Sc. (Michigan): *fluid mechanics, turbo machinery, thermal and wind power*
Donald L. Turcotte, B.S. (California Institute of Technology), M.Aero.E. (Cornell), Ph.D. (California Institute of Technology): *geomechanics, geophysical fluid dynamics*
Zellman Warhaft, B.E. (Melbourne), Ph.D. (London): *experimental fluid mechanics, turbulence, micrometeorology*

The regular faculty is supplemented by distinguished visitors from the United States and abroad. Visitors have included Hannes Alfvén, G. K. Batchelor, J. M. Burgers, L. F. Crabtree, Nima Geffen, Isao Imai, Theodore von Kármán, S. Kitaigorodskii, J. W. Linnett, P. S. Lykoudis, F. E. Marble, R. S. B. Ong, E. R. Oxburgh, D. A. Spence, Ko Tamada, and Itiro Tani.

Further Information

Further information may be obtained by writing to the Graduate Faculty Representative, Aerospace Engineering, Cornell University, Upson Hall, Ithaca, New York 14853.

Agricultural Engineering

The application of engineering to agriculture and the related food production and processing industries is a broad field of work and study. Agricultural engineering activities depend on both the physical and biological sciences and involve many other interdisciplinary specialties.

Diversity of interests characterizes graduate study and research in the Field of Agricultural Engineering at Cornell. This diversity is manifested by theses that range from the entirely theoretical to the almost completely experimental. Usually a thesis blends analytical and experimental work that draws upon strong programs in physical, biological, and engineering sciences at Cornell and reflects the variety of faculty strengths and interests.

Approximately forty graduate students from all regions of the United States and from several other countries are in residence in agricultural engineering. This heterogeneous mix of student educational backgrounds provides a stimulating environment for consideration of new ideas. Nearly all the students receive financial support from the University or other sources.

A student may enter one of four programs leading to advanced degrees in agricultural engineering: Doctor of Philosophy, Master of Science, Master of Engineering (Agricultural), or Master of Professional Studies (Agriculture). For the Ph.D. and M.S. degrees, original research and presentation of a thesis are required; the student's special committee, a faculty group chosen by the student, is solely responsible for the direction of the curriculum and research program.

The M.Eng. degree program is an accredited professional program intended to prepare students for engineering practice. The M.P.S. program provides advanced professional studies in agriculture with an emphasis on applications of agricultural engineering technology. In these two degree programs emphasis is placed on advanced course work and project development; there is no thesis requirement.

In addition to course work in agricultural engineering subjects, graduate students are expected to take courses in the basic sciences and advanced mathematics in order to strengthen their understanding of fundamentals. To assist graduate students to keep abreast of current developments, a general seminar is held weekly during the academic year, and specialized seminars are conducted by individual research groups during the spring term.

Facilities

Riley-Robb Hall provides a center for the graduate programs in agricultural engineering at Cornell. Major laboratories in the building include those for agricultural waste management research, for small-animal calorimetry and environmental physiological studies, and for work in the controlled-atmosphere storage of agricultural materials. In addition, there is a well-equipped machine shop to implement the development of prototype equipment, such as machines for the mechanical harvesting of fruits and vegetables.

Other facilities include the nearby Agricultural Waste Management Laboratory, which is operated by the Department of Agricultural Engineering for pilot-plant studies; the Animal Science Teaching and Research Center; plots for the study of nutrients and runoff; and plant-growth chambers. The University's central computing system, an interactive computing facility located in Riley-Robb Hall, and a library that ranks among the ten largest in the United States are also available to graduate students.

Areas of Research

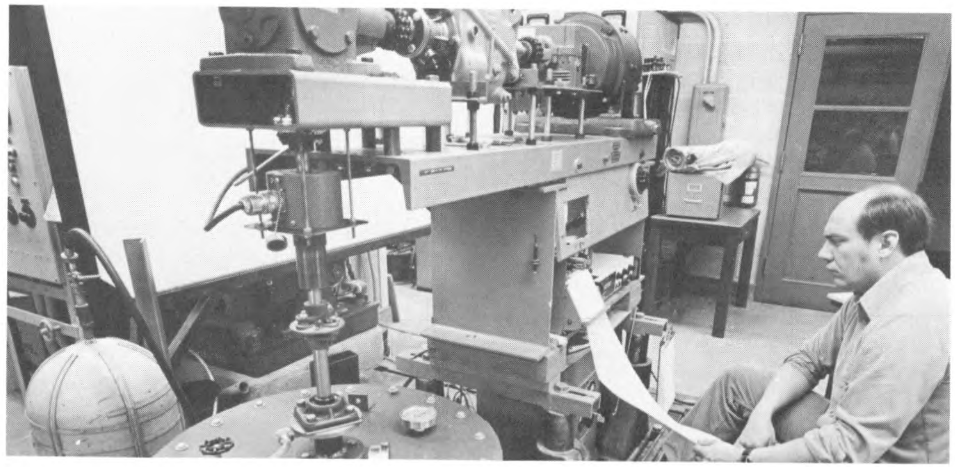
The diversity of the field of agricultural engineering and the breadth of the programs at Cornell are demonstrated by the variety of recent and current research projects. Work on the conservation, production, and use of energy includes projects on wind-powered water heating, the control of heat loss in greenhouses, energy conservation on dairy farms, and biogas production from agricultural wastes. The mechanization of fruit and vegetable harvesting, handling, processing, and storage continues to be a major area of study; projects include investigations of the influence of handling procedures and storage environments on product quality. Research in the area of agricultural waste management includes the investigation of ways to minimize the environmental impact of agricultural production and consideration of requirements for soil and water management. Environmentally sound approaches to the management of animal waste and food-processing waste are also under study.

Systems analysis has been used to examine the influence of a multitude of interacting factors on the agricultural production system and the related environment. Several current projects involve analysis of the behavior of biological systems; specific subjects include estrus detection, the physiological responses of chickens to varying environments, calf-rearing environments, and mathematical modeling of biological systems.

Brief descriptions of the research activity in six general areas are given in the following sections.

Energy

The national focus on energy has increased the need for energy-related research in all fields, and the study of energy problems related to agriculture has become a major area of research in the Field of Agricultural Engineering at Cornell. Projects include investigations into an integrated energy system for farms, the use of producer gas, energy analysis of fertilizers, solar heating of greenhouses, the use of wind energy in dairy operations, the use of waste heat from power plants for greenhouses, alcohol production from New York crops and by-products, and methane production from agricultural wastes. The National Science Foundation, the U.S. Department of Energy, and other federal, state, and industrial groups have provided funding



***Right:* A wind-turbine device heats water by driving a paddle inside a water tank, thus converting mechanical to thermal energy.**

for these projects. Most of them are multidisciplinary activities that use the expertise of graduate students and faculty members from several departments of the University.

The search for new methods and techniques to produce and conserve energy in agricultural practice is part of this program. Nearly 800 million tons of crop residues and animal wastes are produced in the United States each year; by converting these organic wastes into usable fuels, it may be possible to reduce the energy demands of agriculture. Cornell researchers are also looking into ways of scavenging and recycling energy that is now wasted at the farmstead; the magnitude of this energy may equal that of the energy potentially available from animal wastes. The aim of projects in this area is to identify energy-conserving practices that will permit continued high-level production. Two full-scale methane-generation reactors for family-sized farms have been successfully operated for several years. The creation of an on-farm energy system that will make maximum use of local energy resources is planned.

Some recent theses (listed with the name of the supervising professor) and papers are:

Albright, L. D.; Seginer, I.; Langhans, R. W.; and Donohoe, A. 1979. Q-mats as passive solar collectors. In *36th annual progress report to the New York State Food and Energy Council*, ed. D. M. Stipanuk, p. 58. Ithaca, N.Y.: Department of Agricultural Engineering, Cornell University.

Chandra, P. 1979. A time-dependent analysis of thermal energy and moisture exchanges for greenhouses. Ph.D. thesis (L. D. Albright).

This site is used for testing the system for heating water by direct conversion of wind power.

Froehlich, D. P.; Albright, L. D.; Scott, N. R.; and Chandra, P. 1979. Steady-periodic analysis of glasshouse thermal environment. *Transactions of the ASAE* 22(2):387.

Guest, R. W. 1980. Energy costs of manure. *Agriculture News Service*, March 1980. Ithaca, N.Y.: New York State Cooperative Extension, Cornell University.

Gunkel, W. W. 1979. Wind energy. Paper read at "Project Energize" resource workshop, October 27, 1979, at Elmira College, Elmira, New York.

Gunkel, W. W.; Furry, R. B.; and Lacey, D. R. 1980. Wind-powered water heating. In *Selected energy research projects in the Department of Agricultural Engineering*. Agricultural Engineering Extension Bulletin 439.

Gunkel, W. W.; Furry, R. B.; Lacey, D. R.; Neyeloff, S.; and Porter, T. G. 1980. Development of a wind-powered water heating system for dairy application. *Wind energy applications in agriculture*, USDA workshop proceedings, NTI-CONF-7905-109, p. 124.

Gunkel, W. W., and Sigrimis, N. 1980. Producer gas as a petroleum substitute. In *Selected energy research projects in the Department of Agricultural Engineering*. Agricultural Engineering Extension Bulletin 439.

Jewell, W. J. 1979. Future trends in digester design. Paper read at First International Symposium on Anaerobic Digestion, September 21, 1979, Cardiff, Wales.

Jewell, W. J.; Switzenbaum, M.S.; and Morris, J. W. 1979. Sewage treatment with the anaerobic attached film expanded bed process. Paper read at 52nd Annual Water Pollution Control Federation Conference, October 7–12, 1979, Houston, Texas.

Jewell, W. J. et al. 1980. *Anaerobic fermentation of agricultural residues: potential for improvement and implementation*, vol. II. U.S. Department of Energy final report (in press).

Kah, G. F. 1978. Energy management strategies for dairy farms. M.S. thesis (D. R. Price).

Neyeloff, S. 1978. Analysis of a direct wind energy converter to heat water by agitation in closed tanks. Ph.D. thesis (W. W. Gunkel).

Porter, T. 1979. Analysis and optimal design of direct wind energy water heating systems. M.S. thesis (W. W. Gunkel).

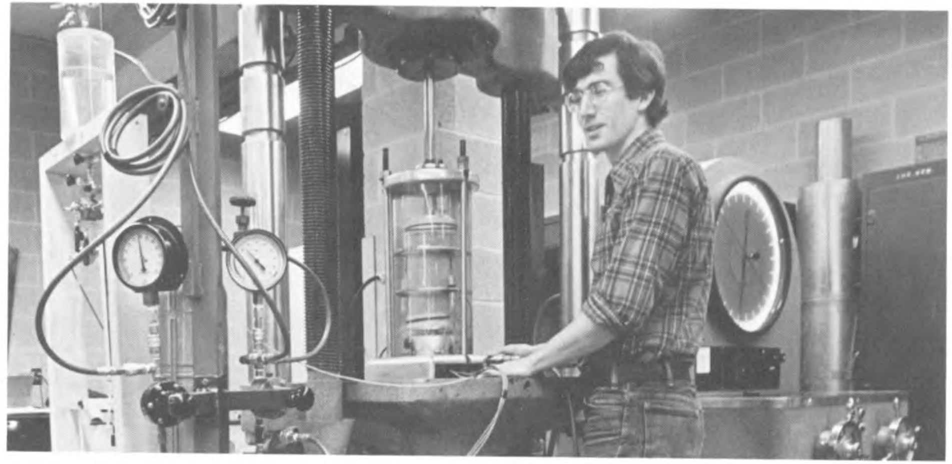
Seginer, I., and Albright, L. D. 1979. *Rational operation of greenhouse thermal curtains.* ASAE paper 79-5431. St. Joseph, Mich.: American Society of Agricultural Engineers.

Sigrimis, N. A. 1980. Performance of a producer gas internal combustion engine system as influenced by gasifier design and fuel type. M.S. thesis (W. W. Gunkel).

Stipanuk, D. M.; Koelsch, R. K.; and Roberg, R. C. 1979. *Energy and economic analysis of heat recovery vs. solar water heating on dairy farms.* ASAE paper 79-3537, St. Joseph, Mich.: American Society of Agricultural Engineers.

Community and Resource Development

The principal objective of research in this area is to improve the quality of life in the nation's rural and suburban communities. Projects include the planning of improvements to local rural road networks, studies of the application of stabilized soils to low-volume road, the design and evaluation of pavements for local roads, and a study of water conservation and groundwater recharge on eastern Long Island. Land disposal of sewage sludge, flood control in small watershed projects, and improvements of marginal agricultural land have also been evaluated.



A kneading compactor is used to test highway materials for low-volume roads.

Examples of publications, theses (listed with the name of the supervising professor), and reports resulting from work in this area are given below (related material is cited in the sections on environmental quality and water management):

Cowell, M. J. 1978. Effect of time delay, multipoint treatment and varying compactive effort on the strength and durability of cement stabilized soils. M.S. thesis (L. H. Irwin).

Cowell, M. J., and Irwin, L. H. 1979. Effects of compaction delays and multiple treatments on the strength of cement stabilized soils. *Transportation Research Record* 702:191.

Hough, G. B. 1978. The development of an instrumentation system and the preliminary investigation of the effective stress strength parameters of stabilized soils. M.S. thesis (L. H. Irwin).

Irwin, L. H. 1978. Use of fracture energy as a fatigue failure criterion. *Proceedings, Association of Asphalt Paving Technologists* 46:41.

Irwin, L. H. 1979. Equipment and methods for deflection-based structural evaluation of pavements. In *Proceedings of 1979 Forest Service geotechnical workshop,* p. 58. Washington, D.C.: U.S. Forest Service.

Environmental Quality

Agricultural waste residues and problems associated with the rural environment are among the greatest challenges to engineers and scientists concerned with environmental quality management. The trend toward confinement feeding of livestock, the increasing size of food-processing operations, the increasing use of rural lands for municipal waste disposal, and the concern for water-quality problems associated with fertilizers and pesticides have created needs for new approaches in managing the rural environment.

Well-equipped laboratories are available at Cornell for research on many aspects of water and waste management, including open-channel flow; soil physics; odor reduction and control; liquid-waste treatment, handling, and disposal techniques; waste characteristics; solid-waste management; treatment process control; and systems analysis and modeling. A large pilot plant and a laboratory are available for demonstrating the handling and treatment processes that prove promising on a smaller scale.

Research activities can be broadly classified as those related to the management of agricultural wastes (animal manures and food-processing wastes), the management of municipal wastes, including land application of wastewaters and sludges, and the control of agricultural nonpoint sources.

Current research efforts include projects on the treatment of animal wastes, on feasible handling and treatment processes and analytical models for animal-waste management, on the development and testing of treatment processes for municipal wastes, and on the design of land-application systems. Additional projects are concerned with the development and testing of mathematical models of nutrient and pesticide runoff from fields and watersheds. Major research projects to determine the feasibility and design of systems for generating biogas are also in progress.

Examples of publications and theses (listed with the name of the supervising professor) on these subjects are:

Chandler, J. A. 1980. Predicting anaerobic fermentation biodegradability. M.S thesis (W. J. Jewell).

Chandler, J. A., and Jewell, W. J. 1980. *Predicting methane fermentation biodegradability*. U.S. Department of Energy final report SERI/TR-09038-1.

Haith, D. A., and Loehr, R. C., eds. 1979. *Effectiveness of soil and water conservation practices for pollution control*. U.S. Environmental Protection Agency report EPA-600/3-79-106.

Hayes, T. D.; Jewell, W. J.; and Kabrick, R. M. 1980. Heavy metal removal from sludge using combined biological-chemical treatment. In *34th annual Purdue University industrial waste conference proceedings*, ed. J. M. Bell (in press). Ann Arbor, Mich.: Ann Arbor Press.

An experimental multipurpose reactor converts waste to three effluents: methane gas; solid float material, potentially useful for bedding or feed; and liquid, containing most of the nutrients, for fertilizer production.

Jewell, W. J. 1979. Sewage sludge leachate assimilation capacity — designing land application of sewage sludge systems. Paper read at NATO Advanced Study Institute on Sludge Characteristics and Behavior, July 1979, at University of Delaware, Newark, Delaware.
Jewell, W. J., and Kabrick, R. M. 1980. Autoheated aerobic thermophilic digestion with aeration. *Journal of the Water Pollution Control Federation* 52(3):512.
Jewell, W. J., and Morris, J. W. 1979. Agricultural wastes. *Journal of the Water Pollution Control Federation* 51(6):1360.
Loehr, R. C. 1978. Hazardous solid waste from agriculture. *Environmental Health Perspectives* 27:261.
Loehr, R. C. 1980. Utilization of agricultural and agro-industry residues — an overview. *Industry and Environment* 3(1):2.
Loehr, R. C.; Haith, D. A.; Walter, M. F.; and Martin, C. S.; eds. 1979. *Best management practices for agriculture and silviculture*. Ann Arbor, Mich.: Ann Arbor Science Publishers.
Lorber, M. N. 1980. Simulating the growth and yield of corn in a humid region under moisture stress. M.S. thesis (D. A. Haith).
Morse, W. 1979. Inhibition of denitrification by nitrite. M.S. thesis (R. C. Loehr).
Moser, M. A. 1979. Methodology for assessing soil series suitability for land treatment of wastewater. M.S. thesis (R. C. Loehr).
Muck, R. E. 1978. The removal of nitrogen and phosphorus from dry poultry manure with simulated rainfall. Ph.D. thesis (D. C. Ludington).
Muck, R. W., and Ludington, D. C. 1979. Simulation of nitrogen and phosphorus leaching from poultry manure. *Transactions of the ASAE* 22:1087.

Instrumentation for monitoring the potential across a soil matrix is used in a laboratory study conducted by a Ph.D. student.

——. 1980. The breakdown of poultry manure aggregates by rainfall impact. *Journal of Environmental Quality* 9:61.
Safley, L. M., Jr.; Haith, D. A.; and Price, D. R. 1979. Decision tools for dairy manure handling systems selection. *Transactions of the ASAE* 22(1):144.
Steenhuis, T. S.; Bubenzer, G. D.; and Converse, J. C. 1979. Ammonia volatilization from winter spread manure. *Transactions of the ASAE* 22:152.
Steenhuis, T. S.; Muck, R. E.; Bubenzer, G. D.; and Converse, J. C. 1980. Modeling nutrient losses from winter spread manure. Paper read at 4th International Symposium on Livestock Wastes, April 15–17, 1980, Amarillo, Texas.
Steenhuis, T. S., and Walter, M. F. 1980. Closed form solution for pesticide loss. *Transactions of the ASAE* 23(3):615.
Switzenbaum, M. 1978. The anaerobic attached film expanded bed reactor for the treatment of dilute organic wastes. Ph.D. thesis (W. J. Jewell).
Tseng, W. T. 1979. A systems procedure for land use and water quality in a rural watershed. Ph.D. thesis (D. A. Haith).
Walter, M. F.; Steenhuis, T. S.; and Haith, D. A. 1979. Nonpoint source pollution control by soil and water conservation practices. *Transactions of the ASAE* 22(4):834.
Wong-Chong, G. M., and Loehr, R. C. 1978. Kinetics of microbial nitrification: nitrite-nitrogen oxidation. *Journal of Water Research* 12(8):605.
Wujcik, W. J. 1980. Dry anaerobic fermentation to methane of organic residues. Ph.D. thesis (W. J. Jewell).

Water Management

Water management is central to the solution of many environmental problems and is a major concern of agricultural engineers. Traditionally, they have worked on production-oriented aspects of water management, such as drainage and irrigation. These continue to be important research topics, but because today's agriculture requires more specialized designs, agricultural engineering research in water

An agricultural engineering graduate student uses a computer to work on a systems analysis of a water-management problem.

management goes beyond the traditional concerns. Flood-damage control, domestic water supply, water quality, and the fundamental processes of soil and water movement are examples of current research areas.

In recent years, research projects at Cornell have focused on the hydrology of variable areas and hill slopes, water movement in shallow and frozen soils, the interaction of water movement and materials transport, erosion and sedimentation processes, and hydrologic modeling.

Examples of publications and theses (listed with the name of the supervising professor) on these subjects are:

Bardaie, M. Z. 1979. Systems approach to salinity problems in irrigation planning. Ph.D. thesis (D. A. Haith).

Louden, G. H. 1978. A qualitative and quantitative analysis of drip irrigation and surface irrigation systems. M.P.S. project report (R. D. Black).

McCarty, T. R. 1980. A field study of water flow over and through a shallow, sloping, heterogeneous soil. Ph.D. thesis (M. F. Walter).

MacVicar, T. K. 1978. A solid state transducer for recording piezometer systems. M.S. thesis (M. F. Walter).

Nieber, J. L. 1979. Hillslope runoff characteristics. Ph.D. thesis (M. F. Walter).

Robillard, P. D.; Walter, M. F.; and Allee, D. J. 1979. Approach to non-structural flood management alternatives. *Water Resources Bulletin* 15(5):1430.

Romocki, R. 1978. Surface drainage of Harford farm soil and water. M.Eng. design project (M. F. Walter).

Schottman, R. W. 1978. Estimation of the penetration of high-energy raindrops through a plant canopy. Ph.D. thesis (M. F. Walter).

Steenhuis, T. S.; Bubenzer, G. D.; and Walter, M. F. 1978. Water movement and infiltration in a frozen soil. Theoretical and experimental considerations. ASAE paper 77-2545. St. Joseph, Mich.: American Society of Agricultural Engineers.

Walter, M. F.; Black, R. D.; and Zwerman, P. J. 1979. Tile flow response in a layered soil. *Transactions of the ASAE* 22(3):577.

Food and Biological Engineering

Knowledge of the biology of animals and plants is of increasing importance to agricultural engineering design. The high priority given to the mechanization of harvesting, handling, and processing of fruits and vegetables requires a greater knowledge of the engineering properties of these products. Similarly, animal production (milk, eggs, and meat) is significantly influenced by environmental, nutritional, reproductive, and pathological conditions; basic information on physiological systems therefore needs to be considered in the engineering design of animal facilities. At Cornell this kind of study is being carried out in a number of projects.

Environmental factors that influence plant growth are being studied in order to promote more intelligent design of the tools and machines used in crop production. The storage of vegetables under controlled conditions of atmosphere and temperature is being studied to identify the environmental control parameters required to maintain product quality for extended periods of storage. This interdisciplinary study also examines plant physiology as it relates to storage life of the plant material.

The mathematical modeling of biological systems has been used to study static and dynamic stomatal mechanics in relation to the control of plant transpiration. Investigations of gaseous exchanges of water vapor and carbon dioxide between plants and the atmosphere include both physiological studies and measurements with instruments such as diffusion porometers and pressure chambers.

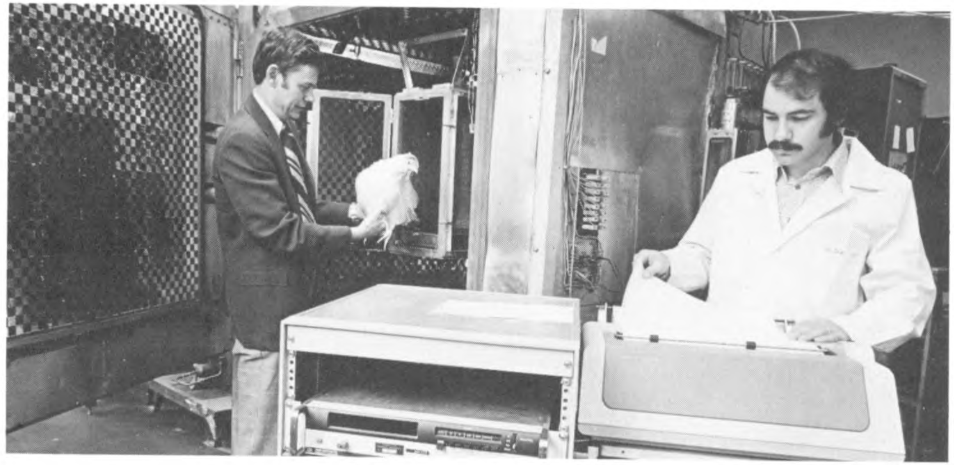
Basic information is being obtained on the influence of environment on physiological mechanisms that limit animal productivity. Biomathematical modeling, calorimetry, simulation, and instrumentation techniques are being applied to studies of thermoregulation, milking systems, and reproduction. Specific projects in this area have included studies of the dynamic responses of the dairy cow's teat to pressure changes, the physiological interaction of young dairy calves with their thermal environment, estrus detection, and the physiological responses of chickens to varying environments.

The human as part of the system of food production, processing, and handling has also been considered. Human visual capacity in the monitoring of trailed vehicles for malfunction has been investigated. Energy demands of the food system have been considered in terms of recommended dietary allowances and guidelines. Studies have been made of energy needs for home preparation of chicken and eggs, and an energy-storage system for domestic cooking has been developed.

Examples of publications and theses (listed with the name of the supervising professor) in this area are:

Cooke, J. R., and Rand, R. H. 1980. Diffusion resistance models. Chapter in *Predicting photosynthesis for ecosystem models*, vol. I, ed. J. D. Hesketh and J. W. Jones, p. 93. Cleveland: CRC Press.

Furry, R. B.; Hicks, J. R.; Jorgensen, M. C.; and Ludford, P. M. 1979. *Effects of ethylene on controlled atmosphere storage of cabbage*. ASAE paper 79-4537. St. Joseph, Mich.: American Society of Agricultural Engineers.



Above: **Environmental effects on the physiological responses of animals are studied in a project headed by Professor Norman R. Scott *(left)*.**

Right: **A graduate student monitors milk flow as part of a basic study of fluid and structural mechanics involved in milk-extraction procedures.**

Gates, R. S. 1980. Two-phase flow in milking pipelines. M.S. thesis (N. R. Scott).

Kaminaka, M. S. 1978. Visual monitoring and the operation of agricultural machinery. Ph.D. thesis (G. E. Rehkugler).

Mabry, C. A. 1978. Thermoregulatory responses of poultry to local heating and cooling of the spinal cord. M.S. thesis (N. R. Scott).

Magee, C. 1980. A comparison of three milking units in terms of milking performance and influence on organism transport. Ph.D. thesis (N. R. Scott).
Marshall, R. N.; Scott, N. R.; Barta, M.; and Foote, R. H. 1979. Electrical conductivity probes for detection of estrus in cattle. *Transactions of the ASAE* 22(5):1145.
Rehkugler, G. E.; Cummings, J. N.; and Markwardt, E. D. 1979. Rupture strength of unions of "Golden Delicious" apple with Malling 9, and vigorous rootstocks. *Journal of the American Society of Horticultural Science* 104(2):226.
Reitsma, S. Y., and Scott, N. R. 1979. Dynamic responses of the dairy cow's teat to step changes in pressure. *Journal of Dairy Research* 46:15.
Shoemaker, C. A. 1979. Optimal timing of multiple applications of pesticides with residual toxicity. *Biometrics* 35:803.
Scooter, C. A., and Millier, W. F. 1978. The effect of pellet coatings on seedling emergence from lettuce seeds. *Transactions of the ASAE* 21(6):1034.
Stroshine, R. L. 1980. Mathematical analysis of pressure chamber efflux experiments. Ph.D. thesis (J. R. Cooke).
van Tienhoven, A.; Scott, N. R.; and Hillman, P. E. 1979. The hypothalamus and thermoregulation. *Journal of Poultry Science* 58:1633.

International Agriculture

Agricultural engineering has had a long-time concern with engineering aspects of international agricultural development. At Cornell the most recent focus of activities has been on water-management problems of tropical agriculture, particularly in the humid tropics. Other areas of interest include agricultural mechanization and rural development activities. The research is interdisciplinary; cooperative field-oriented activities involve several departments as well as such agencies as the International Rice Research Institute, the University of the Philippines, the National Irrigation Administration in the Philippines, the Ministry of Agriculture in Indonesia, and the U.S. Agency for International Development.

Field assistants gauge the flow in an irrigation channel in a field-study area in the Philippines.

Specific field-research projects on critical problems in tropical countries have dealt with both technical and nontechnical factors. An example is a recent study of the effects of water stress on rice yield, considered in concert with the human and technical interactions involved in water management for irrigation systems. Programs for graduate students in this area are characterized by extended residence in developing countries to collect thesis data and to obtain firsthand knowledge and understanding of development problems. On-campus education emphasizes interdepartmental interaction through special research seminars and workshops.

A sampling of research activities is given by these recent theses and projects (listed with the name of the supervising professor):

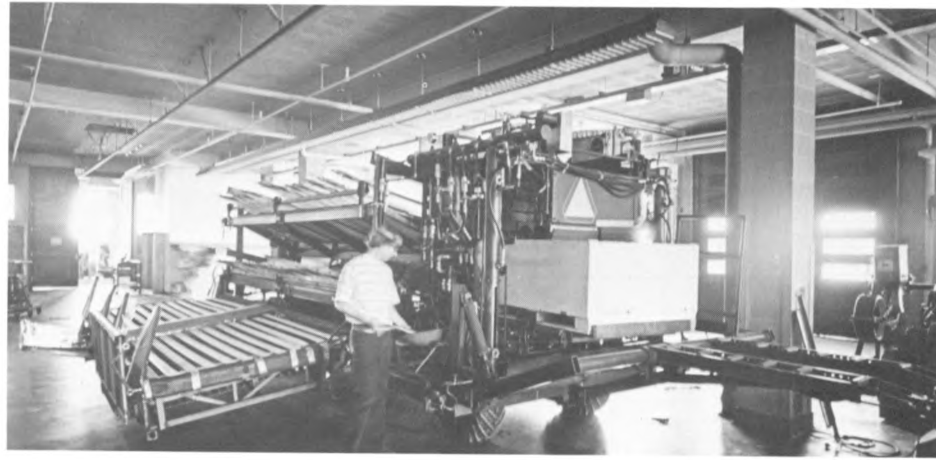
Early, A. C. 1975. The influence of water management policies on operating policies for sugar cane districts in the Philippines. Ph.D. thesis (G. Levine).
Ko, H. S. 1977. Irrigation and systems management and computer programming. M.Eng. design project (G. Levine).
Lecuona-Valenzuela, M. F. 1980. Theoretical and experimental models of infiltration into crusted soils. M.S. thesis (G. Levine).
Moreno, M. F. 1980. The selection of appropriate machinery and power sources for small farms in Colombia, South America. M.S. thesis (W. W. Gunkel).
Ng, P. K. 1976. A model for crop diversification in the Kembu irrigation scheme of Malaysia. M.Eng. design project (G. Levine).
Williamson, J. 1979. Selection of a rice milling process for remote areas in the hills of Nepal. M.Eng. design project (R. Black).

Production Systems

Research on production systems deals with structural, machine, and physical systems related to crop and animal production. The major areas of interest include the development of mechanical harvesting techniques and equipment, the evaluation and design of structures for soil and water management, the improvement of buildings to enhance environmental control, and improvements in the efficiency, safety, and functional effectiveness of agricultural machinery.

Techniques and equipment have been developed for the mechanical harvesting of cabbage, lettuce, grapes, cherries, and apples for processing. Current research in this area is concerned with the harvest of fresh market apples and the development of prototype equipment to harvest apples with an acceptable amount of bruise damage. One aspect of the development of a suitable mechanical system for harvesting fresh market apples is the concurrent development of a suitable horticultural system. Research on the automated detection of product quality is also continuing.

Work on the design of farm buildings takes into account the total animal-production system; factors considered include animal traffic patterns and energy-conservation techniques, as well as structural integrity. Simulations of systems have been used to model the behavior of an entire small dairy farm; on a smaller scale, simulation techniques are being used to model the environment of a structure in relation to the animal units, ambient conditions, and the environmental control system. Other projects have dealt with thermal environments in dairy structures, air flows in slotted inlet ventilation systems, and ventilation patterns in buildings.



A harvester for fresh market apples was developed in a long-term project on the design of harvesting equipment. A tree is vibrated by this highly maneuverable machine, causing the apples to fall on inflated plastic platforms.

Cornell research and development efforts have also been directed to agricultural machinery, a critical component of both animal and crop production systems. Machinery developed to date includes devices for mechanical grape pruning and shoot positioning, and specialized equipment for tillage and harvesting. Tractor safety is being studied in a project involving simulation studies of tractor motion and the examination of criteria for tractor stability.

Research on forage harvesting and handling seeks to increase forage yields while reducing energy requirements and maintaining forage quality. A probabilistic model has been developed that predicts average forage yields and assesses the energy efficiency of existing and proposed forage-harvesting systems. The application of drying agents to fresh-cut forage is being explored as a way of reducing field-curing time and subsequent losses. Experimentation is beginning on the quantity and quality changes that occur during fermentation, and a model describing the complex biological, thermal, and mechanical processes within the silo is being developed.

Examples of publications and theses (listed with the name of the supervising professor) in this area are:

Albright, L. D. 1978. Airflow through baffled, center-ceiling, slotted inlets. *Transactions of the ASAE* 21(5):944.

Hummel, J. A. 1980. Simulation of braking effects on agricultural tractors. M.Eng. design project (G. E. Rehkugler).

Kaminaka, M. S. 1978. Visual monitoring and the operation of agricultural machinery. Ph.D. thesis (G. E. Rehkugler).

Kelly, J. E. 1980. Agricultural tractor motion—computer graphics display and steering induced instability on side slopes. M.Eng. design project (G. E. Rehkugler).

Lorenzen, R. T. 1978. Sequential roof-truss failure under critical snow load. In *Proceedings of the Society of Wood Science and Technology: structural use of wood in adverse environments*. Vancouver, British Columbia, Canada.

Millier, W. F.; Rehkugler, G. E.; Pellerin, R. A.; and Throop, J. A. 1978. High capacity harvesting apparatus. U.S. Patent 4,121,407. Issued October 24, 1978.

Pacheco, A. 1979. Design and development of a spring activated impact shaker for apple harvesting. M.S. thesis (G. E. Rehkugler).

Rehkugler, G. E. 1980. Simulation of articulated steer four-wheel drive agricultural tractor motion and overturns. *Transactions of the ASAE* 23(1):2.

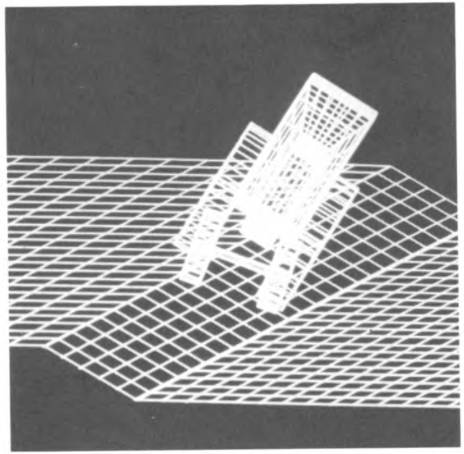
Srivastava, A. K.; Rehkugler, G. E.; and Masemore, B. J. 1978. Similitude modeling applied to ROPS testing. *Transactions of the ASAE* 21(4):633.

Timmons, M. B. 1979. Experimental and numerical study of air movement in slot ventilated enclosures. Ph.D. thesis (L. D. Albright).

Timmons, M. B., and Albright, L. D. 1978. Wind directional dependence of soil-air temperatures. *Transactions of the ASAE* 21(4):742.

Timmons, M. B.; Albright, L. D.; and Furry, R. B. 1978. Similitude aspects of predicting building thermal behavior. *Transactions of the ASAE* 21(5):956.

Upadhyaya, S. K. 1979. A finite element analysis of the dynamics of limb impact harvesting of apples. Ph.D. thesis (J. R. Cooke).



This computer graphics simulation of a tractor overturn was used in a study of tractor stability as related to vehicle design and operation.

Faculty Members and Their Research and Teaching Interests

Louis D. Albright, B.S.A.E., M.S., Ph.D. (Cornell): *environment of agricultural buildings; energy management in agriculture; computer simulation of thermal environment; applications of solar energy to the production and processing of food, feed, fiber, and horticultural products*

James A. Bartsch, B.S., M.S. (Wisconsin), Ph.D. (Purdue): *systems for handling, processing, and storing fruits, vegetables, flowers, and nursery stock; mechanical handling of commodities; processing and storage practices to maintain product quality*

Richard D. Black, P.E.; B.S., M.S., Ph.D. (Illinois): *drainage of agricultural land, small-watershed hydrology, soil conservation practices*

Wilfried H. Brutsaert, B.S. (Ghent), M.S., Ph.D. (California, Davis): *hydraulics, hydrology, groundwater flow*

J. Robert Cooke, B.S., M.S., Ph.D. (North Carolina State): *biological engineering, plant-water relationships, engineering properties of biological materials, mathematical engineering analysis*

Ronald B. Furry, B.S., M.S. (Cornell), Ph.D. (Iowa State): *controlled-atmosphere storage of fruits and vegetables, energy conservation, similitude methodology, plant and animal structures and environments*

Richard W. Guest, P.E.; B.S., M.S. (North Dakota State): *agricultural-waste and energy* *management, dairy and livestock engineering*

Wesley W. Gunkel, B.S. (North Dakota State), M.S. (Iowa State), Ph.D. (Michigan State): *energy use for farms, analysis and design of harvesting and specialized agricultural machinery, thermal agriculture, pest-control methods and equipment, materials handling, international agricultural mechanization*

Douglas A. Haith, B.S., M.S. (M.I.T.), Ph.D. (Cornell): *environmental systems analysis, water-quality management, water resources*

Lynne H. Irwin, B.S., M.S. (California, Berkeley), Ph.D. (Texas A&M): *highway engineering, highway materials evaluation, pavement design and evaluation, soil stabilization, transportation technology for developing countries, community and resource development*

William J. Jewell, B.S. (Maine), M.E. (Manhattan College), Ph.D. (Stanford): *energy and waste treatment and control, unit process development, land-treatment costs, rural environmental engineering, septic tanks, agricultural waste management*

Fred G. Lechner, B.S., M.E. (Colorado A&M), Ed.D. (Michigan State): *the teaching of agricultural engineering technology in secondary schools, two-year technical colleges, and four-year colleges*

Gilbert Levine, B.S., Ph.D. (Cornell): *irrigation system design, tropical irrigation, water management, soil-water-plant relationships*

Raymond C. Loehr, B.S., M.S. (Case), Ph.D. (Wisconsin): *solid wastes, industrial waste treatment systems, agricultural waste management, land application of wastes, nonpoint source control*

Robert T. Lorenzen, P.E.; B.S.A.E. (North Dakota State), B.S.C.E. (Wisconsin), M.S. (California, Davis): *farmstead production systems design, including structural and environmental aspects of enclosures; functional tenets of farmstead production systems*

David C. Ludington, B.S., M.S. (Cornell), Ph.D. (Purdue): *management of agricultural wastes to reduce air and water pollution, energy conservation and scavenging for recycle*

Everett D. Markwardt, B.S. (North Dakota State), M.S. (Cornell): *mechanical fruit and vegetable harvesting, irrigation systems*

William F. Millier, B.S., Ph.D. (Cornell): *tree fruit harvesting and handling, farm power and machinery*

Ronald E. Pitt, B.S., M.S. (Wisconsin), Ph.D. (Cornell): *modeling of forage systems; new techniques for planting, harvesting, and storing forage; strength and fatigue of biological materials; probabilistic analysis of the strength of fibrous materials and structures, mathematical modeling of biological systems*

Richard H. Rand, B.E. (Cooper Union), M.S., Sc.D. (Columbia): *biomechanics, theoretical and applied mechanics, dynamic systems*

Gerald E. Rehkugler, P.E.; B.S., M.S. (Cornell), Ph.D. (Iowa State): *analysis and design of agricultural and food-processing machinery, food engineering, energy use in the food system relative to human nutrition*

Norman R. Scott (Chairman of the Department of Agricultural Engineering), B.S.A.E. (Washington State), Ph.D. (Cornell): *biomathematical modeling of animal systems; animal calorimetry; environmental physiology; thermal environment; integrated application of structural theory, thermodynamics, and biological sciences to synthesis of structural systems; electronic instrumentation techniques in physical and biological measurements*

Christine A. Shoemaker, B.S. (California, Davis), M.S., Ph.D. (Southern California): *water resource systems, mathematical pest management*

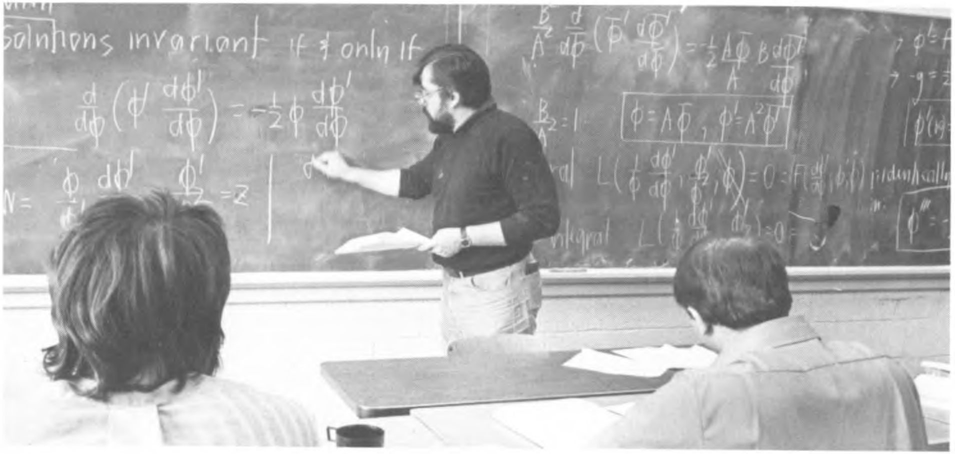
Tammo S. Steenhuis, B.S., M.S. (Wageningen), M.S., Ph.D. (Wisconsin): *water quality modeling, water flow in soils, upland flow transport of waste and substances, water management*

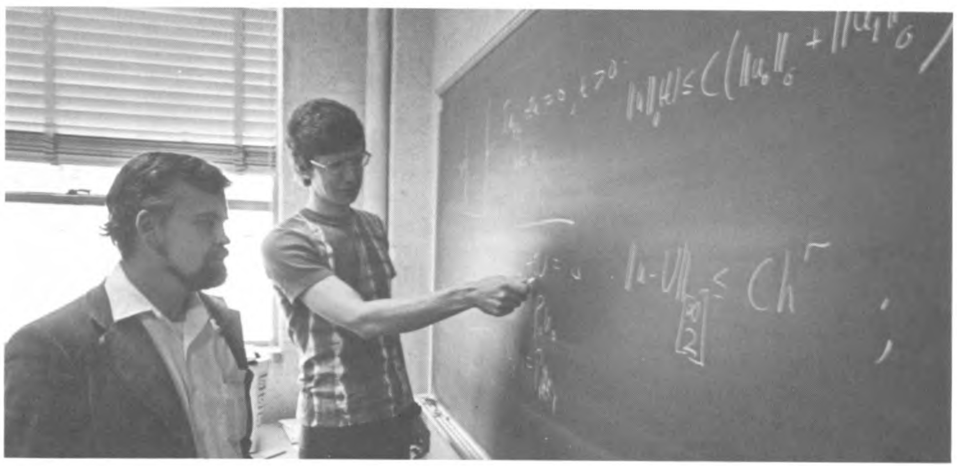
Larry P. Walker, B.S., M.S., Ph.D. (Michigan State): *systems engineering, process control, heat and mass transfer, mathematical modeling, computer simulation and optimization*

Michael F. Walter, B.S., M.S. (Illinois), Ph.D. (Wisconsin): *water resources, water management, small-watershed hydrology, drainage*

Further Information

The publications *Department of Agricultural Engineering: The Staff and Program* and *Agricultural Engineering Research* are also available. Requests for these publications and inquiries regarding any aspect of the graduate program should be sent to the Graduate Faculty Representative, Agricultural Engineering, Cornell University, Riley-Robb Hall, Ithaca, New York 14853.





The following recent theses (listed with the name of the supervising professor) provide a sample of research activities in the field:

Ayeni, R. O. 1978. Thermal runaway. Ph.D. thesis (G. S. S. Ludford).

Baum, S. P. 1978. Integral near-optimal solutions to certain classes of linear programming problems. Ph.D. thesis (L. E. Trotter).

Caginalp, G. 1978. Boundary free energy lattice spin systems. Ph.D. thesis (L. E. Trotter).

Gross, L. J. 1979. Models of the photosynthetic dynamics of *Fragaria virginiana*. Ph.D. thesis (S. A. Levin).

Hwang, W. G. 1978. Consistent estimation of system order. Ph.D. thesis (T. L. Fine).

Lee, C. 1981. Counting the faces of simplicial convex polytopes. Ph.D. thesis (L. J. Billera).

Marwil, E. S. 1978. Exploiting sparsity in Newton-like methods. Ph.D. thesis (J. E. Dennis).

Nedelman, J. 1981. Two problems in mathematical biology I. Examination of the kinetic support for the two-state model of the cell cycle. II. Facilitated diffusion of oxygen and carbon monoxide in the large affinity regime. Ph.D. thesis (S. A. Levin).

Graduate instruction and research activities in the graduate Field of Applied Mathematics include class work and research conferences. *Left above:* Professor James T. Jenkins offers a course in continuum mechanics that is of interest to applied mathematics students. *Left:* At the blackboard Professors James H. Bramble *(left)* and Lars B. Wahlbin discuss a problem in partial differential equations.

Applied Mathematics

The achievements and methodology of classical and modern mathematics have in recent years proved most useful in a variety of other disciplines, including many new subject areas as well as the more traditional ones. At Cornell the Field of Applied Mathematics offers a broadly based interdepartmental program with opportunities for study and research over a wide spectrum of the mathematical sciences. This program is based on a solid foundation in pure mathematics that includes the fundamentals of algebra and analysis, as well as the methods of applied mathematics. The remainder of an individual's program is designed by the student and his or her special committee, comprising three faculty members. Applicants having undergraduate backgrounds that contain a substantial mathematical component are eligible to apply.

There are several different graduate programs at Cornell in which one can pursue studies of applied mathematics. Students with well-defined interests in this general area should investigate the suitability of programs in the Fields of Computer Science, Mathematics, Operations Research, Statistics, and Theoretical and Applied Mechanics, as well as various other fields in the physical sciences and engineering. The Field of Applied Mathematics is particularly appropriate for those interested in classical applied mathematics and for those undertaking truly interdisciplinary studies involving mathematics but lying between the areas encompassed by other graduate fields.

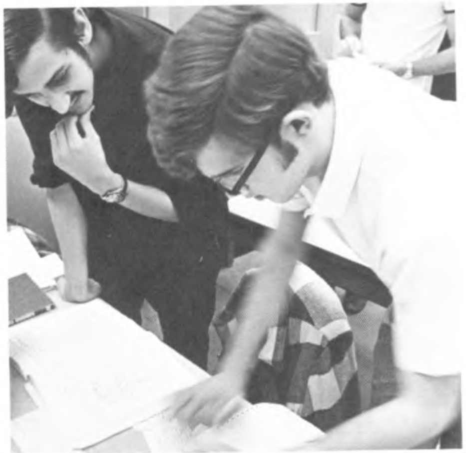
Research and study in this field are coordinated through the Center for Applied Mathematics. There are some forty-five core faculty members in the center, and graduate students occasionally do their research under additional faculty members not formally associated with this field. The center does not offer courses; its twenty-five Ph.D. students select courses from those offered by a dozen related academic departments. Each faculty member in the center also holds an appointment in at least one of these departments.

Facilities

The Center for Applied Mathematics maintains faculty and student offices and seminar rooms in Olin Hall, on the engineering campus. All facilities of the University, including, for example, computer services, are available to graduate students in the Field of Applied Mathematics.

Areas of Research

A large number of research possibilities exist for graduate students in this field. These include the following topics and their applications to other fields: partial differential equations, numerical analysis, functional analysis, mathematical physics, mechanics, aerodynamics, fluid flow, magnetofluid dynamics, astrophysics, statistical mechanics, applied probability, statistics, mathematical biology, population growth, genetics, logic, automata, networks, combinatorics, game theory, and mathematical economics.



Sammon, P. H. 1978. Approximations for parabolic equations with time dependent coefficients. Ph.D. thesis (J. H. Bramble).

White, G. N. 1980. Role of chemotaxis in an intertidal predator-prey system. Ph.D. thesis (S. A. Levin).

Computer work is involved in many research projects in applied mathematics. Services of the University's central facility *(below)* are available to graduate students.

Faculty Members and Their Research Interests

Toby Berger, B.E. (Yale), M.S., Ph.D. (Harvard): *information theory, statistical communication, random processes*

Louis J. Billera, B.S. (Rensselaer), M.S., Ph.D. (City University of New York): *game theory, combinatorics, mathematical economics*

Robert G. Bland, B.S., M.S., Ph.D. (Cornell): *linear programming, combinatorics*

James H. Bramble, A.B. (Brown), M.S., Ph.D. (Maryland): *numerical analysis, partial differential equations*

Herbert J. Carlin, B.S., M.S. (Columbia), D.E.E., Ph.D. (Polytechnic Institute of Brooklyn): *microwave and network techniques*

Claude Cohen, B.S. (American University, Cairo), Ph.D. (Princeton): *fluid dynamics, transport phenomena, light scattering, polymer systems*

Robert Constable, B.A. (Princeton), M.A., Ph.D. (Wisconsin): *theory of computing, automata, logic*

Peter A. Dashner, B.S., M.S., Ph.D. (SUNY, Buffalo): *continuum mechanics, nonlinear field theories, differential geometry*

Eugene B. Dynkin, Ph.D. (Moscow University): *probability theory*

Roger H. Farrell, Ph.B., M.S. (Chicago), Ph.D. (Illinois): *mathematical statistics*

Terrence L. Fine, B.E.E. (City College of New York), S.M., Ph.D. (Harvard): *decision theory, comparative probability, speech recognition*

Michael E. Fisher, B.Sc., Ph.D. (London): *foundations and applications of statistical mechanics, combinatorics*

Wolfgang H. J. Fuchs, B.A., Ph.D. (Cambridge): *mathematical methods of physics*

Leonard Gross, B.S., M.S., Ph.D. (Chicago): *analysis, mathematics of quantum theory*

Keith E. Gubbins, B.S., Ph.D. (London): *statistical mechanics of liquids, computer simulation of liquids*

David C. Heath, A.B. (Kalamazoo), M.A., Ph.D. (Illinois): *applied probability, stochastic control, game theory*

Philip Holmes, B.A. (Oxford), Ph.D. (Southampton): *nonlinear mechanics, dynamical systems, bifurcation theory*

James T. Jenkins, B.S. (Northwestern), Ph.D. (Johns Hopkins): *nonlinear field theories in mechanics, continuum mechanics*

Harry Kesten, Doctorandus (Amsterdam), Ph.D. (Cornell): *probability theory*

Myunghwan Kim, B.S. (Alabama), M.E., Ph.D. (Yale): *biomathematics, bioengineering*

James A. Krumhansl, B.S. (Dayton), M.S. (Case), Ph.D. (Cornell): *solid-state physics, microscopic descriptions of macroscopic properties of materials*

Sidney Leibovich, B.S. (California Institute of Technology), Ph.D. (Cornell): *fluid dynamics, magnetohydrodynamics*

Simon A. Levin, B.A. (Johns Hopkins), Ph.D. (Maryland): *mathematical biology, differential equations*

Richard L. Liboff, A.B. (Brooklyn), Ph.D. (New York University): *kinetic theory, plasma physics, electrodynamics, quantum mechanics*

William F. Lucas, B.S., M.A., M.S. (Detroit), Ph.D. (Michigan): *game theory, combinatorics*

Geoffrey S. S. Ludford, B.A., M.A., Sc.D., Ph.D. (Cambridge): *fluid and magnetofluid dynamics, combustion, related mathematical methods*

Franklin Luk, B.S., M.S., Ph.D. (Stanford): *numerical linear algebra*

Mukul K. Majumdar, B.A. (Calcutta), M.A., Ph.D. (California, Berkeley): *mathematical economics*

Anil Nerode, A.B., B.S., M.S., Ph.D. (Chicago): *logic, recursive functions and computability, automata*

Lawrence E. Payne, B.S., M.S., Ph.D. (Iowa State): *partial differential equations*

Narahari U. Prabhu, B.A. (Madras), M.A. (Bombay), M.Sc. (Manchester): *stochastic processes, analysis and control of stochastic systems*

Richard H. Rand, B.E. (Cooper Union), M.S., Engr.Sc.D. (Columbia): *differential equations, dynamical systems, biomechanics*

Sol I. Rubinow, B.S. (City College of New York), M.S. (Brown), Ph.D. (Pennsylvania): *blood flow, cell proliferation, enzyme kinetics, physiological systems*

Edwin E. Salpeter, B.Sc., M.S. (Sydney), Ph.D. (Birmingham): *theoretical astrophysics, nuclear theory, statistical mechanics*

Alfred H. Schatz, B.S. (City College of New York), M.S., Ph.D. (New York University): *numerical analysis, partial differential equations*

Shan-Fu Shen, B.S. (National Central University, China), Sc.D. (M.I.T.): *aerodynamics, rarefied gas dynamics*

Frank L. Spitzer, B.A., M.A., Ph.D. (Michigan): *probability theory and analysis*

Robert S. Strichartz, B.A. (Dartmouth), M.A., Ph.D. (Princeton): *mathematical analysis*

Murad S. Taqqu, B.A. (Lausanne), M.A., Ph.D. (Columbia): *probability, statistics, econometrics, operations research, computer simulation*

Howard M. Taylor 3d, B.M.E., M.I.E. (Cornell), Ph.D. (Stanford): *applied probability and statistics*

Michael J. Todd, B.A. (Cambridge), Ph.D. (Yale): *mathematical programming, combinatorics*

Leslie E. Trotter, A.B. (Princeton), M.S. (Georgia Institute of Technology), Ph.D. (Cornell): *discrete optimization*

Charles Van Loan, B.S., M.A., Ph.D. (Michigan): *numerical algebra, control theory, nonlinear least squares*

Lars B. Wahlbin, B.A., M.A., Ph.D. (Göteborg, Sweden): *partial differential equations, numerical analysis*

Lionel I. Weiss, B.A., M.A., Ph.D. (Columbia): *statistical decision theory*

Benjamin Widom, A.B. (Columbia), Ph.D. (Cornell): *physical chemistry, statistical mechanics*

Further Information

Further information may be obtained by writing to the Graduate Faculty Representative, Applied Mathematics, Center for Applied Mathematics, Cornell University, Olin Hall, Ithaca, New York 14853.

Applied Physics

The graduate Field of Applied Physics offers opportunities for advanced study and research in many areas of applied science that are based on the principles and techniques of physics. Students with undergraduate training in physics can branch out into applied science while continuing the study of physics, and students with a background in engineering or another science can extend their knowledge of basic physics.

Individual programs are planned to meet the needs and interests of each student. Building on a core of physics courses at the graduate level, the program normally also contains a series of courses in engineering or another science related to the student's research area. In addition to the research-oriented Ph.D. program offered by the Field of Applied Physics, there is available a one-year program leading to the professional degree of Master of Engineering (Engineering Physics). A program leading to the M.S. degree is also available, although applicants with the definite intention of stopping at the M.S. level will not normally be offered financial support. Approximately sixty students are now enrolled in these three degree programs.

The faculty of the Field of Applied Physics is centered in the School of Applied and Engineering Physics of the College of Engineering, but it also includes faculty members from other departments of the University. Many members are associated with one or more of the interdisciplinary laboratories at Cornell, which facilitate work in such areas as plasma studies, experiments using synchrotron radiation, materials science, semiconductor growth and processes, and radiophysics and space research. This diversity permits graduate students to choose from an unusually broad range of specialty areas. Equally important is the extensiveness of the research facilities that are available.

The projected availability of career opportunities is an important consideration in the choice of a field for graduate study. In the area of applied physics the prospects are good. Although the opportunities for a career in basic physics have leveled off substantially in recent years, there is a strong, long-range need in industry, government, and universities for graduates who have not only a sound education in physics but also the capability for attacking practical problems. Approximately four out of five Cornell applied physics graduates assume positions with industrial organizations and government laboratories. About one in five enters academic work.

Facilities

Because of the interdepartmental and interdisciplinary nature of the Field of Applied Physics at Cornell, the research facilities available are much more extensive than those generally provided by a single department. For example, sophisticated equipment for electron microscopy and electron spectroscopy, for x-ray analysis and metallography, for special materials preparation, for chemical analysis, for work with tunable lasers, and for studies at very high or low pressures and temperatures is provided at the University's Materials Science Center. Also, the Field of Applied Physics is closely associated with two recently established major research facilities at Cornell, the National Research and Resource Facility for Submicron Structures (NRRFSS) and the Cornell High Energy Synchrotron Source (CHESS). Other facilities available for applied physics research include the radar-radio observatory in Arecibo, Puerto Rico; the unique high-current ion-beam and relativistic electron-beam facilities of the Laboratory of Plasma Studies; the Cornell synchrotron and electron storage ring; and the Ward Laboratory of Nuclear Engineering.

These facilities are described in the section on interdisciplinary activities.

Areas of Research

The broad applicability of the principles and techniques of physics is illustrated by the many research areas within the Field of Applied Physics. Examples of current programs are described below in nine general categories; the names of professors working with specific projects are given in parentheses. (This material was prepared in the spring of 1980; more recent information may be obtained by contacting the professors named.)

Solid-State Physics

Research in solid-state physics is conducted over a range of specific subject areas, such as defects and physical properties, superconductivity, quantum electronics and microwaves, phase transformations, and surface physics, and employs many theoretical and experimental approaches. For example, phase transformations and transport properties are studied in superconductors, on crystal surfaces, at high pressures, and within single crystals of a two-component solid. The tools for such studies include theoretical analysis, x-ray and electron diffraction, light and microwave scattering, electron spectroscopy, field ion microscopy, and ultrasonics. Many of these research projects involve faculty members who hold appointments in other engineering disciplines, such as electrical engineering, mechanical engineering, and materials science and engineering.

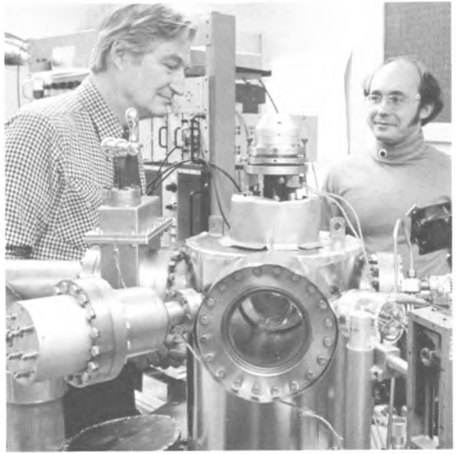
The major focus of current research in superconductivity is quantum Josephson phenomena. Quantum superconductivity provides the basis for a variety of extremely high-performance electronic devices, such as ultrasensitive electromagnetic sensors and ultra-high-speed digital systems. The research program is particularly directed toward improving the knowledge of quantum superconductivity in those systems that are most relevant to potential device applications. The research objectives are to examine the basic phenomena governing quantum superconductivity, to establish the fundamental limits that these phenomena set on device performance, and to develop techniques for producing superconducting devices that will most closely approach this limiting level of performance. (R. A. Buhrman).

The physical scale associated with quantum superconductivity is of the order of one micrometer or less. In order to properly examine superconductivity phenomena, as well as to use them fully, it is necessary that superconducting systems be fabricated with dimensions in the submicrometer range. A major research effort in the electron-beam and x-ray lithography of such submicrometer structures has been initiated in conjunction with NRRFSS, the national facility for research on submicrometer structures. The rapidly developing capability for submicrometer fabrication is already proving to be extremely valuable in advanced research into the microelectronic behavior of metals, both superconducting and normal; moreover, submicrometer fabrication and thin-film processing offer in their own right many exciting and technologically important research opportunities in applied physics and materials science. (R. A. Buhrman).

Other research in the general area of solid-state physics involves structure studies of phase transformations associated with high-field superconductors and with the properties of flux line lattices in Type II superconductors; in such materials, pinning of the flux line by crystal defects can be very important in achieving high critical currents. (E. J. Kramer).

An important area of research on solids is concerned with those atomic and electronic properties that are strongly influenced by limited dimensionality or crystal symmetry, such as is found in surface layers of solids, thin films, and very small particles. Work with many unique and important properties of solids associated with surface or interface phenomena involves considerations of solid-state physics, physical chemistry, and engineering; current research at Cornell includes detailed studies, on a microscopic scale, of the interactions of solids with electrons, photons, and molecules. Important physical and chemical phenomena that reflect the unique nature of solid surfaces are being studied in great detail in terms of electron excitations and chemical bonding, with the use of sophisticated combinations of electron, Auger, photoemission, field-emission, and molecular-beam spectroscopy. Particular emphasis is placed on the use of photon-stimulated electron emission to study electron structure and excitations in metals and the nature of the chemical binding and orientation of molecules at metal surfaces. In a special program carried out at a synchrotron radiation facility, the unique features of a tunable polarized intense photon source are used to explore the electron and atomic physics of molecules interacting with metal surfaces. This technique of angle-resolved photoemission is being applied to a variety of practical problems in chemisorption, catalysis, and microelectronics. The electron accelerator and storage ring facility at the Physical Sciences Laboratory in Stoughton, Wisconsin, is now being used for this purpose; future studies of surfaces and interfaces will also be conducted at the new Cornell High Energy Synchrotron Source (CHESS) in Ithaca. (T. N. Rhodin).

The macroscopic surface properties associated with surface thermodynamics and with transport in ionic crystals and semiconductors are also under active study. Surface studies of gas-metal reactions using low-energy electron diffraction constitute another major research area. (J. M. Blakely).



In graduate research directed by Professor Thor Rhodin *(left)* an ultrahigh vacuum electron spectrometer is used for studies of metal and semiconductor surfaces.

One example of limited dimensionality is the optical and electronic response of inhomogeneous materials. Of particular interest is the optical behavior of ceramic/metal (cermet) composite films. Ongoing research has shown that such materials can be adapted to be extremely viable candidates for application as high-temperature photo-thermal converters of solar energy. The overall theme of the research program on inhomogeneous materials is to advance the understanding of these materials and to develop engineering procedures to adapt them to meet particular technological needs. (R. A. Buhrman).

An active research program is under way in the area of solid-state semiconductor physics. The special facilities provided by the submicron facility recently established at Cornell will be used to study the physics of compound semiconductor interfaces. These studies are concerned specifically with electron behavior at surfaces and interfaces as it applies to the miniaturization of metal-semiconductor-insulator sandwich devices in the submicrometer range; the role of the compositional and structural properties of such interfaces in the scaling down of solid-state devices is an important area of research. (T. N. Rhodin). Also under study is the epitaxial growth of intermetallic compound crystals, such as gallium arsenide, and the use of these crystals for microwave oscillators based on the transferred electron effect. (L. F. Eastman). Similar work is being done on the epitaxial growth and evaluation of sandwich structures for application in semiconductor lasers, solar cells, and integrated optical devices. (J. M. Ballantyne). Other projects involve study of the epitaxial growth of silicon crystals and diffusion and sputtering processes in silicon and other semiconductor microwave devices (C. A. Lee), and tunnel-injection of minority carriers in metal-insulator-semiconductor structures (J. M. Ballantyne).

The chemical nature and associated electronic structure of solids at the microscopic level is studied with the use of transmission electron spectroscopy in combination with electron microscopy. The electron microscope provides a means of exploring thin films on a microscopic scale; the addition of an electron spectrometer enables the scientist to study the way in which — still on a microscopic scale — the sample absorbs energy from the beam. In turn, this reflects the electronic structure and chemical nature of the sample in small regions. The angular dependence of the scattering reflects the momentum dependence with which the specimen absorbs the energy, and this gives new kinds of electronic structural information. Several approaches are being used in current work. The VG HB5 scanning transmission electron microscope is being reworked to provide electron spectrometry capabilities adequate for carrying out studies of electron energy loss from small (10–20Å) regions. Convergent-beam electron-diffraction techniques are being developed to measure thicknesses of thin films, with an accuracy of about 1 percent. A high-energy (approximately 10 meV) resolution device is being designed. Studies are being made of energy losses in boron nitride (low energies, 0–50 eV; boron K-edge, about 92 eV; and nitrogen K-edge, about 400 eV) and in the 3d-transition metals and transition-metal oxides. (J. Silcox).

In a program associated with NRRFSS, a high-intensity, high-resolution ion probe is being developed for use in microstructuring at dimensions in the nanometer range. Gaseous field ionization at cryogenic temperatures is used to produce a source of high angular current density that can be focused to probes 100 to 200 Å in diameter. The interaction of these ion probes with materials for electronic devices and with resists used in lithography is being studied. Structures

Professor John Silcox and students work with an electron microscope modified to include an electron spectrometer under on-line computer control.

fabricated in semiconductor and superconducting materials and having dimensions in the range of 1,000 Å to 100 Å are to be studied to determine their properties in the "microphysical" range, where new transport phenomena are expected to be observed. (B. M . Siegel).

The generation and measurement of extremely high pressures, and the performance of experiments at these pressures, have been the subject of another substantial research effort. Pressures approaching 2 megabars have been achieved with the use of tiny spherical indentors made of diamond, and submicrometer fabrication techniques have made possible the use of interdigitated electrodes on the diamond indentors to probe matter at extreme pressures. (A. L. Ruoff).

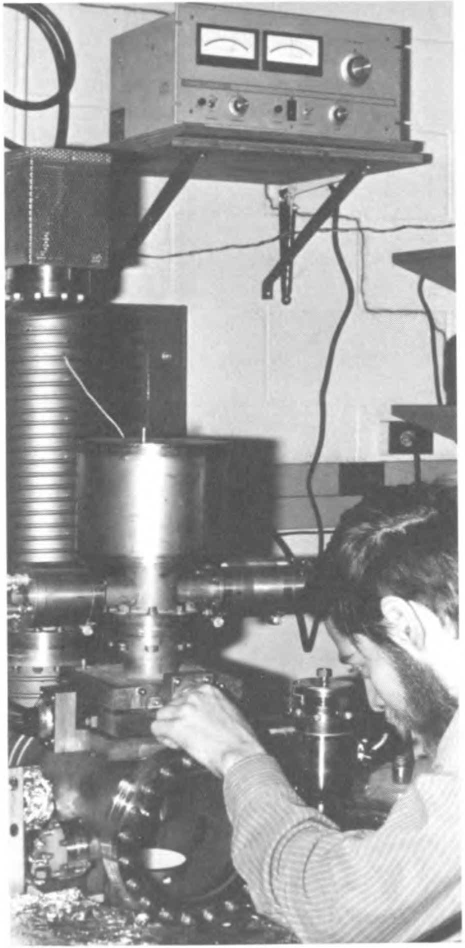
Liquid crystals display a variety of bizarre phenomena because of their unique combination of liquid and solid properties. Defect structures, transport processes, and phase transitions in smectic liquid crystals are currently under study, with the help of special laser-optical techniques. Of particular interest are those properties displaying the two-dimensional intermolecular coupling characteristics of these materials. (W. W. Webb).

The study of crystal imperfections and their relation to the physical properties of crystals is a major area of research in solid-state physics. Imperfections are studied by electron and field-ion microscopy, and individual ions are imaged and identified by mass spectroscopy. (D. N. Seidman).

Anharmonic and bonding properties in solids have been studied, using both the neutron-scattering facilities at Brookhaven National Laboratory and the Cornell 12-GeV synchrotron. The recently acquired Cornell High Energy Synchrotron Source (CHESS) is making possible an expanded program of research. (B. W. Batterman).

Some recent typical publications and theses (listed with the name of the supervising professor) in the area of solid-state physics are:

Anderson, S., and Batterman, B. W. 1978. Energy analysis of diffuse ω-reflections in NbZr by Mossbauer x-ray scattering. *Solid*



State Communications 26:195.

Bastuscheck, C. M. 1980. Superconducting diamagnetism in samples of $(SN)_x$, $TaSe_3$ and $NbSe_3$. Ph.D. thesis (R. A. Buhrman).

Batterman, B. W., and Ashcroft, N. W. 1979. CHESS: the new synchrotron radiation facility at Cornell. *Science* 206:157.

Blakely, J. M., and Thapliyal, H. V. 1978. Structure and phase transitions of segregated surface layers. In *Interfacial segregation.* Metals Park, Ohio: American Society for Metals.

Chen, C. H., and Silcox, J. 1977. Direct non-vertical interband transitions at large wave vectors in aluminum. *Physical Review B* 16:4246.

Chen, C. H.; Silcox, J.; Garito, A. F.; Heeger, A. J.; and MacDiarmid, A. G. 1976. Plasmon dispersion and anisotropy in polymeric sulfur nitride, $(SN)_x$. *Physical Review Letters* 36:525.

Craighead, H. G. 1980. Optical properties and solar selectivity of metal-insulator composite films. Ph.D. thesis (R. A. Buhrman).

Craighead, H. G., and Buhrman, R. A. 1977. Optical properties of selectively absorbing $Ni/A1_2 0_3$ composite films. *Applied Physics Letters* 31:423.

Hanson, G. R., and Siegel, B. M. 1979. H_2 and rare gas field ion source with high angular current. *Journal of Vacuum Science and Technology* 16:1875.

Jensen, E. S.; Seabury, C. W.; and Rhodin, T. N. 1980. Angle-resolved photoemissions for CO on Fe(110). *Solid State Communications* 35(8):581.

In a study of transition metals such as platinum, the surface electron structure of a single crystal is probed with a field emission electron microscope and energy spectrometer.

Kleinsasser, A. W., and Buhrman, R. A. 1980. High quality submicron niobium tunnel junctions with reactive ion beam oxidation. *Applied Physics Letters* 37(9):841.

Kramer, E. J. 1978. Fundamental defect-fluxoid interaction in irradiated superconductors. *Journal of Nuclear Materials* 72:5.

Leapman, R. D., and Silcox, J. 1979. Orientation dependence of core edges in electron energy loss spectra from anisotropic materials. *Physical Review Letters* 42:1361.

Mantese, J. V.; Goldburg, W. I.; Darling, D. H.; Craighead, H. G.; Buhrman, R. A.; and Webb, W. W. 1980. 1/f noise in granular composite films. In *Proceedings of 2d international symposium on 1/f noise,* p. 389. Gainesville: University of Florida.

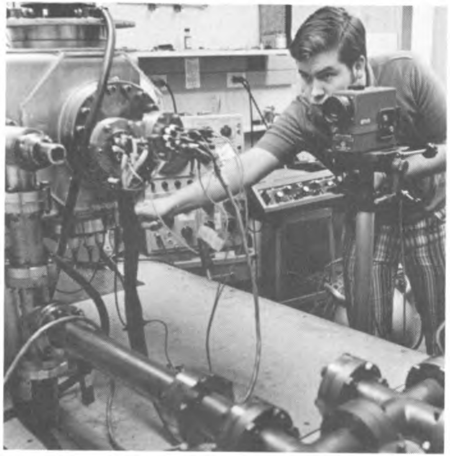
Mills, D. M. 1979. Investigation of higher order forbidden reflections in Si and Ge using synchrotron radiation. Ph.D. thesis (B. W. Batterman).

Mills, D. M.; Bilderback, D. H.; and Batterman, B. W. 1979. Thermal design of synchrotron radiation exit ports at CESR. *IEEE Transactions on Nuclear Science* 26:3854.

Rhodin, T. N., and Gadzuk, J. W. 1979. Electron spectroscopy and surface chemical bonding. In *The nature of the surface chemical bond,* ed. G. Ertl and T. N. Rhodin, p. 113. Amsterdam: North-Holland.

Ruoff, A. 1978. On the ultimate yield strength of solids. *Journal of Applied Physics* 49:197.

Ryan, F. 1978. Tunnel injection electroluminescence and stimulated emission in CdS metal-insulator-semiconductor structures. Ph.D. thesis (J. M. Ballantyne).



The inelastic scattering of electrons from single-crystal metal surfaces is used to study electron excitations in this ultrahigh-vacuum spectrometer.

Seabury, C. W.; Rhodin, T. N.; Purtell, R. T.; and Merrill, R. P. 1980. Chemisorption and reaction of NH_3 on Ni(111). *Surface Science* 93:117.

Seidman, D. N. 1978. The study of radiation damage in metals with the field-ion and atom-probe microscopes. *Surface Science* 70:532.

Silcox, J. 1979. Inelastic electron-matter interactions. In *Proceedings of 9th international congress on electron microscopy*, vol. 3, p. 259. Toronto: Microscopical Society of Canada.

Tang, C. L.; Kreismanis, V. G.; and Ballantyne, J. M. 1977. Wide band electro-optical tuning of semiconductor lasers. *Applied Physics Letters* 30:113.

Tischler, J., and Hartman, P. L. 1980. Photo-electron and ionization chamber position monitors for CHESS. *Nuclear Instruments and Methods* 172:67.

Wei, C.-Y. 1978. The direct observation of the point-defect structure of depleted zones in irradiated metals. Ph.D. thesis (D. N. Seidman).

Plasma Physics

A unified, interdisciplinary approach to plasma studies at Cornell offers the opportunity for graduate work in plasma physics combined with applied physics, aerospace engineering, chemistry, electrical engineering, or physics. A number of professors in the Field of Applied Physics are actively involved in plasma research; approximately equal attention is given to the experimental and the theoretical aspects of plasmas. Some of this work is conducted at the interdepartmental Laboratory of Plasma Studies.

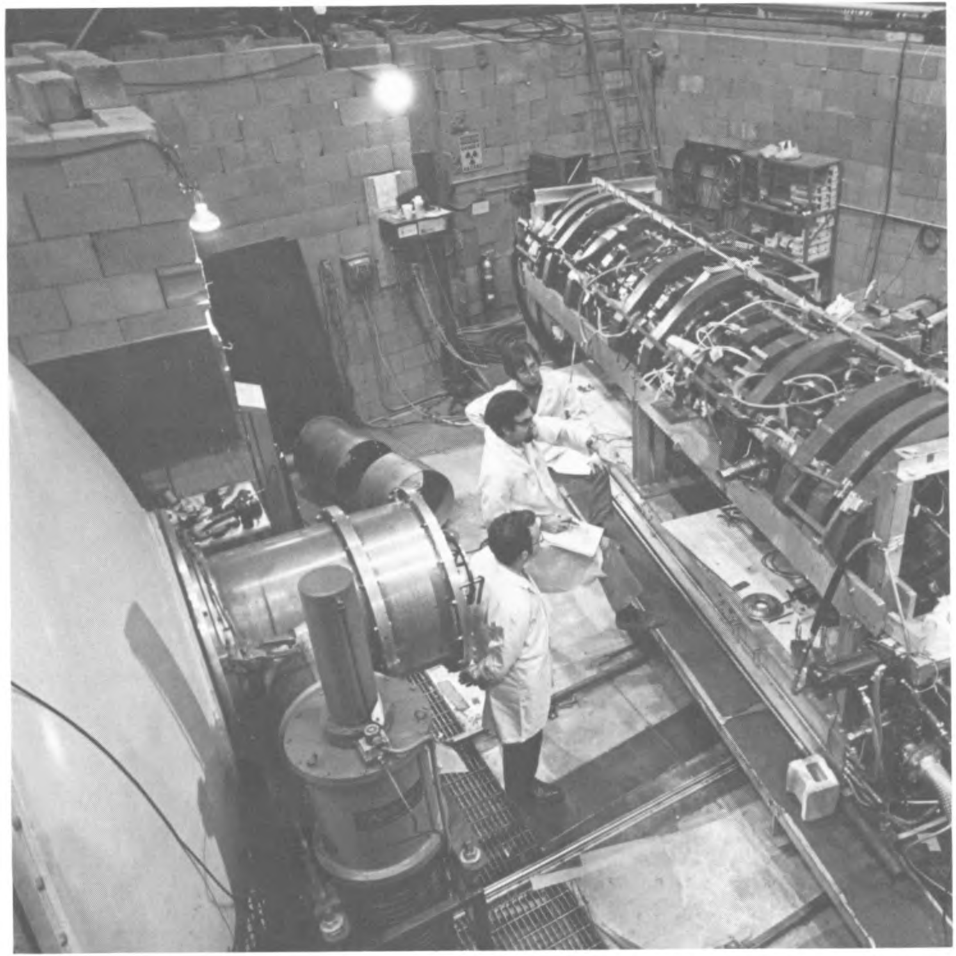
The principal subject of research is the confinement and heating of thermonuclear plasmas. Cornell is recognized as the leading university in the area of the technology of high-current relativistic electron and ion beams and their application in controlled-fusion studies. Current research includes work on magnetic configurations in connection with alternate fusion concepts; particular areas of concern are stability, the confinement and heating of plasmas, and fusion processes in which ion beams are used

Applied physics faculty members David Hammer *(left)* and Ravindra Sudan direct plasma physics research involving ion-beam focusing experiments.

for inertial confinement. In areas other than controlled fusion, investigations are being made of magnetospheric and ionospheric plasmas, plasma turbulence, and astrophysical plasmas.

On the experimental side, valuable facilities for plasma studies include pulsed high-power Marx-Blumlein generators, used in the production of intense electron and ion beams. Two potential applications of these beams in thermonuclear fusion technology are being investigated. One is the use of the magnetic field associated with the beams to form Astron ring configurations, which, according to theoretical predictions, will allow the stable confinement of fusion plasmas. (H. H. Fleischmann, D. A. Hammer, R. N. Sudan). The second potential application, based on the very large total energy content of the beams, is for plasma heating or for compressing and heating small pellets of fusionable material. (D. A. Hammer, B. R. Kusse, R. N. Sudan, C. B. Wharton). The use of intense relativistic electron beams for pulsed microwave generation and for the production of high-velocity ions is also being studied. (J. Nation).

A variety of theoretical plasma problems are under investigation. Part of this effort concentrates on theoretical aspects of the application, mentioned above, of intense ion and electron beams to fusion research and involves the development and use of large-scale computer programs for the simulation of plasma processes (R. V. E. Lovelace, R. N. Sudan). Some of the computer work uses the magnetic fusion energy computer facility at the Lawrence Livermore Laboratory. Also being considered are instabilities in space plasmas (R. N. Sudan), kinetic theory of plasmas (R. L. Liboff), and the dynamics of plasma in the nuclei of galaxies and quasars (R. V. E. Lovelace).



Professor Hans Fleischmann *(center)* uses relativistic electron beam experiments in the plasma physics research he directs. The RECE-CHRISTA shown here is one of three electron-ring machines used in this work.

Typical publications and theses (listed with the name of the supervising professor) in the area of plasma physics are:

Dreike, P. L. 1980. Formation, propagation and reflection of a rotating proton ring in a magnetic mirror. Ph.D. thesis (D. A. Hammer and R. N. Sudan).

Dreike, P. L.; Hammer, D. A.; Sudan, R. N.; and Wiley, L. G. 1978. Generation and propagation of an intense rotating proton beam. *Physical Review Letters* 41:1328.

Fleischmann, H. H.; Rej, D. J.; Tuszewski, M.; and Luckhardt, S. C. 1978. Experiments on the translation and compression of field-reversing E-layers and generation of superdense MeV-proton beams in a magnetically insulated diode. In *Proceedings of 3d international conference on collective methods of acceleration*. Irvine: University of California at Irvine.

Friedman, A.; Ferch, R. L.; Sudan, R. N.; and Drobot, A. T. 1977. Numerical simulation of strong proton rings. *Plasma Physics* 19:1101.

Larrabee, D. A., and Lovelace, R. V. 1980. Particle orbits in ion rings: ergodic or not? *Physics of Fluids* 23:1436.

Larrabee, D. A.; Lovelace, R. V.; and Fleischmann, H. H. 1979. Truncated exponential-rigid-rotor model for strong electron and ion rings. *Nuclear Fusion* 19:499.

Lockner, T. R., and Kusse, B. R. 1978. Intense relativistic electron beam trajectories and their effect on beam heating of toroidally confined plasma. *Journal of Applied Physics* 49:2357.

Lovelace, R. V. 1979. Kinetic theory of ion ring compression. *Physics of Fluids* 22:542.

Neri, J. M.; Hammer, D. A.; Ginet, G. P.; and Sudan, R. N. 1979. Intense lithium, boron and carbon beams from a magnetically insulated diode. *Applied Physics Letters* 37:101.

Tuszewski, M.; Rej, D. J.; and Fleischmann, H. H. 1979. Adiabatic magnetic compression of field-reversing E-layers. *Physical Review Letters* 43:449.

Quantum Optics, Laser Physics, and Nonlinear Optics

One of the more dramatic recent developments in physics has been the discovery and application of the laser as a source of intense coherent radiation. Research in this field combines many aspects of optics, atomic and molecular physics, solid-state physics, and chemistry. Opportunities for research in this field at Cornell include studies of light scattering, chemical and molecular lasers, tunable laser spectroscopy, linear and nonlinear optical properties of materials, the physics of electro-optical devices, and thin-film lasers and nonlinear optical devices for application in integrated optical systems. Laboratory research facilities are modern and sophisticated.

A study of nerve conduction processes is among the research applications of fluorescence correlation spectroscopy, a technique developed at Cornell. Here laser light illuminates fluorescent probes that indicate changes occurring when voltage is applied across an artificial membrane.

In the chemical and molecular laser field, research oriented toward the discovery and study of new laser systems is in progress. The relaxation of vibrational excitation in molecules through atomic and molecular collisions is being studied over a wide range of experimental parameters. In addition, laser-induced selective excitation of molecules is being studied as a means of selectively initiating chemical reactions under nonthermal conditions and for application to research on molecular energy transfer. Rare gas–halogen excimer lasers are used to study energy partitioning in photodissociation of metal halide molecules. (T. A. Cool).

Quantum optics and modern fluctuation correlation methods are being used to study the dynamics of turbulent flows, the kinetics of chemical reactions, and the statistical process as applied to superfluids. Coherent optics also find applications in a variety of biophysical experiments, including studies of the visual process, of diffusion in biological membranes, and of turbulence in flows chosen to simulate artificial blood flows. (W. W. Webb).

With the availability of intense laser sources, the nonlinear optical properties of solids, liquids, and gases have become accessible to detailed experimental study. The information obtained has led to improved understanding of many such materials and to an increasing number of applications of technological importance. Optical properties and applications of such materials as III-V, II-VI, and II-IV-V_2 compounds are being studied. In the electro-optics area, materials problems related to the development of thin-film miniaturized optical components and devices are under study.

Finally, tunable lasers from the ultraviolet to the infrared part of the spectrum are used for excitation spectroscopy and for studies of kinetic processes in atomic and molecular systems. This work is interdisciplinary, involving joint participation of faculty members and students in biology, chemistry, electrical engineering, and physics.

Some representative publications and theses (listed with the name of the supervising professor) in this area are:

Clark, M. D. 1975. Electron tunneling and electroluminescence by tunnel-injection through evaporated aluminum oxide films. Ph.D. thesis (J. M. Ballantyne).

Dragsten, P. R.; Webb, W. W.; Paton, J. A.; and Capranica, R. R. 1974. Auditory membrane vibrations—measurements at sub-angstrom levels by optical heterodyne spectroscopy. *Science* 185:55.

——. 1976. Light scattering heterodyne interferometer for vibration measurements in auditory organs. *Journal of the Acoustical Society of America* 60:665.

Dutta, N.; Warner, R. T.; and Wolga, G. J. 1977. Sensitivity enhancement of a spin-flip Raman laser absorption spectrometer through use of an intracavity absorption cell. *Optics Letters* 1:155.

Hui, K. K., and Cool, T. A. 1978. Experiments concerning the laser-enhanced reaction between vibrationally excited O_3 and NO. *Journal of Chemical Physics* 68:1022.

Koppel, D. E.; Axelrod, D.; Schlessinger, J.; Elson, E. L.; and Webb, W. W. 1976. Dynamics of fluorescence marker concentration as a probe of mobility. *Biophysical Journal* 16:1315.

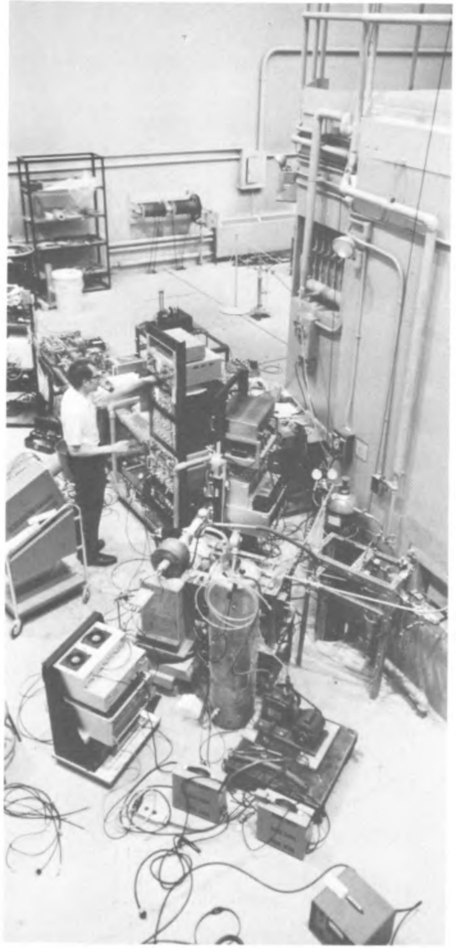
Pirkle, R. J.; Davis, C. C.; and McFarlane, R. A. 1975. Self-mode-locking of an iodine photodissociation laser. *Journal of Applied Physics* 46:4083.

Tang, C. L.; Kreismanis, V. G.; and Ballantyne, J. M. 1977. Wide-band electro-optical tuning of semiconductor lasers. *Applied Physics Letters* 30:113.

Low-Energy Nuclear Physics

Research and instruction in nuclear structure and low-energy nuclear physics are directed by professors who are members of both the graduate Field of Applied Physics and the graduate Field of Nuclear Science and Engineering. A student interested in this area can follow essentially the same program in either field; the choice depends on the aspect to be emphasized. If the student wishes to concentrate or minor in engineering applications such as nuclear power, nuclear science and engineering is the more appropriate field. If the interest is primarily in more basic studies or in applications of nuclear physics in other sciences such as astrophysics or geophysics, applied physics may be the more suitable field. In either field, the student can construct an individualized program in consultation with the faculty members on his or her special committee.

The facilities for experimental research in nuclear physics are housed in the Ward Laboratory of Nuclear Engineering (see the section on interdisciplinary activities).



Research in this area includes the study of isomeric excited states in nuclei, using theoretical models and experimental measurements made with the TRIGA reactor and a fast-transfer system. Several high-spin isomers have been discovered. The decay of isomeric states is frequently accompanied by the emission of x rays that result from internal atomic conversion and the consequent formation of vacancies in the inner electron shells; a method for determining properties of isomeric levels by observation of these x rays has been developed.

Also under investigation is a recently discovered kind of isomer that exhibits spontaneous fission. Shape isomerism, common among elements with atomic numbers of 92 and higher, is characterized by a "stretched" nucleus and a double hump in the fission barrier. Both theoretical and experimental work (using neutron beams from the TRIGA reactor) is in progress. Measurements are made with an inner-shell vacancy detector (ISV) that was developed by the research group.

Examples of recent publications based on thesis research are:

Boyce, J. R.; Cassel, E. T.; Clark, D. D.; Kostroun, V. O.; and McGuire, S. C. 1978. Isomerism in U-236. *Bulletin of the American Physical Society* 23:92.

Clark, D. D. 1971. Shape isomerism and the double-humped fission barrier. *Physics Today* 24(12):23.

Clark, D. D.; Kostroun, V. O.; and Siems, N. E. 1975. Identification of an isomer in Ag-110 at 1-keV excitation energy. *Physical Review C* 12:595.

A facility for research in low-energy nuclear physics is Cornell's TRIGA reactor, a source of neutron and gamma rays. This area is near one of the reactor's six beam ports.

Astrophysics

Astrophysics is an area in which Cornell has gained worldwide recognition. Special efforts are directed toward studies of planetary surfaces and atmospheres, infrared radiation from cosmic objects, the theory of high-energy objects such as quasars and pulsars, and radio and radar astronomy. Some of the faculty members of the Field of Applied Physics who are involved in these projects hold appointments in the Department of Astronomy or in the School of Electrical Engineering.

In addition to the extensive astrophysics laboratory facilities in Ithaca, there is available the National Astronomy and Ionosphere Center observatory, operated by Cornell University at Arecibo, Puerto Rico. This facility, which has a 1,000-foot radio-radar telescope (the world's largest), provides exceptional research opportunities for graduate students. (It is described in this booklet in the section on interdisciplinary activities.) At Arecibo the characteristics of pulsars are being defined through observations made with high signal-to-noise ratio. These observations have already provided the fundamental information that neutron star matter exists in the universe and is encountered in pulsars, and that the enormous energy released from these objects comes from the braking of their spins.

Although the underlying physics are not yet understood, the measurements — made sometimes with microsecond resolution — identify complex sets of phenomena that occur within the individual pulsar pulses; each pulsar has its own signature. (F. D. Drake).

Infrared observations of regions where stars are now being formed have been conducted, using a variety of new techniques. Instruments are developed at Cornell, and ground-based observations are made at observatory sites in the western United States. Because the atmosphere is opaque in most of the infrared spectral range, rocket-borne telescopes have been constructed and launched to observe the sky from above the atmosphere. Besides yielding information on the infrared radiation coming from cosmic sources, rocket flights have also provided new data on the thermal structure and composition of the upper atmosphere. (M. O. Harwit, J. R. Houck).

Theoretical and observational studies are being made of the turbulence in the ionosphere (R. N. Sudan, E. Ott, D. T. Farley) and of the large-scale electric fields and currents in the magnetosphere (M. C. Kelley). The theory of the modes and instabilities of flat disc, self-gravitating systems is being investigated (R. V. E. Lovelace).

Representative publications and theses (listed with the name of the supervising professor) in this area are:

Drake, F. D., and Sagan, C. 1973. Interstellar radio communication and the frequency selection problem. *Nature* 245:257.

Kuckes, A. F. 1971. Lunar electrical conductivity. *Nature* 232:249.

Lovelace, R. V. E. 1976. Dynamo model of double radio sources. *Nature* 262:649.

Lovelace, R. V. E.; MacAuslan, J.; and Burns, M. 1979. Particle acceleration in double radio sources. In *Particle acceleration mechanisms in astrophysics*, AIP conference proceedings no. 56, ed. J. Arons et al., p. 399. New York: American Institute of Physics.

Schaack, D. F. 1975. Infrared astronomical spectroscopy from high altitude aircraft. Ph.D. thesis (J. R. Houck).

Geophysics

Cornell has an expanding program in solid earth geophysics, with emphasis on the application of the basic sciences to the solution of problems of geology.

A program of seismological observations made in various parts of the world provides raw data for studies of earthquakes and of earth structure. Through the unifying new geological theory of plate tectonics, these studies are related to those of other disciplines and lead to a better understanding of the earth and its use. (J. E. Oliver, B. L. Isacks).

A theoretical and experimental investigation of solid-state mantle convection is also under way; its purpose is to determine the structure of convection cells within the earth and to interpret their interactions with the surface in terms of the global plate tectonic theory. These studies are also being extended to the interior of other planets and of the moon. (D. L. Turcotte).

Experimental studies of the electrical properties of the earth are motivated by interest in the geologic processes in the lower portions of the continental crust. Current activity in this area of research includes the application of electromagnetic methods to petroleum-well logging for exploration and for capping runaway wells. (A. F. Kuckes).

Representative publications and theses (listed with the name of the supervising professor) in this field are:

Billington, S., and Isacks, B. L. 1975. Identification of fault planes associated with

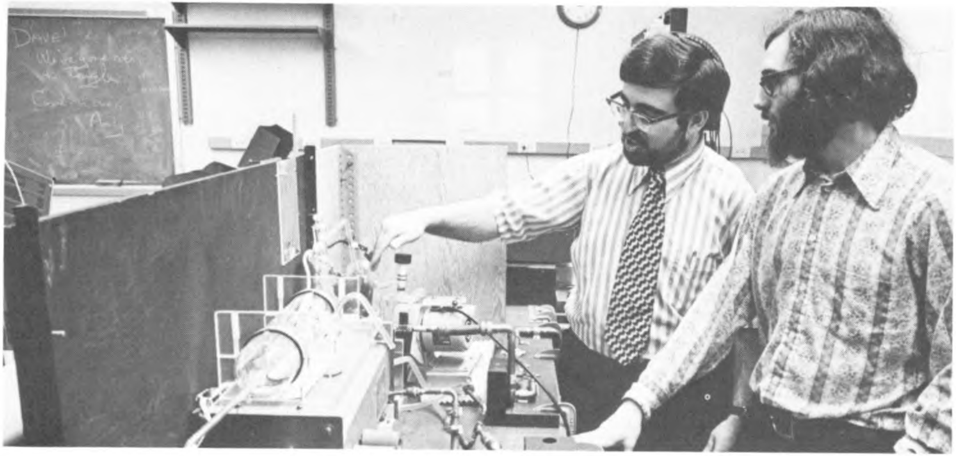
Electrical conductivity of the earth's deep crust is measured at a field station in the Adirondacks as part of a graduate research project.

deep earthquakes. *Geophysical Review Letters* 2:63.
Connerney, J. E. P.; Nekut, A.; and Kuckes, A. F. 1980. Deep crustal electrical conductivity in the Adirondacks. *Journal of Geophysical Research* 85:2603.
Frohlich, C. 1975. Upper mantle structures beneath the Fiji Plateau: seismic observations of second *P* arrivals from the olivine-spinel phase transition zone. Ph.D. thesis (B. L. Isacks).
Oliver, J.; Dobrin, M.; Kaufman, S.; Meger, R.; and Phinney, R. 1975. Continuous seismic reflection profiling of the deep basement: Hardeman County, Texas. *Bulletin of the Geological Society of America* 87:1537.
Turcotte, D. L., and Ahern, J. L. 1977. On the thermal and subsidence history of sedimentary basins. *Journal of Geophysics Research* 82:3766.
Worthington, M. H.; Kuckes, A. F.; and Oristiglio, M. 1980. A borehole induction procedure for investigating the electrical conductivity structure within the broad vicinity of a hole. *Geophysics* 46(1):65.

Biophysics

The interdisciplinary area of biophysics includes the many areas in which the methods and procedures of physics are used to study biological systems and biogenic materials. The members of the faculty and staff of the Field of Applied Physics who direct their research to biophysical problems are particularly interested in photobiology, the functional ultrastructure of cells, the configuration and molecular structure of macromolecules, and membrane processes. Their close collaboration with researchers in the Division of Biological Sciences and in the molecular biophysics program in the Department of Chemistry provides a wide range of research opportunities for interested students. Projects that have applications in biomedical engineering are also under way.

The chemistry of photosynthesis takes place in reaction centers that can be isolated from their natural environment (in photosynthetic bacteria as well as in green plants). The reaction centers, aside from being important in understanding the mechanics of photosynthesis, are interesting objects of study for molecular spectroscopy, quantum electron physics, and oxidation-reduction photochemistry. Experimental research in this area includes biochemical preparations and chemical analyses as well as physical methods of absorption-emission spectroscopy. (R. K. Clayton).



Laser Raman scattering from biologically important molecules is used in biophysical research directed by Professor Aaron Lewis *(left)*.

Recent developments in tunable lasers are being used to study the mechanisms of cellular excitation and the subsequent transduction of a neural response in visual photoreceptor cells. Similar techniques are also applied to a related problem in cell biology: the mechanism of active transport across cell membranes. This work involves study of bacteriorhodopsin, a protein that is similar to rhodopsin, the primary light absorber and initiator of the visual process. The results obtained thus far have yielded new insights into the problems of visual transduction and active transport in cells, and have suggested possible avenues for applying these insights to the development of solar cells to produce hydrogen. (A. Lewis).

Determination of the three-dimensional structure of macromolecules is essential if the molecular mechanisms of their activity are to be understood. The structure of a small, vitamin D–dependent calcium-binding protein involved in some way in the intestinal translocation of calcium is being determined by conventional x-ray macromolecular crystallographic techniques, supplemented by fluorescence studies of the binding of lanthanide and calcium. The structural and functional properties of the oxygen transport protein hemoglobin are being investigated through parallel crystallographic and kinetic studies of a series of hemoglobins that have been reconstituted with chemically modified heme groups. The goal is to clarify the role of the heme group itself in the ligand-binding reactions, and the way in which its properties are modified by interaction with the globin. (K. Moffat).

The electrical properties of plant cell membranes are of particular interest because it is becoming clear that they are controlled by the systems responsible for active transport (ion pumps) rather than by the passive movement of ions. The microelectrode techniques employed in these studies are also being used to investigate the role of intercellular connections in long-distance transport. (R. M. Spanswick).

Physical methods are also used in studies of nerve cells and innervated structures, secretory cells, and developing (embryonic) cells. New methods are being developed for studying the physiology of these cells on a fine-structure level. The most important recent example is the application of quantitative electron microscope autoradiography (that is, the high-resolution detection of radioactivity inside cells) to the study of cellular function. By introducing radioactive precursors into the cell, one can localize the cellular compartments that are involved in the production, storage, and transport of secretory products. Studies are also conducted on the sites of action of neurotransmitters and various enzymes involved in nerve function. (M. M. Salpeter).

Investigations of the configuration and atomic structure of macromolecules are being pursued with the use of very-high-resolution microscopy. In this work, a collaborative program with a Japanese group has been established to develop computer-image processing of high-resolution electron micrographs. The Japanese group in Kyoto has a 500-keV electron microscope with which they are obtaining the highest-resolution images in the world today. Their micrographs of radiation-sensitive materials are processed by computer at Cornell to extend the observable resolution and extract additional information that cannot be observed directly in the images as recorded by the electron microscope. (B. M. Siegel).

The dynamics of biophysical processes are being studied with the help of modern physical optics. Diffusion and the chemical kinetics of

A researcher exposes the sternomastoid muscle of a live anesthetized mouse prior to application of specific radio-labeled reagents that bind to esterase molecules at the nerve-muscle junction. Fixed muscle is prepared in 1000-Å sections for autoradiography using an electron microscope.

membrane processes in model membranes and in living normal and cancer cells are being measured by analysis of the spectrum of the fluctuations of fluorescence emitted by chemical indicators, by the recovery of fluorescence after photobleaching, and by fluorescence polarization. The kinetics of cooperative chemical binding by hemoglobin are studied by optical observation of photolysis dynamics. The dynamics of lateral motion of special cell membrane components involved in essential cell membrane processes

Electron microscopy is used in studies of biogenic macromolecules conducted by Professor Benjamin Siegel *(foreground)* and his research group.

(such as the immune and allergic response, nerve signal transmission, and hormone function) have been measured for the first time, and these processes have thereby been elucidated. The physical nature of membrane fluidity, its effect on lateral motion in the cell membrane, and its dependence on lipid composition and structure are major questions for current study. Since the coupling of membrane components to the cytoskeleton and exoskeleton is an essential feature of the movement in cell membranes, those aspects of cell physiology are also being studied. Molecular mechanisms that drive cytoplasmic streaming in plant cells are being investigated by means of laser-optical techniques for measuring motion, and with the use of fluorescent labels of contractile plant proteins. A video image intensifier system has been developed to perform high-sensitivity fluorescence microscopy in topographic studies of microscopic movements in cells. (W. W. Webb).

Among recent publications and theses (listed with the name of the supervising professor) are:

Barak, L. S.; Yocum, R. R.; Nothnagel, E. A.; and Webb, W. W. 1980. Fluorescence staining of the actin cytoskeleton in living cells with NBD-phallacidin. *Proceedings of the National Academy of Sciences (USA)* 77:980.

Clayton, R. K. 1970 and 1971. *Light and living matter*, vols. I and II. New York: McGraw-Hill.

Dragsten, P. R., and Webb, W. W. 1978. Mechanism of the membrane potential sensitivity of the fluorescent membrane probe merocyanine 540. *Biochemistry* 17:5228.

Kirkland, E. J.; Siegel, B. M.; Uyeda, N.; and Fujiyoshi, Y. 1980. Digital reconstruction of bright field phase contrast images from high resolution electron micrographs. *Ultramicroscopy* 4:450.

Lewis, A. 1978. The molecular mechanism of excitation in visual transduction and bacteriorhodopsin. *Proceedings of the National Academy of Sciences (USA)* 75:549.

Marcus, M. A., and Lewis, A. 1977. Kinetic resonance Raman spectroscopy: dynamics of bacteriorhodopsin. *Science* 195:1328.

Salpeter, M. M.; McHenry, F. A.; and Salpeter, E. E. 1978. Resolution in electron microscope autoradiography. IV. Application to analysis of autoradiographs. *Journal of Cell Biology* 76:127.

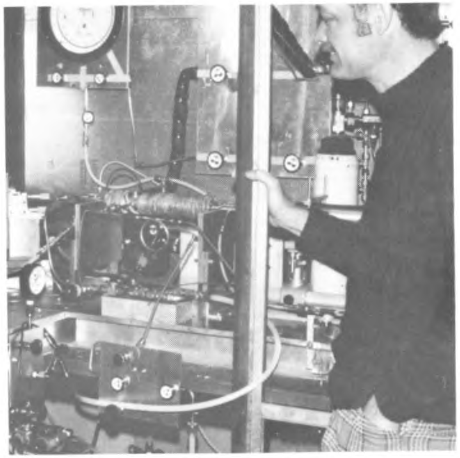
Schlessinger, J.; Barak, L. S.; Hammes, G. G.; Yamada, K. M.; Pastan, I.; Webb, W. W.; and Elson, E. L. 1977. Mobility and distribution of a cell membrane glycoprotein and its interaction with other membrane components. *Proceedings of the National Academy of Sciences (USA)* 74:2909.

Seybert, D. W.; Moffat, K.; Gibson, Q. H.; and Change, C. K. 1977. Electronic and steric factors affecting ligand binding: horse hemoglobins containing 2,4-dimethyldeuteroheme and 2,4-dibromodeuteroheme. *Journal of Biological Chemistry* 252:4225.

Atomic and Molecular Physics

A precise knowledge of the processes that can occur when atoms and molecules interact by collision is of great importance in applied physics. Current efforts in atomic and molecular physics are directed toward an understanding of collisionally induced processes that occur in several different physical environments. These include (1) studies of dissociation, ionization, recombination, molecular energy transfer, and chemical kinetics in gases with thermal kinetic energies; (2) study of gas-surface phenomena, including catalysis, chemisorption, oxidation, and related phase transformations that occur at solid surfaces; and (3) studies of molecular structure using the diffraction of 50–100 keV electrons from gas-phase molecules. The following projects constitute a partial description of current research.

Details of energy transfer and particle rearrangement that occur in collisions involving vibrationally or rotationally excited molecules are being studied in view of their importance in the operation of molecular gas lasers. For this purpose, nonequilibrium distributions of molecular excitation in gases are initiated by nonchemical shocks or electrical discharges. Using various diagnostics, the kinematic evolution of these systems is investigated and the results analyzed in terms of the basic processes involved. (S. H. Bauer, T. A. Cool). Additional studies that are of direct relevance to chemical and molecular gas lasers are based on the laser-induced fluorescence technique. This technique permits the selective initiation and monitoring of specific vibrational and rotational



Professor Terrill Cool is shown with an apparatus for laser-induced fluorescence used to measure the rates of vibrational energy transfer in chemical lasers.

energy transfer processes in laser molecules. (T. A. Cool, G. J. Wolga).

Rare gas–halide excimer lasers are used for studies of photodissociation of small molecules. Direct and laser-induced fluorescences from photofragments are monitored for determinations of energy distributions of the fragments. (T. A. Cool).

Significant applications of electron and x-ray spectroscopy to the determination of the microphysics of chemical bonding and reactivity in atoms and molecules are under way. These employ the high-intensity polarized photon sources available at Tantalus, a synchrotron radiation facility in Wisconsin, and at CHESS, the high-energy electron source at Cornell University. Special effort is focused on polynuclear metal cluster chemistry and its role in heterogeneous catalysis. (T. N. Rhodin).

Radiation from Cornell's 12-GeV electron synchrotron is used in a variety of experiments in atomic and solid-state physics. The experiments are chosen to exploit several unique features of synchrotron radiation; these features include a high intensity of x rays in the 3–100 keV photon range, a continuous spectral distribution, and a high degree of collimation (10 seconds of arc). Among such studies are investigations of the lifetimes of core-excited states of atoms, of the specific decay modes of these states, of the transition rates for the radiative and nonradiative processes involved, and of numerous processes of interaction between electromagnetic radiation and matter. As an example of the latter, extended x-ray absorption fine structure is being studied by both photon detection and x-ray interferometric techniques as a means of investigating the local environment of atoms in substances of solid-state and biological interest. (V. O. Kostroun).

The small-angle scattering of 500–100 keV electrons by gas molecules is being investigated; from the measured diffraction pattern, structural information, particularly on bond distances between atoms, can be derived. This method is applicable to a variety of gases. (S. H. Bauer).

Recent publications and theses (listed with the name of the supervising professor) include:

Brodén, C., and Rhodin, T. 1976. Photoemission spectroscopy of chemical reactions on platinum-group metals — chemisorption of carbon monoxide in iridium. *Solid State Communications* 18:105.

Brucker, C., and Rhodin, T. 1976. Low-energy electron-diffraction, Auger and photoemission studies of oxygen reactions on α-Fe(100) surfaces. *Surface Science* 57:523.

———. 1980. Photoelectron spectra of metal molecular clusters. *Journal of Vacuum Science and Technology* 17(1):221.

Cool, T. A.; McGarvey, J. A., Jr.; and Erlandson, A. C. 1978. Two-photon excitation of mercury atoms by photodissociation of mercury halides. *Chemical Physics Letters* 58:108.

Kostroun, V. O.; Fairchild, R. W.; Kukkonen, C. A.; and Wilkins, J. W. 1976. Systematic structure in the K-edge photoabsorption spectra of the 4d transition metals. *Physical Review B* 13:3268.

Liboff, R. L. 1977. Conjectured superfluidity of deuterium. *Physics Letters* 61A:244.

Madronich, S.; Weisenfeld, J. R.; and Wolga, G. J. 1977. Observation of E→V energy transfer from $O_2(^1\Delta)$ to HF. *Chemical Physics Letters* 46:267.

Muettertries, E. L.; Rhodin, T. N.; Band, E.; Brucker, C. F.; and Pretzer, W. R. 1979. Clusters and surfaces. *Chemical Reviews* 79:91.

Statistical Physics

Statistical physics provides the theoretical connection between the detailed microscopic motions of atomic particles and macroscopic, physically measurable quantities. An active interplay between theory and experiment is characteristic of study in this area and contributes to its vitality. Work in statistical physics has greatly increased the understanding of such varied forms of matter as liquids, gases, plasmas, superfluid gas (helium), superconductors, and magnetic systems.

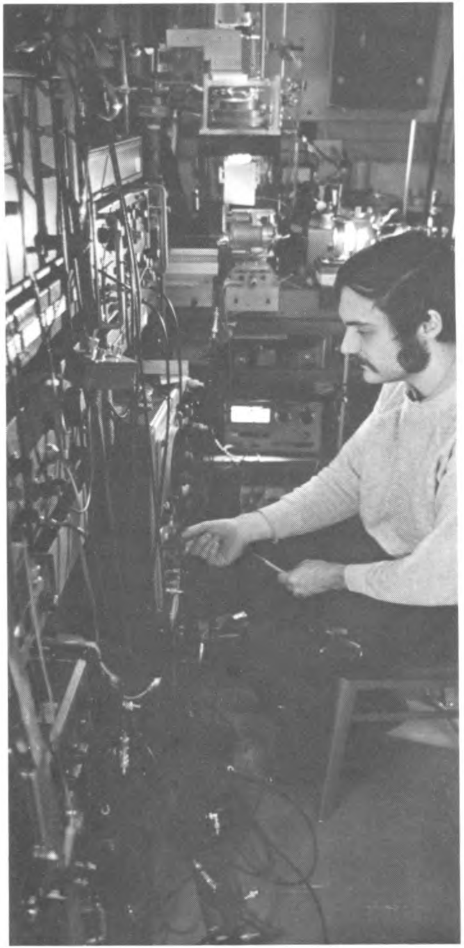
A current theoretical study of phase transitions and critical and multicritical phenomena involves work in statistical mechanics and includes both applications and rigorous mathematical formulation. Systems that have been studied in bulk and in films include ferromagnets and antiferromagnets, superfluids, binary alloys, ternary fluid mixtures, and ferroelectrics. Questions in mathematics concerning spatial dimensionality, combinatorics, counting linear graphs, and special determinants and matrices arise in the course of such work. The renormalization group is a recently invented theoretical tool that has had important applications to these problems. (M. E. Fisher).

Experimental studies of cooperative phenomena are making use of newly devised optical correlation techniques based on modern lasers. For example, time correlation techniques have permitted analysis of inelastic scattering of visible light with an effective resolution of 10^{-16}. Modern optical techniques are also applied to studies of critical phenomena in fluids, turbulence, homogeneous nucleation fluctuations in quantum fields, and surface waves. (W. W. Webb).

Fluctuations in superconductors and cooperative phenomena in metals at extremely low temperatures are also being investigated. Superconducting quantum interference magnetometers have been developed and applied to problems in statistical physics; an absolute thermometer that works at temperatures between 10^{-2} and 10^{-5} °K by measuring nuclear magnetization with a superconducting magnetometer has been developed; and fluctuation-induced diamagnetism above the critical temperature of superconductors has been measured and analyzed. (R. A. Buhrman).

Also of interest is the application in biophysics and geophysical hydrodynamics of approaches that have been developed for observing the chemical physics of cooperative phenomena. (W. W. Webb).

The properties of molecular liquids are being investigated by statistical mechanics and computer simulation techniques. Theoretical methods that are under development and appear promising include perturbation theory and integral equation techniques. These methods are being used to study phase diagrams for polar liquid mixtures, neutron diffraction patterns, and the properties of gas-liquid surfaces. In each of these cases the orientational correlations between molecules (due to the anisotropic electrostatic, shape, and other intermolecular forces) have a pronounced effect on both the correlation



functions and the macroscopic properties. The aim of this work is to clearly establish the relationship between experimentally observed properties and the underlying intermolecular forces. The computer simulation work provides precise data on model liquids for which the intermolecular forces are exactly specified; comparison with theory then provides an unambiguous test of the theoretical approximations, and comparison with experiment tests the intermolecular force model. The simulations provide a wealth of information not accessible by laboratory experiments; this includes static and time correlation functions and properties under extreme conditions of temperature and pressure. In the case of gas-liquid surfaces these simulation studies yield not only time correlation functions and diffusion coefficients parallel and perpendicular to the surface, but also density, concentration, and orientation of the molecules as functions of their position in the surface region. (K. E. Gubbins).

The theory of fully developed hydrodynamic turbulence is being investigated as a problem in statistical physics. This has application in many areas — in particular, to the dynamics of the atmosphere — but the present work emphasizes an improved basic understanding of turbulent fluid flow. During the past several years there have been several contributions to an improved understanding of the small-scale velocity fluctuations that occur at very high Reynolds numbers; these are characterized by scale-similar correlation functions that exhibit a family of universal scaling exponents. There are remarkable analogies to the phenomenological scaling behavior in equilibrium critical phenomena, despite deep differences in the underlying physics. Progress has relied so far on models of a random cascade of energy from large- to small-scale motions. Both the problem of deriving nonlinear dynamical cascade models from the underlying Navier-Stokes equations and the equally interesting problem of the solutions of the resulting approximate dynamical equations are considered. In some cases these model equations have smooth solutions, and in others the deterministic equations have random solutions. A proper mathematical description of these strongly nonlinear systems of equations and their relation to observed statistical properties of turbulent flow continues under study. (M. S. Nelkin).

The kinetics of an important biophysical process are studied with use of a laser beam. Carbon monoxide bound to hemoglobin is "knocked off" by the beam, and the speed of recombination is measured.

Turbulent flow in liquids, elementary thermal excitation and structure of surfaces and interfaces in mixtures, and cooperative deformation of fluid membranes are measured by analyzing the time correlation spectra of fluctuations that are detected by scattering and reflection of coherent laser light. New techniques are being developed to measure the vorticity in turbulent liquids and the electrical polarization of fluid films. (W. W. Webb).

Some recent publications in this area are:

Bell, T. L., and Nelkin, M. S. 1977. Nonlinear cascade models for fully developed turbulence. *Physics of Fluids* 20:345.

Buhrman, R. A., and Halperin, W. P. 1973. Fluctuation diamagnetism in a "zero-dimensional" superconductor. *Physical Review Letters* 30:692.
Fisher, M. E. 1974. The renormalization group in the theory of critical behavior. *Reviews of Modern Physics* 46:597.
Fisher, M. E., and Kerr, R. M. 1977. Partial differential approximants for multicritical singularities. *Physical Review Letters* 39:667.
Frish, M. B., and Webb, W. W. 1980. Direct measurement of vorticity by optical probe. *Journal of Fluid Mechanics* (in press).
Gubbins, K. E.; Gray, C. G.; and Egelstaff, P. A. 1978. Thermodynamic derivatives of correlation functions. *Molecular Physics* 35:315.
Leiderer, P.; Nelson, D. R.; Watts, D. R.; and Webb, W. W. 1974. Tricritical slowing down of superfluid dynamics in ^3He-^4He mixtures. *Physical Review Letters* 34:1080.
Mantese, J. V.; Goldburg, W. I.; Darling, D. H.; Craighead, H. G.; Gibson, U. J.; Buhrman, R. A.; and Webb, W. W. 1980. Excess low frequency conduction noise in a granular composite. *Solid State Communications* (in press).
Nelkin, M., and Bell, T. L. 1978. One-exponent scaling for very high Reynolds number turbulence. *Physical Review A* 17:363.
Streett, W. B., and Gubbins, K. E. 1977. Liquids of linear molecules: computer simulation and theory. *Annual Reviews of Physical Chemistry* 28:373.

The development of a photon radiation source using microwave excitation of a helium gas plasma is the project for this M.Eng.(Engineering Physics) degree candidate. The source is coupled to a photoemission spectrometer used to study surface chemical reactions of transition metals.

M.Eng.(Engineering Physics) Degree Program

The program for the professional degree of Master of Engineering (Engineering Physics) is offered as a fifth year of study following a Cornell undergraduate program in engineering physics, or the equivalent. Students who earn the degree may move into applied physics development or research programs in industrial or government organizations or may proceed to more advanced graduate work in applied physics or related areas. The degree program may be useful, for example, as exploratory study for those who are interested in starting graduate work but not ready to make a commitment to a specific field. Or it can be used to satisfy prerequisite course work for certain new areas of graduate study that involve a combination of engineering or applied physics and another discipline, either technical or nontechnical.

There is considerable flexibility in the curriculum; each student plans an individualized program in consultation with the head of the program committee. Requirements for the degree include a minimum of six credits in a graduate-level course sequence; a graduate-level course in quantum mechanics and an advanced course in statistical mechanics, or their equivalents; and a weekly report on a University seminar or colloquium chosen in consultation with the program head.

The M.Eng. project requirement is satisfied by a study or project, either experimental or analytical, that requires individual effort and is completed with a formal report. This project carries at least six credits. If the project is experimental, one course in mathematics or applied mathematics at the graduate level is required; if the project is analytical, one term in experimental laboratory physics or its equivalent must be taken.

Faculty members of the School of Applied and Engineering Physics available as advisers for M.Eng. projects are B. W. Batterman, R. A. Buhrman, K. B. Cady, D. D. Clark, R. K. Clayton, T. A. Cool, H. H. Fleischmann, V. O. Kostroun, J. A. Krumhansl, A. F. Kuckes, B. R. Kusse, A. Lewis, R. L. Liboff, R. V. E. Lovelace, M. S. Nelkin, T. N. Rhodin, M. M. Salpeter, B. M. Siegel, J. Silcox, R. N. Sudan, W. W. Webb, and G. J. Wolga. Other members of the University staff may also serve as project advisers.

The titles of some recent projects or studies by M.Eng.(Engineering Physics) students, and the names of the supervising professors, are:

Langmuir Probe Plasma Measurements (B. R. Kusse)
Microwave Excited UV Light Source (T. N. Rhodin)
Problem in Electron Microscopy (J. Silcox)
Study of Earth Magnetism (R. L. Liboff)
System Design of Laser Scanning Device as Aid in Looking at Defects and Imperfections (J. M. Ballantyne, in electrical engineering)
Absorptive Properties of Synchrotron Radiation (B. W. Batterman)

Faculty Members and Their Research Interests

The faculty of the graduate Field of Applied Physics includes members of a number of schools and departments in the College of Engineering as well as other units of the University. These include Applied and Engineering Physics, Astronomy, Biological Sciences, Chemistry, Electrical Engineering, Geological Sciences, Materials Science and Engineering, Mathematics, and Mechanical and Aerospace Engineering.

Dieter G. Ast, Dipl.Phys. (Stuttgart), Ph.D. (Cornell): *amorphous materials and polymeric materials*
Peter L. Auer, A.B. (Cornell), Ph.D. (California Institute of Technology): *plasma physics, energy policy*
Joseph M. Ballantyne, B.S., B.S.E.E. (Utah), S.M., Ph.D. (M.I.T.): *semiconductor lasers and detectors, integrated optical devices, solar cells*
Boris W. Batterman, B.S., Ph.D. (M.I.T.): *x-ray and neutron diffraction, synchrotron radiation, solid-state physics*
John M. Blakely, B.S., Ph.D. (Glasgow): *surface physics and chemistry*
Robert A. Buhrman, B.S. (Johns Hopkins), Ph.D. (Cornell): *superconducting devices, solid-state and low-temperature physics, submicron lithography*
K. Bingham Cady, B.S., Ph.D. (M.I.T.): *reactor physics*
David D. Clark, A.B., Ph.D. (California, Berkeley): *experimental nuclear and reactor physics*
Roderick K. Clayton, B.S., Ph.D. (California Institute of Technology): *biophysics, photosynthesis*
Terrill A. Cool, B.S. (California, Los Angeles), M.S., Ph.D. (California Institute of Technology): *molecular lasers, chemical physics*
P. C. Tobias de Boer, Ir.(M.E.) (Delft), Ph.D. (Maryland): *high-temperature gasdynamics, plasma physics*
Frank D. Drake, B.E.P. (Cornell), M.S., Ph.D. (Harvard): *radio emission from pulsars, radio and radar studies of the moon and planets*
Lester F. Eastman, B.E.E., M.S., Ph.D. (Cornell): *microwaves, solid-state plasma*
Thomas E. Everhart, A.B. (Harvard), M.Sc. (California, Los Angeles), Ph.D. (Cambridge): *scanning electron microscopy*
Michael E. Fisher, B.Sc., Ph.D. (London): *mathematical physics, statistical mechanics, phase transitions and critical phenomena*
Hans H. Fleischmann, Dipl.Phys., Dr.rer.nat. (Technical University, Munich): *plasma physics, thermonuclear fusion*
Edward R. Grant, B.A. (Occidental), Ph.D. (California, Davis): *molecular and chemical physics*
Keith E. Gubbins, B.S., Ph.D. (London): *statistical mechanics of liquids, liquid surfaces*

David A. Hammer, B.S. (California Institute of Technology), Ph.D. (Cornell): *plasma physics, thermonuclear fusion*

Martin O. Harwit, B.A. (Oberlin), Ph.D. (M.I.T.): *astrophysics*

James R. Houck, B.S. (Carnegie-Mellon), Ph.D. (Cornell): *astrophysics*

Paul L. Houston, B.S. (Yale), Ph.D. (M.I.T.): *molecular and chemical physics*

Michael S. Isaacson, B.S. (Illinois, Urbana), S.M., Ph.D. (Chicago): *scanning transmission electron microscopy*

Bryan L. Isacks, A.B., Ph.D. (Columbia): *seismology, global tectonics*

Herbert H. Johnson, B.S., M.S., Ph.D. (Case): *mechanical behavior of solids*

Vaclav O. Kostroun, B.Sc., M.Sc. (Washington), Ph.D. (Oregon): *low-energy nuclear and atomic physics*

Edward J. Kramer, B.Ch.E. (Cornell), Ph.D. (Carnegie-Mellon): *low-temperature physics, polymers*

James A. Krumhansl, B.S. (Dayton), M.S. (Case), Ph.D. (Cornell): *theoretical and applied physics*

Arthur F. Kuckes, B.S. (M.I.T.), Ph.D. (Harvard): *geophysics, plasma physics*

Bruce R. Kusse, B.S., Ph.D. (M.I.T.): *electron beam physics, plasma physics*

Charles A. Lee, B.E.E. (Rensselaer), Ph.D. (Columbia): *solid-state physics*

Aaron Lewis, B.S. (Missouri), Ph.D. (Case Western Reserve): *cellular biophysics, transduction mechanisms in visual photoreceptor cells, active transport across cell membranes*

Richard L. Liboff, A.B. (Brooklyn), Ph.D. (New York University): *plasma physics, statistical mechanics*

Richard V. E. Lovelace, B.S. (Washington), Ph.D. (Cornell): *plasma physics theory, astrophysics*

Robert Merrill, Chem.E. (Cornell), Sc.D. (M.I.T.): *surface physics*

Keith Moffat, B.S. (Edinburgh), Ph.D. (Cambridge): *protein crystallography, structure and function of proteins*

John A. Nation, B.Sc., Ph.D. (Imperial College, London): *plasma physics, thermonuclear fusion*

Mark S. Nelkin, B.S. (M.I.T.), Ph.D. (Cornell): *statistical physics, turbulent fluid flow*

Jack E. Oliver, B.A., M.A., Ph.D. (Columbia): *seismology, global tectonics*

Thor N. Rhodin, B.S. (Haverford), A.M., Ph.D. (Princeton): *physics and chemistry of surfaces and interfaces of metals and semiconductors*

Arthur L. Ruoff, B.S. (Purdue), Ph.D. (Utah): *high-pressure phenomena, imperfections in crystals, creep*

Miriam M. Salpeter, B.A. (Hunter), M.S., Ph.D. (Cornell): *biophysics*

David N. Seidman, B.S., M.S. (New York University), Ph.D. (Illinois): *defects in solids, radiation damage*

Benjamin M. Siegel, B.S., Ph.D. (M.I.T.): *electron microscopy, surface physics, biophysics*

John Silcox (Director of the School of Applied and Engineering Physics), B.Sc. (Bristol), Ph.D. (Cambridge): *electron microscopy, imperfections in crystals, superconductivity, ferromagnetism*

Roger M. Spanswick, B.Sc. (Birmingham), Dipl.Biophys., Ph.D. (Edinburgh): *biophysics, ion transport*

Ravindra N. Sudan, B.A. (Punjab, India), M.S. (Indian Institute of Science), D.I.C. (Imperial College, London), Ph.D. (London): *plasma physics*

Chung L. Tang, B.S. (Washington), M.S. (California Institute of Technology), Ph.D. (Harvard): *quantum electronics*

Donald L. Turcotte, B.S. (California Institute of Technology), M.Aero.E. (Cornell), Ph.D. (California Institute of Technology): *aerospace engineering, gasdynamics, geophysics*

Watt W. Webb, B.S., Sc.D. (M.I.T.): *cellular biophysics, chemical physics, cooperative phenomena, hydrodynamics, physical optics, photon correlation spectroscopy*

Charles B. Wharton, B.S., M.S. (California, Berkeley): *plasma physics, microwave electronics*

George J. Wolga, B.E.P. (Cornell), Ph.D. (M.I.T.): *magneto-optics, quantum electronics, light scattering in solids, photoacoustic spectroscopy*

Further Information

Additional information may be obtained by writing to the Graduate Faculty Representative, Applied Physics, Cornell University, Clark Hall, Ithaca, New York 14853.

Chemical Engineering

The graduate Field of Chemical Engineering at Cornell offers advanced-degree programs to better equip students with the skills necessary for productive and rewarding technical careers in industry, education, and government. The programs strike a balance between the science of chemical engineering and more empirical engineering approaches. This blend provides students with a strong base in the fundamentals of chemical engineering and with the ability to apply these fundamentals to significant engineering problems.

Approximately fifty students are now pursuing graduate study in a variety of areas, many of them interdisciplinary. Cornell offers exceptional opportunities for interdisciplinary research, and the system of graduate fields encourages such studies. Faculty members within the School of Chemical Engineering are involved in collaborative work with researchers in the Fields of Applied Mathematics, Applied Physics, Electrical Engineering, Materials Science and Engineering, and Mechanical Engineering. Graduate students broaden their education by taking advantage of courses offered in the many distinguished schools and departments at Cornell. In addition to minors in other engineering fields, the physical sciences, or the biological sciences, students may select minors in such fields as business administration, economics, and law.

The faculty is an outstanding group of sixteen professionals with a strong commitment to scholarly research and teaching. Close student-faculty interaction is encouraged, and the moderate size of the department promotes a friendly and personal educational environment. Many of the faculty members keep in close touch with chemical engineering practice by serving as consultants to industry and government. Five have received the annual Tau Beta Pi–Cornell Society of Engineers Excellence in Engineering Teaching Award, and four are authors or coauthors of the following textbooks that are in common use throughout the country:

Harriott, P. 1964. *Process control*. New York: McGraw-Hill.

McCabe, W. L., and Smith, J. C. 1976. *Unit operations of chemical engineering*. 3rd ed. New York: McGraw-Hill.

Reed, T. M., and Gubbins, K. E. 1973. *Applied statistical mechanics: thermodynamic and transport properties of fluids*. New York: McGraw-Hill.

Rodriguez, F. 1970. *Principles of polymer systems*. New York: McGraw-Hill.

Three graduate degrees are offered in chemical engineering: Master of Engineering (Chemical), Master of Science, and Doctor of Philosophy. The professional M.Eng. (Chemical) degree program, which is described in some detail below, requires advanced course work and a design project. The research-oriented M.S. and Ph.D. programs require a thesis. Each student selects a thesis adviser and a special committee, which is headed by the adviser and includes two additional faculty members (see the section General Information). Students entering the Graduate School with a B.S. degree in chemical engineering generally complete the M.Eng. program in one academic year, the M.S. program in a year and a half, or the Ph.D. program in about four years. Work leading to the M.Eng.(Chemical) or the M.S. degree may be applied toward, but is not required for, the Ph.D. program.

Facilities

The School of Chemical Engineering is housed in spacious Olin Hall, centrally located on the Cornell campus. The many general laboratories (recently refurbished) for graduate research are supplemented by specialized laboratories designed and equipped for work in biochemical engineering, kinetics and catalysis, microscopy, polymer science, surface science, thermodynamics, and transport phenomena.

Many students take advantage of the excellent computing facilities on campus. Cornell's Computer Services maintains a floating point systems array processor in conjunction with an IBM 370/168 central computer. The speed of the array processor is similar to that of a CDC 7600; it has at present 430 kilobytes of memory. A substantial amount of time on this machine (more than a thousand hours a year) is allocated for research conducted by the School of Chemical Engineering on computer simulation of liquid mixtures. In addition to the University computing facilities, the school has its own PDP 11/70 computer, the largest of the PDP 11 series. With 512 kilobytes of core plus 81 megabytes of disk, this machine is comparable in speed to such mainframe computers as the IBM 360, the CDC 6400, and the Honeywell 6000 series. Auxiliary equipment includes eight time-sharing terminals, a tape drive, and a high-speed printer-plotter. The PDP 11/70 is used primarily by graduate students for computer simulation, analysis of experimental data, and control of laboratory experiments housed in Olin Hall.

Cornell also supports such unique facilities as the Materials Science Center, the Cornell High Energy Synchrotron Source, and the National Research and Resource Facility for Submicron Structures (a new research center under the sponsorship of the National Science Foundation). Faculty members and graduate students in the School of Chemical Engineering use these facilities in a variety of research programs, most notably in biochemical engineering and surface science.

Graduate Courses

The school offers a large number of graduate courses covering fundamental areas and many specialty areas of chemical engineering. Most M.S. and Ph.D. students elect to take the following core courses:

711 Advanced Chemical Engineering Thermodynamics
713 Applied Chemical Kinetics
731 Advanced Transport Phenomena
751 Mathematical Methods of Chemical Engineering Analysis

More specialized advanced courses include:

623 Synthetic Fuels
627 Nuclear and Reactor Engineering
640 Polymeric Materials
641 Physical Polymer Science
642 Polymeric Materials Laboratory
644 Microbial Engineering
647 Wastewater Engineering in the Process Industries
648 Polymer Processes
661 Air Pollution Control
673 Applied Surface Chemistry and Physics
680 Chemical Microscopy
681 Electron Microscopy
772 Theory of Molecular Liquids

Additional design-oriented courses, intended primarily for M.Eng. students, are available also to M.S. and Ph.D. students. Further information is given in the catalog *Courses of Study*.

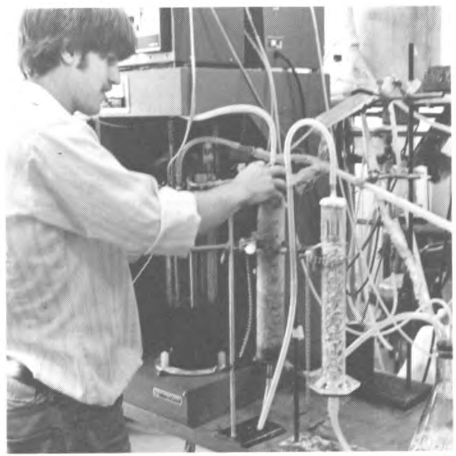
Research Activities

Research in chemical engineering in both industrial and academic environments addresses an enormous range of technical problems. This is evident when one considers some of the new challenges confronting chemical engineers: more efficient use of energy resources, development of alternative energy sources, protection of air and water quality, waste disposal, biomedical engineering, and expansion of food supplies. Although specific projects may address these problems directly, the school's research programs emphasize the fundamental chemical engineering principles that can be broadly applied to diverse technical problems. The school has sought to encompass all fundamental areas of chemical engineering in its research programs; as a result, there is a wide variety of areas from which thesis topics may be selected. Each of these areas is discussed below.

Biochemical Engineering

The goal of the research program in biochemical engineering is to contribute to the basic understanding of cellular kinetics, transport phenomena, and biochemical control mechanisms and to apply the results of these investigations in the synthesis of biological processes that satisfy specific, well-defined technological needs. The methods employed in individual projects within the program often involve a combination of laboratory experimentation on single-cell and many-cell systems, mathematical modeling, computer simulation, and process design. A wide range of problems is under investigation.

M. L. Shuler directs a number of projects aimed at understanding the detailed dynamics of growth at the scale of the individual cell. His research group has developed a computer model capable of simulating cell growth under a variety of conditions. The model not only provides quantitative predictions for the rates of production of specific metabolites but also can be used to test proposed control mechanisms for cell growth. The ultimate use (and test) of a model of this type is to determine optimal conditions for the production of a desired metabolite. An example is L-asparaginase, an enzyme produced by the bacterium *E. coli*. Although L-asparaginase is a promising drug for the treatment of leukemia, yields are currently too low for commercial manufacture of this enzyme. The computer model has been applied to simulate the growth of *E. coli*, primarily to predict the conditions that enhance the production of L-asparaginase. Eventually, predictions from the model will be used in the design of an improved reactor system to increase the yield of this specific metabolite.



The validity of the form of the model will be tested by a comparison between predictions and experimental data to be gathered in a cooperative project with M. Kim of the electrical engineering faculty. To aid in the measurements, a special growth chamber, capable of monitoring the growth of a single cell, is being developed at the University's submicron facility. Ultimately this growth chamber will be equipped to measure precisely the uptake of a variety of nutrients and the concomitant cellular growth rate. Such a technique, permitting direct observation of a single cell, could be used to investigate the control mechanism for cell division.

Professor Shuler's group is also developing techniques to increase production of certain metabolites from cultures of plant cell tissue. Cells from most plants can be cultured in a liquid suspension; however, growth in suspension cultures is most rapid for undifferentiated cells, which exhibit low rates of metabolite production. In order to obtain partially differentiated cells and therefore higher productivity of the desired metabolite, the group is examining multistage continuous-culture and immobilized whole-cell reactors. Among chemical engineering departments, Cornell's is unique in having an active program in this area of research.

Two professors, Shuler and R. K. Finn, direct research that incorporates fundamental kinetics and transport phenomena in the design of biochemical processes. Some projects include investigations of the effects of heat and mass transfer on the growth rate of various microbes in solid-substrate fermentations. This type of fermentation has been employed to upgrade agricultural residues to human food or animal feed and to produce a number of pharmaceuticals. Of particular interest to Professor Finn's group is the synthesis of new processes to enhance the digestibility and nutritional value of cellulosic materials, such as straw, for feeding to ruminants. Solid-substrate fermentations are advantageous compared to liquid suspension cultures in that they use less energy, require less capital, are relatively nonpolluting, and often employ inexpensive agricultural wastes. The project goals, in keeping with the overall objectives of the program, are to gain a fundamental understanding of the interactions among various rate processes, so that more efficient reactor systems and process control strategies can be developed.

Another current effort in Professor Finn's laboratory is concerned with the improvement of fermentation processes, which have the potential of providing a fuel derived solely from agricultural by-products, including cellulose. Work is focused on the development of techniques for the rapid removal of product alcohol by vacuum distillation and solvent extraction. Professor Finn also directs studies of fundamental operations that are particularly significant in the design of many biological processes. These include aeration, agitation, mixing, biopolymerization, and enzyme purification by solvent precipitation.

The research program in biochemical engineering also includes several waste-treatment projects that involve a variety of ecological constraints. For example, wastewater treatment requires a knowledge of the relationship between the chemical and physical properties of organic compounds and their biodegradation. Professor Shuler's group is investigating a variety of biological waste-treatment methods, including domestic and industrial activated-sludge processes. A computer model will be used to study the effects of perturbations in the effluent-waste-stream parameters — such as composition, dissolved oxygen concentration, pH, temperature, and flow rate — on the microbial ecology and settling rates. This information is essential for the optimization of operating and control strategies. The group (in conjunction with NASA) is also studying the feasibility of biological waste treatment in regenerative life support systems for space colonies and long-term space missions.

Selected publications in this area are:

Einsele, A., and Finn, R. K. 1980. Influence of gas flow rate and gas holdup on blending efficiency in stirred tanks. *Industrial and Engineering Chemistry Process Design and Development* (in press).

Finn, R. K., and Fiechter, A. 1979. The influence of microbial physiology on reactor design. In *Microbial technology,* 29th Symposium of the Society for General Microbiology, ed. A. Bull, D. C. Ellwood, and C. Ratledge, p. 83. London: Cambridge University Press.

Kan, J. K., and Shuler, M. L. 1978. Urocanic acid production using whole cells immobilized in a hollow fiber reactor. *Biotechnology and Bioengineering* 20:217.

Kargi, F.; Shuler, M. L.; Vashon, R.; Seeley, H. W., Jr.; Henry, A.; and Austic, R. E. 1980. Continuous aerobic conversion of poultry waste into single-cell protein using a single reactor: kinetic analysis and determination of optimal conditions. *Biotechnology and Bioengineering* (in press).

Kubek, D. J., and Shuler, M. L. 1980. The effect of variations in carbon and nitrogen concentrations on phenolics formation in plant cell suspension cultures. *Lloydia* 43:87.

Ramalingam, A., and Finn, R. K. 1977. The vacuferm process: a new approach to fermentation alcohol. *Biotechnology and Bioengineering* 19:583.

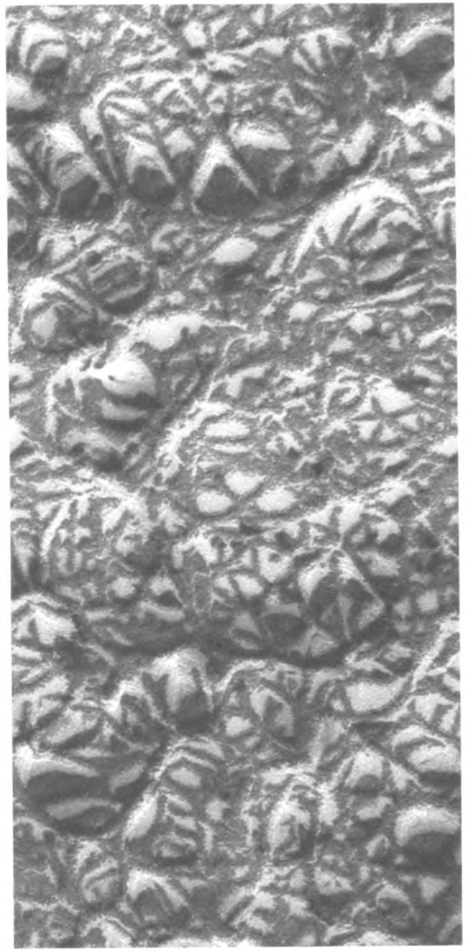
Shuler, M. L. 1979. Waste treatment options for use in closed systems. In *Space manufacturing* 3, ed. J. Grey and C. Krop, p. 381. New York: American Institute of Aerodynamics and Astronautics.

Shuler, M. L.; Leung, S.; and Dick, C. C. 1979. A mathematical model for the growth of a single bacterial cell. *Annals of the New York Academy of Sciences* 326:35.

Chemical Microscopy

Chemical microscopy has been taught at Cornell since the turn of the century and is still an important field of study. In recent years many new microscopical techniques have been developed that are now widely used in chemical engineering research. For example, powerful electron microscopes have been adapted to permit examination of a catalyst surface in a reaction environment. Phenomena such as the growth of carbon fibers from the surface of iron catalysts, via carbon-deposition reactions, have been observed using this technique.

Research programs under the direction of G. G. Cocks use various microscopical techniques to study the structure and properties of gels, and the nucleation and growth of crystals. Many biologically and technologically important materials are formed by the growth of crystals in gels to produce a composite structure; examples include teeth, mollusc shells, cement, and concrete. The primary research objective is improved understanding of gel structure and properties and how these can be controlled, ultimately to produce materials for specific applications. One example is the development of cement and concrete for use in geothermal wells. These materials must withstand high temperatures and pressures and endure many years of exposure to underground waters. Experiments are being conducted to determine the dependence of cement and concrete structure and properties on such variables as gel composition, crystallization temperature, and the magnitudes of temperature and concentration gradients during crystallization.



A somewhat different crystal-growth phenomenon, resulting in a highly oriented crystal structure, is exhibited by oyster shells. These shells are formed by precipitation of inorganic material in an organic matrix. Research is directed toward fundamental understanding of the control mechanisms for oriented crystal growth and to some specific practical problems, such as the effects of seawater pollution on the growth of oyster shells.

Selected publications in this area are:

Cocks, G. G. 1978. Chemical microscopy. *Analytical Chemistry* 50:205R.

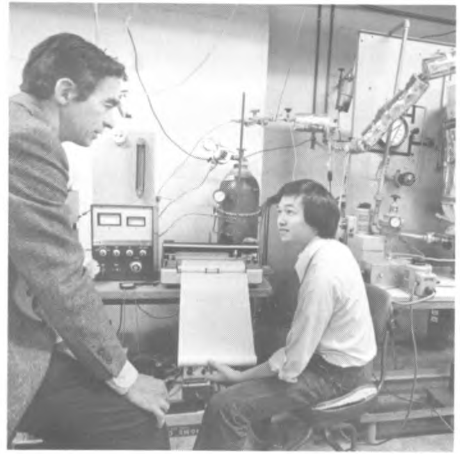
Weissman, R. C., and Cocks, G. G. 1979. A microscopical study of the gelation of collagen cross-linked with glutaraldehyde. In *Proceedings, Electron Microscopy Society of America*, ed. G. W. Bailey. New Orleans: Claitors.

This electron micrograph (magnified 100,000 times) of a collagen gel was obtained in an investigation of the structure and mechanical properties of gels. It is a freeze-etched replica of a 0.5 percent collagen gel.

Chemical Reaction Engineering, Kinetics, and Catalysis

A systematic study of the macroscopic behavior of reacting systems can provide information about reaction mechanisms and the basis of catalytic action, and guide efforts to manipulate a reaction environment (temperature, pressure, choice of catalyst, type of reactor, etc.) to obtain a desired product distribution. The interpretation of kinetic data and the design of chemical reactors require an understanding of the coupling between chemical and physical rate processes. This is particularly important in heterogeneous reaction systems, a number of which are currently under study in the School of Chemical Engineering.

Energy-related problems in heterogeneous catalysis, kinetics, and chemical reaction engineering are the focus of research directed by J. F. Cocchetto. For example, an important step in the production of environmentally acceptable synthetic liquid fuels from coal and oil shale is catalytic hydrodenitrogenation (HDN), whereby organonitrogen contaminants are converted to clean hydrocarbons and by-product ammonia. Current industrial hydrotreating catalysts have shown insufficient activity and selectivity in HDN of the high-nitrogen feedstocks derived from nonpetroleum sources. Reaction studies are being conducted with representative organonitrogen compounds and relatively simple, well-characterized catalysts to gain insight into the nature of the active sites necessary for effective catalysis of HDN reactions, especially hydrogenolysis reactions involving the carbon-nitrogen bond. The



Recent graduate research under Professor Harriott *(at left)* includes kinetic studies of catalytic methanation.

complex HDN reaction networks demand careful experimentation and astute kinetic modeling to reveal the effects of controlled variations in catalyst properties and reaction conditions on the rates of the individual reaction steps. Complex reaction networks, including reversible and irreversible reactions in series-parallel configurations, are also encountered in other petroleum and chemical processes. A more general theoretical study of the dynamics of complex reaction networks is planned, with the use of computer simulation to determine the extent to which chemical kinetics, competitive adsorption effects, and chemical equilibria can control product distributions for different reaction scenarios.

Two professors, Cocchetto and P. Harriott, are initiating a research program in fuel cells, reactors in which fuel is oxidized electrochemically via half-cell reactions that take place at catalytic electrodes separated by a suitable electrolyte. Fuel cells convert the chemical energy of a fuel directly into electricity and are, in principle, much more efficient than conventional combustion power cycles. However, serious technical problems must be solved before fuel cells find widespread application. Cornell research in this area is directed toward improved fundamental understanding of electrode processes in low- and medium-temperature fuel cells. The mechanism of operation of porous gas-diffusion electrodes is of particular interest. Reaction is believed to occur primarily on that portion of the electrode surface that is covered by a thin film of liquid electrolyte; in such regions, reactant gas can easily diffuse through the electrolyte film to the active electrode surface. The fraction of the total electrode surface that is film covered and utilized effectively for electrochemical reaction is not known, however. Improved models of gas-diffusion electrodes are needed, and the structure of porous electrodes must be optimized for effective mass transfer, maximum utilization of electrocatalyst (often an expensive metal such as platinum), and minimization of voltage losses that reduce the efficiency and power density of the fuel cell.

A new approach to an old reaction is perhaps the best way to describe R. L. Von Berg's project on ammonia synthesis promoted by gamma radiation. Using gamma radiation to promote the vapor-phase ammonia synthesis reaction has not been very successful compared to the high-temperature, high-pressure catalytic process. Since the limiting step in the radiolytic reaction is the formation of nitrogen radicals, an alternate approach — reacting liquid nitrogen with gaseous hydrogen — is being investigated both with and without catalysts. It is expected that a much higher concentration of nitrogen radicals will be formed by the action of gamma radiation on liquid nitrogen, resulting in substantial acceleration of the rate of ammonia synthesis.

Publications in this area include:

Cocchetto, J. F., and Satterfield, C. N. 1980. Chemical equilibria among quinoline and its reaction products in hydrodenitrogenation. *Industrial and Engineering Chemistry Process Design and Development* (in press).

Ho, S., and Harriott, P. 1980. The kinetics of methanation on nickel catalysts. *Journal of Catalysis* 64:272.

Matson, S. L., and Harriott, P. 1978. The kinetics of the ruthenium-catalyzed reduction of nitric oxide by hydrogen. *Industrial and Engineering Chemistry Product Research and Development* 17:322.

Satterfield, C. N., and Cocchetto, J. F. 1975. Pyridine hydrodenitrogenation: an equilibrium limitation on the formation of piperidine intermediate. *AIChE Journal* 21:1107.

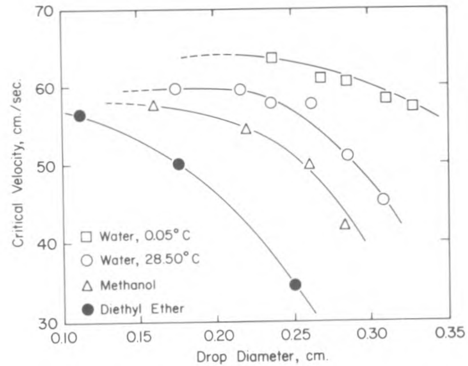
Satterfield, C. N., and Cocchetto, J. F. 1980. Reaction network and kinetics of the vapor-phase catalytic hydrodenitrogenation of quinoline. *Industrial and Engineering Chemistry Process Design and Development* (in press).

Tsuto, K; Harriott, P.; and Bischoff, K. B. 1978. Intraparticle mass transfer effects and selectivity in the palladium-catalyzed hydrogenation of methyl linoleate. *Industrial and Engineering Chemistry Fundamentals* 17:199.

Fluid Dynamics, Rheology, and Biorheology

The application of fluid dynamics and rheology to fundamental problems that appear to be relevant to a large number of industrial and natural processes is a major thrust of the school's research in transport phenomena. Both experimentation and applied mathematical methods are used to gain insight into the hydrodynamic features of "simplified" systems, an insight that provides, in turn, a basis for engineering analysis of complex problems.

An example of this approach is G. F. Scheele's research on the flow behavior of a suspension of liquid drops in a second, immiscible liquid. Of primary concern is the role played by drop coalescence in such systems. In turbulent flow, for example, coalescence in liquid-liquid dispersions must be rapid, because two colliding drops will be in apparent contact for only a fraction of a second. Factors that influence the probability that a collision will result in coalescence are being studied under controlled conditions in hydrodynamically "simple" systems. Experimental and theoretical studies are being made both of binary (drop-drop) collisions and of collisions between a drop and a planar liquid-liquid interface. High-speed motion-picture photography is used to determine the effects of impact velocity, drop size, and physical parameters on the probability of coalescence. The results will be used to develop and test theoretical models that should ultimately be useful in predicting the rates of mass transfer and chemical reaction in liquid-liquid systems.



The critical velocity that must be attained by a drop of mercury in order for rapid coalescence to occur at a planar interface is shown as a function of drop diameter for four different continuous-phase liquids.

Another fundamental problem of interest to Professor Scheele is the injection of one liquid into a second, immiscible liquid. This process is important in a variety of operations, including liquid-liquid extraction and wet spinning of rayon and acrylic fibers. Recent experimental results show that the relative motion of the continuous phase can significantly affect injection phenomena. Additional experimental and theoretical work is needed to develop and test models for the effects of continuous-phase flow on discrete-drop formation, jet formation, and jet breakup.

The modeling of transport processes in many industrial and biological systems requires a detailed description of the fluid dynamics and rheology of suspensions and macromolecular solutions. The non-Newtonian flow characteristics exhibited by this class of fluids often arise from flow-induced changes in the shape and orientation of the suspended elements or macromolecules that determine the microscopic structure of the fluid. The research program of W. L. Olbricht is directed toward understanding the microdynamics of suspensions and the connection between deformation of the microelements and the bulk, or macroscopic, fluid properties.

Certain flows are capable of inducing gross changes in the conformation of the microelements. These are flows that have a relatively large degree of elongational or "stretching" motion. The non-Newtonian response exhibited by polymer solutions or suspensions in elongation-dominated flows differs considerably from the response in simple shear flow, which is relatively weak in its deformational character. Flows containing significant elongation are common in a variety of technologically important operations, and several are being studied at Cornell.

Professors Scheele *(at left)* and Olbricht direct research in the area of fluid dynamics and rheology.

One prominent example is the flow of emulsions through porous media and packed beds, in which the flow geometry can induce significant elongational motion. Experiments are being conducted to determine the influence of drop deformation on transport properties; special attention is given to the case in which one or both of the individual liquid phases are non-Newtonian. Another example is the flow of blood through extracorporeal circuits. This flow, which can cause significant deformation of red blood cells and platelets, is particularly interesting because it can produce permanent changes in the cell morphology, with critical effects on the cell's rheological and mass-transfer characteristics. The response of the cell to a variety of flow types (degrees of elongation) *other* than simple shear provides crucial information for the design of blood-transport devices.

Selected publications in this area are:

Leal, L. G.; Fuller, G. G.; and Olbricht, W. L. 1980. Flow-induced stretching of macromolecules in dilute polymer solutions. In *Progress in aeronautics.* New York: American Institute of Aerodynamics and Astronautics (in press).

Olbricht, W. L., and Leal, L. G. 1980. The motion of immiscible liquid drops through a converging/diverging tube. *Journal of Fluid Mechanics* (in press).
Scheele, G. F., and Clark, D. B. 1980. The effect of impact velocity on the coalescence of tetrachloroethylene drops at a planar tetrachloroethylene-water interface. *Chemical Engineering Communications* (in press).
Scheele, G. F., and Pendergrass, J. H. 1980. Rapid coalescence of mercury drops at planar mercury-liquid interfaces. *Chemical Engineering Communications* (in press).

Heat and Mass Transfer

The effects of heat and mass transfer limitations on the design and scale-up of separation and reaction processes are being studied in connection with research on a novel desalination process and on multiphase chemical reactors.

In 1958 H. F. Wiegandt described direct contact freezing as a method of desalting seawater, and since then, the U.S. Department of the Interior has sponsored the school's research on this attractive desalination process. The main steps are partial freezing by contacting seawater with an organic refrigerant such as n-butane, separating the ice from the brine, washing the ice crystals, and melting the ice. The process is thermodynamically favorable and particularly well suited for large plants; energy consumption is lower than it is for evaporation processes. There is a major obstacle to commercial application, however: the very small size of the ice crystals makes separation and washing difficult. Under the direction of Professors Wiegandt and R. L. Von Berg, efforts are being made to maximize crystal growth rates and size and to produce spheroidal ice crystals, which form beds with high permeability. Techniques for rapidly melting product ice by direct-contact condensation of butane are also under study. The butane serves as a secondary, immiscible, direct-contact medium for heat transfer between the cold products (ice and brine) and warm incoming seawater. Conventional heat exchangers are inefficient in this application because of the relatively small driving forces (temperature differences of a few degrees). A multistage countercurrent heat-transfer system with stagewise cocurrent contacting has been proposed, but this configuration poses some problems (interesting in themselves) in hydraulic stability. The basic goals of the desalination program are to improve heat and mass transfer and to achieve high stage efficiency, as well as overall process efficiency.

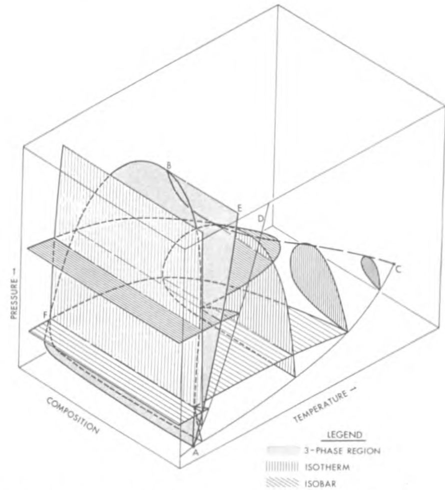
Considerations of heat and mass transfer are almost always a part of reactor design. In many cases laboratory reactors cannot be scaled up directly to larger units because the overall reaction rate is influenced by heat- and mass-transfer limitations, which change with reactor size. These problems are the subject of some of the research supervised by Professor Harriott. Current work includes studies of heat transfer in packed tubular reactors and heat transfer to suspensions or emulsions in stirred tanks. Published correlations differ by as much as 50 percent; their use in design could be either unduly conservative or unsafe because of the possibility of a runaway reaction. Another design problem is that performance of fluidized-bed reactors is strongly dependent on the rate of gas exchange between bubbles and the dense phase. Models based on the behavior of single bubbles are often used for low velocities, but for the high-velocity regions, in which turbulence promotes rapid bubble coalescence and splitting, there are no accepted models and very little data. In the Cornell research, physical adsorption of a tracer gas is being used to obtain data on the rate of gas interchange in a fluidized bed six inches in diameter. It is hoped that this technique will be applicable to larger beds, simplifying data acquisition by avoiding the necessity of carrying out a chemical reaction.

Recent publications in this area include:

Bustany, S. T.; Harriott, P.; and Wiegandt, H. F. 1979. Growth of ice in a saltwater drop falling in an organic phase. *AIChE Journal* 25:439.
Harriott, P. 1975. Thermal conductivity of catalyst pellets and other porous particles. *Chemical Engineering Journal* 10:65.
Wiegandt, H. F., and Von Berg, R. L. 1980. Myths about freeze desalting. *Desalination* (in press).
Wiegandt, H. F.; Von Berg, R. L.; and Patel, P. R. 1978. The crossflow piston bed. *Desalination* 25:303.

Molecular Thermodynamics and Computer Simulation

Precise knowledge of the physical and thermodynamic properties of dense fluid mixtures is essential to the design and efficient operation of many industrial processes. In calculating fluid properties, chemical engineers have traditionally relied heavily on empirical methods based upon equations of state and the principle of corresponding states. Although these methods work well for simple hydrocarbon systems, they are inadequate for many other systems, particularly those containing strongly polar liquids and those in which multicomponent liquid-liquid and high-pressure gas-liquid phase separations occur. New developments in coal liquefaction and gasification, enhanced oil recovery, hydrogen energy technology, and synthetic fuel processes demand more precise and flexible methods of property prediction. Further progress in this field must be based upon an understanding of the properties of molecules and the forces between them, and the use of statistical mechanics to relate macroscopic properties to intermolecular forces. This is the direction of the school's molecular thermodynamics research, which is under the joint supervision of K. E. Gubbins and W. B. Streett. Complementary experimental, theoretical, and computer-simulation approaches are used in a coordinated program. Graduate students have the opportunity to work closely with several visiting professors and postdoctoral research associates, in addition to Professors Gubbins and Streett.



This pressure-temperature-composition phase diagram for the H_2/CO_2 system was constructed from laboratory measurements at pressures up to 25,000 psi. AC and AD, in the near P-T face of the diagram, are the vapor-pressure and melting curves pertaining to CO_2.

Experimental research is concentrated on phase-equilibrium, equation-of-state (PVT), and heat-of-mixing measurements over wide ranges of temperature (70 to 500 K) and pressure (up to 10,000 atmospheres). The application of pressure is particularly significant, since this is the most direct means of decreasing the distance between molecules in condensed matter in order to explore the nature and effects of short-range intermolecular forces. A combination of phase-equilibrium, PVT, and heat-of-mixing data yields the three principal excess properties of fluid mixtures — excess Gibbs free energy, excess volume, and excess enthalpy — which are particularly useful for comparison with predictions from molecular theories of dense fluids. Vapor-liquid and liquid-liquid equilibria in binary and multicomponent mixtures composed of species such as hydrogen, carbon monoxide, methane, and methanol are studied experimentally. These studies cover the entire region of fluid phase separation for each system to provide the topology of phase diagrams at high pressures as well as comprehensive data for comparison with theoretical predictions. PVT measurements are carried out for both pure and mixed fluids and are the principal source of raw data for the calculation of thermodynamic properties of fluids. Recent studies have focused on liquid methanol, liquid ethylene, and dense fluid mixtures of hydrogen and methane and of hydrogen and carbon dioxide. In order to expand its experimental capabilities, the research group is constructing a heat-of-mixing calorimeter for direct measurement of the excess enthalpies of liquefied gases. This calorimeter will be controlled by the school's PDP 11/70 computer.

Theoretical research is aimed at developing improved methods for predicting thermodynamic properties of liquid mixtures. The observed properties of a particular fluid are determined by the intermolecular forces, and exact relationships between observed properties and intermolecular forces are provided by statistical thermodynamics. The governing equations can be solved for gases and for liquids composed of spherical molecules. For liquids composed of more complex molecules, the approach is to use a perturbation method, in which the properties of the complex liquid are related to those of the simple one. In the past five years, techniques have been developed that show promise for polar liquids, such as those encountered in coal-derived synthetic fuels. Current research is aimed at developing these methods for mixtures involving methanol, hydrogen sulfide, ethylene, carbon monoxide, and other industrially important compounds. Particular applications include liquefied natural gas, synthetic fuels derived from coal, hydrogen mixtures, and high-pressure phase equilibria. Theoretical predictions are compared with experimental results whenever possible.

Professor Gubbins *(above, at left)* and his students make extensive use of a recently equipped computer facility in Olin Hall.

Computer simulation studies support experiment and theory. Modern fast digital computers provide a means of carrying out "brute-force" statistical mechanical "experiments" on hypothetical fluids composed of precisely defined molecules that obey specified intermolecular potential functions and classical mechanics. Experiments on systems of several hundred interacting molecules provide detailed information about structure and motion at the molecular level and about the subtle relationships between intermolecular forces and macroscopic properties. Two simulation methods are used: the Monte Carlo method and the molecular dynamics method. The former employs random numbers and is based on the ensemble-averaging concepts of Gibbs; the latter requires numerical solution of the Newtonian equations of motion for the molecules and is based on the time-averaging concepts of Boltzmann and Maxwell. Comparison of simulation results with theoretical predictions provides a severe test of the mathematical approximations inherent in the theory, and comparison with experimental data provides a test of the adequacy of the models used to describe molecular shape and intermolecular forces. The principal goals of these studies at present are: (1) development of improved mathematical and programming methods for simulation of molecular liquids, including techniques for direct calculation of Gibbs free energy and phase equilibria; and (2) development of accurate intermolecular potential functions for real liquids and investigation of molecular structure and motion in bulk liquids.

Although the focus of this work is on molecular liquids, the methods and techniques of computer simulation are applicable to a variety of problems in modern chemical engineering. The computing facilities that support this work are unsurpassed by those of any university in the country. They include the school's PDP 11/70 computer, devoted largely to this project, as well as substantial amounts of time (more than a thousand hours per year) on a floating point systems array processor used in conjunction with the University's IBM 370/168 computer.

Selected publications in this area are:

Clancy, P.; Gubbins, K. E.; and Gray, C. G. 1979. Thermodynamics of polar liquid mixtures. *Faraday Discussions* 66:116.

Holland, P. M.; Hanley, H. J. M.; Gubbins, K. E.; and Haile, J. M. 1979. A correlation of the viscosity and thermal conductivity data of gaseous and liquid propane. *Journal of Physical and Chemical Reference Data* 8:559.

Murad, S.; Evans, D. J.; Gubbins, K. E.; Streett, W. B.; and Tildesley, D. J. 1979. Molecular dynamics simulation of dense fluid methane. *Molecular Physics* 37:725.

Nicolas, J. J.; Gubbins, K. E.; Streett, W. B.; and Tildesley, D. J. 1979. Equation of state for the Lennard-Jones fluid. *Molecular Physics* 37:1429.

Steele, W. A., and Streett, W. B. 1980. Computer simulations of dense molecular fluids. I. Time-dependent statistical properties of single diatomic molecules. *Molecular Physics* 39:279.

Streett, W. B., and Calado, J. C. G. 1978. Liquid-vapor equilibrium for hydrogen and nitrogen at temperatures from 63 to 110 K and pressures to 57 MPa. *Journal of Chemical Thermodynamics* 10:1089.

Polymers and Materials Science

Hundreds of industries and millions of people are involved in the production of plastics, rubber, coatings, adhesives, and fibers. These materials are made of synthetic long-chain (polymer) molecules that have their counterpart in nature in the form of cotton, wool, proteins, and nucleic acids. Chemical engineering, chemistry, and materials science and engineering are among the academic fields at Cornell currently pursuing research in this area.

Research directed by C. Cohen is concerned with the application of thermodynamics, statistical mechanics, fluid dynamics, and transport phenomena to polymer systems. Recent theoretical and experimental work has focused primarily on three areas:

1. *Diffusion in bulk polymers.* Sorption of small organic molecules by glassy polymers often results in a transformation of the solid polymer into a swollen rubbery material. Large internal stresses exist in the swollen and glassy parts of the polymer and are thought to contribute significantly to so-called anomalous diffusion phenomena observed in many penetrant-polymer systems. Experiments and theoretical modeling are in progress to improve the understanding of these phenomena.

2. *Dynamic light scattering.* Laser light scattering has become an established characterization tool for the measurement of static (thermodynamic) and dynamic (transport) properties of liquids. Efforts are directed toward making this technique equally effective in the characterization of bulk polymers. To this end the group has set up a light-scattering spectrometer for the study of polymer relaxation mechanisms and solvent diffusion in bulk polymers above and below their glass transition temperatures. Anticipated work includes development of the phenomenological equations that provide the basis for an accurate analysis of the light-scattered spectra of these systems.

3. *Structure formation in polymers*. The theory of phase separation and phase transformation (precipitation, gelation, glass transition, crystallization) in polymer solutions and bulk polymers has been developed for many years. Attention is now directed toward the structures generated in industrial processes in which these thermodynamic transitions are coupled with macroscopic dynamic phenomena such as bulk flow, diffusion, and energy flux. Representative problems under investigation include structure development during synthetic membrane formation, distribution of orientation in injection molded parts, and heterogeneities in gel formation.

Professor Cohen is also a member of an interdisciplinary group of chemical, mechanical, and materials engineers who are conducting experimental and theoretical investigations of injection molding. Numerical simulations of mold filling have been developed, taking into account non-Newtonian rheology, viscous heating, and cooling in the mold; these simulations compare well with experimental results obtained in the industrial laboratories of Cincinnati Milacron and Xerox.

Polymer studies directed by F. Rodriguez concentrate on the kinetics of free-radical polymerization. The conversion of monomer to polymer in solution polymerization can be followed by monitoring either the temperature rise in an adiabatic reactor or the volume shrinkage in an isothermal reactor. These two techniques have been applied to a number of monomers, including acrylamide, methacrylamide, vinyl pyrrolidone, and vinyl imidazole.

Professor Cohen *(at left)* is among the faculty members who work with graduate students in the area of polymers.

Recently, efforts have focused on characterizing the behavior of bicomponent systems that produce free radicals; such systems are used for initiating polymerization near room temperature. To extract the needed information from polymerization kinetics, the propagation and termination reactions should be characterized separately. This can be accomplished through the technique of photoinitiation, in which the rate of radical generation is almost independent of temperature. Thus the energies of activation for propagation and termination can be determined with some ease. Separation of the actual rate constants for propagation and for termination requires the use of a special method known as the rotating sector technique, and this has been applied in a few instances.

Another research area of interest to Professor Rodriguez is the production of gels from dilute solutions of monomers and polymers. In addition to chemical methods, both gamma radiation and ultraviolet light are used to tailor the polymer networks characteristic of gels. The kinetics of the reactions and the properties of the gels are studied by a combination of techniques, with a primary reliance on the torsion pendulum. The work on gels is done in collaboration with Professors Cohen and Cocks.

Some recent publications in this area are:

Anderson, C. C.; Rodriguez, F.; and Thurston, D. A. 1979. Crosslinking aqueous poly(vinyl pyrrolidone) solutions by persulfate. *Journal of Applied Polymer Science* 23:2453.

Cohen, C.; Tanny, G. B.; and Prager, S. 1979. Diffusion-controlled formation of porous structures in ternary polymer systems. *Journal of Polymer Science* A17:477.

Janas, V. F.; Rodriguez, F.; and Cohen, C. 1980. The ageing and thermodynamics of polyacrylamide gels. *Macromolecules* (in press).

Rodriguez, F. 1981. *Principles of polymer systems*. 2nd ed. New York: McGraw-Hill (in press).

Ware, R. A., and Cohen, C. 1980. Strain effects in the mass flux of methanol in poly(methyl methacrylate). *Journal of Applied Polymer Science* 25:717.

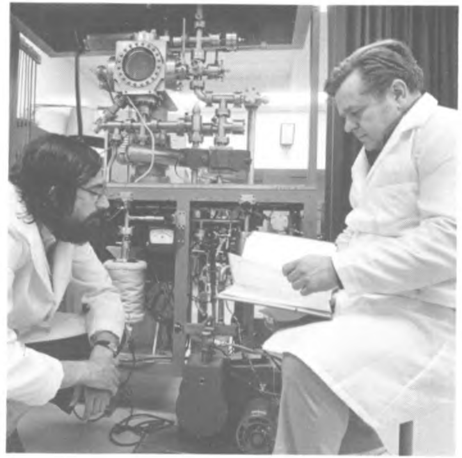
Surface Science

The contrast between surface and bulk properties of condensed phases has long been recognized but is not yet fully understood. At Cornell, surface science is an important area of study by research groups in materials science and engineering, chemistry, applied physics, and chemical engineering. Progress in surface science is a key to understanding heterogeneous catalysis, mass transfer across interfaces, adsorption, and other important surface phenomena.

Research directed by R. P. Merrill involves the chemistry and physics of reactive solid surfaces. The composition, structure, and electronic properties of surfaces are studied in situ during interactions with gas-phase species. Electron diffraction, Auger spectroscopy, photoemission, molecular beam scattering, soft x-ray emission spectroscopy, extended x-ray absorption fine structure, and temperature-programmed desorption are among the techniques used.

These studies are applied to technological problems as diverse as catalysis, corrosion, adhesion, and the aerodynamics of vehicular flight. Ongoing research projects include the catalytic decomposition kinetics of rocket monopropellants, the reactive chemistry of ruthenium, the structure of cobalt-molybdate catalysts, and the control of impregnation processes in catalyst preparation. In addition, research has been initiated on the effect of vibrational excitation on gas-solid reactions, on the structure and electronic properties of defect aluminum oxides, and on the use of synchrotron radiation to study local structure and bonding configurations of adsorbed molecules.

K. E. Gubbins directs surface-science research aimed at understanding the behavior of liquid surfaces at gas-liquid and liquid-solid interfaces. This research has application in the use of surfactants for enhanced oil recovery, or in processes involving the spreading of thin liquid films, mass transfer across interfaces, and liquid-solid reactions. Direct experimental study of a liquid surface is difficult, since many experimental probes yield signals that are determined largely by the properties of the bulk phase. Accordingly, a combination of theoretical and computer-simulation studies is used in the Cornell research. Molecular models are devised to reproduce the experimentally determined properties of the bulk liquid and the interface. Computer simulation is then used to obtain surface properties that cannot be determined by present experimental techniques. Such properties include molecular packing, orientation, and diffusion at the surface; surface viscosity; capillary wave phenomena; and nucleation rates. Computer simulations also provide a test for theories of surface behavior and suggest new experimental investigations.



Studies in surface science are directed by Professor Merrill *(at right in the top photograph)*. A recently established laboratory for this research includes equipment for low-energy electron diffraction (LEED) optics.

Selected publications describing work in this program are:

Dion, D. R.; Barker, J. A.; and Merrill, R. P. 1980. Double rainbow features in classical scattering from solid surfaces — Ne on Ag(111). *Chemical Physics Letters* 57:117.

Gubbins, K. E., and Haile, J. M. 1977. Molecular theories of interfacial tension. In *Oil recovery by surfactant and polymer flooding*, ed. D. O. Shah and R. S. Schechter, p. 119. New York: Academic Press.

Gubbins, K. E.; Haile, J. M.; and McDonald, I. R. 1977. Surface tension of polar liquids. *Journal of Chemical Physics* 66:364.

Komiyama, M.; Merrill, R. P.; and Harnsberger, H. R. 1980. Concentration profiles in impregnation of porous catalysts: nickel on alumina. *Journal of Catalysis* 63:35.

Merrill, R. P. 1977. A molecular view of diffusion and reaction in porous catalysts. *Journal of Catalysis* 50:184.

Monroe, D. R., and Merrill, R. P. 1980. Adsorption of oxygen on Pt(111) and its reactivity to hydrogen and carbon monoxide. *Journal of Catalysis* (in press).

Sawin, H. H., and Merrill, R. P. 1980. Angularly resolved temperature programmed decomposition-nitrogen emission from the decomposition of hydrazine on Ir(111). *Journal of Chemical Physics* (in press).

Thompson, S. M., and Gubbins, K. E. 1979. Molecular orientation at a vapor-liquid interface: theoretical and computer simulation results for a model of chlorine. *Journal of Chemical Physics* 70:4947.

M.Eng.(Chemical) Degree Program

The professional master's degree program in chemical engineering is intended to prepare graduates for industrial practice; its orientation is therefore toward applied subject matter in the areas of process equipment, process design, process control, numerical methods, and economics. This is in contrast to the more mathematical and theoretical course work offered for the Master of Science and Doctor of Philosophy degree programs, which are oriented toward research.

The present M.Eng.(Chemical) curriculum includes four required courses, a design project for three or six credits, and four or five technical elective courses, for a total of thirty credits. The required courses are Process Equipment Design, Design of Chemical Reactors, Numerical Methods, and Process Control. Technical electives may be chosen from the offerings of the School of Chemical Engineering and other units in the College of Engineering and the University. Frequently selected chemical engineering electives are Computer-Aided Process Design, Phase Equilibria, Petroleum Refining, Polymeric Materials, Polymeric Materials Laboratory, Microbial Engineering, Wastewater Engineering, Advanced Thermodynamics, Synthetic Fuels, and Air Pollution Control.

Design projects are related to the specialties of the faculty. Recent projects have been in the areas of petroleum refining, organic and inorganic chemical processes, polymerization, biochemical processes, environmental problems, and coal-conversion processes. Examples of recent project titles and the supervising professors are:

Production of Hydrogen by Chemical Means (J. C. Smith)
Direct-Contact Heat Transfer in a Desalination Process (H. F. Wiegandt)
Gasoline from Methanol by the Mobil Process (R. L. Von Berg)
Regeneration of Spent Carbon Adsorbents in a Fluidized Bed (P. Harriott)
Alcohol from Corn for Gasohol (R. K. Finn)
Waste Treatment in a Space Capsule (M. L. Shuler)
Clean Fuels from Solvent Refined Coal (J. F. Cocchetto)

Faculty Members and Their Research Interests

Joseph F. Cocchetto, B.S. (Cornell), S.M., Ph.D. (M.I.T.): *chemical reaction engineering, kinetics and heterogeneous catalysis, fuel cells*

George G. Cocks, B.S. (Iowa State), Ph.D. (Cornell): *light and electron microscopy, properties of materials, crystallography, solid-state chemistry, polymer gels and crystallization in gels*

Claude Cohen, B.S. (American University, Cairo), Ph.D. (Princeton): *thermodynamic and transport properties of polymer solutions, physical properties of bulk polymers, light scattering*

Robert K. Finn, Chem.E. (Cornell), Ph.D. (Minnesota): *waste treatment, agitation and aeration, microbial kinetics*

Keith E. Gubbins, B.S., Ph.D. (London): *molecular thermodynamics of liquid mixtures, phase equilibria, computer simulation studies of liquids*

Peter Harriott, Chem.E. (Cornell), Sc.D. (M.I.T.): *kinetics, catalysis, and reactor design; synthetic fuels; air pollution control; diffusion in membranes and porous solids*

Robert P. Merrill, Chem.E. (Cornell), Sc.D. (M.I.T.): *chemistry and physics of reactive solid surfaces, catalysis, corrosion, electron spectroscopy of surfaces, atomic and molecular beam scattering*

William L. Olbricht, B.S. (Stanford), Ph.D. (Caltech): *non-Newtonian fluid mechanics, rheology, flow in porous media, biorheology*

Ferdinand Rodriguez, B.S., M.S. (Case), Ph.D. (Cornell): *polymerization, properties of polymer systems*

George F. Scheele, B.S. (Princeton), Ph.D. (Illinois): *hydrodynamic stability, coalescence, fluid mechanics of liquid drops and jets, computer-aided design*

Michael L. Shuler, B.S. (Notre Dame), Ph.D. (Minnesota): *biochemical engineering, unconventional foods, plant cells, novel biological reactors, mathematical models of cell growth, waste treatment, immobilized cells*

Julian C. Smith (Director of the School of Chemical Engineering), Chem.E. (Cornell): *mixing, solids handling, phase equilibria*

William B. Streett, B.S. (West Point), Ph.D. (Michigan): *measurement of thermodynamic properties of fluids at high pressures, computer simulation of molecular liquids*

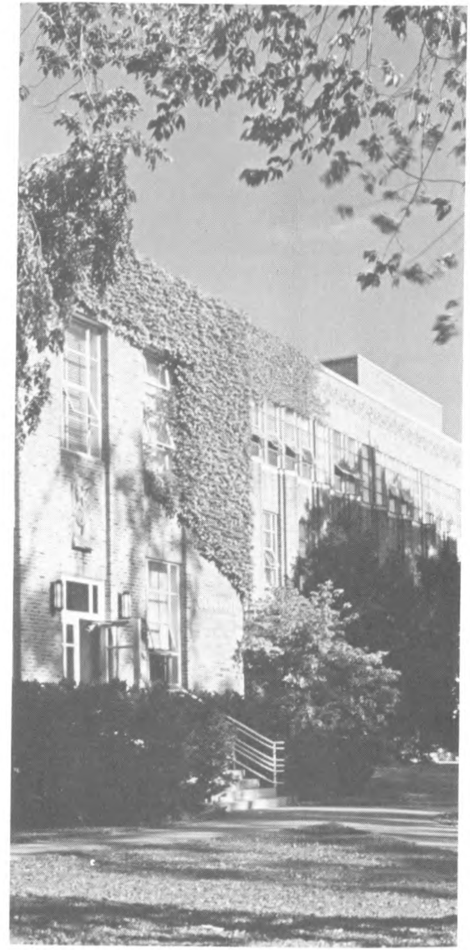
Raymond G. Thorpe (Director of the Division of Unclassified Students), B.Ch.E. (Rensselaer), M.Ch.E. (Cornell): *phase equilibria, fluid flow*

Robert L. Von Berg, B.S., M.S. (West Virginia), Sc.D. (M.I.T.): *liquid-liquid extraction, effects of radiation on chemical reaction, saline-water conversion*

Herbert F. Wiegandt, B.S., Ph.D. (Purdue): *hydraulics of porous moving beds, petroleum processing, saline-water conversion*

Further Information

Prospective candidates for graduate degrees in chemical engineering may obtain further information by writing to the Graduate Faculty Representative, Chemical Engineering, Cornell University, Olin Hall, Ithaca, New York 14853.



Civil and Environmental Engineering

Civil and environmental engineering deals primarily with the large fixed works, systems, and facilities that are basic to community living, industry, and commerce and vital to human well-being. The planning, design, construction, and operation of transportation systems, bridges, buildings, water and sewage treatment facilities, dams, and other major artifacts of society are civil and environmental engineering activities. Civil and environmental engineers, as major contributors to the solution of problems of urbanization, city planning, and environmental quality control, will continue to be in demand to meet the basic needs of society with efficiency, economy, and safety.

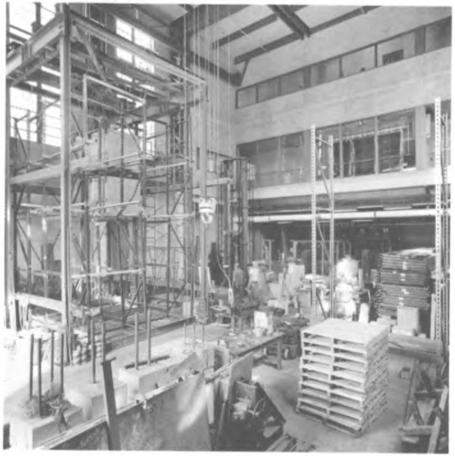
The wide range of subjects of concern to civil and environmental engineers are generally grouped into a number of subfields and specializations. At Cornell there are two departments in civil and environmental engineering: structural engineering and environmental engineering. In addition, there is a program of environmental sensing, measurement, and evaluation.

More than one hundred students are now enrolled in graduate programs at Cornell in civil and environmental engineering. These programs lead to the degrees of Doctor of Philosophy, Master of Science, and Master of Engineering (Civil). Major subject areas for Ph.D. and M.S. candidates are aerial photographic studies and remote sensing, environmental systems engineering, geodetic and photogrammetric engineering, geotechnical engineering, hydraulics and hydrology, sanitary engineering, structural engineering, transportation engineering, and water resource systems (Ph.D. only). Minor subjects may be in these areas, in structural mechanics, in other branches of engineering, or in mathematics, physics, chemistry, or computer science. In the M.Eng.(Civil) degree program, emphasis is on design and design-oriented courses.

Facilities

A considerable volume of research, sponsored by government agencies and industry, is carried out in three structural laboratories. The structural testing facility in Thurston Hall is one of the largest and best equipped in any university. The main test bay is a three-dimensional space frame permitting heavy loads to be applied in any direction to large structural assemblages. Major equipment items include large-capacity testing machines, portable static and dynamic loading devices, and automatic data-acquisition systems. A separate concrete materials laboratory, also in Thurston Hall, is equipped for all types of basic and applied research in concrete. The structural models laboratory is among the most active and best-equipped University facilities for research and instructional modeling.

The environmental engineering facilities include controlled-temperature rooms, laboratories for course work and research in specialized areas such as biological oxidation kinetics and aquatic chemistry, and rooms specially equipped for bench and pilot-level unit process studies in biological treatment, carbon adsorption, ion exchange, electrodialysis, and reverse osmosis.



The main bay of the structural testing facility is four thousand square feet in area and forty-five feet high. Heavy steel columns, embedded in reinforced concrete walls, and floor anchors embedded in bed rock are capable of sustaining heavy loads upward, downward, and horizontally.

Airphoto and remote-sensing facilities available in the school include an extensive library of satellite, high-altitude-aircraft, and other multispectral and thermal imageries, in addition to more than 600,000 worldwide aerial photographs. To supplement a variety of visual image analysis equipment, the school maintains an active file of computer routines for analyzing multispectral digital data.

The geotechnical engineering laboratories contain a variety of both standard and specialized soil-testing equipment and a developing rock-testing facility. There are special facilities for large-scale-model testing of foundations and for the testing of stabilized soils and asphaltic mixtures.

The hydraulics laboratory is well equipped for research in environmental fluid mechanics, hydraulics, and wave mechanics. Equipment includes a large modeling basin and a recirculating flume for stratified flow research, a wave flume sixty feet in length, and several wind and water tunnels. In addition, a modern measuring system for fluid velocities (hot-film anemometry), temperature, and admixtures is linked to a computerized high-speed data-acquisition system with interactive display and storage.

Research in environmental law is greatly facilitated by the accessibility of the nearby Law School library.

New interactive computer graphics facilities, directed by D. P. Greenberg and located in Rand and Hollister Halls, are some of the finest in American universities. This interdisciplinary system is used for research on structures, geotechnical engineering, fluid mechanics, and environmental systems engineering.

Areas of Research

Aerial Photographic Studies and Remote Sensing

Because of the interests and experience of faculty members and the facilities available, graduate programs have developed in the following areas: (1) the investigation and refinement of methods for analyzing and interpreting aircraft and satellite imageries; (2) specific applications in engineering, geology, agriculture, natural resources, and planning; (3) specific applications in various climate regions, including arctic, temperate, and tropical areas; and (4) the incorporation of airphoto or other remotely sensed data into systems that inventory the resources of large geographical areas. In addition excellent opportunities for graduate study in cooperation with other units of the University exist and are encouraged.

The following faculty publications and graduate theses (listed with the supervising professor) are representative of research in this area:

Hafker, W. R. 1980. A comparative study of small scale remotely sensed data for monitoring clearcutting in hardwood forests. M.S. thesis (T. Liang).

Jamnongpipatkul, P. 1980. Remote sensing studies of some ironstone gravels and plinthite in Thailand. Ph.D. thesis (T. Liang).

Philipson, W. R. 1980. Problem-solving with remote sensing. *Photogrammetric Engineering and Remote Sensing* 46:1335.

Stereoscopic airphoto study is used in resource inventory projects.

Sangrey, D. A., and Philipson, W. R. 1979. *Detecting landfill leachate contamination using remote sensors*. Research report EPA–600/4–79–060. Las Vegas, Nev.: U.S. Environmental Protection Agency.

Environmental (Sanitary) Engineering

Graduate study in the major subject of environmental (sanitary) engineering is concerned with the principles, phenomena, and engineering techniques that are applicable to the maintenance of natural environmental quality at beneficial levels. Instruction and research focus on pertinent biological, chemical, physical, and engineering knowledge and on the use of this knowledge, along with analytical, computational, and laboratory skills, in the planning, analysis, and design of processes, facilities, systems, and policies that are essential to the achievement of environmental quality objectives.

More than fifteen advanced courses are offered by faculty members of the Department of Environmental Engineering who are specialists in this subject area. First-year graduate students take core courses in the major subject and electives in a minor subject of their choice. These electives are selected from a wide range of supporting courses in the biological and physical sciences, applied mathematics, planning, and engineering; included are such subjects as environmental quality, hydraulics and hydrology, environmental systems engineering, and water resources planning and management.

Graduate students and faculty members carry out research in the phenomena and the technology fundamental to water quality control and to waste processing, disposal, and management.

The following papers and theses (listed with the name of the supervising professor) are representative of recent research in the area:

Dentel, S. K. 1978. Anaerobic digestibility of chemically-coagulated organic materials. M.S. thesis (J. M. Gossett).

Driscoll, C. T. 1980. Chemical characterization of some dilute acidified lakes and streams in the Adirondack region of New York State. Ph.D. thesis (J. J. Bisogni, Jr.).

Driscoll, C. T.; Baker, J. P.; Bisogni, J. J., Jr.; and Schofield, C. L. 1980. The effect of aluminium speciation on fish in dilute acidified waters. *Nature* 284:161.

Gossett, J. M. et al. 1978. Anaerobic digestion of sludge from chemical treatment. *Journal of the Water Pollution Control Federation* 50:533.

Moore, K. A. 1980. The effect of mean cell residence time in the activated sludge process on settleability and dewaterability of the sludge. M.S. thesis (R. I. Dick).

Shin, B. S., and Dick, R. I. 1980. Applicability of the Kynch theory to flocculent suspensions. *ASCE Journal of the Environmental Engineering Division* 106:505.

Environmental Systems Engineering

This area of study is concerned primarily with public policy planning and analysis such as in environmental quality management, public health, urban planning, and technology assessment. The approach emphasized is the use of mathematical modeling techniques to define and evaluate alternative solutions to public-sector problems. Faculty members from other departments and interdisciplinary centers at Cornell participate in the graduate program in environmental systems engineering.

Current research projects cover a range of topics, including agricultural pest management, epidemiology, control of infectious diseases, methodologies for assessing environmental impacts and effects, urban noise, water quality management, and solid-waste control.

Representative recent publications and theses (listed with the name of the supervising professor) on these subjects are given below (related material is cited under Water Resource Systems):

Brainar, J. P. 1976. Economic and nutritional impact of prescribed diet alterations in Colombia. Ph.D. thesis (W. R. Lynn).

Dworsky, L. B. 1978. The management of water-land-environmental resources at international boundary regions. *Natural Resources Journal* 18(1):143.

Orloff, N. 1979. Buttressing the traditional approach to enforcement of environmental requirements: noncompliance penalties under the Clean Air Act. *Environmental Law Reporter* 9(12):50029.

Orloff, N., and Brooks, G. 1980. *The National Environmental Policy Act—cases and materials*. Washington, D.C.: BNA Books.

Schuler, R. E. 1979. The long run limits to growth: renewable resources, endogenous population and technological change. *Journal of Economic Theory* 21:166.

Schuler, R. E., and Holahan, W. 1977. Optimal size and spacing of public facilities in metropolitan areas: the maximum covering location problem revisited. *Regional Science Association Papers* 39:139.

Shoemaker, C. A. 1979. Optimal timing of multiple applications of pesticides with residual toxicity. *Biometrics* 35:803.

Shoemaker, C. A.; Huffaker, C. B.; and Kennett, C. E. 1979. A systems approach to the integrated management of a complex of olive pests. *Environmental Entomology* 8:182.

Geodetic and Photogrammetric Engineering

Cornell offers an integrated program of research and instruction in geodetic and photogrammetric engineering coupled with remote sensing, photographic interpretation, and cadastral engineering. The purpose of this program is to provide graduate training for civil engineers, land planners, conservationists, geologists, foresters, geographers, and others who require surveys and inventories of cultural and earth resources and who must be able to present information from such inventories in the form of maps, diagrams, and displays of one, two, three, and four dimensions. Work in this field is supported by University resources in related areas such as agricultural engineering, electrical engineering, geology, land planning, natural resources, and theoretical and applied mechanics.

Geotechnical Engineering

Graduate instruction in geotechnical engineering emphasizes the development of an understanding of soil and rock as engineering materials—of how they behave as construction materials, as supporting media for structures, as host media for structures (such as tunnels), and as structures in themselves (as in earth or rockfill dams). In addition, a program in highway engineering and materials is offered in coordination with the graduate Field of Agricultural Engineering. Students frequently broaden their capabilities in geotechnical engineering by taking courses in airphoto interpretation, geological sciences, mechanics, and structures.

Research activities can be grouped into soil and rock behavior; soil dynamics; soil-structure interaction; analytical, finite element, and probabilistic modeling; marine and coastal geotechnique; and geomechanics.

A sampling of recent papers and theses (listed with the name of the supervising professor) indicates some of the current research in this area:

Fitzpatrick, L.; Kulhawy, F. H.; and O'Rourke, T. D. 1981. Flow patterns around tunnels and their use in evaluating construction problems. In *Soft ground tunneling*, ed. D. Resendiz (in press). Rotterdam: A. A. Balkema.

Ingraffea, A. R., and Heuzé, F. E. 1980. Finite element models for rock fracture mechanics. *International Journal for Numerical and Analytical Methods in Geomechanics* 4:25.

Using this test chamber, which is filled with prepared instrumented soil deposits, Professor Fred H. Kulhawy and a graduate student test models of instrumented deep foundations subjected to a variety of loading conditions.

Kulhawy, F. H., and Goodman, R. E. 1980. Design of foundations on discontinuous rock. In *Proceedings, international conference on structural foundations on rock*, ed. P. J. N. Pells, p. 209. Rotterdam: A. A. Balkema.

O'Rourke, T. D. 1979. Systems and practices for rapid transit tunneling. *Underground Space* 4(1):33.

O'Rourke, T. D., and Trautmann, C. H. 1980. Buried pipeline response to permanent earthquake ground motions. Paper 80-C2/PVP-78 read at ASME Pressure Vessels and Piping Conference, August 1980, San Francisco.

Stewart, J. P. 1981. Physical modeling of the uplift load-deformation behavior of drilled shaft foundations. Ph.D. thesis (F. H. Kulhawy).

Turner, S. M. 1981. Evaluation of subsidence caused by longwall mining. M.S. thesis. (T. D. O'Rourke).

Weiler, W. A., Jr. 1979. Behavior of stress cells in soil. M.S. thesis (F. H. Kulhawy).

Withiam, J. L., and Kulhawy, F. H. 1979. Analytical model for drilled shaft foundations. In *Proceedings, 3d international conference on numerical methods in geomechanics*, ed. W. Wittke, p. 1115. Rotterdam: A. A. Balkema.

Hydraulics and Hydrology

At Cornell the graduate program in hydraulics and hydrology is centered on the study of air and water in the environment. Instruction progresses from basic fluid mechanics to courses oriented toward specific applications. Consideration of the effects of engineering works on the environment is included, as are studies that lead to a better understanding of the natural processes involved. Proper application of the principles of fluid mechanics, hydraulics, and both ground- and surface-water hydrology is essential for the solution of many problems in environmental engineering and water resource planning, especially those affected by the hydrologic cycle. Such problems include the dispersion of residual materials and heat energy in ground and surface waters and in the atmosphere, the flow of water over and through natural soil and rock, drought and flood prediction and control, circulation and stratification in lakes and coastal areas, the dispersion of pollutants in water bodies, and the beneficial use of water resources.

Recent research projects undertaken by faculty members have included studies of lake circulation; unsteady flows in channels; near-shore currents; dynamic coastline processes and wave studies; evaporation from water and land surfaces; fluid mechanics of porous materials; turbulent transport and diffusion processes in lakes, rivers, or oceans; waste heat disposal; and fluid mechanics in alternative energy technologies, such as ocean thermal energy conversion. Many of these projects have analytical, numerical, and laboratory or field experimental components.

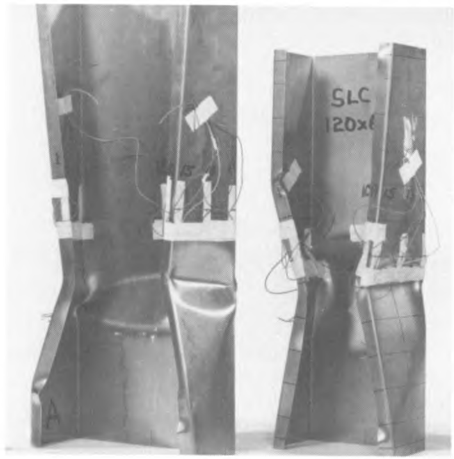
A sampling of recent faculty publications and theses (listed with the name of the supervising professor) is given below:

Brutsaert, W. H., and Stricker, H. 1979. An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resources Research* 15:443.

Fong, H. L. M. 1980. Bifurcation phenomenon of buoyant jets in stratified or homogeneous crossflow. M.S. thesis (G. H. Jirka).

Jirka, G. H. 1980. Fluid mechanical aspects of ocean thermal energy conversion. In *Energy conversion and fluid mechanics*, ed. J. D. Buckmaster. Philadelphia: Society of Industrial and Applied Mathematics.

Lafe, O. E. 1980. The simulation of two-dimensional confined flow in zoned porous media. M.S. thesis (J. A. Liggett).



Right above: **Laboratory installations such as this stratified flow modeling basin are used in the study of hydrodynamic transport and dispersion processes. Professor Gerhard Jirka is shown here with a model of an ocean thermal energy conversion plant in the basin center.**

Right: **Cold-formed steel specimens are shown after undergoing testing for local buckling.**

Lennon, G. P.; Liu, P. L.-F.; and Liggett, J. A. 1980. Boundary integral solutions to three-dimensional unconfined Darcy's flow. *Water Resources Research* 16:651.

Liu, P. L.-F.; Lozano, C. J.; and Pantazaras, N. 1979. An asymptotic theory of combined wave refraction and diffraction. *Applied Ocean Research* 1:137.

Structural Engineering

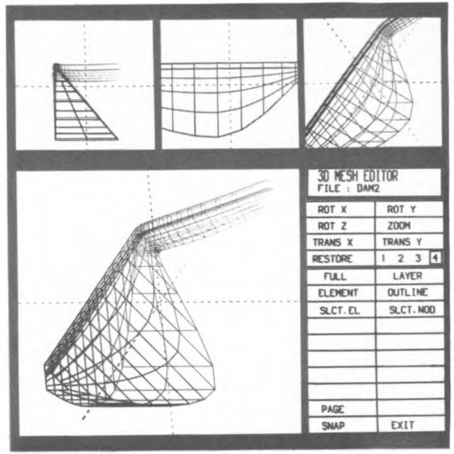
Structural engineering is one of the major branches of Cornell's program in civil and environmental engineering. Research projects involving graduate students are grouped into the following areas:

Light-gauge steel structures. A long-term program of research at Cornell, sponsored largely by the American Iron and Steel Institute, has provided the basis for United States design specifications for this broad class of structures. Current research topics include postbuckling interaction of plate elements, ultimate strength of cold-formed steel purlins, and stability of compression and flexural members.

Reinforced concrete structures. Cornell has long been regarded as one of the important centers for research on reinforced concrete structures; building code provisions relating to deflections, cracking, and bond have followed directly from research here. Current programs include sponsored research on design of splices in reinforced concrete for earthquake effects, finite-element analysis of reinforced concrete in cyclic loading, and seismic membrane shear transfer and punching shear in secondary containment vessels.

Left: **Sections of concrete nuclear containment vessels are tested for seismic shear transfer.**

Right: **Interactive computer graphics is an important modern tool for structural analysis and design. This is from a menu page for a three-dimensional interactive graphics editor for finite-element meshes. Isometric views at different elevations of a dam are displayed simultaneously to assist the user in selecting nodes and elements for modification.**



Modeling behavior of reinforced concrete. Pioneering work during the past fifteen years has developed techniques for small-scale modeling of the behavior of reinforced and prestressed concrete structures, such as shells, frames under reversing loads, and concrete pressure vessels.

Concrete materials. Fundamental research on microcracking in concrete has provided a rational explanation for the unique shape of the stress-strain curve. Recently attention has been directed to the stress-strain relations and strength of plain concrete under biaxial stresses and to properties of high-strength concrete.

Finite element analysis. Recent major sponsored research projects have dealt with the finite element analysis of shells, including dynamic response and stability. Finite element analysis is also an integral part of many of the other areas of research discussed here.

Computer graphics. Current sponsored research in computer graphics includes projects in finite element grid optimization, shell geometry representation, progressive collapse, and interactive design of domes, frames, cable structures, and membrane roofs. The linking of the powerful tools of computer graphics and modern structural analysis promises to become one of the most fruitful approaches to research in structures.

Structural dynamics. Several faculty members are interested in the analysis of structures for dynamic loads, in the behavior of structures under repeated reversed loading, and in earthquake-resistant design.

Some of the research efforts in these various areas of structural engineering are indicated by the following faculty publications and theses (listed with the name of the supervising professor):

Abel, J. F.; Greenberg, D. P.; McGuire, W.; and Gallagher, R. H. 1979. Interactive graphics for finite element analysis. In *Proceedings, 7th conference on electronic computation,* ASCE. New York: American Society of Civil Engineers.

Carrasquillo, R. L. 1980. Microcracking and engineering properties of high-strength concrete. Ph.D. thesis (A. H. Nilson).

Dat, D. T. 1980. The strength of cold-formed steel columns. Ph.D. thesis (T. Peköz).

Fagundo, F. E., Jr. 1980. The behavior of lapped splices in reinforced concrete beams subjected to repeated loads. Ph.D. thesis (P. Gergely).

Gergely, P.; Jirsa, J. P.; and Lutz, L. A. 1979. Rationale for suggested development, splice, and standard hook provisions for

deformed bars in tension. *Concrete International* 1(7):47.
Grigoriu, M.; Veneziano, D.; and Cornell, C. A. 1979. Probabilistic modelling as decision making. *ASCE Journal of the Engineering Mechanics Division* 104(EM4):585.
Gross, J. L. III. 1980. Design for the prevention of progressive collapse using interactive computer graphics. Ph.D. thesis (W. McGuire).
Ingraffea, A. R., and Manu, C. 1980. Stress-intensity factor computation in three dimensions with quarter-point elements. *International Journal for Numerical Methods in Engineering* (in press).
Kalyanaraman, V., and Peköz, T. 1978. Analytical study of unstiffened elements. *ASCE Journal of the Structural Division* 104(ST9):1507.
Peköz, T., and Winter, G. 1980. Cold formed steel construction. *Periodica, International Association for Bridge and Structural Engineering* (February).
Perdikaris, P. C. 1980. Stiffness and strength of biaxially tensioned orthogonally reinforced concrete panels subjected to membrane shear. Ph.D. thesis (R. N. White).
Slate, F. O. 1978. Indigenous materials for developing countries. Paper read at International Conference on Materials of Construction for Developing Countries, August 1978, at Asian Institute of Technology, Bangkok, Thailand.
Tasuji, E. M.; Slate, F. O.; and Nilson, A. H. 1979. Stress-strain response and fracture of concrete in biaxial loading. *Journal of the American Concrete Institute* 75(7):306.

Structural Mechanics

The subject area of structural mechanics can be studied as a minor in the M.S. or Ph.D. degree programs. Courses emphasize the analytical aspects of structural engineering, such as advanced analysis techniques, dynamics of structures, and shell theory. A minor in structural mechanics is especially suitable for M.S. candidates who have an interest in analysis but who do not have time to satisfy the requirements for a major in structural engineering and a full minor in theoretical and applied mechanics.

Transportation Engineering and Planning

Transportation, an indispensable element of modern society, is a major area of interest to civil and environmental engineers. The principal focus of study and research is the application of quantitative techniques to the analysis, planning, and design of transportation systems. Graduate students specializing in transportation engineering and planning take foundation courses in travel-demand forecasting, transportation systems analysis and design, and transportation economics and systems evaluation, as well as selected mode-oriented courses in, for example, public transit, airports, marine transport, freight transportation, and passenger and freight terminal design. Current research projects, in which graduate students have strong involvement, embrace short-range transit planning, railroad operations and economics, air service to small communities, and transportation-communications relationships.

A major commitment has been made to the development of computer graphics methods for research and teaching in transportation, methods that are finding increasing application in modern professional practice. Cornell is a leader among universities in advancing this exciting, new, and versatile tool for analysis and design of transportation systems.

Examples of recent Cornell theses (listed with the name of the supervising professor) and publications in transportation are:

Bloch, A. 1977. The small shipper mode choice decision. M.S. thesis (A. H. Meyburg).
Brög, W., and Meyburg, A. H. 1980. The non-response problem in travel surveys—an empirical investigation. *Transportation Research Record* (in press).
Daughety, A. F.; Turnquist, M. A.; and Braeutigam, R. R. 1979. A new approach to railroad cost estimation. In *Proceedings of Transportation Research Forum*, XX, p. 188. Oxford, Ind.: Richard B. Cross.
Fisher, G. P., ed. 1978. *Goods transportation in urban areas*, proceedings of the Engineering Foundation conference, December 1977. Report FHWA-PL-78-012, Federal Highway Administration, U.S. Department of Transportation, June 1978.
Jordan, W. C., and Turnquist, M. A. 1979. Zone scheduling of bus routes to improve service reliability. *Transportation Science* 13:3.
Lavine, M. J.; Meyburg, A. H.; and Butler, T. J. 1980. Use of energy analysis for assessing environmental impacts due to transportation. *Transportation Research Record* (in press).
Schuler, R. E., and Coutler, J. W. 1978. The effect of socio-economic factors on the value

of time in commuting to work. *Transportation* 7:381.
Schweiger, C. L. 1980. Design-oriented decision aids for transit system design using interactive graphics. M.S thesis (G. P. Fisher).
Siu, S.-M. 1979. Subway station location. M.S. thesis (G. P. Fisher).
Stopher, P. R., and Meyburg, A. H. 1975. *Urban transportation modeling and planning*. Lexington, Mass.: Lexington Books, D. C. Heath.
———. 1976. *Transportation systems evaluation*. Lexington, Mass.: Lexington Books, D. C. Heath.
Turnquist, M. A., and Gur, Y. 1980. Estimation of trip tables from observed link volumes. *Transportation Research Record* no. 730.

Professor Leonard Dworsky *(standing)* heads an interdisciplinary project on Great Lakes management.

Water Resource Systems

For graduate students interested in water resource planning and management, there are numerous interdisciplinary degree programs available through the Field of Civil and Environmental Engineering. Ph.D. degree candidates who want to obtain some quantitative skills in the development of mathematical management and planning models and their application to the solution of water resource problems can arrange a major in water resource systems; minors can be taken in economic theory, operations research, environmental quality, public policy, or other appropriate subjects. Both Ph.D. and M.S. degree candidates who want to become acquainted with some of the management and planning issues of water resource development and with some of the relevant legislation can select a minor in the area of water resources, described below.

Throughout the University, there are more than one hundred courses offered, and about an equal number of staff members involved, in some aspect of water resources or aquatic sciences. Several projects use advanced interactive computer graphics techniques to improve water resource planning.

The variety of research projects in this area is suggested by the following faculty publications and theses (listed with the name of the supervising professor):

Baskin, L. B. 1977. A groundwater recharge model for Nassau and Suffolk Counties, New York. M.S. thesis (C. A. Shoemaker).
Dworsky, L. B., and Berger, B. B. 1979. Water resources planning and public health: 1776–1976. *ASCE Journal of the Water Resources Planning and Management Division* 105(WR1):133.
French, P. N. et al. 1980. Water resources planning using computer graphics. *ASCE Journal of the Water Resources Planning and Management Division* 106(WR1):21.
Haith, D. A. 1976. Land use and water quality in New York rivers. *ASCE Journal of the Environmental Engineering Division* 102(EE2):1.
Hashimoto, T. 1980. Robustness, resilience and vulnerability criteria for planning water

resources systems. Ph.D. thesis (D. P. Loucks).

Loucks, D. P.; Stedinger, J. R.; and Haith, D. A. 1981. *Water resource systems planning and analysis*. Englewood Cliffs, N.J.: Prentice-Hall.

Sidrane, S. D. 1979. Implementation strategies for PL 92-500 section 208. M.S. thesis (L. B. Dworsky).

Stedinger, J. R. 1980. Fitting lognormal distributions to hydrologic data. *Water Resources Research* 16(3):481.

Water Resources

Students who plan to major in an area of civil and environmental engineering may be interested in a minor in water resources. Such a program enables advanced-degree candidates to gain broad knowledge in water resource planning and management.

Thesis research is carried out in the major subject area.

M.Eng.(Civil) Degree Program

The Master of Engineering (Civil) degree program, a professional program that has developed into one of the major operations of the School of Civil and Environmental Engineering, encompasses the broad areas of structural, geotechnical, sanitary, hydraulic, and environmental systems engineering, transportation planning, and remote sensing.

An outstanding feature of the program is the involvement of practicing engineers as consultants in project work, which is carried out partly during an intensive three-week work period between academic semesters. Often the project assignments are provided by firms that either are doing or have recently done designs for the same projects, so that they are timely and pertinent to current professional practice. The work is carried out by groups of two to thirty students and normally involves many aspects of a design problem. Faculty members of the school supervise each project, from its preliminary design in the fall term prior to the intensive design period to the subsequent writing and presentation of a comprehensive report.

M.Eng.(Civil) projects are frequently carried out by teams of students with the help of consultants from industry. The designs usually pertain to actual works under construction or recently completed.

The M.Eng.(Civil) program is designed for students who hold a B.S. degree in civil and environmental engineering. Graduates with other majors may find it necessary to extend their programs beyond the normal one year in order to meet the degree requirements, which include completion of a set of courses similar to those of programs in civil engineering accredited by the Engineers' Council for Professional Development (ECPD). Each M.Eng.(Civil) degree candidate chooses an area of concentration and a related minor subject. Required course work includes, in addition to the six-credit design project, professional engineering practice that encompasses aspects of economics, management, and law.

Recent group projects accomplished partly during the intensive intersession work periods, listed with information about the participants, are:

Olympic Facilities (twenty-eight students; Elio D'Appolonia, of D'Appolonia Consulting Engineers, Inc., and Anton Tedesko, consultants; Professors Gergely, Kulhawy, and White)
Wastewater Treatment Plant for Ithaca (ten students; A. Gordon Wheler, of Stearns and Wheler, consultant; Professor Gates)
Design of Bridge across Piscataqua River (thirty students; Richard Christie, of Hardesty and Hanover, consultant; Professors Abel and Sexsmith)
Development of an Economical Wastewater Treatment Plant for the Doe Run Effluent, Olin Chemicals Group, Brandenburg, . Kentucky (fourteen students; H. H. Hogeman, D. R. Vaughn, and C. T. Avery, of Olin Chemicals Group, and Paul L. Busch, of Malcolm Pirnie, Inc., consultants; Professor Behn)
Reservoir Systems Planning for Irrigation in Northern Africa (three students; Professors Loucks, Shoemaker, and Willis)
High-Rise Building, New York City (twenty students; L. Robertson, of Skilling, Helle, Christiansen, and Robertson, consultant; Professors O'Rourke, Gergely, and Ingraffea)
Gulf of Alaska Offshore Platforms (twenty-seven students; Robert Bea, of Woodward-Clyde Assoc., and Rudy Hall, of Petro-Marine Corp., consultants; Professors Sangrey, Gergely, and Ingraffea)
Design of a Radioactive Waste Treatment System for the Offshore Atlantic Generating Station (two students; Robert Cherdack, of Burns and Roe, Inc., consultant; Professor Gates)
Municipal Wastewater Treatment by Automation and Computer Control (ten students; Elmer Ballotti, of Greeley and Hansen Engineers, consultant; Professor Behn)
Liquified Natural Gas Terminal at Cove Point, Chesapeake Bay, Maryland (fifteen students; M. Esrig, of Woodward-Clyde Assoc., consultant; Professor Kay)
Offshore Floating Nuclear Power Station: Structural and Foundation Site Aspects (twenty-three students; Eugene Harlow, of F. R. Harris, and Harcharan Singh, of Dames and Moore, consultants; Professors Sexsmith and Kay)
Boeing 747 Hangar and Maintenance Facility for LaGuardia Airport, New York (twenty-six students; Lev Zetlin, of Lev Zetlin Assoc., consultant; Professors DiPasquale, Sangrey, and Thomas)
Upgrading the Binghamton–Johnson City, New York, Joint Sewage Treatment Plant (nine students; Paul L. Busch, of Malcolm Pirnie, Inc., consultant; Professor Gates)

Other recent M.Eng.(Civil) design projects, carried out by one or two students under faculty supervision, are:

Airphoto Studies of Environmental Impact of Highway Construction (T. Liang)
Industrial Site Location in Essex County, New York (W. R. Philipson)
The Relocation and Design of the Amtrac Passenger Station in Syracuse, New York (F. J. Cesario)
Toward the Development of a Mass Transit System for Tompkins County, New York (A. H. Meyburg)
Water Quality Surveillance by Remote Sensing (T. Liang)

Faculty Members and Their Research and Teaching Interests

John F. Abel, P.E.; B.S. (Cornell), M.S. (Stanford), Ph.D. (California, Berkeley): *numerical methods in structural mechanics, finite element analysis, computer graphics*
James J. Bisogni, Jr., B.S. (Lehigh), M.S., Ph.D. (Cornell): *sanitary engineering, applied aquatic chemistry*
Wilfried H. Brutsaert, Eng. (State University, Ghent), M.S., Ph.D. (California, Davis): *hydraulics, hydrology, groundwater flow*
Richard I. Dick, B.S. (Iowa State), M.S. (State University of Iowa), Ph.D. (Illinois): *sanitary engineering, sludge treatment and disposal*
Leonard B. Dworsky, B.S. (Michigan), M.S. (American): *water resource planning management and policy*
Gordon P. Fisher, P.E.; B.E., Dr.Eng. (Johns Hopkins): *transportation systems analysis, traffic flow theory, public systems, engineering economics, urban goods movement*
Peter Gergely, P.E.; B.Eng. (McGill), M.S., Ph.D. (Illinois): *structural mechanics, shells, dynamics, earthquake engineering, reinforced concrete*

James M. Gossett, B.S., M.S., Ph.D. (Stanford): *sanitary engineering, biological treatment processes*

Donald P. Greenberg, B.C.E., Ph.D. (Cornell): *structural engineering, computer graphics, cable structures*

Mircea Grigoriu, Dipl.Ing. (Bucharest Institute of Civil Engineering), Dipl.Math. (University of Bucharest), Ph.D. (M.I.T.): *structural reliability, structural analysis*

Douglas A. Haith, B.S., M.S. (M.I.T.), Ph.D. (Cornell): *water resource systems, nonpoint-source pollution*

Anthony R. Ingraffea, B.S. (Notre Dame), M.S. (Polytechnic Institute of New York), Ph.D. (Colorado): *structural mechanics, fracture mechanics, numerical modeling and testing of rock and concrete fracture*

Gerhard H. Jirka, Dipl.Ing. (Vienna, Austria), M.S., Ph.D. (M.I.T.): *fluid mechanics, hydraulics, thermal pollution*

Fred H. Kulhawy, P.E.; B.S.C.E., M.S.C.E. (Newark College of Engineering), Ph.D. (California, Berkeley): *soil-structure interaction, rock engineering, finite element modeling, marine and coastal geotechnique, geomechanics*

Ta Liang, B.E. (Tsing Hua), M.C.E., Ph.D. (Cornell): *aerial photography, physical environment, remote sensing*

James A. Liggett, B.S. (Texas Technological), M.S., Ph.D. (Stanford): *hydraulics, fluid mechanics and hydrology*

Philip L.-F. Liu, B.S. (National Taiwan), S.M., Sc.D. (M.I.T.): *fluid mechanics, coastal engineering*

Raymond C. Loehr, B.S., M.S. (Case), Ph.D. (Wisconsin): *agricultural wastes*

Daniel P. Loucks, B.S. (Pennsylvania State), M.S. (Yale), Ph.D. (Cornell): *water resource and environmental management systems, interactive computer graphics*

Walter R. Lynn, P.E.; B.S.C.E. (University of Miami), M.S.C.E. (North Carolina), Ph.D. (Northwestern): *environmental systems analysis, public health, water quality management models*

George B. Lyon, P.E.; B.S. (Illinois), M.S. (State University of Iowa): *surveying*

William McGuire, P.E.; B.S.C.E. (Bucknell), M.C.E. (Cornell): *performance and design of metal structures, computer graphics*

Arnim H. Meyburg, B.A. Equiv. (Free University of Berlin), M.S., Ph.D. (Northwestern): *urban transportation, transportation systems analysis, mass transit operations, transportation and communications, freight transportation*

Arthur H. Nilson, P.E.; B.S. (Stanford), M.S. (Cornell), Ph.D. (California, Berkeley): *behavior and design of reinforced concrete, prestressed concrete, light-gauge steel structures*

Neil Orloff, B.S. (M.I.T.), M.B.A. (Harvard), J.D. (Columbia): *environmental law, social implications of technology*

Thomas D. O'Rourke, B.S. (Cornell), M.S., Ph.D. (Illinois): *soil-structure interaction, analytical methods, underground structures, geotechnical instrumentation*

Teoman Peköz, B.S. (Robert College), M.S. (Harvard), Ph.D. (Cornell): *stability; cold-formed, thin-walled steel structures; experimental methods*

Warren R. Philipson, B.C.E., M.S., Ph.D. (Cornell): *remote sensing, aerial photography, physical environment*

Richard E. Schuler, B.E. (Yale), M.B.A. (Lehigh), M.A., Ph.D. (Brown): *urban, spatial, and energy economics; public finance problems; transportation economics*

Christine A. Shoemaker, B.A. (California, Davis), Ph.D. (Southern California): *pest management, water resource systems, mathematical ecology*

Floyd O. Slate, B.S., M.S., Ph.D. (Purdue): *physical and chemical properties of engineering materials*

Jery R. Stedinger, A.B. (California, Berkeley), A.M., Ph.D. (Harvard): *stochastic hydrology, water resource systems, ecosystem management*

Mark A. Turnquist, B.S. (Michigan State), S.M., Ph.D. (M.I.T.): *transportation systems analysis, transportation economics*

Richard N. White (Director of the School of Civil and Environmental Engineering), P.E.; B.S., M.S., Ph.D. (Wisconsin): *model analysis, nuclear reactor structures, concrete structures*

Further Information

Further information may be obtained by writing to the Graduate Faculty Representative, Civil and Environmental Engineering, Cornell University, Hollister Hall, Ithaca, New York 14853.

Computer Science

Research in computer science at Cornell is concerned with the fundamental concepts and characteristic phenomena that arise in the creation and use of computing systems. This includes study of the limitations of computers, the principles underlying the mechanical processing of information, the design of efficient and reliable algorithms, and the organization of information for computer processing. It also involves the development of methods for writing good programs and engineering large-scale systems.

Various aspects of computer science are closely related to many other fields. The fundamental theory of information processing and the exploration of the limits of the abilities of computing machines are topics in pure and applied mathematics. Numerical analysis, which has to do with the development as well as the accuracy and efficiency of practical numerical procedures, is in the area of applied mathematics. Students of computer science and of electrical engineering share an interest in the characteristics of physical machines and in computer design. Language structure and translation are of concern in both computer science and linguistics. The implications of current data-processing technology for the organization and control of industrial and business operations are also pertinent to industrial engineering and business administration. Investigations in the area of artificial intelligence are of interest in psychology and biology.

In the past these subjects have usually been pursued as parts of various fields; today their common basis is being increasingly recognized, and computer, or information, science has become an independent discipline at many leading institutions.

Cornell's leadership in the development of computer science is indicated by the following texts written at Cornell and widely used by other institutions:

Aho, A.; Hopcroft, J. E.; and Ullman, J. D. 1974. *The design and analysis of computer algorithms*. New York: Addison-Wesley.

Constable, R. L., and O'Donnell, M. J. 1978. *A programming logic*. Cambridge, Mass.: Winthrop.

Conway, R. W. 1977. *A primer on disciplined programming*. Cambridge, Mass.: Winthrop.

———. 1978. *Programming for poets*. Cambridge, Mass.: Winthrop.

Conway, R. W., and Gries, D. 1976. *A primer on structured programming*. Cambridge, Mass.: Winthrop.

———. 1979. *An introduction to programming: a structured approach using PL/1 and PL/C*. 3d ed. Cambridge, Mass.: Winthrop.

Conway, R. W.; Gries, D.; Bass, C.; and Fay, M. 1979. *An introduction to microprocessor programming*. Cambridge, Mass.: Winthrop.

Conway, R. W.; Gries, D.; and Wortman, D. 1977. *An introduction to structured programming in SP/K*. Cambridge, Mass.: Winthrop.

Conway, R. W.; Gries, D.; and Zimmerman, C. 1976. *A primer on Pascal*. Cambridge, Mass.: Winthrop.

Conway, R. W.; Maxwell, W. L.; and Miller, L. W. 1967. *Theory of scheduling*. New York: Addison-Wesley.

Donahue, J. 1976. *Complementary definitions of programming language semantics*. New York: Springer-Verlag.

Gries, D. 1971. *Compiler construction for digital computers.* New York: Wiley.
———. 1979. *Programming methodology: a collection of articles by members of IFIP WG2.3.* New York: Springer-Verlag.
Hartmanis, J., and Stearns, R. E. 1966. *Algebraic structure theory of sequential machines.* Englewood Cliffs, N.J.: Prentice-Hall.
Hopcroft, J. E., and Ullman, J. D. 1969. *Formal languages and their relation to automata.* New York: Addison-Wesley.
———. 1979. *Introduction to automata theory, languages, and computation.* New York: Addison-Wesley.
Salton, G. 1969. *Automatic information organization and retrieval.* New York: McGraw-Hill.
———. 1975. *Dynamic information and library processing.* Englewood Cliffs, N.J.: Prentice-Hall.
Salton, G. et al. 1971. *The SMART retrieval system: experiments in automatic document processing.* Englewood Cliffs, N.J.: Prentice-Hall.

There are about fifty graduate students in computer science at the present time. From approximately two hundred applicants, the field admits fifteen to twenty new students each fall. Persons who cannot enroll as full-time students are discouraged from applying (students having assistantships or fellowships are normally regarded as full-time students).

To be admitted to graduate study in computer science, a student is expected to have had significant experience in programming, a solid background in mathematics (at least calculus and linear algebra and preferably other subjects such as logic, statistics, or analysis), and the appropriate background to permit immediate enrollment in graduate-level courses in the specialization chosen. In addition to the materials required for application to the Graduate School, the Field of Computer Science requires a third letter of recommendation, a supplemental application form (available from the graduate faculty representative of the field), and Graduate Record Examination scores (verbal, quantitative, and, if possible, an appropriate advanced test score).

The University's central IBM 370/168 computer *(above)* is reached by terminals such as the one in Upson Hall used by graduate student Fred Follert *(right).*

Students who are interested primarily in computer components and logical design rather than in the use of computers may find it more appropriate to apply to the Field of Electrical Engineering.

Facilities

For its own research the department owns a VAX, two microprogrammable PDP 11/60s, and a number of Teraks (LSI-11s). The University also has a VAX-based graphics laboratory, with a number of sophisticated graphics devices. The central Cornell computing facility is a six-megabyte IBM 370/168 running under VM/CMS, which is linked to high-speed terminals at various locations on campus. The College of Engineering is served through two such terminals at Upson Hall, as well as through a number of slow-speed terminals for time-sharing. A DEC-20 is also available for instructional and research computing.

Areas of Research

The research program is designed to provide an atmosphere in which both the students and the faculty can influence the development of computer science.

Graduate students make frequent use of the PDP-11/60 computer terminals. This microprogrammable system is a research facility of the Department of Computer Science. The supervising faculty member is Alan Demers *(at center)*.

Among the professors who direct research in computational theory are Robert L. Constable *(left)* and Juris Hartmanis *(center).*

Major research efforts are directed toward analysis of algorithms, theory of computation, programming methodology, programming languages, program verification, operating systems, distributed systems, information storage and retrieval, and numerical-analysis.

Instruction and research in related topics are carried out in other graduate fields. These subjects include simulation, data processing, graphics, control theory, mathematical programming, network and graph theory, and electrical engineering. The Field of Computer Science maintains a close relationship with the Fields of Operations Research and Electrical Engineering at Cornell.

The major research activities of the Field of Computer Science are briefly described in the following pages. The examples range from abstract mathematics to practical implementations and experiments in programming systems.

Theory of Algorithms

There is a growing belief that a relatively small number — perhaps a score — of fundamental processes dominate all computing, in both applications and systems programs. The study of algorithms is the attempt to identify these fundamental processes and to find efficient and possibly optimal algorithms for their execution. Recent results have concerned high-precision multiplication, matrix multiplication, evaluation of polynomials, pattern matching, sorting, and manipulation of graphs. In many cases, marked improvements in performance have been obtained. For example, although it had been known that matrix multiplication varies with the cube of the order n, it was recently shown that at most $n^{2.81}$ operations are required.

The work of J. E. Hopcroft concentrates on fundamental features of the basic algorithms. Concise models of the pertinent features are being formulated, and theoretical results concerning asymptotic running times and lower bounds are being obtained.

Examples of recent theses, listed with the name of the supervising professor, are:

Brassard, G. 1979. Relativized cryptography. Ph.D. thesis (J. E. Hopcroft).
Fortune, S. 1979. Topics in computational complexity. Ph.D. thesis (J. E. Hopcroft).
Wyllie, J. 1979. The complexity of parallel computations. Ph.D. thesis (J. E. Hopcroft).

Theory of Computation

Primary concerns in this area are the theory of automata, formal languages, computational complexity, and program schemata.

As a result of recent work in theoretical computer science, a unified theory of feasible computation is emerging that has strong connections to recursive function theory, formal language theory, and the theory of algorithms. This theory and these connections are being investigated by several professors and their students.

Theses in this area, listed with the name of the supervising professor, include:

Chan, T. 1980. Computational complexity of reversal-bounded Turing machines. Ph.D. thesis (R. L. Constable).
Immerman, N. 1980. Formula length and computational complexity. Ph.D. thesis (J. Hartmanis, A. Nerode).
Kozen, D. 1977. Complexity of finitely presented algebras. Ph.D. thesis (J. Hartmanis).

Program Verification and Formal Semantics

R. L. Constable, A. Demers, J. Donahue, and their students are working on various aspects of program verification, programming language design, and formal semantics. Constable is concerned with theoretical issues arising in this area, particularly with questions about the underlying logical systems and models. He is director of the PL/CV verifier project. The verifier, which has been distributed to several research groups, allows the user to write formal proofs of correctness of programs written in a subset of PL/C. As an experiment, the verifier is being used as the vehicle for teaching programming in an undergraduate course.

Demers and Donahue are involved in developing a programming language, called Russell, based on a novel treatment of data types. Work is proceeding on its implementation and on the study of various aspects of its semantics. Constable and Demers are also involved in designing a "refinement logic": a system for developing programs by refining their specifications, thus guaranteeing the correctness of the resulting programs. Work is beginning on an interactive system on the VAX for program development using refinement logic.

Some examples of recent work in this area are:

Bates, J. 1979. A logic for correct program development. Ph.D. thesis (A. Demers).
Constable, R. L., and O'Donnell, M. J. 1978. *A programming logic, with an introduction to the PL/CV verifier.* Cambridge, Mass.: Winthrop.
Demers, A., and Donahue, J. 1980. Data types, parameters and type checking. In *Proceedings of the symposium on principles of programming languages*, p. 12. New York: Association for Computing Machinery.
——— 1980. "Type-completeness" as a language principle. In *Proceedings of the symposium on principles of programming languages*, p. 234. New York: Association for Computing Machinery.
Hauser, C. 1980. Specification and verification of communication in parallel systems. Ph.D. thesis (R. L. Constable).

Professor David Gries works with the department's teaching assistants in the basic computer science course.

Concurrent Programming

Operating systems, data-base management systems, and distributed systems can all be viewed as large concurrent programs. D. Gries, F. B. Schneider, S. Toueg, and their students are studying the design, construction, and analysis of concurrent programs in order to gain insight into such systems.

A recent project has been to find ways to ensure that concurrent programs exhibit reproducible behavior, making them easier to understand and analyze. A second project has been concerned with developing techniques to solve synchronization problems in distributed systems; results have application both in operating systems and in distributed database systems. Another research effort is to develop ways of proving the correctness of communicating sequential processes and to derive methods for developing concurrent programs. Also, issues involved in the implementation of a systems programming language suitable for a distributed multimicroprocessor network are being studied. The department's VAX and twin PDP 11/60 processors, as well as access to the prototype microprocessor network that will be operating in Cornell's National Research and Resource Facility for Submicron Structures, provide ample facilities to conduct such research.

The following papers describe some of the recent research:

Akkoyunlu, A. J.; Bernstein, E. A.; Schneider, F. B.; and Silberschatz, A. 1978. Conditions for the equivalence of synchronous and asynchronous systems. *IEEE Transactions on Software Engineering,* SE-4:507.

Levin, G. 1980. An axiomatic proof technique for communicating sequential processes. Ph.D. thesis (D. Gries).

Owicki, S., and Gries, D. 1976. An axiomatic proof technique for parallel programs. *Acta Informatica* 6:319.

Schneider, F. B. 1980. Ensuring consistency in a distributed data-base system. In *Distributed Data Bases,* ed. C. Delobel and W. Litwin, p. 183. Amsterdam: North Holland.

Programming Methodology

Various aspects of programming methodology are being studied in research directed by D. Gries. The work includes investigating and refining methods for program development and the teaching of that subject; it touches on concurrent programming, semantics of programming languages, program verification, and programming language design.

Examples of recent papers are:

Gries, D. 1979. The Schorr-Waite graph marking algorithm. *Acta Informatica* 11:223.

Gries, D., and Levin, G. 1980. Assignment and procedure call proof rules. *Transactions on Programming Languages and Systems* (in press).

Holm, J. 1980. A study of proof of correctness of programs that use floating point arithmetic. Ph.D. thesis (D. Gries).

Program-Development Systems

The current work in systems for program development continues a project that led to the PL/C compiler, a highly diagnostic compiler for a subset of PL/1. The system has been used in more than two hundred universities throughout the world.

The original PL/C work emphasized automatic error repair to help overcome inherent inefficiencies of batch systems. The current work is oriented toward interactive systems, screen displays, and microprocessor implementations; it emphasizes integrated development environments, including editors, file systems, and language translators.

There are two parallel implementation efforts to allow exploration of several alternative strategies for effective development of programs. R. Teitelbaum heads the Cornell program synthesizer project, an effort to develop an interactive system that resists introduction of syntactic errors and encourages programming discipline. The synthesizer, implemented under UNIX on a Terak (LSI-11), has been used in introductory programming courses at Cornell since 1979 and is being distributed to other universities. A second project, under the direction of R. W. Conway, is exploring an alternative approach, adapting the automatic error repair strategy to an interactive environment.

Information Organization and Retrieval

Research directed by G. Salton deals with the analysis of information retrieval algorithms and the design of fully automatic retrieval systems. This work includes the design and evaluation of file organization systems, automatic classification and search methods, language analysis procedures, and interactive retrieval processes. A research project headed by Salton has led to the publication in the past

few years of three textbooks (cited previously). The participation of graduate students in this program is indicated by thesis work completed recently (the name of the supervising professor is shown in parentheses):

Williamson, R. E. 1974. Real time document retrieval, Ph.D. thesis (G. Salton).
Wong, Y. C. A. 1978. Studies on clustered files. Ph.D. thesis (G. Salton).
Yu, C. 1973. Theory of indexing and classification. Ph.D. thesis (G. Salton).

In another project in this area, R. W. Conway and W. L. Maxwell have designed and implemented a data-base maintenance and information retrieval system. Work continues on this system, which features unusual facilities for file security. It is described in the following publication:

Conway, R. W.; Maxwell, W. L.; and Morgan, H. L. 1972. On the implementation of security measures in an information system. *Communications of the ACM* 15(4):211.

Numerical Analysis

F. Luk and C. Van Loan conduct research in matrix computations; their current work involves the development and analysis of stable and reliable algorithms for applied problems in statistics, control theory, and related areas. Specific topics under investigation include inverse eigenvalue problems, algorithms for the fitting of "noisy" data, the Lanczos method for sparse

Left above: **Nancy Eland, a recent Ph.D., discusses her thesis work on data-base systems with her adviser, Professor Richard W. Conway.**

Above: **Professor Gerard Salton is a leading authority on information organization and retrieval.**

eigenvalue problems, rank determination of structured matrices, and methods for solving both the algebraic and the differential Riccati equation.

Other work in this area includes the research of J. Bramble in the numerical solution of partial differential equations. Possibilities also exist for thesis work with faculty members in the Field of Applied Mathematics and other related graduate fields.

Recently published articles in this area include:

Bramble, J.; Schatz, A. H.; Thornee, V.; and Wahlbin, L. 1977. Some convergence estimates for semi-discrete Galerkin-type approximations for parabolic equations. *SIAM Journal on Numerical Analysis* 14:218.

Luk, F., and Pagano, M. 1980. Quadratic programming with M-matrices. *Journal of Linear Algebra and Applications* (in press).

Van Loan, C., and Moler, C. 1978. Nineteen dubious ways to compute the exponential of a matrix. *SIAM Review* 20:801.

Faculty Members and Their Research Interests

The faculty of the graduate Field of Computer Science consists of the staff of the Department of Computer Science and members of other departments who teach graduate courses and supervise students in areas of study related to computer science. The field members are listed below.

James Bramble, A. B. (Brown), M.S., Ph.D. (Maryland): *numerical analysis*

Robert L. Constable, B. A. (Princeton), M.A., Ph.D. (Wisconsin): *computational complexity, theory of programming logics and program verification*

Richard W. Conway, B.M.E., Ph.D. (Cornell): *digital simulation, management, information systems, compiler construction, operating systems*

Alan Demers, B.S. (Boston), M.A., Ph.D. (Princeton): *programming languages, compiler construction*

James Donahue, B.A. (Michigan), M.S (Rutgers), Ph.D. (Toronto): *programming languages, program semantics*

Donald P. Greenberg, B.S.E., Ph.D. (Cornell): *computer graphics, computer-aided design, image processing*

David Gries, B.S. (Queens), M.S. (Illinois), Dr.rer.nat. (Technical University, Munich): *programming languages, programming methodology, compiler construction*

Juris Hartmanis (Chairman of the Department of Computer Science), Cand.Phil. (Marburg), M.A. (Kansas City), Ph.D. (California Institute of Technology): *theory of computation*

John E. Hopcroft, B.S., M.S., Ph.D. (Stanford): *theory of computation, analysis of algorithms*

Franklin Luk, B.S. (California Institute of Technology), M.S., Ph.D. (Stanford): *numerical analysis*

Anil Nerode, A.B., B.S., M.S., Ph.D. (Chicago): *logic, applied mathematics*

Gerard Salton, A.B., M.A. (Brooklyn), Ph.D. (Harvard): *information organization and retrieval*

Fred B. Schneider, B.S., M.S. (Cornell), Ph.D. (SUNY, Stony Brook): *concurrent programming, operating systems, distributed systems*

Ray Teitelbaum, B.S. (M.I.T.), Ph.D. (Carnegie-Mellon): *programming languages and systems*

Sam Toueg, B.S. (Technion, Israel), M.S.E., M.A., Ph.D. (Princeton): *computer networks and protocols, theory of computation*

Charles Van Loan, B.S., M.A., Ph.D. (Michigan): *numerical analysis*

Further Information

Additional information may be obtained by writing to the Graduate Faculty Representative, Computer Science, Cornell University, Upson Hall, Ithaca, New York 14853.

Electrical Engineering

Graduate study in electrical engineering at Cornell is stimulated by a wide range of interests and aspirations. Some students want to engage in research on basic electrical phenomena or in a broad field such as the processing of signals. Others wish to design and develop electrical solutions to specific problems.

At the master's degree level there are two avenues by which a student may proceed: the Master of Engineering (Electrical) degree program, which places major emphasis on design capability at a high level of professional competence, and the Master of Science degree program, which focuses attention on independent research. Beyond this stage the two routes coalesce in the Doctor of Philosophy degree program, in which research is conducted on topics that vary from optical electronics to space communication. Some examples of current activities are projects in the areas of planetary magnetospheres, the application of control theory to power-system stability, optical communication systems, signal encoding in animal nervous systems, algorithmic design of computer networks, microwave field-effect transistors, insensitive multivariable control systems, probabilistic coding, electron microscopy in integrated-circuit fabrication, high-energy plasmas and thermonuclear fusion, solid-state and ultraviolet lasers, and electric vehicles.

The two general areas of electrophysics and systems underlie most research and design activity in electrical engineering. Electrophysics encompasses the study of the physical properties of matter and the environment, and the study of devices that use these properties. Systems research is concerned with the complexes formed by the interconnection of devices and with the response of these networks to various excitations. In electrical engineering these two areas impinge on one another. At Cornell, research projects are distributed widely over the separate disciplines as well as in the areas of overlap.

Currently more than one hundred seventy full-time graduate students are enrolled in the Field of Electrical Engineering. Of these, approximately fifty are working for the Ph.D. degrees. This number is large enough to achieve the critical mass that is conducive to effective research in most areas, yet small enough to enable the students and faculty to work together in close association. Moreover, since graduate students often learn as much from each other as they do from their formal studies, it is important to provide an environment like that at Cornell that encourages interaction among people working in related research areas. In addition to these graduate students, there are about twenty doctoral-degree candidates in fields such as physics, applied physics, and applied mathematics now working with electrical engineering faculty members who are members of other graduate fields as well.

The M.Eng.(Electrical) degree program is a course of study requiring thirty credits of technical work, which must include two two-semester course sequences in electrical engineering. Three to ten credits are earned for a design project. Neither the M.S. nor the Ph.D. degree program has specific course requirements. Each student, in consultation with the faculty members of the student's special committee, devises a program of courses and research tailored to her or his own background and objectives. The formal courses in any of these programs may be selected from the more than sixty graduate-level courses offered by the School of Electrical Engineering or from the many other advanced courses offered throughout the University that are of interest to graduate students in electrical engineering. Of particular relevance are courses in the areas of applied physics, astronomy and space sciences, computer science, mathematics, neurobiology and behavior, and physics.

Facilities

Many of the research projects in the Field of Electrical Engineering are carried out in the laboratories of Phillips Hall, the center of activity in electrical engineering at Cornell. Several other University laboratories and research centers also accommodate electrical engineering research groups.

In the area of electrophysics, the facilities include special laboratories for ionospheric physics and radiowave propagation, microwave solid-state devices, optics and spectroscopy of solids and thin films, and quantum electronics. The National Research and Resource Facility for Submicron Structures, an NSF-funded operation to develop knowledge and techniques essential to the design and construction of extremely small electronic devices, is housed in Phillips Hall. The facilities of Cornell's Materials Science Center and of its Laboratory of Plasma Studies are used by groups working in these areas. Some of the research in ionospheric physics and radar astronomy is carried out at the National Astronomy and Ionosphere Center, which is operated by Cornell in Puerto Rico.

In the area of systems, the facilities include special laboratories for research on active networks and digital filters, bioelectronics, control systems, and digital systems. Some groups also use the facilities of the Section of Neurobiology and Behavior in the Division of Biological Sciences.

The various computer facilities available at Cornell are highly important for electrical engineering research, particularly in the area of systems. The University's extensive central computer services and on-campus terminals, which give access to several of the largest computing networks in existence, are used in many of the research projects in both electrophysics and systems. Several projects in the school, including those in the areas of submicrometer and atmospheric physics, have computer facilities that are available for use by researchers working on other projects. In addition, the School of Electrical Engineering has several computer systems with extensive peripheral devices that are available to all faculty members and students for research and instructional use.

Areas of Research

The research activities of faculty members in the Field of Electrical Engineering may be grouped into a number of broad areas. Some of the current research topics and design problems are given below under each area heading; also listed are a few recent design reports, research theses, and publications that have resulted from this work. A complete list of faculty publications is available from the School of Electrical Engineering, Phillips Hall.

Bioelectronics and Bioelectric Systems

Much of the research in bioelectronics and bioelectric systems is concerned with the application of electrical engineering techniques to basic medical and biological problems: signal-processing techniques are used in the decoding of peripheral nervous-system information; integrated-circuit technology is used to fabricate microelectrodes for electrophysiological studies; techniques of circuit design are used in developing amplifiers for signal-measurement systems. Research on sound communication and hearing in animals includes behavioral and physiological studies in conjunction with electronic measurements. The dynamics of cancer-cell proliferation, including implications for cancer therapy, is another area of current research.

Projects involve a variety of approaches. For example, a current project is the fabrication of microelectrode sensor arrays to facilitate the extracellular recording of electrical signals from the peripheral nervous system; included in this electrode structure are several

Above: **In studies of animal communication directed by Professor Robert R. Capranica *(standing)*, sounds are generated electronically and transmitted to an animal subject inside a soundproof chamber. In experiments with anurans (toads and frogs), the resulting vibrations of the eardrum are measured by a sensitive laser interferometry technique developed at Cornell.**

Left: **Current research in bioelectronics includes the development of electrodes for chronic recording and of signal processing techniques for decoding information carried on the peripheral nerves of frogs and cats. This work is under the direction of Professors William J. Heetderks *(center)* and M. Kim *(right)*.**

preamplifier configurations of either JFET or MOSFET design. In another project, electrodes for chronic recording from small nerves are being evaluated. Signal-processing methods are being developed to identify single-cell activity in extracellular recordings of multiple neural units. A program on vocal communication in frogs and toads includes work on the encoding of complex signals in the auditory nervous system.

R. R. Capranica, W. J. Heetderks, and M. Kim direct these research efforts. Examples of publications and of theses and reports (listed with the name of the supervising professor) are:

Batruni, R. 1980. Multivariate statistical analysis of the response of cockroach giant interneurons to windpuffs. M.Eng. report (W. J. Heetderks).

Capranica, R. R. 1978. Auditory processing and animal sound communication. *Federation Proceedings* 37:2315.

———. 1980. Neural basis for detection of complex sounds. In *Advances in prosthetic devices for the deaf: a technical workshop*, ed. D. L. McPherson. Rochester, N.Y.: National Institute for the Deaf.

Capranica, R. R., and Moffat, A. J. M. 1980. Nonlinear properties of the peripheral auditory system of anurans. In *Comparative studies of auditory processing in vertebrates*, ed. A. Popper and R. Fay. Berlin: Springer-Verlag.

Chen, J.-N. 1980. Remote monitoring of animal deep-body temperatures by implanted transmitters. M.Eng. report (M. Kim).

Kim, M.; Shin, K.; and Perry, S. 1980. Design of optimal chemotherapy schedules using kinetic models of cancerous and normal tissues. *Journal of Cybernetics and Information Science* (in press).
Larson, L. 1980. Integrated multielectrode biopotential recording array employing LSI MOSFET technology. M.Eng. report (M. Kim).
Mestais, C. 1979. Electrode design and signal processing techniques to extract a nervous signal out of a frog's peroneal nerve. M.Eng. report (W. J. Heetderks).
Shin, K. G. 1978. System identification for kinetics of a cellular proliferation of a cancer cell population. Ph.D. thesis (M. Kim).
Tse, F. K.-P. 1980. Development of transient response method to measure the transfer function of the eardrum with a laser homodyne scattering interferometer. M.S. thesis (R. R. Capranica).
Wheeler, B. C. 1980. The evaluation of neural multi-unit separation techniques. Ph.D. thesis (W. J. Heetderks).

Communication, Information, and Decision Theory

Research efforts in communication, information, and decision theory are directed primarily toward fundamental contributions to the theory of representing and processing information. In addition there is ongoing research into the formulation and solution of selected probabilistic and statistical problems that arise in the design and analysis of systems for signal processing, communication, computation, and decision making.

Studies of multiterminal information theory are concerned with situations in which correlated sources of information observed at different locations must be conveyed, either exactly or approximately, to several destinations over networks of communication channels. In Cornell work the optimum performance attainable by communication systems designed for such multiterminal information transmission has been determined or accurately bounded in many interesting cases. Interrelations between ergodic theory and multiterminal information theory constitute a recently opened research area. Related problems in multiterminal estimation and decision theory are also under investigation.

New characterizations of chance and uncertainty, based on concepts of interval-valued and comparative probabilities, are being developed. Methods of inference and decision making that are compatible with these new characterizations and that can yield new designs for information-processing systems are being explored.

T. Berger, T. L. Fine, and J. C. Walrand direct research in this area. Examples of publications and of theses and reports (listed with the name of the supervising professor) are:

Berger, T., and Kaspi, T. 1980. Rate-distortion for correlated sources with partially separated encoders. *IEEE Transactions on Information Theory* (in press).
Campello de Souza, F. M. 1979. Probabilistic models for binary choice behavior. Ph.D. thesis (T. L. Fine).
Fine, T. L., and Hwang, W. G. 1979. Consistent estimation of system order. *IEEE Transactions on Automatic Control* AC-24:387.
Fine, T. L., and Walley, P. 1979. Varieties of modal (classificatory) and comparative probability. *Synthese* 41:321.
Ong., L. 1980. Simulation of a tree protocol for packet data communications with feedback. M.Eng. report (T. Berger).
Walrand, J. C., and Varaiya, P. 1980. Sojourn times and the overtaking condition in networks of queues. *Advances in Applied Probability* (in press).
Wolfenson, M. 1979. Inference and decision making based on interval-valued probability. Ph.D. thesis (T. L. Fine).

Computer Engineering

Research efforts in this area are stimulated and defined by the demand for various cost-effective computer configurations and the advent of very-large-scale integrated circuit (VLSI) technologies.

New methods are being sought for the design and analysis of VLSI computer systems, particularly with regard to the interaction between central processing units (CPUs) and memory units. Studies are also being conducted on VLSI memory structures.

Algorithmic and quantitative approaches to the design, implementation, and evaluation of microcomputers, minicomputers, and computer networks are being developed. Interactions with the Department of Computer Science allow application of computational complexity theory to this work to determine areas of compatible feasibility. Also under study is the interpretation of higher-level, directly executable languages with microprocessors and microcomputers.

Design efforts are directed toward specific applications of digital and computing technologies. The need for control, input-output, and interface subsystems, to be used with student-constructed digital computers and in the microprocessor laboratory, provides many design projects. The digital systems laboratory has been designed to facilitate activities in this area.

J. Hartmanis, M. Kim, C. Pottle, H. C. Torng, and N. M. Vrana and their students work on these projects. Recent publications, and theses and reports (listed with the name of the supervising professor), include:

In the microprocessor laboratory of the School of Electrical Engineering, computer engineering students design and implement hardware and software for experimental systems based on microprocessors.

Carroll, L. 1979. Design of a floppy disk controller for an Intel 8080 microprocessor. M.Eng. report (H. C. Torng).

Fischell, S. 1979. Data systems for a field seismic recorder. M.Eng. report (C. Pottle).

Fujise, M. 1980. The design of RAM address space for the 8022 microprocessor. M.Eng. report (N. M. Vrana).

Hartmanis, J. 1980. On the succinctness of different representations of languages. *SIAM Journal on Computing* 9(1):114.

Pottle, C. et al. 1980. Conformational analysis of proteins: algorithms and data structures for array processing. *Journal of Computational Chemistry* 1(1):46.

Tao, A. 1979. The direct execution of a high-level language on microcomputers. M.S. thesis (H. C. Torng).

Torng, H. C., and Fung, K. T. 1979. On the analysis of memory conflicts and bus contentions in a multi-microprocessor system. *IEEE Transactions on Computers* C-28:28.

Zaino, L. 1980. Microprocessor enhancements for a SDK-85. M.Eng. report (N. M. Vrana).

Control Theory

Theoretical problems associated with the control of linear and nonlinear systems, including problems of stochastic control, are being studied. The techniques developed in these investigations are applied to control problems in the areas of power systems (improving transient stability), tracking systems, and guidance systems for reentry vehicles.

In the area of multivariable linear systems, the design of insensitive control systems is being investigated. By identifying certain invariant properties of a system and relating them to the design objectives, it is possible to produce an insensitive solution.

An important part of the research in control theory focuses on successive approximation techniques. Computer techniques (analog, digital, and hybrid) are emphasized, particularly for optimization in real time. The application of the theory of functional analysis to control problems provides a background for new computational procedures.

In one application of modern control theory, the dynamics of cancer cell populations and the design of various modes of cancer therapy are studied, using system identification and optimization techniques.

The design of terminal guidance systems for reentry vehicles is studied, using either the classical approach based on proportional navigation or modern control theory.

M. Kim, R. J. Thomas, J. S. Thorp, and J. C. Walrand direct research projects in this area. Recent reports and theses (listed with the name of the supervising professor) and publications include:

Kowalski, R. V. 1980. The analysis and design of the power-system stabilizer as a control device. M.Eng. report (R. J. Thomas).

Lee, D. Y.-W. 1980. Pattern recognition for a low-altitude flight guidance system. M.Eng. report (M. Kim).

Ludwig, L. F. 1980. Bilinear controllability applied to a geometric variant of the holding problem. M.S. thesis (J. S. Thorp).

Quijano, I. M. 1978. A predictive strategy for power-system transient control via dynamic braking. M.S. thesis (R. J. Thomas).

Thomas, R. J.; Barmish, B. R.; and Thorp, J. S. 1978. On the soundness of instantaneous control strategies for large-scale power systems in the emergency state. In *Proceedings of the 1978 Canadian conference on communication and power*, p. 392. IEEE catalog no. 78CH1373-0 Reg. 7.

Varaiya, P., and Walrand, J. C. 1979. Decentralized control in packet switched satellite communication. *IEEE Transactions on Automatic Control* AC-24(5):794.

Electromagnetic Theory and Applications

High-power pulse generators are being used in the Laboratory of Plasma Studies to produce electron beams carrying currents of tens of kiloamperes at megavolt levels. Electromagnetic wave propagation along these beams is being studied as part of a program concerned with new techniques for accelerating intense proton beams to relativistic velocities. This research has potential application to electronuclear breeding.

Studies have been made of transition radiation that is due to a relativistic charge incident on a metal sheet, and also of the transition radiation that occurs when a charge passes through a hole in a metal plate. The related problem of the energy decrement that is lost to a cavity by a charged particle in transit is also of interest. These problems find application in work with linear accelerators and sources of radiation.

Symmetry analysis techniques based on group theory are being developed for boundary-value problems in electromagnetic theory. Current projects include the study of the consequences of structure symmetry in (1) the modal propagation characteristics of periodic circuits and (2) the scattering matrices of junctions with multimode ports. These studies have applications to microwave and millimeter circuits and devices. An investigation of the propagation characteristics of gyromagnetoelectric media is also in progress.

Work on these and other subjects in the area of electromagnetic theory is supervised by R. Bolgiano, Jr., R. L. Liboff, P. R. McIsaac, and J. A. Nation. Recent papers include:

McIsaac, P. R. 1979. A general reciprocity theorem. *IEEE Transactions on Microwave Theory and Techniques* MTT-27:340.

Gammel, G.; Nation, J. A.; and Reed, M. E. 1978. A technique for the measurement of the amplitude and phase velocity of a slow space charge wave on a relativistic beam. *Review of Scientific Instruments* 49:507.

Electronic Circuits and Instrumentation

Electronic circuitry is needed for research in almost all fields of science and technology, and the design of instruments is an important aspect of graduate work in electrical engineering.

At Cornell, Master of Engineering candidates in particular may choose from a wide variety of subjects for projects in instrumental design. For example, in several recent projects flight hardware for rocket and satellite experiments has been developed; other design projects have been carried out in such fields as bioelectronics, power systems, plasma physics, optoelectronics, neurobiology and behavior, meteorology, high-energy physics, and veterinary medicine. Many projects entail working with groups in other units of the University; occasionally electrical engineering M.Eng. students become interested in pursuing doctoral study in the fields in which their M.Eng. instrumentation projects were accomplished.

Graduate work in this area is supervised by P. D. Ankrum, N. H. Bryant, T. E. Everhart, M. C. Kelley, J. L. Rosson, and N. M. Vrana. Recent reports (listed with the name of the supervising professor) and papers include:

A center for collecting weather satellite data was designed and assembled in a doctoral research project.

Clouser, J. 1980. A digital cassette subsystem. M.Eng. report (N. M. Vrana).

Everhart, T. E., and Spreadbury, P. J. 1979. Ultra-stable portable voltage sources. Paper read at TESTMEX 79, sponsored by IEEE Electronics Division, June 1979, in London.

Gaska, T. 1979. A microcomputer–test equipment system, the MTG-1. M.Eng. report (N. H. Bryant).

Shindel, W. 1975. Solid state regulator for D-C generator. M.Eng. report (P. Ankrum).

Wildnauer, K. 1980. Successive approximation discrete logarithmic amplifier. M.Eng. report (N. H. Bryant).

Energy Conversion and Power Systems

The problems associated with the national energy crisis have stimulated research in areas of related interest. For the past several years energy research by members of the electrical engineering faculty and their students has focused on cooperative efforts within interdisciplinary groups or centers, such as Cornell's Laboratory of Plasma Studies, and with energy programs in other divisions of the University. Activities of such broad scope continue, and investigations are also under way on energy topics of specific interest to electrical engineers.

In the general area of power-system network analysis, research is being conducted on the application of control theory and computer science techniques to the transient-stability problem that exists after a major power-system disturbance. Control mechanisms such as dynamic braking, capacitor switching, high-voltage–direct-current (HVDC) transmission modulation, and governor and exciter regulation are being investigated. An integral part of these studies is the development of algorithms to provide on-line decisions for the optimal, coordinated application of the various control mechanisms to systems in the emergency state; particular emphasis is placed on the use of microprocessors for these functions. S. Linke, C. Pottle, R. J. Thomas, and J. S. Thorp are conducting research in these areas of power-system control.

Linke and Thomas are also studying electromechanical energy conversion and associated controls, with attention to both intuitive and analytical procedures for the development of representative models. W. H. Erickson continues his interest in conventional AC and DC machinery studies, and J. L. Rosson and P. D. Ankrum are interested in the application of solid-state devices to electric machinery control.

Analysis of the University campus utilities system is a popular energy-related student-project activity. Recent topics have included examination of the possibilities for operating the University steam plant in a cogeneration mode, and consideration of restoring the old University hydroelectric plant to full service. These studies are of an interdisciplinary nature and have involved faculty members and students from the Schools of Electrical Engineering, Mechanical and Aerospace Engineering, Operations Research and Industrial Engineering, and Civil and

Environmental Engineering and also University personnel responsible for planning and facilities.

In the area of high-voltage breakdown and dielectric phenomena, research techniques and instrumentation developed in the Laboratory of Plasma Studies could be applied to investigations of corona insulation behavior and to switching phenomena. Several impulse-power facilities, which function at voltages ranging from 0.5 million to 5 million volts with duration periods of between 50 nanoseconds and a few microseconds, could be made available for such studies. S. Linke, J. A. Nation, R. N. Sudan, and C. B. Wharton are interested in these and related research topics that overlap the subject matter of plasma physics.

Recent theses and M.Eng. reports (listed with the name of the supervising professor) and publications include:

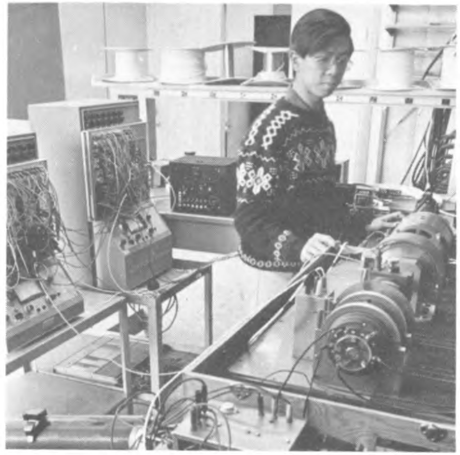
Gallai, A. M. 1980. Coherency-based dynamic equivalents for transient-stability studies of power systems. Ph.D. thesis (R. J. Thomas).

Holstein, R., and Wagner, R. 1980. An investigation of magnetic levitation utilizing a linear induction motor. M.Eng. report (S. Linke).

Murdock, J. 1979. A power frequency converter (60 to 120 Hz). M.Eng. report (J. L. Rosson).

Pottle, C. 1979. Solution of sparse linear equations arising from power systems simulation on vector or parallel processors. *ISA Transactions* 18(3):81.

Pottle, C.; Happ, H. H.; and Wirgau, K. A. 1979. Future computer technology for large power system simulation. *Automatica* 15(6):621.



Doctoral candidates are working on a project to devise techniques for on-line fault analysis that would help ensure stability of large electric power systems. A model is used to simulate a large power generating plant.

Teshome, A. 1980. Transient stability analysis of AC-DC power systems. Ph.D. thesis (S. Linke).

Thomas, R. J. 1980. Uncertainties in large scale electric power systems. In *Proceedings of 1980 joint automatic control conference*, vol. 1, p. TA3-E. IEEE publication no. 80CH1580-0.

Thomas, R. J.; Oey, K. K.; and Linke, S. 1980. Dynamic braking strategies for transient-stability control applied to a computer-driven micromachine. *IEEE Transactions on Power Apparatus and Systems* PAS-99(4):1324.

Thorp, J. S. 1980. A microcomputer based ultra-high-speed distance relay: field tests. In *Proceedings of IEEE summer power meeting*, paper no. 80SM649-4.

Yehsakul, P. D. 1978. A suboptimal meter allocation algorithm for power system static-state estimation. Ph.D. thesis (J. S. Thorp).

Integrated Circuits and Submicrometer Technology

Programs in this area benefit from, and are largely conducted in, the laboratories of the National Research and Resource Facility for Submicron Structures housed in Phillips Hall. This facility provides state-of-the-art equipment to conduct research on devices and materials for large-scale integrated circuits and other devices that have very small dimensions and require complex processing. Included is equipment for device fabrication with use of electron-beam lithography, x-ray lithography, high-resolution projection optical lithography, ion implantation, diffusion, and molecular-beam epitaxy. Scanning transmission and Auger microscopes, as well as standard scanning electron microscopes and SIMS, are available for the study of the composition and electronic properties of small devices and their interfaces. Students involved in research programs in this area have the opportunity to interact with visiting scientists who come to this national facility from industrial and university laboratories across the country to carry out their own research.

Research programs under way in the facility include fundamental development of new machines to provide finer line definition or improve the analysis of submicrometer structures; the application of these machines to the production of advanced electronic devices; and investigation of fundamental physical processes that are important in devices constructed on a submicrometer scale. Much of this work is done by faculty members in other graduate fields, such as Applied Physics, Materials Science and Engineering, and Chemistry. Within the Field of Electrical Engineering, research on quantum electronics and optoelectronics and semiconductor materials for electronic devices, described elsewhere in this publication, is also carried out in the facility.

Professor Edward D. Wolf instructs students in the use of equipment in the submicron facility.

Central to the work of the facility are programs that apply the lithographic and processing capabilities of the laboratory to the fabrication of new components and subsystems for VLSI. One program is concerned with the physical limits to reduction in size of silicon MESFETs and Schottky-gate MESFETs, and studies are continuing on the properties of devices that have submicrometer dimensions and are made of compound semiconductors.

The possibilities of ion-beam exposure of resists are being investigated. Because resists are highly sensitive to ion exposure, and because the small scattering range of ions permits high resolution, this is a promising technique for defining features of the order of 0.1 micrometer or smaller. Another project involves using focused laser radiation to anneal damage in ion-implanted specimens for use in electronic devices. Experiments on the laser annealing of compound semiconductor materials are also in progress.

The mechanisms of plasma etching are being investigated as part of a program to develop fabrication processes for devices with dimensions in the 0.1-micrometer region. In related work the accuracy and speed of electron-beam pattern-generation equipment is being extended by the design of new hardware and software for computer control of the beams.

These various projects are directed by J. M. Ballantyne, L. F. Eastman, T. E. Everhart, J. Frey, W. J. Heetderks, C. A. Lee, J. W. Mayer, C. L. Tang, and E. D. Wolf. Some relevant publications and reports (listed with the name of the supervising professor) are:

Eastman, L. F. 1980. Near ballistic electron transport in GaAs devices at 77 C. *Solid State Electronics* (in press).

Frey, J.; Barnard, J.; Lee, K. F.; and Gibbons, J. F. 1980. Micron-gatelength MESFET's on laser-annealed polysilicon. *Electronics Letters* 16:297.

Frey, J., and Wada, T. 1979. Physical basis of MESFET operation. *IEEE Journal of Solid State Circuits* SC-14:398.

Gammel, J. C., and Ballantyne, J. M. 1980. An integrated photoconductive detector and waveguide structure. *Applied Physics Letters* 36:149.

Lee, C. A.; Leta, D. P.; Morrison, G. H.; and Harris, G. L. 1980. SIMS determination of ion-implanted depth distributions. *International Journal of Mass Spectrometry and Ion Physics* 34:147.

Rechtin, M. D.; Pronko, P. P.; Foti, G.; Csepregi, L.; Kennedy, E. F.; and Mayer, J. W. 1978. An electron microscopy study of defect structures in recrystallized amorphous layers of self-ion irradiated silicon. *Philosophical Magazine A* 37:605.

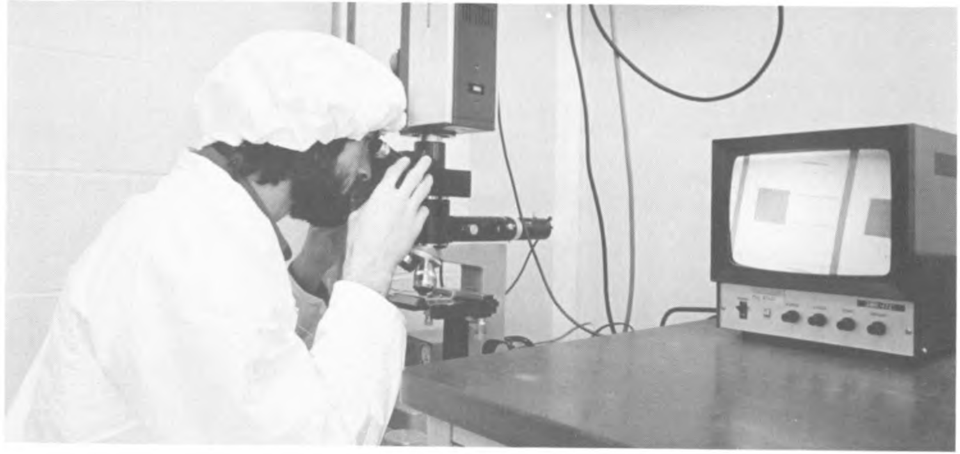
Sanderson, A. 1980. A digital pattern generator for use in electron beam lithography. M.Eng. report (J. M. Ballantyne).

Tang, C. L.; Levin, K.; Gammel, J.; and Ballantyne, J. M. 1978. Dithered beam metrology. *Applied Optics* 17:3865.

Wolf, E. D. 1979. Submicron lithograph. In *Proceedings of 7th biennial Cornell electrical engineering conference*, vol. 7, p. 53.

Microwave Semiconductors: Circuits and Device Physics

Research in the area of microwave semiconductor devices emphasizes experimental studies that have potential engineering applications. Under investigation are active elements for the generation and amplification of microwave signals at both low and high power levels, as well as the growth and processing of the key semiconductor crystals of gallium arsenide, indium phosphide, silicon, and other materials necessary for the construction of these elements.



Above: **In a graduate research project, a microwave FET device fabricated in the photolithography laboratory is inspected to verify materials properties predicted theoretically. The student is wearing prescribed clean-room apparel.**

Left: **As part of the laboratory work required by his graduate program, a doctoral candidate is entering a microwave network analyzer error-correction program on a small computer.**

Current projects are concerned with the principles of operation and the means for improving the performance of such devices as both low-noise and high-power microwave field-effect transistors (FETs), Gunn diodes, and various types of avalanche diodes. Monolithic and hybrid microwave integrated circuits of GaAs and Si are also being studied. The design and fabrication of these devices, and the design of circuits for their use as oscillators and amplifiers, involve application of the latest techniques in such areas as the growth of ultrapure materials, ion implantation, integrated-circuit technology, the characterization of automated devices, and computer optimization of circuits.

In the area of circuit design, automated network-analyzer facilities are being used to measure device parameters; circuit optimization is facilitated by an on-line connection to the school's PDP 11/45 and LSI 11 computers. New and highly versatile design techniques are being implemented for very-broad-band microwave FET and diode amplifiers.

This research is aided by the presence of the National Research and Resource Facility for Submicron Structures at Cornell. Ultraclean areas in Phillips Hall are available for the growth of semiconductor crystals used in studies of impurity diffusion, metallization, photolithography, and ion implantation.

H. J. Carlin, G. C. Dalman, L. F. Eastman, W. Ku, and C. A. Lee are directing this work. Representative reports and theses (listed with the name of the supervising professor) and publications are:

Dalman, G. C.; Lee, C. A.; and McClymonds, J. W. 1979. Linear high power IMPATT amplifiers using constant voltage bias. In *Proceedings of 7th biennial Cornell electrical engineering conference,* vol. 7, p. 349.

Eastman, L. F.; Metze, G. M.; Stall, R. A.; and Wood, C. E. C. 1980. Dependence of the electrical characteristics of heavily Ge-doped GaAs on molecular beam epitaxy growth parameters. *Applied Physics Letters* 37(2):165.

Frey, J.; Morgan, D. V.; and Devlin, W. J. 1980. Rectifying and ohmic contacts to GaInAsP. *Journal of the Electrochemical Society* 127:1202.

McClymonds, J. W. 1980. High power IMPATT amplifiers using constant voltage bias. Ph.D. thesis (G. C. Dalman).

Salim, K. R. 1978. Conductance derivative bridge for measuring metal oxide–metal junction nonlinearities. M.Eng. report (C. A. Lee).

Schelhorn, S. 1980. A 6 to 12 GHz high power GaAs MESFET amplifier design. M.Eng. report (W. H. Ku).

Network and System Design

Problems of current interest in this area are concerned primarily with microwave circuit design, computer-aided circuit design, digital filters, nonlinear systems, and active networks. Research is being done in the theory and design of broadband active systems, including microwave circuits containing solid-state devices such as avalanche diodes, Gunn and LSA oscillators and amplifiers, and transistors.

The synthesis of networks that have distributed parameters is being investigated. New results have been obtained in gain-bandwidth theory, broadband and highly selective narrowband filters, lump-loaded transmission line structures, and linear phase microwave structures. Recent contributions also include the use of circuit methods for analyzing dispersion in dielectric-loaded and dielectric (optical) waveguides.

The CORNAP computer program, developed at Cornell, is widely used in industry and at other universities to analyze complicated active linear networks, using a state-space approach. These methods are currently being extended to nonlinear and time-varying networks; particular emphasis is given to design optimization methods, sparse matrices, and simulation of stiff linear systems. Also under investigation are simulation techniques using novel parallel computer architectures.

H. J. Carlin, W. H. Ku, and C. Pottle are working in these research areas. Recent publications include:

Carlin, H. J., and Denton, G. 1979. Selective constant delay wave digital filters. *International Journal of Circuit Theory and Applications* 7(2):171.

Ku, W. H., and Ng, S. M. 1980. Computer-aided simulation and analysis of recursive digital filters using pseudostate formulation. *International Journal of Circuit Theory and Applications* (in press).

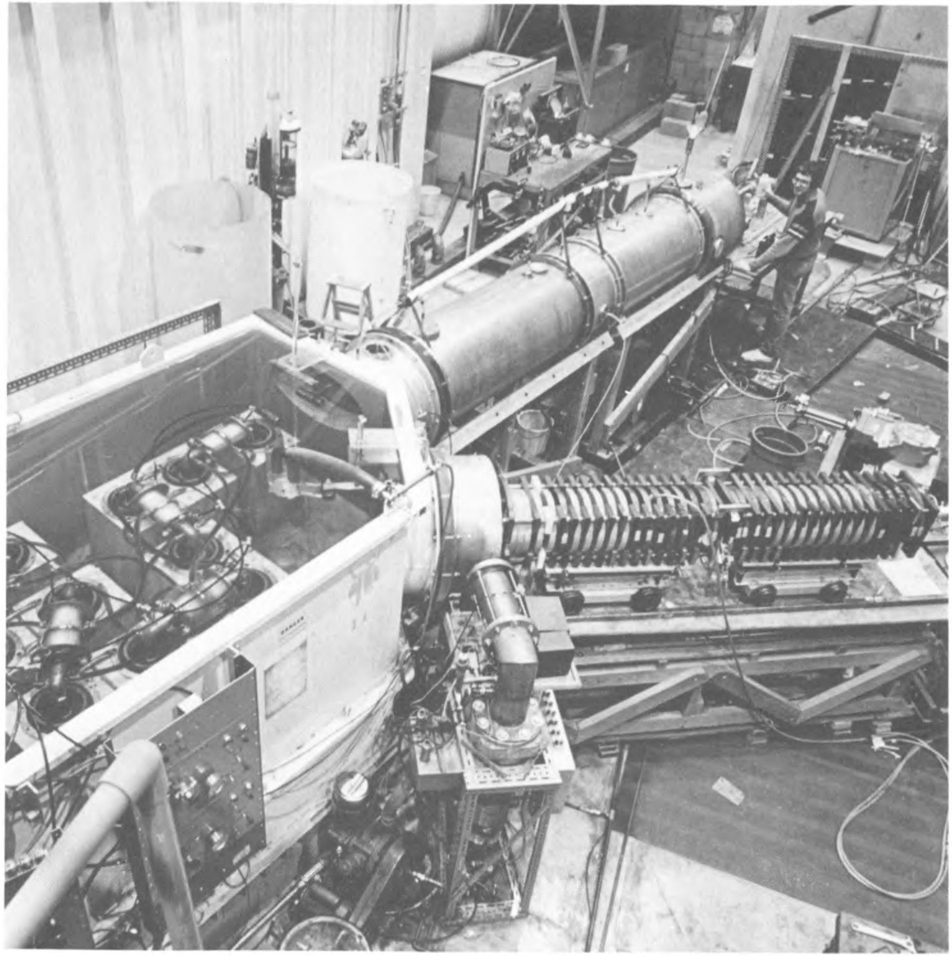
Pottle, C.; Pottle, M; Tuttle, R.; Kinch, R.; and Scheraga, H. A. 1980. Conformational analysis of proteins: algorithms and data structures for array processing. *Journal of Computational Chemistry* 1(1):46.

Plasma Physics and Applications

Plasma research conducted by the faculty and students of the School of Electrical Engineering is coordinated by the interdepartmental Laboratory of Plasma Studies. Both theoretical and experimental programs are pursued. The extensive laboratory facilities include large-scale plasma devices and small-scale apparatus.

Programs in which members of the school are participating include projects and studies on intense relativistic electron beams and their interaction with plasmas; intense ion beams; injection and trapping of ion rings; lasers and their interaction with plasmas; collisionless plasma turbulence (waves and transport); nonlinear waves and plasma instabilities; and numerous problems involved in research on controlled thermonuclear power.

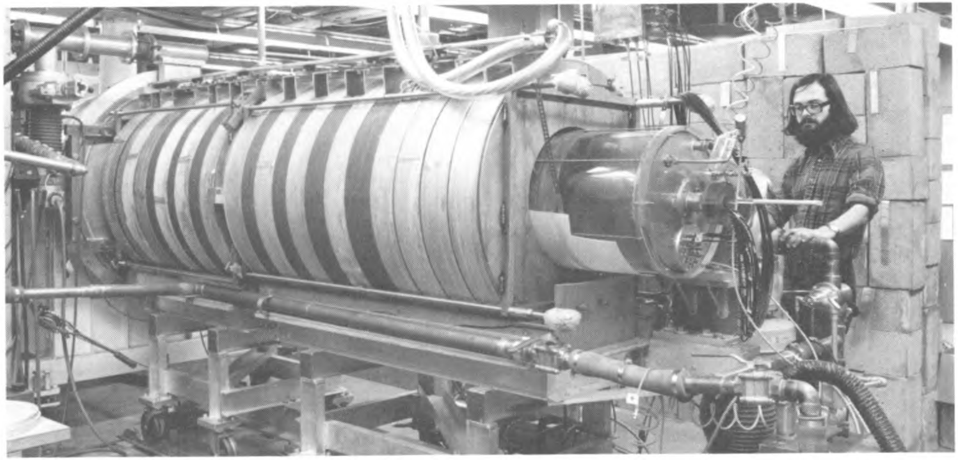
Research on megavolt-terawatt electron beams, high-current megavolt ion beams, and turbulent heating is especially noteworthy; pioneering work in these areas has been carried out at Cornell. The research on electron and ion beams is directed largely to the study of heating and confinement of thermonuclear plasmas. Other work using these beams is directed to microwave generation, collective ion acceleration, the generation of large currents of positrons, and beam dynamics. In



A high-voltage pulse power facility is used in Cornell plasma physics research. A graduate student is standing next to a water-dielectric pulse-forming line, part of a system used in electron beam research directed by Professor John A. Nation.

the turbulent heating experiments, the possibilities for heating a fusion plasma by strong turbulence are being investigated. Theoretical investigations include studies of the stability of field-reversed equilibria; ion rings; collective processes by which relativistic beams transfer their energy to plasmas; the stability and equilibrium of electron beams in different geometrical configurations; and plasma turbulence. Some of these problems are simulated by numerical models that are solved on the largest modern digital computers.

The area of plasma research, and related studies of high-power electron and ion beams, offer a number of opportunities for engineering design projects. Much of the experimental equipment needed to carry out the basic research must be designed and built at Cornell. To achieve the acceleration and confinement of charged particles and plasma arcs, electromagnetic principles must be applied in designing the machines that generate the beams. Furthermore, many instrumentation problems that arise are peculiar to the very high voltages and intense magnetic fields involved in this research and require creative engineering design for their solution.



Right above: **Research on the heating of plasmas, part of a study of controlled thermonuclear processes, is supervised by Professor Charles B. Wharton *(left).***

Right: **Research directed by Professors David A. Hammer and Ravindra N. Sudan on the production of intense ion beams and their formation into ion rings provides the doctoral research project of this graduate student.**

Electrical engineering faculty members directing plasma research include D. A. Hammer, R. L. Liboff, J. A. Nation, E. L. Resler, R. N. Sudan, and C. B. Wharton. Other academic units at Cornell that participate in the Laboratory of Plasma Studies activities include those in applied and engineering physics, chemistry, mechanical and aerospace engineering, nuclear science and engineering, and physics.

Recent theses (listed with the name of the supervising professor) and papers in this area include:

Adler, R. J. 1980. Collective acceleration of ions in vacuum. Ph.D. thesis (J. A. Nation).

Ferrentino, G. L. 1980. Production and investigation of a multiampere positron source. Ph.D. thesis (C. B. Wharton).

Maenchen, J.; Wiley, L.; Humphries, S., Jr.; Peleg, E.; Sudan, R. N.; and Hammer, D. A. 1979. Magnetic focusing of intense ion beams. *Physics of Fluids* 22:555.

Nation, J. A.; Gammel, G.; and Read, M. 1979. Slow space charge wave propagation on a relativistic electron beam. *Journal of Applied Physics* 50:5603.

Wharton, C. B. 1979. Diagnostics for fusion experiments. *Physics Today* 32:5.

Quantum Electronics and Optical Physics

Programs in these areas include research on chemical and molecular lasers, active devices for integrated optics, nonlinear optics, and optical properties of insulators and semiconductors.

In the field of chemical and molecular lasers, research oriented toward the discovery and study of new laser systems is in progress. The relaxation and transfer of vibrational and electronic excitation in molecules through atomic and molecular collisions is being studied over an extremely wide range of experimental parameters. Tunable infrared lasers that have planned application to tunable laser spectroscopy and laser-induced chemistry are being developed. This work is interdisciplinary and involves joint participation of faculty members and students in the graduate Fields of Electrical Engineering, Chemistry, and Applied Physics.

Nonlinear optics is a relatively new field of research that became important with the advent of lasers. Because of the availability of such intense light sources, the nonlinear optical properties of solids, liquids, and gases have become accessible to detailed experimental study; for example, the corresponding nonlinear susceptibilities of many crystals have now been measured. The information obtained has led to an improved understanding of these materials and to an increasing number of applications of technological importance, such as in harmonic generators, tunable optical oscillators, and frequency shifters. Also under study are rapidly tunable dye lasers that can be used to

Left above: **The development of a very high power laser to produce pulses in the megawatt range is a project for this graduate student.**

Left: **A tunable semiconductor laser is being developed in research sponsored by Professors Joseph M. Ballantyne and Chung L. Tang.**

investigate nonlinear optical effects and other related phenomena.

In the optoelectronics area, programs are under way to develop nonlinear and active thin-film devices that are compatible with integrated optical systems. New thin-film lasers, harmonic generators, and tunable oscillators that use the advantages of periodic structures and optical waveguides to provide previously unattainable performance are under development. The laboratory growth of semiconductor materials for active optical devices is being studied. A new class of high-speed photoconductive detectors using the III-V compounds is being developed for applications in optical communications. Monolithically integrated optical receivers and transmitters are being constructed in the III-V compound system. Solar-cell materials are also being developed, in work that is described in a following section.

Faculty members involved in these various research efforts are J. M. Ballantyne, C. L. Tang, and G. J. Wolga. Among recent publications and reports (listed with the name of the supervising professor) in this area are:

Basu, A., and Ballantyne, J. M. 1979. Second and higher-order waveguide grating filters. I. Theory. II. Experiment. *Applied Optics* 18:3620.

Gammel, J. C., and Ballantyne, J. M. 1979. An epitaxial photoconductive detector for high speed optical detection. In *Technical digest, international electron devices meeting*, p. 634. New York: IEEE.

Liboff, R. L. 1979. On the potential x^{2N} and the corresponding principle. *International Journal of Theoretical Physics* 18:185.

Medwin, L. B. 1979. Two approaches towards a low power solid state laser. Ph.D. thesis (J. M. Ballantyne).

Tang, C. L.; Olsson, A.; and Green, E. L. 1980. Active stabilization of a Michelson interferometer. *Applied Optics* 19:1897.

Wang, W.-I. 1979. Comparison of dynamic behavior of semiconductor lasers in integrated forms and in external cavities. M.Eng. report (C. L. Tang).

Wolga, G. J., and Dutta, N. 1979. On the interaction of stimulated spin-flip Raman scattering and stimulated recombination radiation in InSb. *Applied Physics* 19:185.

Radiophysics and Geophysical Plasmas

In this area both remote probing with radiowaves and in situ probing from satellites and rockets are used to investigate the properties of geophysical plasmas and the neutral atmosphere.

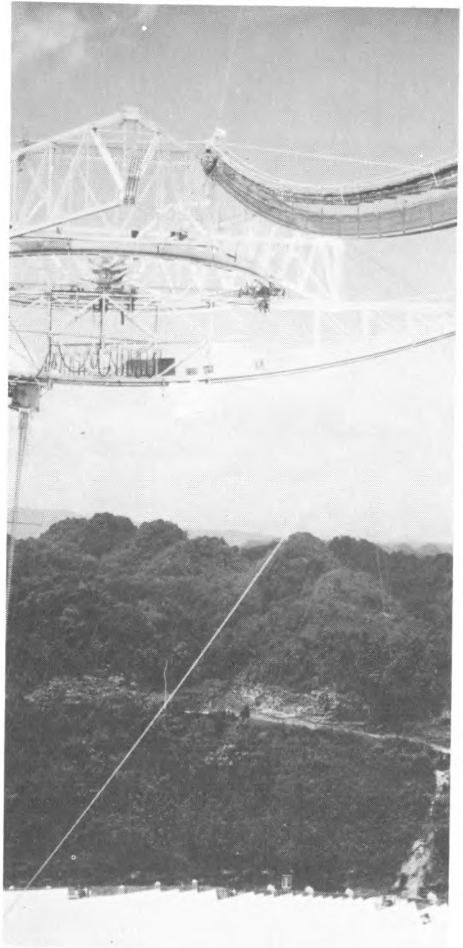
Current topics of study include the interaction of the solar wind with the earth's magnetosphere and resulting electric fields and convection processes in the magnetosphere, ionosphere, and neutral atmosphere; possible relationships between solar activity and the weather; photochemical processes and their incorporation into models of the magnetospheres of the earth and Jupiter; dynamical processes in the ionosphere and coupling to the magnetosphere; plasma instabilities in the ionosphere and magnetosphere; scattering of electromagnetic waves by both unstable plasma waves and the weak random density fluctuations present even in stable plasmas; and scattering from turbulent regions in the neutral atmosphere.

Some of this work uses data from the giant radar installation (which has an antenna diameter of a thousand feet and a 2.5-megawatt transmitter) operated by Cornell in Arecibo, Puerto Rico, under contract with the National Science Foundation. Research is also performed at a similar large radar installation near Lima, Peru, and auroral research is being done with a smaller radar in Ithaca. Some work in the systems area is devoted to developing efficient techniques for processing the vast quantities of data produced by these radar measurements. Related theoretical research includes numerical simulations of certain plasma interactions and wave propagation phenomena.

An active program involving rocket- and satellite-borne experiments is in progress; particular emphasis is placed on studies of plasma instabilities and wave-particle interactions in the upper atmosphere. Rocket launchings have been made or are planned from sites in Peru, Brazil, India, Scandinavia, Greenland, Wallops Island, and Antarctica.

Other research is concerned with the often turbulent microstructure of the neutral atmosphere (troposphere, stratosphere, and mesosphere), winds and wave structures in the neutral atmosphere, and the study of these using electromagnetic probing techniques.

Many of these investigations require the development of remote-sensing instrumentation, data-processing electronics (for both on-board and laboratory installation),



Above: **Auroral studies in Alaska were part of doctoral thesis work directed by Professor Michael C. Kelley. Researchers are shown with a Cornell payload that was launched on a Nike-Tomahawk from Poker Flat, Alaska.**

Left: **The Arecibo laboratory in Puerto Rico is available for graduate work in radiophysics. This photograph shows the largest antenna of the giant radio-radar telescope: 96 feet long and weighing almost 10,000 pounds, it hangs from a triangular support structure some 500 feet above the 19.8-acre spherical reflector. Access to the platform is by a 700-foot catwalk *(visible at right)* and a cable car.**

and other specialized measurement, control, and navigation equipment. The design and construction of such devices provide ample opportunity to develop state-of-the-art engineering expertise.

R. Bolgiano, D. T. Farley, T. Gold, M. C. Kelley, and R. N. Sudan are involved in these research efforts. Recent theses (listed with the name of the supervising professor) and papers in this area include:

Duff, J. 1980. A switched capacitor filter based spectrum analyzer. M.Eng. report (M. C. Kelley).

Farley, D. T.; Ierkic, H. M.; and Fejer, B. G. 1980. The dependence on zenith angle of the strength of 3-meter equatorial electrojet irregularities. *Geophysical Research Letters* 7:497.

Gonzales, C. A. 1979. Electric fields in the low latitude ionosphere and their relationship to magnetospheric and interplanetary phenomena. Ph.D. thesis (M. C. Kelley).

Ierkic, H. M. 1980. Radar observations of the equatorial electrojet irregularities and theory of type 1 turbulence. Ph.D. thesis (D. T. Farley).

Kelley, M. C., and Temerin, M. 1980. Rocket borne wave measurements in the dayside auroral oval. *Journal of Geophysical Research* 85:2915.

Pereira, E. 1979. Numerical modeling of high latitude winds in the upper atmosphere. Ph.D. thesis (M. C. Kelley).

Reed, R. W. 1980. Spectra from 50 MHz auroral radar echoes. Ph.D. thesis (D. T. Farley).

Schroeder, K. 1980. DARE 1 — a micro-processor-based data acquisition and reduction system. M.Eng. report (M. C. Kelley).

Sudan, R. N.; Keskinen, M. J.; and Ferch, R. L. 1979. Temporal and spatial power spectrum studies of numerical simulations of type II gradient drift irregularities in the equatorial electrojet. *Journal of Geophysical Research* 84:1419.

Several papers based on the above thesis research have appeared in the *Journal of Geophysical Research* and *Geophysical Research Letters*.

Semiconductor Materials for Electron Devices

Graduate research in this area emphasizes the growth, characterization, and processing of materials for microwave and optical devices.

Several liquid-phase epitaxial semiconductor growth stations, each with laminar airflow filtering, are available. A molecular-beam epitaxial growth station — the first of its kind at any university — is part of the recently established National Research and Resource Facility for Submicron Structures at Cornell. In the molecular-beam method of semiconductor growth, streams of atoms and molecules are shot at a seed-crystal face in a vacuum chamber, producing extremely thin layers and allowing fine control of thickness and electrical properties. Crystals of gallium arsenide, germanium, and such alloys as aluminum gallium arsenide are grown at state-of-the-art levels of purity in a 3,200-square-foot clean room that was financed by grants from ten United States companies.

A program is under way to grow single-crystal layers of GaAs on microscopically patterned foreign substrates by a process called graphoepitaxy. Laser recrystallization of the grown films is employed to increase grain size.

The semiconductor materials are tested electrically to determine electron density and mobility; other physical and chemical properties are tested by such techniques as photoluminescence, transient capacitance spectroscopy, scanning Auger, and secondary-ion mass spectrometry. Techniques to measure spatial variations in material properties such as carrier-diffusion length, impurity concentration, internal potentials, and recombination times are being developed to characterize polycrystalline semiconductors for solar cells.

The materials are processed to produce semiconductor electron devices such as microwave field-effect transistors and Gunn and avalanche devices, as well as lasers, solar cells, and light detectors. Equipment provided at the national submicron facility is particularly useful in projects of this kind.

Professors J. M. Ballantyne, L. F. Eastman, J. Frey, C. A. Lee, and J. W. Mayer are principally responsible for the work carried out in this area. Among recent theses (listed with the name of the supervising professor) and publications are:

Cavanagh, R. 1979. Development of a calibration technique for ion implanted impurities in semiconductors. M.Eng. report (C. A. Lee).

Eastman, L. F., and Chandra, A. 1979. Rectification at n-n GaAs: (Ga,Al)As heterojunction. *Electronics Letters* 15:90.

Eastman, L. F.; Ohno, H.; Barnard, J.; and Wood, C. E. C. 1980. Double heterostructure $Ga_{0.47}In_{0.53}As$ MESFET by MBE. *IEEE Electron Development Letters* EDL-1:154.

Eastman, L. F.; Stall, R.; Wood, C.; and Kirchner, P. 1980. Growth parameter dependence of deep levels in molecular beam epitaxial GaAs. *Electronics Letters* 6(5):171.

Fletcher, R. M.; Wagner, D. K.; and Ballantyne, J. M. 1980. Study of grain boundaries in GaAs by scanning light microscopy. *Solar Cells* 1:263.

Frey, J. 1980. Ballistic transport in scaled devices. Paper read at IEEE Solid-State Circuits and Technology Symposium on Scaling, April 1980, in New York, New York.
Frey, J., and Smith, P. 1980. Electron transport measurements with a microwave time-of-flight experiment. Paper read at Conference on Physics of Submicron Devices, July 1980, at Colorado State University, Ft. Collins, Colorado.
Kimura, A., and Lee, C. A. 1975. Effect of thermal etching on silicon epitaxial growth by vacuum sublimation. *Solid-State Electronics* 18:901.
Law, H. D. 1977. Interband scattering effect on secondary ionization coefficients of GaAs and the related technological development. Ph.D. thesis (C. A. Lee).
Lawrence, D. J., and Eastman, L. F. 1978. Use of current controlled GaAs L.P.E. for optimum doping profiles in LSA diodes. *Electronics Letters* 14:77.
Pearsall, T. P., and Lee, C. A. 1974. Electron transport in ReO_3: DC conductivity and Hall effect. *Physical Review B* 10:10.

***Right above:* This molecular beam epitaxial growth system is used to grow GaAs and related semiconductor materials for electronic devices. This research is directed by Professor Lester F. Eastman.**

***Right:* An ion implanter is used by Professor Charles A. Lee *(right)* and a graduate student for processing semiconductor materials into electron devices.**

Spencer, M. G. 1980. Electrical characterization of grain boundaries in gallium arsenide and their relationship to solar cell performance. Ph.D. thesis (L. F. Eastman).
Stall, R. A. 1980. Growth, characterization, and applications of gallium arsenide and germanium layers grown by molecular beam epitaxy. Ph.D. thesis (L. F. Eastman).
Wagner, D. K.; Fletcher, R. M.; and Ballantyne, J. M. 1980. High resolution optical methods for characterization of polycrystalline GaAs thin films. *IEEE Transactions on Electron Devices* ED-27(12):2213.
Wittmer, M.; Roth, J.; Revesz, P.; and Mayer, J. W. 1978. Epitaxial regrowth of Ne and Kr implanted amorphous silicon. *Journal of Applied Physics* 49:5207.
Yang, J. L. 1979. Study of submicron periodic structure in GaAs–GaAlAs double heterostructures: fabrication and distributed-feedback injection lasers. Ph.D. thesis (J. M. Ballantyne).

Signal Processing

Research in this area is concerned with advanced signal-processing concepts and device design. Current research projects include the design of recursive and adaptive filter structures using charge-coupled devices (CCDs), high-order ladder and lattice filter structures for speech processing and digital communications systems, and cross-correlation algorithms for extraction of parameters from radar, sonar, and interferometric signals.

Microprocessors and minicomputers are being used at Cornell in projects ranging from industrial process control to studies of geophysical plasmas and neurological information encoding. Master of Engineering students have designed special-purpose digital systems for tasks such as data logging, data compression, radar control and on-line data processing, on-line experiment control, and process control.

Advanced signal-processing techniques involving speech synthesis, adaptive filters, and new structures of recursive-digital and sampled-analog filters are currently being investigated. A new class of adapting-delay comb filters, and an adaptive filter and speech synthesizer that is microcomputer-based and uses charge-transfer devices, are being studied, together with high-speed signal-processing techniques using VLSI components. Design of optimal FIR filters in which flatness is implicitly defined in the performance index is in progress, and new convergence algorithms for adaptive filters are being formulated.

T. Berger, D. T. Farley, T. C. Fine, W. J. Heetderks, M. C. Kelley, and W. H. Ku direct research in this area. Recent reports (listed with the name of the supervising professor) and publications include:

Berger, T. 1981. Bias and variance of differential time of arrival estimates based on noisy, sampled, clipped data. In *Proceedings of 1981 IEEE international symposium on information theory* (in press).

Childress, J. 1980. TI 9900 microcomputer based adaptive filters. M.Eng. report (W. H. Ku).

Hutchins, B. A., and Ku, W. H. 1979. CTD adaptive filters for interference cancellation and pitch extraction. In *Proceedings of 12th Asilomar conference on circuits, systems, and computers*, ed. C.-C. Hsieh. Piscataway, N.J.: Institute of Electrical & Electronics Engineers.

Kwan, P. 1979. Instrument design for detecting and differentiating the neural signal. M.Eng. report (W. J. Heetderks).

Long, C. 1980. An investigation of advanced signal processing techniques using adaptive filtering and switching capacitor networks. M.Eng. report (W. H. Ku).

Rubinstein, J. 1979. The design and construction of a microcomputer for signal processing. M.Eng. report (W. H. Ku).

A Master of Engineering student works on a microprocessor-based system being designed for on-line signal analysis.

Faculty Members and Their Research Interests

Paul D. Ankrum, B.S.E.E. (Indiana Technical), A. B. (Ashland), M.S. (Cornell): *solid-state devices, power electronics*

Joseph M. Ballantyne (Director of the School of Electrical Engineering), B.S., B.S.E.E. (Utah), S.M., Ph.D. (M.I.T.): *optoelectronic materials and devices, integrated optics, submicrometer lithography*

Toby Berger, B.E. (Yale), M.S., Ph.D. (Harvard): *information theory, signal processing*

Ralph Bolgiano, Jr., B.S., B.E.E., M.E.E., Ph.D. (Cornell): *tropospheric radiophysics, communication theory*

Nelson H. Bryant, E.E., M.E.E. (Cornell): *electronic circuits, instrumentation*

Robert R. Capranica, Ch.E., B.S. (California, Berkeley), M.S. (New York University), Sc.D. (M.I.T.): *sensory communication, electrophysiological studies of neural processing, bioelectric systems*

Herbert J. Carlin, B.S., M.S. (Columbia), D.E.E., Ph.D. (Polytechnic Institute of Brooklyn): *microwave circuits, network theory*

G. Conrad Dalman, B.E.E. (City College of New York), M.E.E., D.E.E. (Polytechnic Institute of Brooklyn): *microwave solid-state devices and circuits*

Lester F. Eastman, B.E.E., M.S., Ph.D. (Cornell): *microwave solid-state devices, gallium arsenide and indium phosphide techniques*

William H. Erickson, B.S., M.S. (Carnegie Institute of Technology): *power engineering, instrumentation*

Thomas E. Everhart (Dean of the College of Engineering), A.B. (Harvard), M.S. (California, Los Angeles), Ph.D. (Cambridge): *microfabrication technology*
Donald T. Farley, B.E.P., Ph.D. (Cornell): *ionospheric physics, radio propagation*
Terrence L. Fine, B.E.E. (City College of New York), S.M., Ph.D. (Harvard): *decision theory, estimation*
Jeffrey Frey, B.E.E. (Cornell), M.Sc., Ph.D. (California, Berkeley): *microwave solid-state devices, integrated electronics*
Thomas Gold, B.A., M.A. (Cambridge), M.A. (Harvard), Sc.D. (Cambridge): *radiation mechanism of pulsars, magnetosphere of Jupiter and other planets, origin of solar system*
David A. Hammer, B.S. (California Institute of Technology), Ph.D. (Cornell): *plasma physics, thermonuclear fusion, high-power electron and ion-beam physics*
Juris Hartmanis, Cand.Phil. (Marburg), M.A. (University of Kansas City), Ph.D. (California Institute of Technology): *theory of computation*
William J. Heetderks, B.S., M.S., M.S.E.E., Ph.D. (Michigan): *bioelectronics, information coding in neural systems*
Michael C. Kelley, B.S. (Kent State), Ph.D. (California, Berkeley): *space plasma physics, rocket and satellite instrumentation*
Myunghwan Kim, B.S. (Alabama), M.E., Ph.D. (Yale): *bioelectronics, control theory*
Walter H. Ku, B.S.E.E. (Pennsylvania), M.E.E., Ph.D. (Polytechnic Institute of Brooklyn): *active and microwave circuit design, digital signal processing*
Charles A. Lee, B.E.E. (Rensselaer), Ph.D. (Columbia): *solid-state physics and devices*
Richard L. Liboff, A.B. (Brooklyn College), Ph.D. (New York University): *fusion theory, electrodynamics, basic quantum mechanics*
Simpson Linke, B.S.E.E. (Tennessee), M.E.E. (Cornell): *energy systems, high-voltage transmission*
Paul R. McIsaac, B.E.E. (Cornell), M.S.E., Ph.D. (Michigan): *electromagnetic theory, microwave circuits and devices*
James W. Mayer, B.S., Ph.D. (Purdue): *ion implantation in semiconductors, thin-film reactions, Rutherford backscattering and channeling*
John A. Nation, B.Sc., Ph.D. (Imperial College, London): *plasma physics, high-energy electron beams*
Benjamin Nichols, B.E.E., M.E.E. (Cornell), Ph.D. (Alaska): *educational techniques*
Christopher Pottle, B.E. (Yale), M.S., Ph.D. (Illinois): *computer-aided design, power system simulation, network theory*
Edwin L. Resler, Jr., B.S. (Notre Dame), Ph.D. (Cornell): *high-temperature gasdynamics, pollution control, ferrofluid mechanics*
Joseph L. Rosson, B.S.E.E. (Tennessee), M.E.E. (Cornell): *power engineering, instrumentation*
Ravindra N. Sudan, B.A. (Punjab, India), M.S. (Indian Institute of Science), D.I.C. (Imperial College, London), Ph.D. (London): *plasma physics, thermonuclear fusion, high-power electron and ion-beam physics*
Chung L. Tang, B.S. (Washington), M.S. (California Institute of Technology), Ph.D. (Harvard): *lasers, quantum electronics*
Robert J. Thomas, B.S.E.E., M.S.E.E., Ph.D. (Wayne State): *applications of control theory to power systems*
James S. Thorp, B.E.E., M.S., Ph.D. (Cornell): *applications of optimization and control theory to power systems*
Hwa-Chung Torng, B.S. (National Taiwan), M.S., Ph.D. (Cornell): *computer engineering, microcomputer systems, digital circuits*
Norman M. Vrana, B.E.E. (New York University), M.E.E. (Cornell): *switching theory, central-processor design, microprocessor systems*
Jean C. Walrand, Ingenieur Civil (Liege, Belgium), Ph.D. (California, Berkeley): *stochastic control, large-scale systems, computer communication networks*
Charles B. Wharton, B.S., M.S. (California, Berkeley): *plasma physics, microwave diagnostics*
Edward D. Wolf, B.S. (McPherson), Ph.D. (Iowa State): *fabrication and diagnostics of microstructures*
George J. Wolga, B.E.P. (Cornell), Ph.D. (M.I.T.): *lasers, atomic and molecular physics, applied spectroscopy*

Further Information

Members of the faculty welcome inquiries about the various graduate programs and research projects. These may be addressed to the Graduate Faculty Representative, Electrical Engineering, Cornell University, Phillips Hall, Ithaca, New York 14853.

Geological Sciences

The geological sciences are currently experiencing a period of major new insights, demands, developments, and growth. The effects of the rapidly increasing consumption of the world's mineral and energy resources and demands for an environment of quality have caused society to seek geological solutions to many problems. There is also an increasing awareness of major geological hazards such as earthquakes and volcanic eruptions. Exploration of the moon, the planets, and the oceans has provided a wealth of new scientific information. The concept of plate tectonics has provided a framework for understanding many previously unexplained geological phenomena. Quantitative answers to many fundamental questions appear within reach.

In recognition of these major new developments in geology and of the corresponding promise of this science, Cornell reorganized its Department of Geological Sciences during the 1970s. The faculty was expanded, new facilities were made available, and innovations in curricula and research were introduced. Continued expansion is envisioned in the 1980s; a major building project is under way.

The graduate Field of Geological Sciences includes, in addition to department members, faculty members of other departments who maintain an active interest in geological problems. There are approximately sixty graduate students, all of whom participate in one or more of the research activities of the field. Programs leading to the M.S. and Ph.D. degrees are available; major fields of study may be chosen from a variety of specialties, including economic geology, geobiology, paleontology and stratigraphy, geochemistry, mineralogy, petrology, geomorphology, geophysics, geotectonics and structural geology, marine geology, and seismology. In all areas there is a strong emphasis on application of the basic sciences to an understanding of the earth and on learning through participation in research projects.

Because of the many types of careers available to geologists, the Field of Geological Sciences at Cornell seeks graduate students with a variety of interests and backgrounds. Previous training in geology is not required of applicants who have strong backgrounds in the basic sciences or in engineering. A graduate student may be involved primarily in field studies, or in theoretical work requiring analysis mathematics or a computer, or in laboratory studies that use sophisticated instruments of high precision and sensitivity. Possible employers include the energy and mineral industries, environmental and engineering firms, many branches of the federal and state governments, and educational institutions.

Facilities

A variety of modern research facilities are available. These include a geochemistry laboratory, a rock-preparation laboratory, an instrument shop, darkrooms, x-ray machines, a petrographic laboratory, and a paleontological laboratory. More specialized equipment includes transmission electron microscopes, a high-pressure-and-temperature creep apparatus, internally heated diamond anvil pressure cells, an electron microprobe,

facilities for neutron activation and counting, portable analog and digital seismographs, gravity meters, tiltmeters, and magnetometers. The varied collection of computing equipment includes an electrostatic plotter, a microprocessor-controlled digitizing table, a microcomputer system with graphics, and an interactive terminal for the University's main IBM 370 computer system. The department also has a MEGASEIS seismic data-processing system and extensive software.

Most of the geological sciences classrooms, laboratories, and offices are located in Kimball Hall on the Engineering Quadrangle. Housed here are outstanding collections of minerals, rocks, and fossils, and a large library of seismograms from the World Wide Standardized Seismograph Network and from other stations.

Recent field projects have been carried out at a variety of sites, including Indonesia, the Philippines, Fiji and the New Hebrides, the Aleutian Islands, Greenland, the Rhine graben, the Scottish highlands, Ireland, and many parts of the United States and Canada. Graduate students participate in cruises on oceanographic research vessels. The field projects are varied and expanding, and the outlook is global in scope.

Basic research instrumentation available in Kimball Hall includes microscopes and a permanent seismograph station.

Areas of Research

The major unifying themes of research activity are plate tectonics and continental evolution. These concepts are being explored and developed at Cornell through their relation to economic geology, geodesy, geomorphology, gravimetry, paleontology, petroleum geology, petrology, rock mechanics, sedimentology, seismology, structural geology, and stratigraphy, among other specialized fields.

Current research projects include, for example, comprehensive investigations of the tectonics of the ocean trenches and island arcs. Among these are studies interpreting seismological data concerning the tectonics of convergent plate margins and the generation of earthquakes, including data from worldwide and local seismological networks and measurements of tilt in the New Hebrides island arc; geological studies of the accretionary prism of sediments landward of the tectonics of the ocean trenches on a number of island arcs and continental margins, integrated with seismic and drilling programs; studies of ancient melanges and petrologic studies of island-arc volcanic rocks, including field and laboratory work; studies of the evolution of sedimentary basins on and adjacent to island arcs; quantitative studies of vertical tectonics adjacent to island arcs, involving observations of exposed beaches and terraces; and complementary theoretical studies of the mechanics of subduction.

Cornell is the operating institution in the Consortium for Continental Reflection Profiling (COCORP), a major United States research project being carried out with other universities, companies, and government agencies. The object is to determine the geological structure of the continental crust, using seismic reflection techniques developed by the oil industry. Graduate students have the opportunity to participate in the fieldwork, data processing, and data interpretation phases of this project. This is a major part of a developing program for integrated studies of the continental crust that includes petrological and geochemical studies of xenoliths from the lower crust.

Studies are being carried out to understand the history of surface rocks that have originated in the deep crust and upper mantle. Examples are rocks associated with kimberlites, native iron deposits, and platinum-group metal deposits. There are indications, for example, that some native iron samples had a deep origin and may represent accretional material not assimilated in the core. Many types of geologic information suggest that there was a change in the nature of the crust at the end of the Archean and the beginning of the Proterozoic era. The Guiana and West African shields have a wide range of rocks that were formed during this transition period, and studies of these are revealing an important stage in crustal evolution, as well as improving the effectiveness of mineral exploration in these little-known but promising areas.

Deep-crustal and upper-mantle electrical conductivity experiments are being carried out with the use of controlled electromagnetic sources and natural geomagnetic fluctuations. These studies are also being applied to the San Andreas fault, as part of the national earthquake-prediction program.

In a cooperative project to study the geological structures of the deep continental crust, truck-mounted vibrators are used to obtain seismic data. Graduate students *(right)* work with Professors Jack E. Oliver and Sidney Kaufman in studies of the seismic profiles.

A combined field, laboratory, and theoretical study is focused on the structure of faults. Faults that have been eroded to various depths are being investigated; measurements of grain sizes and dislocation densities are being used to infer paleostress and temperature levels. The basic mechanics of faulting are being studied.

High-pressure, high-temperature laboratory creep experiments are being used to develop a basis for the analysis of field samples.

Defects in minerals that have been deformed both naturally and in the laboratory, and also phase transformations, are studied by transmission electron microscope and electron microprobe techniques.

For studies of the earth's interior, minerals are subjected to pressures and temperatures comparable to conditions in the deep interior. This is done by squeezing the minerals in diamond cells and heating them with laser beams. Data collected by x-ray diffraction, optical observations, electrical resistance measurements, and other techniques are used to interpret the constitution of the earth's interior.

Structures in the mountain belts of the western United States are being examined to identify the time and orientations of changing stress systems in the Mesozoic and the Cenozoic. Mechanical modeling of the associated sedimentary basins is also being carried out. A project to study mountain-belt evolution and segmentation in the South American Andes is in progress.

An understanding of recent crustal movements is sought in a program involving analysis of leveling observations throughout the United States and the correlation of such data with seismic and geological information.

Seismic reflection and geological data from the eastern margin of the United States, offshore California, and the Mediterranean are being used to further refine seismic stratigraphic modeling techniques for the prediction of sedimentary facies within reflection sequences.

The overall chemical and thermal evolution of the earth is being studied in a variety of ways. The fractionation of trace elements into the oceanic crust, into the continental crust, and within the continental crust is being considered. Studies of the effects of sedimentary recycling on the chemistry and general evolution of the earth and, in particular, of the continental crust are being carried out. Calculations using parameterized convection determine the thermal evolution of the earth, as well as its chemical fractionation.

Fieldwork in the Mohawk Valley yields fossils 400 million years old of trilobites, crablike organisms whose evolution is being studied. This graduate student is working with Professor John L. Cisne on the project.

Many other research programs are being carried out in the field. These include studies on the ecology and evolution of fossil organisms, the development of new ways of using fossils in geochemistry, studies of the Viking missions to Mars, and studies of the mechanical and thermal evolution of sedimentary basins.

Recent publications include:

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Brewer, J. A.; Smithson, S. B.; Oliver, J. E.; Kaufman, S.; and Brown, L. D. 1980. The Laramide orogeny: evidence from COCORP deep crustal seismic reflection profiles in the Wind River Mountains, Wyoming. *Tectonophysics* 62:165.
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Fieldwork is carried out at many locations around the world. *Upper right:* Professor Robert W. Kay *(center)* and Dr. Suzanne M. Kay *(left)*, shown in front of Kanaga volcano, head Cornell's petrologic field research effort in the Aleutian Islands. *Right:* A 35-day western field-trip course is offered by the department.

Left: **An x-ray machine is part of the equipment used by Professor William A. Bassett in studies of minerals under conditions comparable to those in the earth's deep interior. High pressures and temperatures are achieved with use of diamond cells and laser beams.**

Right: **Professor Donald L. Turcotte's research includes studies of volcanism on Earth and the other planets. This Viking image of Mars shows huge volcanoes up to 24 kilometers high.**

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Travers, W. B. 1978. Overturned Nicola and Ashcroft strata and their relation to the Cache Greek group, southwestern Intermontane Belt, British Columbia. *Canadian Journal of Earth Sciences* 15:99.

Turcotte, D. L. 1979. Flexure. *Advances in Geophysics* 21:51.
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Faculty Members and Their Research Interests

Steven B. Bachman, B.S. (Washington), M.S. (California, Los Angeles), Ph.D. (California, Davis): *sedimentation and tectonics, seismic stratigraphy, sedimentary petrology*
Muawia Barazangi, B.S. (Damascus), M.S. (Minnesota), Ph.D. (Columbia): *seismology, tectonics, geophysics*
William A. Bassett, B.A. (Amherst), M.A., Ph.D. (Columbia): *optical microscopy, x-ray diffraction, light absorption, light scattering and electrical resistance studies at high pressures and temperatures using laser heating in diamond cells*

Cornell is situated in a region especially good for studies in stratigraphy and glacial erosion, as shown in this photograph taken several hundred yards from Kimball Hall. Also, the Ithaca area is one of the few places in the world where kimberlites have been found.

John M. Bird, B.S. (Union), M.A., Ph.D. (Rensselaer): *geotectonics, plate tectonics, orogeny, economic geology, ophiolites, origin of terrestrial metals, geology of the Appalachians, paleostress indicators*

Arthur L. Bloom, B.A. (Miami University), M.A. (Victoria, New Zealand), Ph.D. (Yale): *geomorphology, Quaternary tectonics and sea-level changes (especially in uplifted coral-reef terranes), Holocene sea-level changes, coastal geomorphology, glacial geomorphology and stratigraphy, denudation rates, planetary surfaces*

Larry D. Brown, B.S. (Georgia Institute of Technology), Ph.D. (Cornell): *exploration seismology, deep structure of continental crust, recent crustal movements, digital signal processing*

John L. Cisne, B.A. (Yale), Ph.D. (Chicago): *invertebrate paleontology, population and community paleoecology, biostratigraphy*

Allan K. Gibbs, A.B., M.A. (Harvard), M.Sc. (Imperial), Ph.D. (Harvard): *economic geology, Precambrian geology*

Bryan L. Isacks, A.B., Ph.D. (Columbia): *seismology and tectonics*

Daniel E. Karig, B.Sc., M.Sc. (Colorado School of Mines), Ph.D. (Scripps): *marine geology and geophysics, structural geology of orogenic belts, marginal basins, geomechanics*

Sidney Kaufman, A.B., Ph.D. (Cornell): *exploration geophysics, structure of the deep crust and upper mantle, geothermal resource development*

Robert W. Kay, A.B. (Brown), Ph.D. (Columbia): *petrology, geochemistry, application of trace-element and isotope geochemistry to the petrogenesis of igneous rocks*

David L. Kohlstedt, B.S. (Valparaiso), Ph.D. (Illinois): *high-temperature plasticity of rocks and minerals, study of stress-levels along faults, electron microscopy of defects in minerals*

Arthur F. Kuckes, B.S. (M.I.T.), Ph.D. (Harvard): *geophysics, geomagnetism, electrical conductivity distribution in the earth and moon, analysis of crustal flexure and gravity*

Fred H. Kulhawy, B.A., Ph.D. (California, Berkeley): *rock mechanics, finite element calculations*

George H. Morrison, B.A. (Brooklyn College), M.A., Ph.D. (Princeton): *analytical geochemistry, trace-element abundances, ion microprobe studies*

Jack E. Oliver (Chairman of the Department of Geological Sciences), B.A., M.A., Ph.D. (Columbia): *geophysics, seismology, geotectonics, recent vertical movements, deep crustal reflection studies*

Frank H. T. Rhodes (President of Cornell University), B.Sc., Ph.D. (Birmingham): *invertebrate paleontology, stratigraphy, history and philosophy of geology, conodont biostratigraphy*

Arthur L. Ruoff, B.S. (Purdue), Ph.D. (Utah): *properties of materials at pressures above 1 megabar, plastic flow phenomena, synthesis of metallic hydrogen*

Carl E. Sagan, A.B., S.B., S.M., Ph.D. (Chicago): *physics and chemistry of planetary atmospheres and surfaces, spacecraft results, planetary geomorphology*

William B. Travers, B.S., M.S. (Stanford), Ph.D. (Princeton): *structural geology, tectonics, petroleum geology*

Donald L. Turcotte, B.S. (California Institute of Technology), M.S. (Cornell), Ph.D. (California Institute of Technology): *geophysics, geomechanics, mantle convection, convection in porous media*

Joseph Veverka, B.S., M.S. (Queens), M.A., Ph.D. (Harvard): *planetology, interpretation of spacecraft imagery, physics and morphology of planetary and satellite surfaces*

Further Information

Questions about the graduate program in geological sciences may be addressed to the Graduate Faculty Representative, Geological Sciences, Cornell University, Kimball Hall, Ithaca, New York 14853.

Materials Science and Engineering

The graduate Field of Materials Science and Engineering at Cornell provides the opportunity to students with widely differing undergraduate backgrounds to undertake research and study in the area of materials. The fifty-three students now enrolled in graduate programs in the field have undergraduate degrees in physics and applied physics and in mechanical, metallurgical, chemical, and electrical engineering, as well as in materials science.

Much of the research in this field of study is conducted in connection with the interdisciplinary Materials Science Center, the largest such university center supported by the federal government. This center makes available to students and faculty members modern, and often very expensive, equipment, and it provides financial assistance for graduate students through research assistantships. The materials science and engineering department also cooperates closely with the National Research and Resource Facility for Submicron Structures (NRRFSS) and with the Cornell High Energy Synchrotron Source (CHESS).

In addition to research-oriented M.S. and Ph.D. programs in the graduate Field of Materials Science and Engineering, a one-year professional Master of Engineering (Materials) degree program is available.

Facilities

Laboratories and equipment are located in Bard and Thurston Halls on the engineering quadrangle and in Clark Hall of Science, which houses some of the University's physics groups and most of the Materials Science Center facilities.

The extensive facilities available at Cornell make possible a variety of research in materials science. For example, a 50,000-pound electrohydraulic materials-testing system enables researchers to test engineering specimens of high-strength materials under various loading conditions, including cyclic loading of any arbitrary wave form. This testing system complements various Instron testing machines to provide a broad capability for studying macroscopic mechanical behavior of materials.

For other types of investigation, there are available four field-ion microscopes, seven electron microscopes, high-field magnets, x-ray diffraction equipment including a high intensity source, ultrahigh-vacuum apparatus, low-energy electron diffraction and Auger spectroscopy apparatus, high-pressure systems, ultrasonic equipment, cryostats, residual-gas mass spectrometers, r.f. sputtering equipment, and various pieces of optical and electronic equipment. The properties of materials can be probed down to the atomic scale.

The electron microscopes that graduate students in the field may use are located in two laboratories. In Clark Hall there are AEI EM 802, Siemens Elmiskop 1A, and Hitachi HU 11A microscopes. In Bard Hall there are JEM 200-keV, JEM 100B, JEM 200CX, and Siemens 102 microscopes, as well as an AMR 900 scanning electron microscope and a JEOL 733 super electron microprobe. These instruments are equipped with special stages, such as

two-directional tilting stages, a liquid-helium stage, a high-temperature stage, and a tensile-straining stage, for various special applications.

Above: **A radio frequency sputtering apparatus in Bard Hall is used for the fabrication of thin-film metals, alloys, and ceramic materials.**

Left: **Equipment in the Materials Science Center facility includes this high-resolution Siemens 102 electron microscope, used here by a graduate student in materials science and engineering. This microscope has provided images with line resolution of 2 angstroms.**

Areas of Research

A wide range of research projects is available to graduate students. Faculty members are continually developing new areas of materials research; for example, during the past several years projects were started on catalysis, ceramic oxides, amorphous materials, biomaterials, silicon for solar cells, materials for energy storage, and laser holography. Some of the current research areas are described briefly in the following paragraphs.

Imperfections in Solids

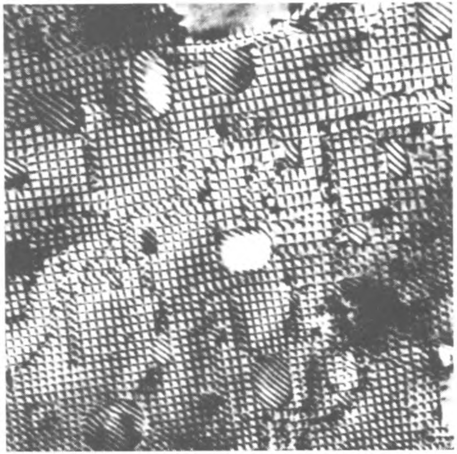
In an extensive research program supervised by D. N. Seidman, point defects and their interactions are being studied in irradiated metals by means of field-ion and atom-probe microscopy. The field-ion microscope (FIM), with its atomic resolution, allows the direct observation of individual atoms in the perfect crystal lattice, as well as self-interstitial atoms and vacant lattice sites. In addition to the conventional FIM, the group is using an atom-probe FIM. This instrument allows the determination of the charge-to-mass ratio of a single, preselected atom appearing in the FIM image. Since the operation of the atom-probe FIM is controlled by a Nova 1220 computer, it is possible to gather and analyze a statistically significant quantity of data in a short period of time. The atom-probe FIM is being used to study the interaction between solute atoms and both radiation-induced vacancies and self-interstitial atoms, as well as segregation problems. Areas of research are
(1) the point-defect structure of depleted zones in heavy-ion irradiated refractory metals

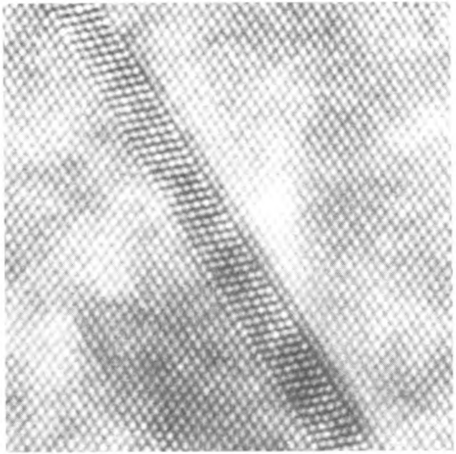
and order-disorder alloys, (2) the radiation-damage profiles in order-disorder alloys, (3) the diffusivity of helium and hydrogen in refractory metals, (4) the range profile of low-energy implanted helium and hydrogen, (5) nonequilibrium segregation to voids in ion- or neutron-irradiated refractory metals and alloys, and (6) segregation to grain boundaries or stacking faults.

Work with highly perfect crystals is proceeding under the supervision of B. W. Batterman. With these crystals, internal x-ray crystal interfaces can be observed, and the technique is being used to obtain independent measurements of the atomic form factors of elements that can form structurally perfect crystals. In recent dynamical diffraction studies, an experiment was devised by which the site of an impurity atom in a host lattice could be determined. Experiments under way are designed to use synchrotron x-radiation as a high-intensity source for the study of boundary electron distribution and anharmonic vibrations in solids.

The electrical activity and structure of defects in silicon (prepared by new techniques) are studied by D. Ast's group. Both electron-beam induced-current microscopy (EBIC) and transmission electron microscopy (TEM), including high-voltage TEM, are used.

High-resolution electron microscopy, including weak-beam and direct-lattice imaging techniques, is being used by researchers in D. L. Kohlstedt's group to examine in detail defects in minerals and ceramics. Structures being analyzed by high-resolution methods include the interfaces between fine precipitates and an enstatite matrix, the separation of partial dislocations in olivine, and possibly the distribution of vacancies in the transition-metal carbides.





The structure of crystal lattice defects and their interaction is being studied by C. B. Carter and his students. Recent investigations have been concerned with the geometry and properties of jogs on dislocations and the interaction of dislocations and jogs with vacancies and interstitial atoms. Experiments now in progress are extending these studies from pure metals and alloys to semiconductor materials.

Recent publications and theses (listed with the supervising professor) in the area of imperfections in solids include:

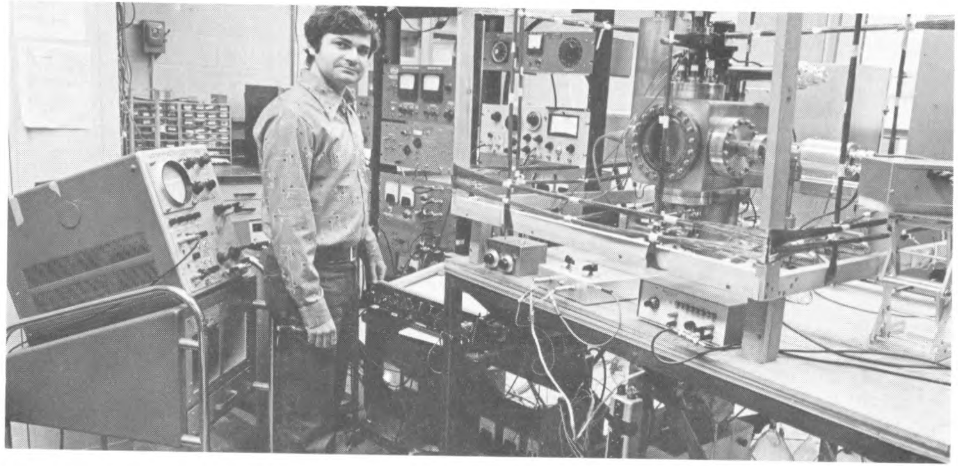
Carter, C. B. 1979. The extension of jogs on dissociated dislocations in fcc metals. *Physica Status Solidi* A54:395.

——— 1980. The influence of jogs on the extension of dislocation nodes. *Philosophical Magazine* A41:619.

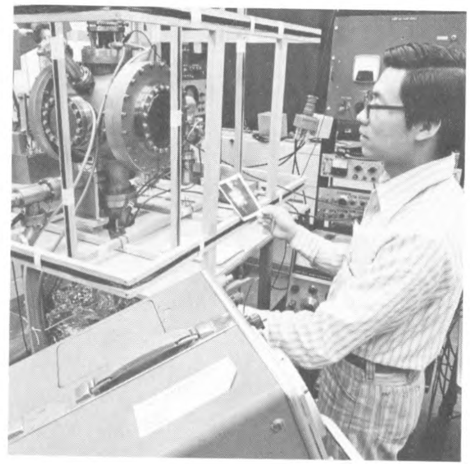
Left above: **The study of imperfections in solids is a major area in materials science research. This micrograph, showing a grain boundary parallel to the thin crystal surface in gold, was obtained with a 200-keV electron microscope.**

Left: **This high-resolution micrograph of silicon, taken with the Siemens 102 electron microscope, shows a twin five planes thick. The white dots are the open channels in the silicon lattice. The material was prepared as part of a program to investigate new methods of economical fabrication of solar cells.**

—— 1980. Observations on the climb of extended dislocations due to irradiation in the HVGM. *Philosophical Magazine* A42:31.
Foll, H., and Ast, D. G. 1979. TEM observations of grain boundaries in sintered silicon. *Philosophical Magazine* A40:589.
Golovchenko, J.; Batterman, B. W.; and Brown, W. L. 1975. Observation of internal x-ray wave fields with an application to impurity lattice location. *Physical Review B* 10:4239.
Hall, T. M.; Wagner, A.; and Seidman, D. N. 1977. A computer-controlled time-of-flight atom-probe field-ion microscope for the study of defects in metals. *Journal of Physics E: Scientific Instruments* 10:884.
Kohlstedt, D. L., and Van der Sande, J. B. 1976. On the detailed structure of ledges in an augite-enstatite interface. In *Electron Microscopy in Mineralogy,* ed. H. R. Wenk, p. 234. Berlin: Springer-Verlag.
Roberto, J.; Batterman, B. W.; Kostroun, V.; and Appleton, B. R. 1975. Positive ion-induced Kossel lines in copper. *Journal of Applied Physics* 46:936.
Seidman, D. N. 1978. The study of radiation damage on metals with the field-ion and atom-probe microscopes. *Surface Science* 70:532.
Strunk, H., and Ast, D. G. 1980. Combined HVTEM and EBIC studies of EFG silicon. In *Proceedings of 38th annual meeting of Electron Microscopy Society of America,* ed. G. W. Bailey, p. 322.
Van der Sande, J. B., and Kohlstedt, D. L. 1976. Observations of dissociated dislocations in deformed olivine. *Philosophical Magazine* 34:653.
Wagner, A. 1978. An atom-probe field-ion microscope study of the range and



Surface studies include *(above)* research on surface segregation and defects in transition metals and *(right)* analysis of the low-energy diffraction pattern from a single-crystal surface of silver reacting with chlorine.



diffusivity of helium in tungsten. Ph.D. thesis (D. N. Seidman).
Wei, C.-Y. 1978. Direct observation of the point-defect structure of depleted zones in ion-irradiated metals. Ph.D. thesis (D. N. Seidman). A paper by the same title was published in 1978 in *Philosophical Magazine* 37:257.

Surfaces, Interfaces, and Thin Films

New methods to fabricate thin alloy films of controlled composition are being investigated by D. G. Ast and his students by comparing experimental output, as determined by electron microprobe analysis, with theoretical models. The structure of thin amorphous and crystalline films is being studied with the use of high-resolution electron microscopy.

J. W. Mayer and his group use a 1-MV tandem accelerator in Rutherford backscattering and channeling analysis of thin-film reactions and ion-beam modification of materials. This apparatus allows precise profiling of the chemical composition of thin films.

In a project directed by S. L. Sass, diffraction techniques have been developed for studying the structure of grain boundaries. X-ray diffraction studies of planar grain boundaries in thin-film bicrystal specimens are being carried out in order to answer the following questions: (1) Is the boundary structure periodic? (2) What patterns of relaxation exist in the boundary? (3) What is the detailed atomic structure of the boundary? The x-ray results are being used to check the validity of computer modeling studies of the structure of grain boundaries. The possibility of using x-ray techniques to study the surface structure of thin films is also being explored. D. L. Kohlstedt, R. Raj, and S. L. Sass are collaborating on the use of electron-diffraction techniques to study the structure of grain boundaries in ceramic materials.

J. M. Blakely and his research group are engaged in studies of various aspects of solid surfaces. The techniques of secondary-electron (including Auger) spectroscopy and low-energy electron diffraction, as well as other analytical methods, are being applied in studies of the phenomena of surface oxidation, adsorption, and segregation. Surface defect structures in ionic systems are being investigated by Kelvin probe and other techniques. Chemical reactions on surfaces of predetermined structure are being studied by modulated molecular-beam methods.

A research group under the direction of T. N. Rhodin is concerned with the physics and chemistry of chemical bond formation on metal surfaces. Both valence- and core-level electron spectroscopes, as well as the field-emission and field-ion microscopes, are used to study electron excitations and structure associated with both clean and chemisorbed surfaces. Investigations of atomic composition using Auger spectroscopy and of surface structure using LEED-intensity analysis are combined with information on electron processes to study the microscopic and atomistic nature of surface reactions. The work on transition-metal single crystals is concerned with the kinetic behavior of corrosion-resistant metals; the studies of platinum-group metals in the form of both crystals and powders is directed toward developing a more systematic understanding of heterogeneous catalysis.

R. Merrill is conducting an extensive research program on the structure and properties of solid surfaces, including work on a variety of problems in heterogeneous catalysis. Techniques for studying reactive and nonreactive atomic- and molecular-beam scattering processes are now available.

Typical publications and theses (listed with the name of the supervising professor) in this area are:

Ast, D. G., and Krenitsky, D. J. 1976. Preparation of constant composition alloy films by diffusion-limited evaporation from the liquid state. *Journal of Vacuum Science and Technology* 13:969.

Blakely, J. M., and Thapliyal, H. V. 1978. Structure and phase transition of segregated surface layers. In *Proceedings of A.S.M. symposium on interfacial segregation*, ed. J. M. Blakely and W. C. Johnson. Cleveland: American Society for Metals.

Brodén, G., and Rhodin, T. 1976. Photoemission spectroscopy of chemical reactions on platinum-group metals—chemisorption of CO on iridium. *Solid State Communications* 18:105.

Dionne, N. J. 1975. Field emission energy spectroscopy of the fcc platinum group metals. Ph.D. thesis (T. N. Rhodin).

Ducros, R., and Merrill, R. P. 1976. The interaction of oxygen with Pt (110). *Surface Science* 55:277.

Gaudig, W.; Guan, D. Y.; and Sass, S. L. 1976. X-ray diffraction study of large angle twist grain boundaries. *Philosophical Magazine* 34:923.

Goldfarb, W.; Krakow, W.; Ast, D. G.; and Siegel, B. 1975. Imaging of amorphous objects by tilted bright field illumination. In *Proceedings of 33rd annual meeting of the Electron Microscopy Society of America*, p. 186.

Guan, D. Y. 1976. Diffraction study of the structure of grain boundaries and dislocations. Ph.D. thesis (S. L. Sass).
Guan, D. Y., and Sass, S. L. 1973. Diffraction from periodic arrays of dislocations. *Philosophical Magazine* 27:1211.
Isett, L. C. 1975. The binding energy of carbon on Ni(100) and a stepped Ni surface from equilibrium segregation studies. Ph.D. thesis (J. M. Blakely).
Rhodin, T., and Tong, D. 1975. Structure analysis of solid surfaces — a discussion of some recent advances in the determination of surface crystallography by low-energy electron diffraction. *Physics Today* 28:23.
Thapliyal, H. V. 1978. Morphology of vicinal surfaces of nickel and equilibrium segregation of carbon to Ni(111). Ph.D. thesis (J. M. Blakely).
Tu, Y. Y. 1978. Energetics and structures of chlorine adsorbed on silver surfaces. Ph.D. thesis (J. M. Blakely).
Tu, Y. Y., and Blakely, J. M. 1978. Chlorine adsorption on Ag surfaces. *American Vacuum Society*, March/April.
Unertl, W. N., and Blakely, J. M. 1977. Growth and properties of oxide films on Zn(0001). *Surface Science* 69:23.

Mechanical Behavior of Materials

The influence of hydrogen on the mechanical behavior of steels is under study by H. H. Johnson and his students. One problem they are considering is hydrogen attack on steels at high temperatures, where the hydrogen reacts with carbon to produce methane bubbles at the grain boundaries. Also under investigation is the diffusion and trapping of hydrogen in the region of lower temperature and lower concentration, where hydrogen embrittlement is prominent.

The design of advanced power-generation systems requires better descriptions of the mechanical behavior of solids over long periods of time. To meet this need E. W. Hart is developing a theory of inelastic deformation (both anelastic and plastic) in terms of a mechanical equation of state. Constitutive relations have been proposed that can be integrated to predict behavior in multiaxial loading. Biaxial loading experiments are being performed to validate this theory.

C.-Y. Li and his students work closely with Hart in establishing experimentally the parameters of these constitutive relations for a large variety of metals and alloys of practical significance. In a cooperative program between these two groups and investigators in the Department of Theoretical and Applied Mechanics, methods of engineering design based on the mechanical equation-of-state concept are being developed. At the same time Li is working to extend this approach experimentally to fatigue and other situations in which time-dependent recoverable (anelastic) deformations are important.

In a related program, D. L. Kohlstedt and his students have found that the mechanical equation of state developed by Hart and Li for metals can also describe the deformation of ionic and covalently bonded solids. Transmission electron microscopy and etch-pit studies yield direct observations of the dislocation structure, allowing connections to be made between the phenomenological parameters of the theory and dislocation descriptions of deformation.

The high-temperature mechanical behavior of olivine, the primary mineral in the earth's upper mantle, is a topic of particular importance to geophysicists. Convective flow in the mantle, which to a first approximation can be considered to be flow of olivine, is coupled to the large-scale motion of the overlying lithospheric plates and is manifested as continental drift. D. L. Kohlstedt is investigating the relationship between the imposed macroscopic conditions of stress, temperature, and strain rate used to deform olivine crystals in his laboratory and the resulting dislocation microstructures as observed in the transmission electron microscope. Confident application of laboratory creep data obtained on a time scale of 10^{-4} years to problems involving geologic times on the order of 10^6 years requires a thorough understanding of the role of microscopic defects in producing macroscopic plastic flow.

Studies of two-phase glass-ceramic systems are being carried out by D. L. Kohlstedt, R. Raj, and their associates. Kohlstedt's group is investigating the deformation of glass ceramics under high temperature and pressure; these studies have application to new fabrication methods for ceramic-based materials. Raj's group is investigating the kinetics of precipitation of the ceramic phase in these systems and the effect of the residual glassy phase on deformation and fracture at elevated temperatures.

R. Raj and his group are also concerned with the fracture and fatigue behavior of high-temperature materials such as austenitic

The effects of pulse changes in load on the growth of crazes and cracks in polymers are measured in a holographic interferometry experiment. This research is directed by Professor Edward J. Kramer.

stainless steels, nickel-base superalloys, and silicon nitride. The understanding of the microstructural mechanisms of failure is a key to the optimum design and use of such materials. These fundamental studies are being carried out by a combination of micromechanical modeling, microstructure analysis, and mechanical testing.

In the area of polymers, E. J. Kramer and his students are determining the mechanisms responsible for fracture, crazing, and plastic deformation of polymers below the glass transition. A transmission electron microscopy method of measuring stresses and strains in very local regions of a craze (within about 1,000 angstroms) has been developed and is being used to investigate the mechanical and fracture properties of crazes as a function of polymer molecular weight, molecular orientation, crosslinking, and environmental crazing agents, if any. Small-angle and wide-angle x-ray scattering, as well as optical techniques such as moire analysis and microscopic birefringence measurements, are also important tools in this study.

E. J. Kramer, D. G. Ast, and their students are collaborating on a project in which holographic interferometry is used to map the dynamic strain fields in the vicinity of growing crazes and cracks. Ast is especially interested in developing holographic interferometry of very small areas.

The mechanical properties of metallic glasses with a Ni-Fe base are being investigated by D. G. Ast and his associates. The group has studied the influence of annealing on fracture toughness, crack growth under cyclic loading, the temperature dependence of the flow stress, and the anelastic stress-relaxation of coiled ribbons; a current topic is the properties of shear bands and the influence of composition on the yield stress. This program is complemented by x-ray, transmission, and scanning electron microscopy, as well as by calorimetric measurements and measurements of magnetic and electrical properties to identify phase changes.

A. L. Ruoff has developed techniques for measuring the yield stress of extremely hard and strong materials; his group has measured the yield strength of WC and will study Al_2O_2, B_4C, Si, Si_3N_4, SiC, cubic BN, and diamond. In addition to elucidating the yielding process in these ordinarily brittle materials, these researchers are investigating the increase of fracture stress under point-contact loads (Auerback's law). At the present time they are constructing a device to study in a scanning electron microscope the deformation (either by fracture or yielding) that is produced by tiny indentors. The intent of this research is to measure the properties of perfect crystalline solids.

Representative papers in this area are:

Ast, D. G., and Krenitsky, D. J. 1979. Stress relaxation of Fe-Ni based metallic glasses. *Journal of Materials Science* 14:287.

——. 1980. Ideal elastic plastic deformation in Fe-Ni based metallic glasses. *Materials Science and Engineering* 43:241.

Hadnagy, T. D.; Krenitsky, D. J.; Ast, D. G.; and Li, C.-Y. 1978. Load relaxation studies of a metallic glass. *Scripta Metallurgica* 12:45.

Hart, E. W. 1978. Constitutive relations for non-elastic deformation. *Nuclear Engineering and Design* 46:179.

Huang, F. H.; Ellis, F. V.; and Li, C.-Y. 1977. Comparison of load relaxation data of type 316 austenitic stainless steel with Hart's deformation model. *Metallurgical Transactions A* 8:699.

Kohlstedt, D. L.; Goetze, C.; and Durham, W. B. 1976. Experimental deformation of single crystal olivine with application to flow in the mantle. In *The physics and chemistry of minerals and rocks,* ed. R. G. J. Strens, pp. 35–49. London: Wiley.

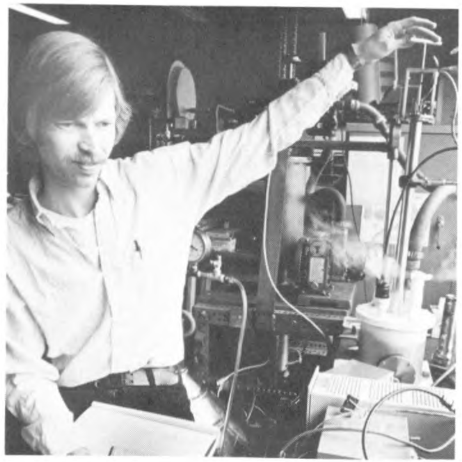
Kramer, E. J.; Krenz, H. G.; and Ast, D. G. 1978. Mechanical properties of methanol crazes in polymethylmethacrylate. *Journal of Polymer Science and Polymer Physics* 16:349.

Krenitsky, D. J., and Ast, D. G. 1979. Temperature dependence of the flow stress and ductility of annealed and unannealed amorphous $Fe_{40}Ni_{40}P_{14}B_6$. *Journal of Materials Science* 14(2):275.

Krenz, H. G.; Kramer, E. J.; and Ast, D. G. 1976. Structure of solvent crazes in polystyrene. *Journal of Materials Science* 11:2211.

Min, B. K., and Raj, R. 1978. Hold-time effects in high temperature fatigue. *Acta Metallurgica* 26(6):1007.

Pavinich, W., and Raj, R. 1977. Fracture at elevated temperature. *Metallurgical Transactions A* 8:1917.



Ruoff, A. L. 1978. The fracture and yield strength of diamonds, silicon and germanium. In *Proceedings of 6th AIRAPT international high pressure conference* (held July 1977 at the University of Colorado, Boulder, Colorado). New York: Plenum.

Van der Sande, J. B., and Kohlstedt, D. L. 1976. Observations of dissociated dislocations in deformed olivine. *Philosophical Magazine* 34:653.

Wire, G. L.; Ellis, F. V.; and Li, C.-Y. 1976. Work hardening and mechanical equation of state in some metals in monotonic loading. *Acta Metallurgica* 24:677.

High-Pressure Studies

The research program on materials under high pressure is directed by A. L. Ruoff. Recently the emphasis has been on generating and measuring extremely high pressures and on carrying out experiments at these pressures. It is hoped that static pressures in excess of three million atmospheres, which approaches the pressure at the earth's center, can be generated.

Left above: **A postdoctoral associate working with Professor Arthur L. Ruoff makes an attempt at 900 kbars to produce metallic hydrogen. He is using the diamond indentor–diamond anvil system.**

Left: **A graduate student adjusts the force that changes the pressure in the diamond indentor–diamond anvil system. In this experiment, metallic xenon was produced at 330 kbars.**

Working with tiny spherical indentors of diamond, the researchers have created pressures approaching two megabars. Studies they have made of the theoretical strength of perfect crystalline diamond suggest that even higher pressures are possible within its elastic range. Using submicron fabrication techniques, the researchers have made interdigitated electrodes on the diamond sample (see figure) with spacings and widths as small as 0.3 microns. This makes possible the study of insulator-to-metal phase transitions in tiny volumes at extreme pressures.

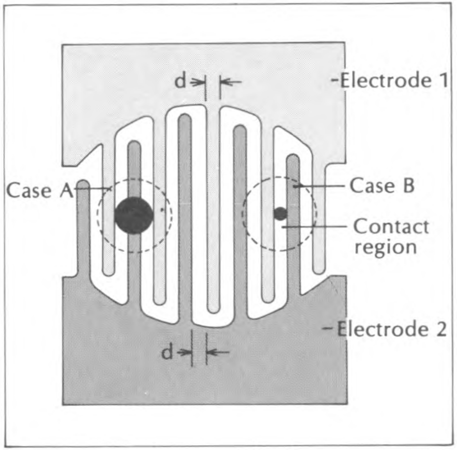
Such transitions are being or will be studied in the III-V compounds, in the solidified halogens, in the solidified rare gases, in oxygen, and in hydrogen. Metallic hydrogen, for example, is a high-pressure form that may be metastable at atmospheric pressure; it is generally considered to be the major fraction of the planet Jupiter. Theorists have predicted that hydrogen may be a high-temperature superconductor. The superconducting behavior of materials that become metallic at high pressures is also being investigated; sulfur and iodine are currently under study.

Some recent papers in this area are:

Chhabildas, L. C., and Ruoff, A. L. 1977. The transition of sulfur to a conducting phase. *Journal of Chemical Physics* 66:983.

Ruoff, A. L. 1977. Prospects for metallic hydrogen. Paper read at International Conference on High Pressure and Low Temperature Physics, July 1977, at Cleveland State University, Cleveland, Ohio.

——. 1978. On the ultimate yield strength of solids. *Journal of Applied Physics* 49:197.



This schematic shows interdigitated electrodes on a diamond anvil, as used in high-pressure work at Cornell. The actual grids contain hundreds of fingers that are only a few hundred angstroms thick and may be only 0.3 micron wide. The sample is deposited over the electrodes to a thickness of a few thousand angstroms. Then the spherically tipped diamond indentor is pressed against the assembly, generating a hemispherical pressure distribution. Indentor contact perimeters are shown by the dashed circles. The dark center spots represent sample that has undergone an insulator-to-conductor transition. The conducting phase in each is just large enough to close the circuit.

Ruoff, A. L., and Chan, K. S. 1978. Transformation pressure of ZnS by a new primary pressure technique. In *Proceedings of 6th AIRAPT international high pressure conference* (held July 1977 at the University of Colorado, Boulder, Colorado). New York: Plenum.

Phase Transformations

Researchers headed by S. L. Sass are studying the omega-phase transformation that occurs in titanium and zirconium alloys and that has an important effect on their mechanical and superconducting properties. Direct lattice-imaging, high-resolution dark-field electron microscopy, and electron diffraction are being used to study the local structure of these alloys before transformation, as well as the mechanism of transformation. The structure of a new type of defect in the bcc phase has been determined using diffuse-scattering observations.

A new technique developed by B. W. Batterman's group makes use of the Mössbauer effect to study the dynamics of phase transformations. Mössbauer gamma rays scattered from crystals can be separated into elastic and inelastic components, and these can be related to the dynamic aspects of the omega-phase transition.

Representative publications and theses (listed with the name of the supervising professor) in this area are:

Batterman, B. W.; Maracci, G.; Merlini, A.; and Pace, S. 1973. Diffuse Mössbauer scattering applied to dynamics of phase transformations. *Physical Review Letters* 31:227.

Chang, A. L. J.; Krakow, W.; and Sass, S. L. 1976. A high resolution electron microscope study of the omega phase transformation in Zr-Nb alloys. *Acta Metallurgica* 24:29.

Kuan, T. S. 1977. Diffraction and high resolution electron microscopy studies of a linear defect in Zr-Nb bcc solid solutions. Ph.D. thesis (S. L. Sass).

Kuan, T. S., and Sass, S. L. 1976. The structure of a linear omega-like vacancy in Zr-Nb bcc solid solutions. *Acta Metallurgica* 24:1053.

Ceramic and Geologic Materials

C. B. Carter's group is studying the structure of grain boundaries in $A1_2O_3$ and in several oxides with cubic symmetry. The aim of this study is to understand how the structure of grain boundaries in ceramic materials influences their motility at high temperatures, particularly under the influence of applied stress.

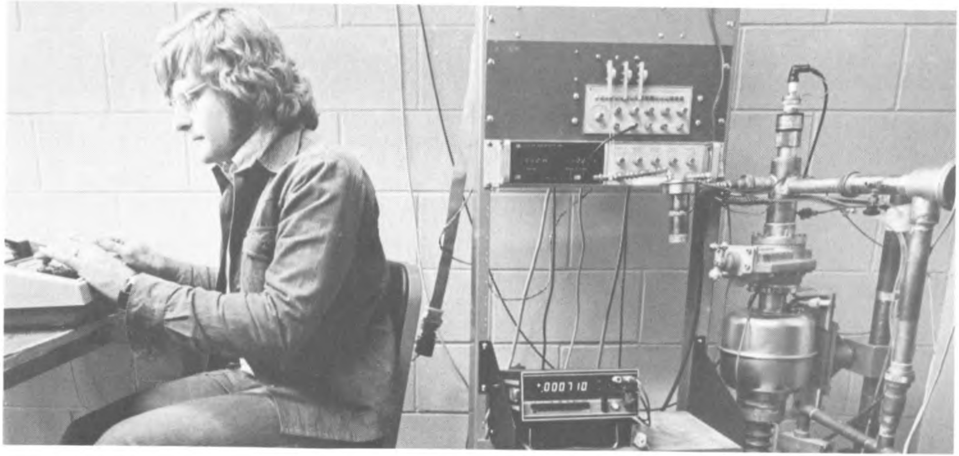
In a new program being carried out with H. Schmatzried at the University of Hanover, Carter and his research group are investigating the mechanisms of heterogeneous phase boundary motion.

D. L. Kohlstedt's group is using electron microscopy to study the dislocation microstructure produced during high-temperature deformation of transition metal carbides, a group of extremely hard ceramic materials. Members of this carbide family — for example, TiC — show a marked decrease in mechanical strength at temperatures above one-third of their melting points. This weakening severely limits the use of the carbides as high-temperature structural components. Improvement in the creep resistance of the carbides is being sought by precipitating microscopic grains of a second phase that can act to impede dislocation motion.

Students in this group are also studying the deformation behavior of alkali halides and semiconducting materials. The main purpose of this research is to test for the existence of a mechanical equation of state to describe the plastic flow in these nonmetallic crystalline solids.

Kohlstedt and his students are also studying the creep behavior of geological materials that are important in the earth's upper mantle and lower crust. Of particular interest is olivine-rich partially melted rock, a system that is likely to prove important in convective flow and associated continental drift. Little is known about the mechanical strength of partially molten rock or about the transport of melt (magma) through such rocks. Also, as part of a program to assess the possible deformation mechanisms and differential stress levels operative during major earthquakes, an extensive study is being made of the rocks deformed during large-scale faulting like that at the San Andreas fault.

A recent project involved microprocessor-controlled measurement of the AC ion conductivity of a solid electrolyte, sodium-ß-alumina. This ceramic is under consideration for use in lightweight batteries.



The relationship between microstructure and mechanical behavior of glass-ceramic systems — for example, hot pressed silicon nitride and glass — is being investigated by R. Raj and his group. The morphology and composition of the glass, particularly at grain interfaces, is important to the thermal shock and fracture behavior of these materials. Included in this work are investigations of the kinetics of separation of the ceramic phase from the glass and a study of the glass-ceramic interface.

P. C. Schultz and G. H. Beall, courtesy professors in materials science, are also senior staff members at the research laboratories of the Corning Glass Works. Schultz's interests include vapor-phase reaction processes for preparing refractive and high-purity glasses, such as optical wave-guide fibers; property studies of many-doped fused silicates, such as O-expansion titania-silica glass; magnetic and semiconducting glass ceramics; and the properties of high-purity alumina.

Beall is primarily concerned with nucleation and crystallization phenomena in glass and with applications and physical properties of glass ceramics. His current research involves photo heat and chromatic effects derived from the precipitation of silver colloids in glass, control of microstructures in the use of fine-grain and transparent polycrystalline materials, and synthesis of layer-lattice silicides with emphasis on the development of known brittle characteristics in nonceramic materials.

High-pressure apparatus is used for deformation experiments on materials by Professor David L. Kohlstedt *(left)* and a graduate student.

Representative publications and theses (listed with the name of the supervising professor) are:

Allender, J. 1978. Hydrogen reduction of nickel-ferrite and aluminum doped nickel-ferrite. Ph.D. thesis (L. C. DeJonghe).

Beall, G. H. 1972. Structure, properties and applications of glass-ceramics. In *Advances in nucleation and crystallization in glasses,* American Ceramic Society Special Publication number 5, ed. L. L. Hench and S. W. Freiman.

Carter, C. B. 1980. The study of grain boundaries in ceramics by electron diffraction. In *Proceedings of 38th annual meeting of Electron Microscopy Society of America,* ed. G. W. Bailey, p. 370.

Carter, C. B.; Kohlstedt, D. L.; and Sass, S. L. 1980. Electron diffraction and microscopy study of the structure of grain boundaries in $A1_2O_3$. *Journal of the American Ceramic Society* (in press).

Goetze, C., and Kohlstedt, D. L. 1977. The dislocation structure of experimentally deformed marble. *Contributions to Mineralogy and Petrology* 59:293.

Hornack, P. 1978. The effect of oxygen partial pressure on the creep strength of olivine. M.S. thesis (D. L. Kohlstedt).

Kohlstedt, D. L.; Goetze, C.; and Durham, W. B. 1976. Experimental deformation of single crystal olivine with application to flow in the mantle. In *The physics and chemistry of minerals and rocks,* ed. R. J. G. Strens, p. 35. London: Wiley.

Lerner, I.; Chiang, S.-W.; and Kohlstedt, D. L. 1978. *Load relaxation studies of four alkali halides*. Cornell University Materials Science Center report no. 3012.

Mosher, D. R.; Raj, R.; and Kossowsky, R. 1976. Measurement of viscosity of the grain boundary phase in hot-pressed silicon nitride. *Journal of Materials Science* 2:49.

Rey, M. C. 1978. Hydrogen reduction of cobalt-ferrite and aluminum doped cobalt-ferrite. Ph.D. thesis (L. C. DeJonghe).

Schultz, P. C. 1976. Binary titanium silicate glasses containing 10 to 20 Wt. % TiO_2. *Journal of the American Ceramic Society* 59(5/6):214.

———. 1977. Ultraviolet absorption of titanium and germanium in fused silica. In *11th international congress on glass*, vol. III, p. 153.

Stookey, S. D.; Beall, G. H.; and Pierson, J. E. 1978. Full-color photosensitive glass. *Journal of Applied Physics* 49(10):5114.

Electrical and Magnetic Properties

A study of the electronic conductivity of As_xTe_{1-x} films as a function of composition is supervised by D. G. Ast. Percolation theory in connection with a bond picture is being applied to explain the results. The structure of amorphous As-VI compounds is being studied, using diffraction as well as indirect methods based on known relationships among the glass transition temperature, the viscosity, and the molecular weight of chain polymers.

Ast also heads a project to produce by controlled vapor deposition multilayered composite superconductors with very fine lamellar spacings (of the order of angstroms). The goal is to produce a structure in which flux lines are pinned very effectively, thereby obtaining superconductors with high critical fields and low AC losses.

Work directed by E. J. Kramer seeks to elucidate the mechanisms of pinning of the flux line lattice by crystal defects, such as dislocations or surface configurations; an understanding of these mechanisms is basic to the production of superconducting wire with a high critical current. Also under investigation is the pinning due to defects produced by neutron irradiation, because of its importance in projected controlled nuclear fusion applications of superconductors.

Examples of publications and theses (listed with the name of the supervising professor) are:

Ast, D. G. 1974. Evidence for percolation controlled conduction in amorphous As_xTe_{1-x}. *Physical Review Letters* 33:1042.

Ast, D. G., and Brodsky, M. H. 1980. Conductivity of P-doped amorphous hydrogenated silicon. *Philosophical Magazine* B41:273.

Haywood, T. W., and Ast, D. G. 1978. Critical fields of multilayered films of Al and Ge. *Physical Review B* 18:2225.

Lauterwasser, B. D., and Kramer, E. J. 1975. Mechanisms of flux line lattice motion in a peak effect superconductor. *Physics Letters* 53A:410.

Osborne, K. E., and Kramer, E. J. 1974. The influence of plastic deformation on the peak effect in a type II superconductor. *Philosophical Magazine* 29:685.

Putz, A. G. 1972. Flux motion and pinning in a type II superconductor. M.S. thesis (E. J. Kramer).

Electron Microscopy

Weak-beam and lattice-fringe imaging techniques are being extensively used by C. B. Carter and his group to study line defects, stacking faults, and grain boundaries in ceramics and electronic materials, including Si, Ge, and III-V compounds such as GaAs. Together with S. L. Sass, Carter has developed the use of electron-diffraction techniques to study both the periodicity and thickness of grain boundaries.

Transmission electron microscopy (TEM), high-resolution TEM, and high-voltage TEM are used by D. G. Ast's group to study defects in silicon. An understanding and control of these defects is necessary in order to produce high-efficiency solar cells and also to increase the yield in the semiconductor industry.

High-resolution electron microscope techniques are being used by S. L. Sass and his research group to study the fine structure of phase transformations in titanium and zirconium alloys and defects in metals. Dark-field imaging with the diffuse scattering yields microstructural information at resolutions approaching atomic dimensions.

A program directed by J. Silcox is concerned with the understanding and exploitation of inelastic electron scattering at electron microscope energies (about 80 to 100 keV). The central instrument is a combination of a Hitachi 11A electron microscope, a Wien spectrophotometer, and a PDP-11 minicomputer, with which it is possible to carry out a variety of experimental observations. These include separation of electron loss spectra with an energy resolution of about 0.5

to 1.5 eV (depending on settings) of either an electron micrograph (with a spatial resolution extending to 20 angstroms, depending on the features of interest) or an electron diffraction pattern (with angular resolution of 10^{-4} to 10^{-5} radians, depending on instrumental settings). The primary focus in recent years has been on understanding losses rather than on attempting to exploit the losses in microanalysis. Surface losses such as surface plasmons in metals, surface-guided modes in insulators, and anisotropies in band structure have been studied, and losses due to excitation of single-particle valence states are under consideration. Future work is expected to include studies in more detail of contrast features and the role played by inelastic scattering.

An experimental high-resolution electron microscope, developed by B. M. Siegel and his group, is being used to extend the application of electron microscopy in studies of the molecular structure of biomacromolecules and biomaterials. The microscope is equipped with a field-emission source and uses computer processing of the image; it provides an optimum environment for the specimens, an ultrahigh vacuum (about 10^{-10} torr) and a liquid-helium cryostat to keep the specimens at liquid-helium temperature. The limitations on the observation of these materials by electron microscopy are now set by their high sensitivity to radiation damage from the electron beam.

This scanning electron microscope is useful in studies of the surfaces of materials and for biological applications.

Other problems of interest to this group are the preparation of very thin film crystalline substrates and amorphous materials and the study of their structural and physical properties. The substrates are used to support the electron microscope specimens and can be crucial in obtaining images with adequate signal-to-noise ratios after image processing.

Papers and theses (listed with the name of the supervising professor) of relevance include:

Carter, C. B.; Donald, A. M.; and Sass, S. L. 1980. The study of grain boundary thickness using electron diffraction techniques. *Philosophical Magazine* A41:467.

Chen, C. H. 1974. Studies of optical excitations in thin solid films by electron scattering. Ph.D. thesis (J. Silcox).

Chen, C. H., and Silcox, J. 1975. Surface guided modes in an aluminum oxide thin film. *Solid State Communications* 17:273.

Chen, C. H.; Silcox, J.; and Vincent, R. 1975. Electron energy losses in silicon: bulk and surface plasmons and Cerenkov radiation. *Physical Review B* 12:64.

Chiang, S.-W.; Carter, C. B.; and Kohlstedt, D. L. 1980. Faulted dipoles in germanium: a high resolution electron microscopy study. *Philosophical Magazine* A42:103.

Foll, H.; Carter, C. B.; and Wilkens, M. 1980. Weak-beam contrast of stacking faults in transmission electron microscopy. *Physica Status Solidi* A58:393.

Kuan, T. S., and Sass, S. L. 1977. The direct imaging of a linear defect using diffuse scattering in Zr-Nb bcc solid solutions. *Philosophical Magazine* 36:1473.

Pettit, R. B.; Silcox, J.; and Vincent, R. 1975. Measurement of surface plasmon dispersion in oxidized aluminum films. *Physical Review B* 11:3116.

Submicron Research

The techniques of submicron fabrication are being applied rapidly not only in electronic device technology, but also in materials science and other scientific fields. At Cornell, research in this area of materials science is sponsored in part by the National Research and Resource Facility for Submicron Structures, located on campus. In general, the studies here involve optical lithography, electron lithography, and x-ray lithography. Included are the development of techniques, research on resists, and applications of techniques in various areas of materials science.

The formation of shallow contacts is being investigated by J. W. Mayer and his group. They use ion implantation and two-metal layers to control the amount of silicon consumed in silicide formation.

A. L. Ruoff and his group use optical and electron lithography in making interdigitated electrodes for their research involving high pressures. They are currently working on the fabrication of electrodes with 0.1-micron spacing by means of electron-beam lithography. They have also carried out work using diamond anodes for the x-ray generation of carbon K radiation, which is an ideal source for extremely fine-scale (100 angstrom) resolution x-ray lithography. As part of this program, they are studying ion implantation in diamond.

Recent publications include:

Nelson, D. A., Jr., and Ruoff, A. L. 1978. Diamond: an efficient source of soft x rays for high resolution x-ray lithography. *Journal of Applied Physics* 49(11):5365.

Ruoff, A. L., and Chan, K. S. 1978. Transformation pressure of ZnS by a new primary pressure technique. In *Proceedings of 6th AIRAPT international high pressure conference* (held July 1977 at the University of Colorado, Boulder, Colorado). New York: Plenum.

M.Eng.(Materials) Degree Program

Students who have completed a four-year undergraduate program in engineering or the physical sciences are eligible for consideration for admission to the Master of Engineering (Materials) degree program. Candidates for the degree carry out independent projects that provide experience in defining objectives, planning and carrying through systematic work, and reporting conclusions. In addition they have the opportunity to develop their knowledge and skill in specialized areas of materials science. Program requirements include:

1. A project qualifying for twelve hours of credit and requiring individual effort and initiative. This project, carried out under the supervision of a member of the faculty, is usually experimental, although it can be analytical.

2. Six credits in mathematics courses, such as Advanced Engineering Analysis. Students who already meet this requirement may select other courses acceptable to the faculty.

3. Courses in materials science and engineering selected from those offered at the graduate level, or other courses approved by the faculty, sufficient to bring the total credits for the degree to thirty.

Faculty members of the Department of Materials Science and Engineering available to supervise M.Eng. project work are D. G. Ast, B. W. Batterman, J. M. Blakely, M. S. Burton, C. B. Carter, D. Grubb, E. W. Hart, H. H. Johnson, D. L. Kohlstedt, E. J. Kramer, C.-Y. Li, J. W. Mayer, R. Raj, A. L. Ruoff, S. L. Sass, and D. N. Seidman.

Examples of recent design projects (listed with the supervising professor) are:

Electron Microscope Study of Radiation Damage (D. N. Seidman)
Interaction of Interstitial Gas Atoms with Radiation Damage in Group Vb Metals (Niobium, Tantalum) (D. N. Seidman)
Electron Microscope Study of Carbides in Inconel (S. L. Sass)

Electron microscope studies are among the projects available for Master of Engineering students. This instrument is a 200-keV electron microscope.

Faculty Members and Their Research Interests

Dieter G. Ast, Dipl.Phys. (Stuttgart), Ph.D. (Cornell): *amorphous materials, defects in semiconductors, metallic glasses*

Boris W. Batterman, B.S., Ph.D. (M.I.T.): *x-ray and neutron diffraction, solid-state phenomena*

George H. Beall, B.S. (McGill), Ph.D. (M.I.T.): *glass-ceramic materials, nucleation crystallization, silicate mineralogy, photosensitive glass*

John M. Blakely, B.S., Ph.D. (Glasgow): *surface science, catalysis, photographic materials*

Malcolm S. Burton, B.S. (Worcester), S.M. (M.I.T.): *mechanical properties of solids*

Clive B. Carter, B.A., M.A. (Cambridge), M.Sc. (London), Ph.D. (Oxford): *electron microscopy of ceramics, semiconductors*

Claude Cohen, B.S. (American University, Cairo), Ph.D. (Princeton): *transport phenomena, light scattering, polymeric materials*

David Grubb, B.A., M.A., Ph.D. (Oxford): *electron microscopy of polymers, radiation damage, mechanical properties of polymers*

Edward W. Hart, B.S. (City College of New York), Ph.D. (California, Berkeley): *theory of the mechanical behavior of solids, thermodynamics of interfaces*

Herbert H. Johnson (Director of the Materials Science Center), B.S., M.S., Ph.D. (Case): *gases in metals, cyclic deformation, environment and fracture*

David L. Kohlstedt, B.S. (Valparaiso), Ph.D. (Illinois): *ceramic materials, electron microscopy, physics of geological materials*

Edward J. Kramer, B.Ch.E. (Cornell), Ph.D. (Carnegie-Mellon): *superconductivity, mechanical properties, high-polymer physics*

Che-Yu Li, B.S.E. (Taiwan College of Engineering), Ph.D. (Cornell): *mechanical behavior, irradiation effects*

James W. Mayer, B.S., Ph.D. (Purdue): *ion implantation in semiconductors, thin-film reactions, Rutherford backscattering and channeling*

Robert Merrill, Chem.E. (Cornell), Sc.D. (M.I.T.): *chemistry and physics of surfaces, catalysis, corrosion, atomic and molecular scattering*

Rishi Raj, B.S. (Allahabad, India), B.S. (Durham), M.S., Ph.D. (Harvard): *fracture and cyclic deformation at elevated temperatures in two-phase materials (metals and ceramics)*

Thor N. Rhodin, B.S. (Haverford), A.M., Ph.D. (Princeton): *physics and chemistry of solid surfaces, electron properties of metals and alloys*

Arthur L. Ruoff (Director of the Department of Materials Science and Engineering), B.S. (Purdue), Ph.D. (Utah): *high-pressure phenomena, higher-order elastic constants, hot isostatic compaction, mechanical properties*

Stephen L. Sass, B.Ch.E. (City College of New York), Ph.D. (Northwestern): *grain boundary structure, phase transformations, transmission electron microscopy, diffraction techniques*

Peter C. Schultz, B.S., Ph.D. (Rutgers): *glasses and glass ceramics, vapor deposition technology, optical properties, fiber optics*

David N. Seidman, B.S., M.S. (New York University), Ph.D. (Illinois): *lattice defects, radiation damage, field-ion microscopy and atom-probe field-ion microscopy*

Benjamin M. Siegel, B.S., Ph.D. (M.I.T.): *molecular structure of biomacromolecules, high-resolution electron microscopy, radiation damage of biomaterials, thin films*

John Silcox, B.Sc. (Bristol), Ph.D. (Cambridge): *electron microscopy, spectroscopy, diffraction*

Floyd O. Slate, B.S., M.S., Ph.D. (Purdue): *concrete, engineering materials*

Watt W. Webb, B.S., Sc.D. (M.I.T.): *biophysics, superconductivity, critical and cooperative phenomena*

Further Information

Inquiries about graduate study in materials science and engineering may be addressed to the Graduate Faculty Representative, Materials Science and Engineering, Cornell University, Bard Hall, Ithaca, New York 14853.

Mechanical Engineering

The graduate Field of Mechanical Engineering at Cornell offers advanced instruction and research opportunities in a wide range of contemporary topics. Primary emphasis is on the engineering sciences that are basic to the field and on research and advanced design in modern engineering applications. Two graduate fields — Mechanical Engineering and Aerospace Engineering — are centered in the Sibley School of Mechanical and Aerospace Engineering, which also offers a variety of undergraduate courses and an undergraduate field program in mechanical engineering.

Candidates for the M.S. and Ph.D. degrees in mechanical engineering choose mechanical engineering as their major subject, selecting one of the following areas of concentration: fluid mechanics, heat transfer, combustion, energy and power systems, mechanical systems and design, materials and manufacturing engineering, and bio-mechanical engineering. Candidates also choose a minor subject that is generally from some other field such as mathematics, physics, or mechanics, or aerospace, electrical, or nuclear engineering. Strong emphasis is placed on learning through participation in research projects. The work of an M.S. or Ph.D. candidate is supervised by a special committee headed by the professor representing the major subject; this chairperson normally is the student's research and thesis adviser as well.

Also offered is a professional graduate program leading to the degree of Master of Engineering (Mechanical). This program provides a one-year course of study for those who wish to develop a high level of competence in current technology and engineering design. In addition to their course work, the M.Eng.(Mechanical) candidates work on design projects of their choice. The design project may be undertaken individually or by a small team. Often it is carried out in cooperation with an industrial organization; company representatives suggest the problem, participate in its formulation, and review the solution upon its completion.

A weekly colloquium and a weekly research conference, both held jointly and with the graduate Field of Aerospace Engineering, encourage an informal relationship between graduate students and faculty members. The colloquium speakers, who are recognized authorities in their fields, are from Cornell or other universities, industry, or government. Graduate students engaged in thesis research present progress reports on their work at the research conference and benefit from suggestions offered by other students and faculty members. New graduate students find these conferences helpful in choosing research projects of their own.

There are currently about sixty full-time graduate students enrolled in the Field of Mechanical Engineering.

Facilities

Special equipment available for graduate research in the Field of Mechanical Engineering includes an environmental wind tunnel; several low-turbulence wind tunnels; Schlieren systems; holographic interferometers; extensive hot-wire anemometry equipment; laser-doppler anemometry instrumentation; minicomputers for the analysis of experimental data; experimental internal combustion engines and dynamometers; experimental gas-turbine combustors; extensive exhaust-gas analysis facilities; a five-foot-diameter parabolic mirror for collecting and concentrating solar energy; a combined steady-torque and reversed-bending fatigue testing machine; bearing-test machines for eccentric loading, for programmed load variations, and for shaft oscillations; special rigs for the dynamic loading of machine parts; automatic data-recording instruments; and an extensive laboratory of machine tools and gauges.

Other facilities available to mechanical engineering graduate students include the University's large-scale computer system, with both digital and analog capability; computer terminals that allow interactive and batch processing are located in Upson Hall. A nuclear reactor facility is available for student use. A geothermal energy laboratory is operated by the Sibley School in conjunction with the Department of Geological Sciences.

By special arrangement some thesis work may be carried out at the Brookhaven National Laboratory.

Areas of Research

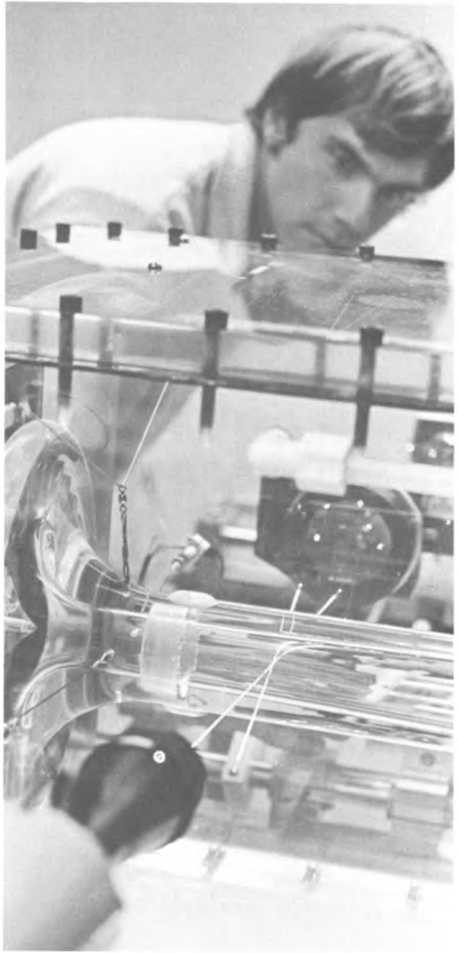
Graduate work in mechanical engineering at Cornell is largely divided into two areas. One is characterized by a concern with the dynamics of fluids and thermal phenomena; its subjects are thermodynamics, fluid mechanics, heat transfer, and combustion, and the application of these disciplines to energy and power systems. The other area is characterized primarily by a concern with solid mechanics and mechanical phenomena; it involves mechanical systems and design, and materials and manufacturing engineering. These two mainstreams of study and research are supplemented by an area that embraces both: biomechanical engineering.

Research is also carried out in cooperation with the graduate Fields of Aerospace Engineering, Applied Mathematics, Applied Physics, Chemical Engineering, Chemistry, Operations Research, and Theoretical and Applied Mechanics.

Current research activities are described briefly under the general subject headings below.

Fluid Mechanics

Fundamental research in fluid mechanics at Cornell includes studies of turbulence, rotating flows, wave propagation and stability, acoustics and noise, non-Newtonian flows, internal and external aerodynamics of cooling towers, and large-scale motions in the upper mantle of the earth and in the mixed layer of the ocean. Current applications center on atmospheric turbulence, air pollution, flows in industrial injection-molding processes, and the fluid dynamical aspects of energy conversion and consequent environmental impact.



A graduate student working with Professor Sidney Leibovich uses a laser-doppler anemometer to study the mechanics of vortex flows.

Investigations of fluid turbulence now under way include theoretical and experimental studies of small-scale turbulence in meteorological and oceanographic flows; transport and diffusion of additives such as heat, moisture, and pollutants in turbulent atmospheres; the construction of consistent computational turbulence models using the methods of rational mechanics; and theoretical analyses of statistical errors in the measurement of fluid flows.

Non-Newtonian flows that are sensitive to temperature, pressure, and deformation are being studied both theoretically and experimentally to assist in the design of injection-molding equipment and also for research on solid-state convection in the earth's mantle. Computational techniques are being developed for use with general viscoelastic constitutive equations and to treat problems involving moving boundaries subject to constraints.

Linear and nonlinear wave propagation and stability studies constitute one aspect of a research program on vortex flows. Other problems considered include experimental investigations of vortex structure with use of a laser-doppler velocimeter, and a computational study of turbulent swirling flows. This work has application to swirling flows in combustion chambers and furnaces.

A vertical wind tunnel two stories high was installed recently in Grumman Hall for research on atmospheric turbulence. Among those working on the project are *(left to right)* Professor Zellman Warhaft; Edward Jordan, research support specialist; and Professor John L. Lumley.

Experimental facilities include extensive hot-wire and laser-doppler (counter and frequency tracker) anemometry equipment, an on-line minicomputer with a very fast A/D converter for data acquisition and processing, a variety of equipment for vortex flow experiments, a vertical wind tunnel specially designed for the study of free-stream turbulence with and without buoyancy (more than one additive may be simultaneously studied in the tunnel), an environmental wind tunnel, and other smaller wind tunnels and shock tubes.

Representative publications and theses (listed with the name of the supervising professor) are:

Chan, V. W.-C. 1978. A thermally driven fracture-flow model for warm springs. M.S. thesis (K. E. Torrance).

Garg, A. 1977. Oscillatory behavior in vortex breakdown flows: an experimental study using a laser doppler anemometer. M.S. thesis (S. Leibovich).

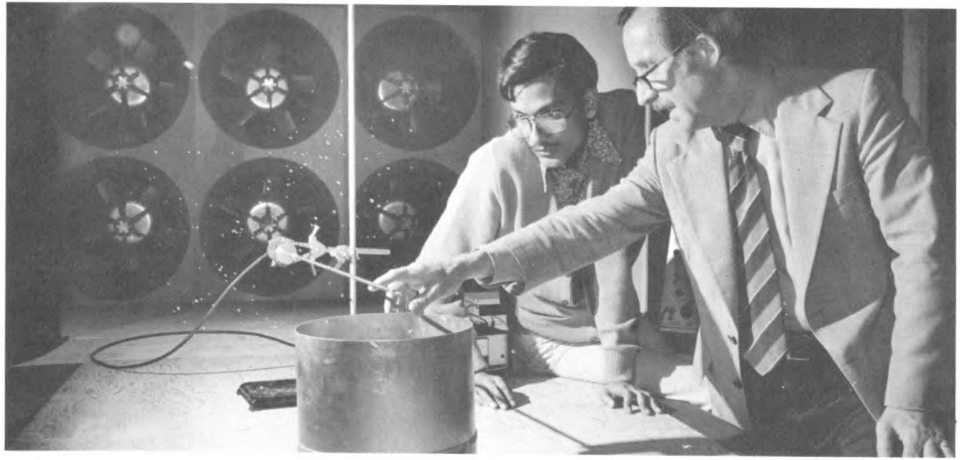
Leibovich, S., and Randall, J. D. 1980. Soliton amplification. *Physics of Fluids* 22:12.

Lumley, J. L.; George, W.; and Buchhave, P. 1979. Turbulence measurements with the laser-doppler anemometer. In *Annual reviews of fluid mechanics*, vol. 11, p. 443. Palo Alto: Annual Reviews, Inc.

Paolucci, S. 1979. Langmuir circulations as a convective instability mechanism and its effect on the ocean mixed layer. Ph.D. thesis (S. Leibovich).

Shen, S.-F.; Heiber, C. A.; and Upadhyay, R. K. 1980. Flow analysis applicable to the moving-front region in injection molding processes. *American Institute of Chemical Engineers Journal* (in press).

Warhaft, A., and Lumley, J. L. 1978. An experimental study of the decay of temperature fluctuations in grid generated turbulence. *Journal of Fluid Mechanics* 88:659.



Professor Franklin K. Moore *(right)* and a graduate student test a model cooling tower in a study of aerodynamic problems of large cooling devices for electricity-generating plants.

Heat Transfer

Problems of current interest are concerned with heat rejection to the environment, natural convection flows, geophysical heat transfer, and heat transfer in combustion systems. Both experimental and theoretical programs are pursued. Heat-transfer systems are also simulated and studied with the aid of computers.

The heat-transfer and aerodynamic phenomena associated with natural-draft cooling towers for closed-cycle cooling of large power plants are being studied with a view to optimizing heat-exchange performance. The object of this research is to minimize cost and environmental and aesthetic impacts. An environmental wind tunnel is employed for studies of cooling-tower heat transfer.

Studies of droplet evaporation and droplet boiling that apply to the microexplosive burning of emulsified fuels are under way.

Heat transfer and flow processes in porous media and in continuum fluids are being studied for both single-phase systems and two-phase boiling systems. Geothermal reservoirs and naturally occurring hydrothermal circulations are considered. Measurements include the determination of critical heat flux conditions and boiling instabilities.

Examples of recent publications and theses (listed with the name of the supervising professor) on these subjects are:

Bau, H. H. 1980. Experimental and theoretical studies of natural convection in laboratory-scale models of geothermal systems. Ph.D. thesis (K. E. Torrance).

Moore, F. K., and Ristorcelli, J. R., Jr. 1978. Turbulent flow and pressure losses behind oblique high-drag heat exchangers. *International Journal of Heat and Mass Transfer* 22:1175.

Pimputkar, S. M. 1978. Flow losses in oblique heat exchangers for dry cooling towers of large power plants. Ph.D. thesis (F. K. Moore).

Sheu, J.-P. 1980. Hydrothermal flows in porous media. Ph.D. thesis (K. E. Torrance).

Sheu, J.-P.; Torrance, K. E.; and Turcotte, D. L. 1979. On the structure of two-phase hydrothermal flows in permeable media. *Journal of Geophysical Research* 84:7524.

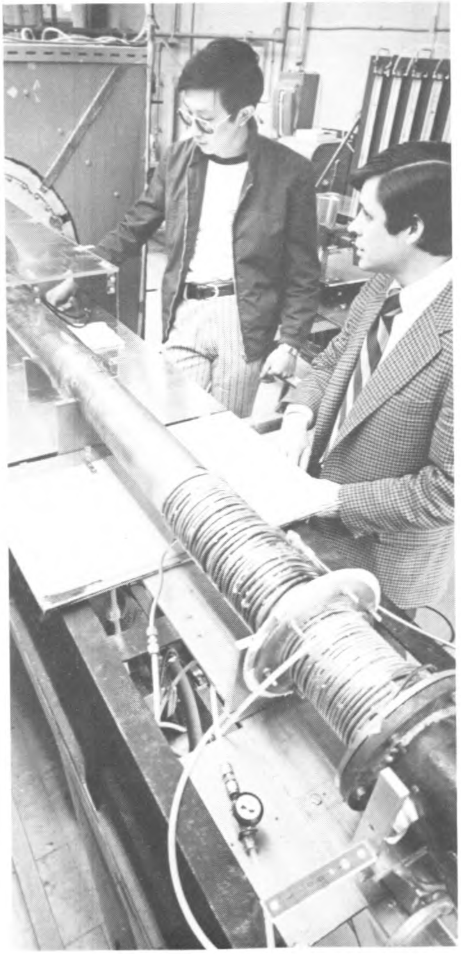
Torrance, K. E., and Chan, V. W. C. 1980. Heat transfer by a free convection loop embedded in a heat-conducting solid. *International Journal of Heat and Mass Transfer* 23:1091.

Combustion

Current programs include studies of chemical kinetics, fluid mechanics, turbulence, and air-pollutant generation as they pertain to combustion processes in practical energy-conversion devices operating on conventional and alternative fuels. A large experimental program with advanced diagnostic equipment is under way, and complementary theoretical and numerical analyses are being carried out.

A shock tube, a fast-flow reactor, and a novel laser-induced pyrolysis reactor are being used to study the chemical kinetics of alternative fuels. Fuel pyrolysis, soot formation, and oxidation of fuel-bound nitrogen are among the processes under study, and hydrogen and methanol are among the fuels being considered. A swirl combustor and a turbulent-flame experiment are used to study the role of fluid mixing in the performance of steady-flow combustors. Analytical and numerical studies of swirling reacting flows with turbulence are under way.

Research facilities include engine and chassis dynamometers, a gas chromatograph, a mass spectrometer, optical spectrographic equipment, hot-wire anemometers, two laser-doppler velocimeters, and a minicomputer system. Research opportunities exist in all of the programs described.



Laser-doppler velocity measurements are used to study fluid mixing processes in a swirl combustor in a project supervised by Professor Frederick C. Gouldin *(right)*. This research has potential applications in gas turbines.

Recent publications and theses (listed with the name of the supervising professor) in this area include:

de Boer, P. C. T., and Hulet, J. F. 1978. Performance of a Hydrogen–Oxygen–Noble Gas Engine. Paper read at 2d World Hydrogen Energy Conference, August 21–24, 1978, Zurich, Switzerland.

Gouldin, F. C.; Oven, M.; and McLean, W. J. 1979. Temperature and species concentration measurements in a swirl-stabilized combustor. In *17th symposium (international) on combustion*, p. 262. Pittsburgh: The Combustion Institute.

MacDonald, J. T. 1979. An investigation of the reduction in oxides of nitrogen emissions from reciprocating spark-ignited engines via diluent stratification. M.S. thesis (E. L. Resler, Jr.).

McLean, W. J.; de Boer, P. C. T.; Homan, H. S.; and Fagelson, J. J. 1977. Hydrogen as a reciprocating engine fuel. In *Future automotive fuels*, ed. J. M. Colucci and N. E. Gallopoulus, p. 297. New York: Plenum.

Smith, K. O., and Gouldin, F. C. 1978. Experimental investigation of flow turbulence effects on premixed methane-air flame. In *Progress in astronautics and aeronautics*, vol. 58, ed. L. A. Kennedy, p. 37. New York: AIAA.

Power and Energy Systems

In general the area of power and energy systems encompasses studies of modern methods of energy use and their corresponding environmental effects. Current faculty interests reflect concern over problems that result from the rapidly increasing use of energy in a society faced with limited energy resources and requirements for stringent environmental controls.

Among the topics receiving attention are combustion and transport processes in gas turbine combustors; these processes are being studied with a view toward the development of clean-burning turbine engines. Experimental and analytical investigations of the feasibility of synthetic fuels for high-efficiency operation of reciprocating internal combustion engines are also under way.

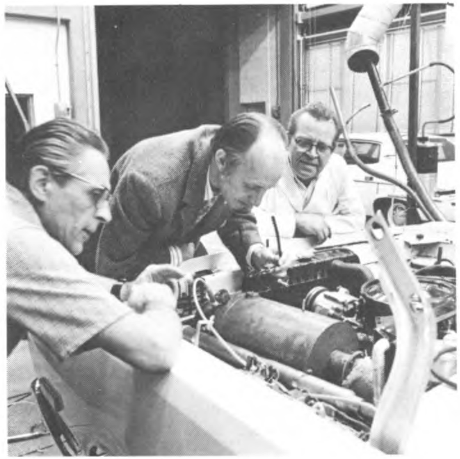
The reduction of air pollutants from conventional internal combustion engines has been achieved by improving the design of engine components. The design innovations resulting from research at Cornell allow present air-pollution standards to be met with current engine technology. Efforts are being made in continuing research projects to improve engine efficiency and to permit further reduction of emissions.

The generation of waste heat is of growing concern as energy use increases. Studies are being carried out to determine the effects of heat rejection from sources widely distributed in area and from intense local sources. Also, research in cooling tower technology is under way.

A Schlieren optical system is used by Professor Kenneth E. Torrance to visualize plume flow for a cooling-tower project.

Examples of recent publications and theses (listed with the name of the supervising professor) in this area are:

Auer, P. L. 1978. Balancing entropy and expansion. *Society* 15(2):39.
Auer, P. L.; Box, P.; Gough, W., and Roberts, V. 1978. Unconventional energy resources. In *World energy resources 1985–2020.* London: IPC Science and Technology Press.
Moore, F. K. 1977. Problems of dry cooling. In *Proceedings of the first waste heat management and utilization conference,* Miami Beach, p. 2C.
Shepherd, D. G. 1977. A comparison of three working fluids for the design of geothermal power plants. In *Proceedings of 12th intersociety energy conversion engineering conference,* vol. 1, p. 832. LaGrange Park, Ill.: American Nuclear Society.
Shepherd, D. G. 1978. Wind power. In *Advances in energy systems and technology*, vol. 1, ed. P. L. Auer, p. 1. New York: Academic Press.
Wynne, M. J. 1979. Experimental study of a natural draft cooling tower model with emphasis on cold inflow at exit. M.S. thesis (K. E. Torrance).



Engine and spark plug modifications for the control of pollutants in automobile emissions are being developed under the direction of Professor Edwin L. Resler, Jr. *(center).* This photograph shows adaptations, subsequently patented, that were made in an initial phase of the work.

Mechanical Systems and Design

Research in this area is concerned with the design, analysis, and manufacture of devices, machines, and systems. At Cornell these terms are broadly interpreted and encompass areas such as lubrication, vibrations, mechanical reliability, controls, and dynamics. The common theme of the work is the application of analytical models, optimization techniques, finite-element methods, and computer simulation to important practical problems ranging from vehicle dynamics to space technology.

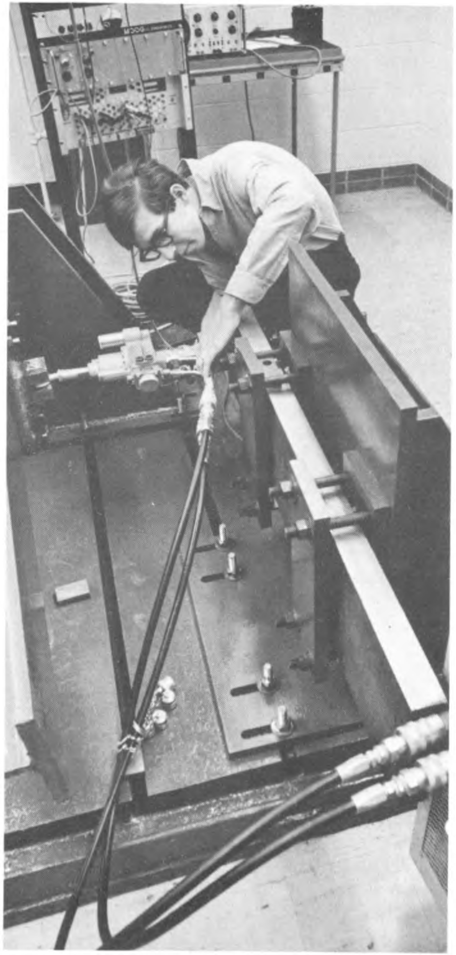
Lubrication studies have been concerned with porous and elastic bearings and include both mechanical and biological applications. Work in this area encompasses investigations of bearing characteristics, as well as dynamic effects in large systems with bearings. Current work includes studies of magnetic bearings.

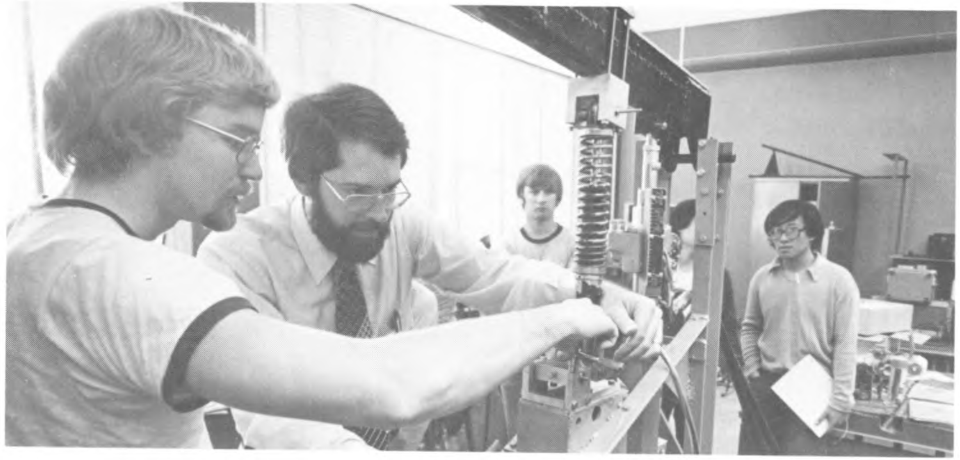
Vibration and dynamic studies have dealt with the nonlinear response of advanced-technology systems such as vehicle suspensions. In many of the projects in this area, computer-based methods are used for the efficient analysis of problems; computer graphics are being used to help interpret complicated nonlinear system responses such as limit-cycle behavior.

Mechanical reliability studies have been concerned with the probabilistic modeling of structural systems in which load sharing among members is a key feature. Current work concerns the development of useful models for representing the stress-rupture, dynamic fatigue, and brittle fracture of structural members under a variety of load histories. Work on reliability aspects of mechanical design is also in progress.

Recent publications and theses (listed with the name of the supervising professor) in this area include:

Goenka, P. K. 1980. Effect of surface ellipticity on the dynamically loaded spherical and cylindrical joints and bearings. Ph.D. thesis (J. F. Booker).
Goenka, P. K., and Booker, J. F. 1980. Spherical bearings: static and dynamic analysis via the finite element method. *Journal of Lubrication Technology* (in press).
Phelan, R. M. 1977. *Automatic control systems*. Ithaca, N.Y.: Cornell University Press.
Phoenix, S. L. 1978. The asymptotic time to failure of a mechanical system of parallel members. *SIAM Journal of Applied Mathematics* 34(2):227.





Above:* The stability and suspension characteristics of a motorcycle front fork are tested in a project supervised by Professor Dean L. Taylor *(second from the left).

***Left:* An electrohydraulic device is used in a gimballing system to simulate the launching control for a space vehicle. This research was supervised by Professor John F. Booker.**

——. 1978. Mechanical response of a tubular cable with an elastic core. *Textile Research Journal* 48:81.

Pitt, R. E. 1980. Statistical strength of fibrous systems under variations on load sharing and geometric configuration. Ph.D. thesis (S. L. Phoenix).

Rohde, S. M.; Whicker, D.; and Booker, J. F. 1979. Elastohydrodynamic squeeze films: effects of viscoelasticity and fluctuating load. *Journal of Lubrication Technology* 101:74.

Taylor, D. L. 1978. Wheel rotations and trailer dynamics. *Journal of Applied Mechanics* 45:206.

——. 1979. Simulation of off-road motorcycle ride dynamics. SAE paper 790261.

Materials and Manufacturing Engineering

Research in this area is concerned with the analysis of engineering materials in service, the selection of materials for specific applications, the analysis of manufacturing operations, and the selection of manufacturing operations for specific designs.

Recent work has included studies of the mechanism of friction welding, thermal fracture of cutting tool materials, ultrasonic testing of solid-state bonds, computer-aided design of injection-molding systems for polymers, mechanisms of friction and wear, and deformations associated with materials forming.

Representative papers and theses (listed with the name of the supervising professor) in this area are:

Dawson, P. R. 1978. Viscoplastic finite element analyses of steady state forming processes including strain history and stress flux dependence. *Applications of numerical methods to forming processes,* Applied Mechanics Division, vol. 28. New York: American Society of Mechanical Engineers.

Dawson, P. R., and Thompson, E. G. 1978. Finite element analysis of steady-state elasto-visco-plastic flow by the initial stress-rate method. *International Journal for Numerical Methods in Engineering* 12:47.

Galskoy, A. 1978. Melt temperature measurement in the mold during the injection molding of plastics. M.S. thesis (K.-K. Wang).

Khullar, P. 1978. Computer-aided design and manufacture of molds for injection molding of plastics. M.S. thesis (K.-K. Wang).

Wang, K.-K., and Frankel, E. 1978. Energy transfer and bond strength in ultrasonic welding of thermoplastics. In *Proceedings of 36th annual technical conference of the Society of Plastic Engineers*, p. 57.

Wang, K.-K.; Foltz, R. G.; and Stevenson, J. F. 1978. An experiment to measure the pressure dependence of the zero–shear-rate viscosity. *Journal of Non-Newtonian Fluid Mechanics* 3:347.

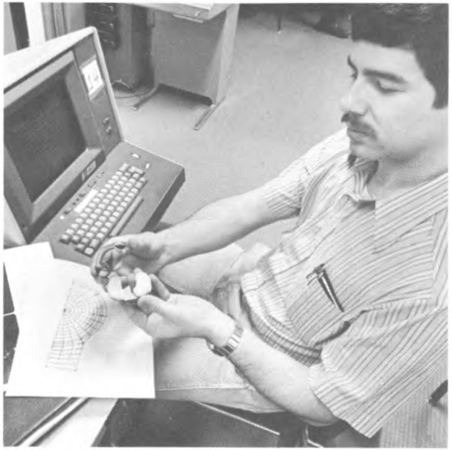
Biomechanical Engineering

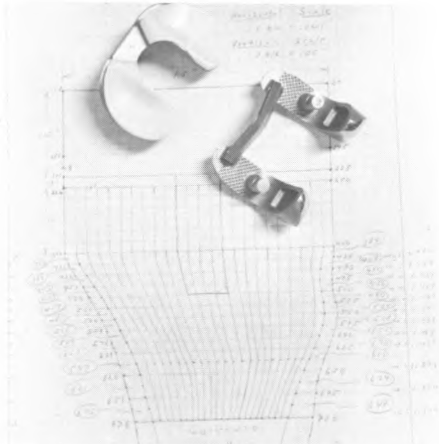
Research in the area of biomechanics is concerned with the analysis and design of biomechanical systems encountered in orthopedic surgery and rehabilitation medicine. The overall goal is to understand the structure and function of normal, impaired, and reconstructed components of the musculoskeletal system. Work is in progress on the analysis of locomotor disorders and the analysis and design of bone-implant systems and surgical procedures. Current projects are concerned with the determination of joint forces in statically indeterminate systems, the determination of the mechanical characteristics of tendons and ligaments, the design of fixation systems for internal artificial joints, the analysis and design of hip and knee prostheses, and the study of the mechanical aspects of degenerative joint disease.

Examples of recent publications and theses (listed with the name of the supervising professor) are:

Bartel, D. L. 1979. Theoretical modeling: stress analysis, the effect of geometry. In *Proceedings of the AAOS/NIH workshop on mechanical failure of total joint replacement*, ed. A. H. Burstein, p. 141. Chicago: American Academy of Orthopedic Surgeons.

The design of systems for injection molding of plastics is a joint project with industry for which Professor K.-K. Wang *(right)* is one of the principal investigators.





***Above:* A graduate researcher examines plastic and metal parts designed for a knee prosthesis in a project directed by Professor Donald L. Bartel.**

***Above right:* A stress distribution obtained by computer-aided analysis is used in specifying materials and dimensions.**

Bartel, D. L.; Schryver, H. F.; Lowe, J. E.; and Parker, R. A. 1978. Studies of locomotion in the horse. I. A procedure for computing the internal forces in the digit. *American Journal of Veterinary Research* 39(11):1721.

Drew, W. E. 1978. An investigation of seating systems for the prevention of decubitus ulcers. M.S. thesis (D. L. Bartel).

Loh, P. 1979. The determination of joint loads in statically indeterminate biomechanical systems. M.S. thesis (D. L. Bartel).

Santavicca, E. A. 1979. The analysis and design of tibial components for total knee replacement. M.S. thesis (D. L. Bartel).

M.Eng.(Mechanical) Degree Program

The Master of Engineering (Mechanical) degree program provides a one-year course of study for those who wish to develop a high level of competence in current technology and engineering design. The program is designed to be flexible so that candidates may concentrate on any of a variety of specialty areas. The M.Eng., M.S., and Ph.D. mechanical engineering degree programs at Cornell share areas of particular interest. These include bioengineering, machine dynamics and control, mechanical analysis and development, vehicles and propulsion, propulsion engines, energy systems, thermal environment, manufacturing engineering, and materials processing.

A coordinated program of courses for the entire year is agreed upon by the student and his or her adviser. It includes a six-credit design project, a major consisting of a minimum of twelve credits, and sufficient technical electives to meet the degree requirement of thirty credits. The courses that constitute the major must be graduate-level courses in mechanical and aerospace engineering or a closely related field such as theoretical and applied mechanics. At least twenty-one credits of the total required for the degree must be in mechanical engineering or related areas. The technical electives may be courses of appropriate level in mathematics, physics, chemistry, or engineering; a maximum of six credits may be taken in areas other than these if the courses are part of a well-defined program leading to specific professional objectives.

The design project, which may be undertaken individually or by a small team, is a significant part of the program. In most cases the project is engendered by a real need of an external organization or by an ongoing program within the University. It is intended to give experience in a situation similar to that of professional practice, in which there is a time limit, and the data available for the problem have to be sought and evaluated.

In the Sibley School of Mechanical and Aerospace Engineering there is overlapping

The construction of a racing bicycle for an attempt at a speed record was a project for M.Eng.(Mechanical) students.

faculty interest in design and research, and all the professors are available to supervise M.Eng. projects. Each student chooses a project from a list of those offered by the faculty or proposes a project and finds a faculty member who will agree to serve as adviser. Although "design" is interpreted broadly, the project should clearly involve the creation and evaluation of alternative solutions to an engineering problem.

Projects offered by faculty members in the past few years include:

Analysis and Design Considerations for Reducing the Vibrational Energy Losses through the Saddle of a Competition Bicycle (S. L. Phoenix, D. L. Taylor)
Cornell Environmental Wind Tunnel for the Testing of Structures Exposed to Atmospheric Winds (K. E. Torrance)
Design and Construction of a Temperature Control System for an Environmental Test Chamber (R. M. Phelan)
Design and Construction of a Testing Rig for Small Suspensions, Springs, and Shock Absorbers (D. L. Taylor)
Design and Evaluation of a Two-Stage Combustor for Emission Control (F. C. Gouldin)
Design of Cooling Lines for Injection Molding of Plastics (K.-K. Wang)
Design of Improved Methods for the Fixation of Implants to Bone (D. L. Bartel)
Design of Total Hip Replacement for Limb Salvage Procedures (D. L. Bartel)
Design of Two-Wheeled Vehicles and/or Trailers (D. L. Taylor)
Draft Enhancement by Vortex Generators (F. K. Moore)
Human Powered Speed Record Attempt Vehicle (A. R. George)
Impact Testing of Motorcycle Forks (D. L. Taylor)
Improvement of the Upson Hall Sun Tracking Control System (R. M. Phelan)
Inertia— Internal Combustion Engine Hybrid Drive for a Short-Range Car (R. L. Wehe)
The Problem of Self-Sufficiency and Electrical Power— Is There a Solution? (B. Conta)
Six-Degree-of-Freedom Displacement/Load Transducer (J. F. Booker)
Stress Analysis of Fittings for Tackle Blocks Used in Shipping (R. L. Wehe)
Thermal Design of a Spacecraft Component (K. E. Torrance)
Use of Cascade to Reduce Heat-Exchanger Loss (F. K. Moore)
Waste Heat Utilization (K. E. Torrance)
Wind Tunnel Equipment for Automotive Applications (A. R. George)

Faculty Members and Their Research Interests

Peter L. Auer, A.B. (Cornell), Ph.D. (California Institute of Technology): *plasma physics, fusion power, energy policy analysis*

C. Thomas Avedisian, B.S. (Tufts), S.M. (M.I.T.), Ph.D. (Princeton): *heat transfer, combustion, boiling dynamics*

Donald L. Bartel, B.S., M.S. (Illinois), Ph.D. (Iowa): *design optimization and reliability, computer-aided design, biomechanics*

John F. Booker, B.E. (Yale), M.A.E. (Chrysler Institute), Ph.D. (Cornell): *hydrodynamic lubrication, finite-element methods, computer-aided simulation and design*

David A. Caughey, B.S.E. (Michigan), A.M., Ph.D. (Princeton): *fluid dynamics, transonic flow, computational aerodynamics*

Bart J. Conta, B.S. (Rochester), M.S. (Cornell):*thermodynamics, thermal power, energy conversion*

Paul R. Dawson, B.S. (Montana State), Ph.D. (Colorado State): *materials and manufacturing engineering, finite-element methods, elastoplastic flows*

P. C. Tobias de Boer, Ir.(M.E.) (Delft), Ph.D. (Maryland): *combustion processes, alternative fuels for combustion engines, high-temperature gasdynamics*

Albert R. George (Director of the School of Mechanical and Aerospace Engineering), B.S.E., A.M., Ph.D. (Princeton): *fluid dynamics, acoustics and noise control, turbulence*

Frederick C. Gouldin, B.S.E., Ph.D. (Princeton): *fluid dynamics, combustion, air pollution*

Sidney Leibovich, B.S. (California Institute of Technology), Ph.D. (Cornell): *fluid dynamics, wave propagation, air-sea interactions*

John L. Lumley, B.A. (Harvard), M.S.E., Ph.D. (Johns Hopkins): *fluid dynamics, turbulence and turbulence modeling, geophysical turbulence, stochastic processes*

Franklin K. Moore, B.S., Ph.D. (Cornell): *fluid dynamics, energy systems, thermal pollution*

Richard M. Phelan, B.S.M.E. (Missouri), M.M.E. (Cornell): *mechanical design, vibration, controls, lubrication*

S. Leigh Phoenix, B.Sc., M.Sc. (Guelph), Ph.D. (Cornell): *mechanical reliability, probabilistic theories of material failure, composite materials*

Edwin L. Resler, Jr., B.S. (Notre Dame), Ph.D. (Cornell): *high-temperature gasdynamics, pollution control, ferrofluid mechanics*

Shan-Fu Shen, B.S. (National Central, China), Sc.D. (M.I.T.): *aerodynamics, computational fluid mechanics, polymer processing*

Dennis G. Shepherd, B.Sc. (Michigan): *fluid mechanics, turbo machinery, thermal and wind power*

Dean L. Taylor, B.S. (Oklahoma State), M.S., Ph.D. (Stanford): *vibrations, dynamics, mechanical systems and analysis, vehicle dynamics, computer methods*

Kenneth E. Torrance, B.S., M.S.M.E., Ph.D. (Minnesota): *heat transfer, computational fluid mechanics, geophysical heat transfer*

Kuo-King Wang, B.S.M.E. (National Central, China), M.S.M.E., Ph.D. (Wisconsin): *manufacturing engineering, materials processing*

Zellman Warhaft, B.E. (Melbourne), Ph.D. (London): *experimental fluid mechanics, turbulence, micrometeorology*

Robert L. Wehe, B.S. (Kansas), M.S. (Illinois): *lubrication, product and component design*

Further Information

Further information about the M.S. and Ph.D. degree programs may be obtained by writing to the Graduate Faculty Representative, Mechanical Engineering, Sibley School of Mechanical and Aerospace Engineering, Cornell University, Upson Hall, Ithaca, New York 14853. Requests for further information about the M.Eng.(Mechanical) degree program may be addressed to the Faculty Representative, Master of Engineering (Mechanical) Program, at the same address.

Nuclear Science and Engineering

Nuclear science and engineering is concerned with the understanding, development, and application of the science of nuclear reactions and radiations. The graduate programs at Cornell allow specialization in basic nuclear science, in applied nuclear engineering, or in a combination of the two. Minors may be chosen in a variety of other engineering or science fields.

A planned broadening of the nuclear science and engineering program is under way with the addition of new faculty members in the area of fusion technology. This developing area bridges conventional nuclear engineering and research in plasma physics, a field in which Cornell has an international reputation. Applicants who have a potential interest in this new aspect of the program should inquire for additional, updated information.

Three graduate degree programs are offered. The Master of Engineering (Nuclear) is a professional degree; the Master of Science and the Doctor of Philosophy degrees are intended for those who plan to pursue research or teaching careers. Degree program requirements and course offerings are described fully in two other publications that may be obtained upon request: *Announcement of the Graduate School* and *Courses of Study*. Only a brief summary is provided here.

The M.Eng.(Nuclear) degree program is intended primarily for individuals who want a terminal professional degree, but it may also serve as preparation for doctoral study in nuclear science and engineering. The two-term curricular program covers the basic principles of nuclear reactor systems and places major emphasis on reactor safety and radiation protection and control. There is a growing need in the nuclear industry for engineers who have a thorough knowledge of these safety provisions and who are able to apply it to the design of reactor plants and auxiliary equipment and to the implementation of environmental monitoring systems. Required courses treat reactor safety and radiation protection and control in depth; an elective course in environmental radioactivity and an elective seminar in physical biology are available. The recommended background includes a baccalaureate degree or its equivalent in engineering or applied science; physics, including atomic and nuclear physics; mathematics, including advanced calculus; and thermodynamics. Students should have fulfilled these requirements before beginning the program. In some cases, deficiencies in preparatory work may be made up by informal study during the preceding summer.

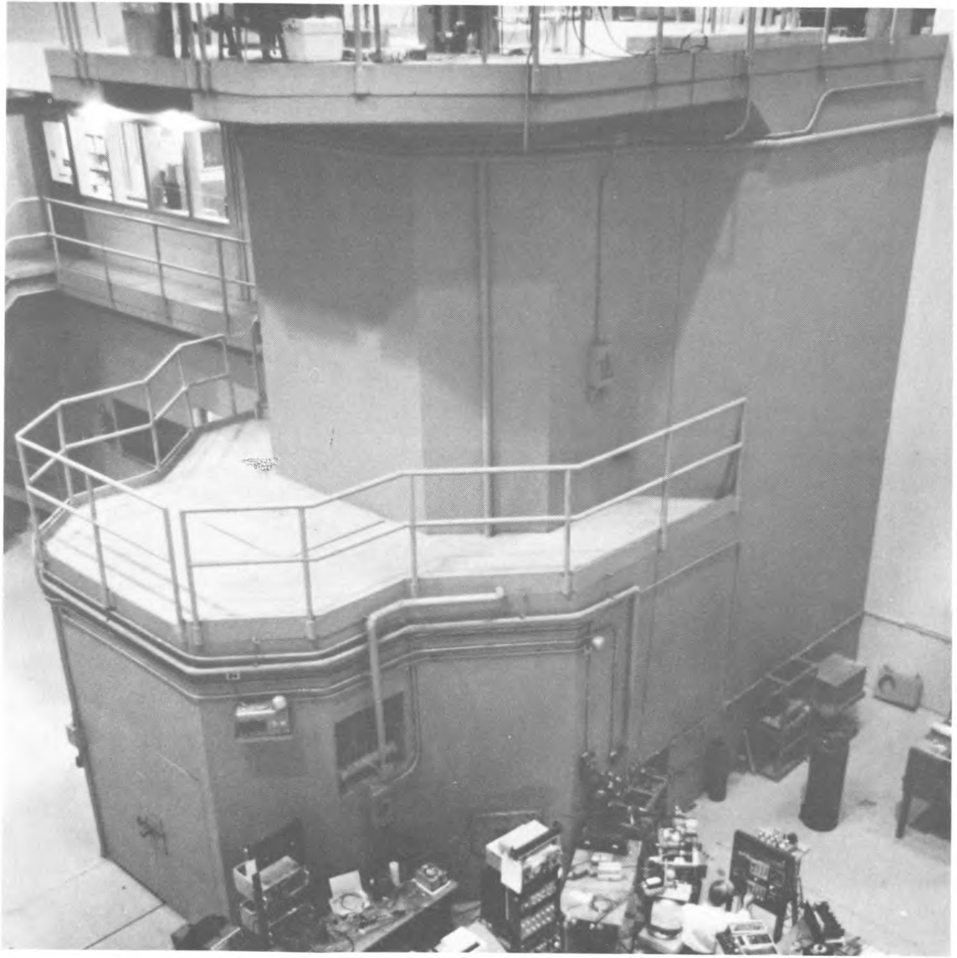
The M.S. and Ph.D. programs are oriented toward research and require completion of a thesis as well as course work. Candidates for one of these degrees choose either nuclear science or nuclear engineering as their major subject; because each student plans an individual program in consultation with the faculty members on her or his special committee, there are no detailed degree requirements. This approach, long a tradition of graduate study at Cornell, is well suited to interdisciplinary fields such as nuclear science and engineering. Minor subjects may be in any related engineering or science field. Independent thesis research and formal and informal interactions with staff members and other students are vital parts of the program.

The appropriate preparation for graduate work in these programs is an undergraduate education in science, applied science, or engineering, with special emphasis on mathematics and modern physics.

Facilities

The Ward Laboratory of Nuclear Engineering is the major facility at Cornell for graduate research and teaching in reactor physics and engineering, low-energy nuclear structure physics, and nuclear and radiation chemistry. The following primary facilities are housed in the laboratory:

A TRIGA reactor, which has a steady-state power of 500 kilowatts and a pulsing capability of up to 1,000 megawatts. The reactor is a source of neutrons and gamma rays for activation analysis, solid-state studies, and research in nuclear physics. In addition to standard pneumatic and mechanical transfer systems, the reactor has a 40-millisecond rapid transfer mechanism that allows study and use of radionuclides having a relatively short half-life. A special feature that is not available in other university research reactors in the United States is a neutron guide tube, which operates through the total reflection of neutrons by nickel layers on glass substrates. This guide tube provides a strong slow-neutron flux with almost no fast-neutron and gamma components. The resultant combination of



Cornell's TRIGA reactor, a source of neutrons and gamma rays, is located in the Ward Laboratory of Nuclear Engineering.

intense beam and low background permits a variety of otherwise unfeasible experiments in nuclear physics and in chemical analysis. The guide tube, 11 meters long and 2 by 5 centimeters in cross section, is installed at one of the TRIGA's beam ports.

A critical facility, or "zero-power" reactor, of versatile design. This facility, unique to Cornell among universities, is used for basic studies in reactor physics and dynamics. Auxiliary equipment includes a pulsed 14-MeV neutron generator used for studies of reactor transients.

A shielded gamma cell with a 10,000-curie ^{60}Co gamma ray source. This is used for studies of radiation chemistry and radiation damage. Experimental versatility is facilitated by a viewing window and remote manipulators.

A 3-MV Dynamitron, or positive ion accelerator, with a beam current of up to 2.5 mA. This is used for studies of atomic and nuclear structure and of high-intensity radiation damage. A lithium target capable of power dissipation approaching 10,000 watts per square centimeter has been developed for use in controlled-energy neutron production.

Other special items of equipment in the Ward Laboratory include three minicomputers that supplement the University's computing system, which includes a central machine, satellite stations, and teletypewriter terminals. Special facilities of other departments are also available for research in nuclear science and engineering.

The core of the TRIGA is twenty feet under water.

Areas of Research

Because of the wide range of available facilities, thesis research may be undertaken in any of several major areas. Research subjects in *nuclear science* include low-energy nuclear structure physics, the interaction of atomic and nuclear processes, synchrotron radiation studies using the Cornell 8-GeV electron storage ring, nuclear geochemistry and cosmochemistry, and activation analysis. Subject areas in *nuclear engineering* include nuclear environmental engineering, reactor plant dynamics and safety, experimental and analytical reactor physics, neutron transport theory, radiation effects on materials (including fast-neutron damage), and radiation protection and control. Another area is *fusion physics and technology,* which includes inertial confinement by ion beams and first-wall effects of fast hydrogen isotopes, both charged and neutral. Some of the current projects are described below.

Nuclear Reactor Engineering

A current research project is to develop models and computer codes for analyzing fast-reactor plant accidents and transients. Another project involves probabilistic safety analysis of nuclear systems.

Graduate research is represented by the following publications and theses (listed with the supervising professor):

Cady, K. B., and Raber, J. R. 1980. EPRI-CURL dynamic analysis of pool type LMFBRs. Electric Power Research Institute report no. NP-1001.

Kenton, M. A. 1981. A general sensitivity theory for reactor plant systems. Ph.D. thesis (K. B. Cady).

Khatib-Rahbar, M., and Cady, K. B. 1981. Dynamic models and numerical simulations of system-wide transients in loop-type LMFBRs. *Journal of Nuclear Engineering and Design* (in press).

Mitra, S. 1979. Stochastic models and reliability parameter estimation applicable to nuclear power plant safety. Ph.D. thesis (K. B. Cady).

Fission Reactor Physics

Basic research in the kinetics of the neutron chain reaction is carried out in conjunction with the studies of reactor-plant dynamics discussed above. The Cornell critical facility is used for most of the experimental work in basic reactor physics. One example of research is the measurement of neutron importance functions; another is the measurement and interpretation of neutron density waves propagating through multiplying media. Because the critical facility is of very flexible design, a variety of cores of different shapes, sizes, and water-to-fuel ratios can be investigated. It is a unique educational tool for acquiring an operational understanding of nuclear reactor cores.

A paper that provides a good representation of work in this area is:

Greenspan, E., and Cady, K. B. 1970. The measurement of neutron importance functions. *Journal of Nuclear Energy* 24:529.

Right above: A recent project in which two M.Eng.(Nuclear) students combined efforts was the conceptual design of a fast-reactor park in which various facilities needed for a complete nuclear power generating plant would be centralized.

Right: A group of students inspects the zero-power reactor core in the Ward Laboratory of Nuclear Engineering.

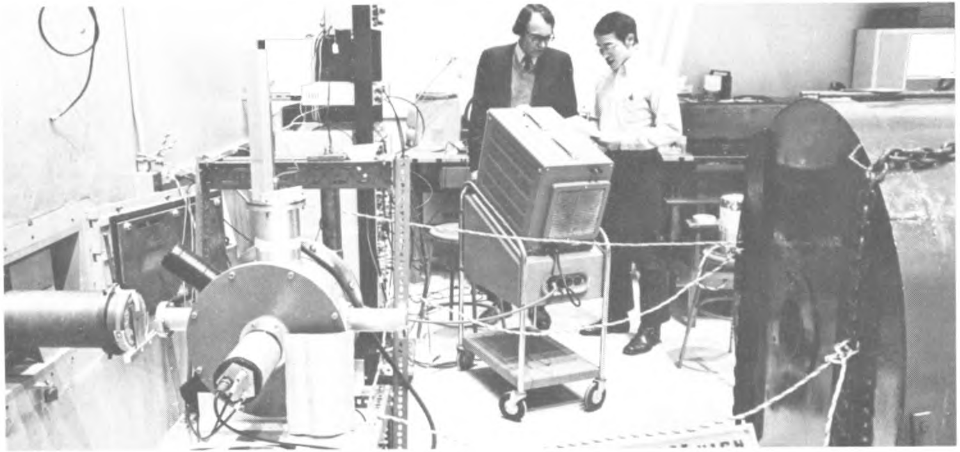
Nuclear Materials Research

The economic and orderly development of fast-reactor and fusion-reactor technology requires an understanding of radiation-induced swelling and creep and of the effect of radiation on mechanical properties. An example of research in this area that has been done at Cornell is the development of a theory of void coalescence and growth that accounts for the observed swelling and decrease in void density of stainless steels at low doses and that predicts behavior at high doses.

Two publications based on this research are:

Mancuso, J. F.; Huang, F. H.; and Li, C.-Y. 1975. The growth of grain boundary cavities under applied stress and irradiation. In *Fundamental aspects of radiation damage in metals*, vol. II, p. 1279. DOE report CONF-751006-P2.

Mansur, L. K.; Okamoto, P. R.; Taylor, A.; and Li, C.-Y. 1976. *Surface-reaction-limited void growth*. ASTM special technical publication no. 570.



Equipment for experimental work with the TRIGA is set up near one of the reactor's six beam ports. Professor David D. Clark works with a graduate student.

Low-Energy Nuclear Physics

Among projects now under way in this area is an experimental study of isomeric (metastable) excited states in nuclei. Several high-spin isomers have been discovered at Cornell using the TRIGA reactor and the fast-transfer system.

Theoretical and experimental research at various laboratories in the last decade led to the hypothesis of shape isomerism, which is described in an article in *Physics Today* (December 1971) by D. D. Clark. The phenomenon, which is widespread among elements of atomic number 92 and higher, is due to a double hump in the fission barrier. Nuclei in the isomeric state are "stretched" into a cigarlike shape, with the polar axis almost twice the equatorial diameter. Experiments designed to measure the degree of "stretch" and other properties such as the expected decay of the isomer by modes other than fission are under way, using neutrons from the guide tube at the TRIGA reactor. A new type of detector—the inner-shell-vacancy (ISV) detector—was conceived and developed at Cornell in order to make feasible a key series of shape-isomer experiments using reactor neutron beams.

Prompt gamma rays emitted in neutron capture are also being studied in the low background conditions afforded by the neutron guide tube. These gammas are important clues to nuclear structure. A related application is chemical analysis by prompt gamma spectroscopy. This method, which is as yet incompletely developed, is particularly suitable for hydrogen and other light elements for which activation analysis is not possible.

Another project is an investigation of short-lived mass-separated fission products. This work is carried out at Brookhaven National Laboratory in collaboration with Gertrude S. Goldhaber, adjunct professor of nuclear science and engineering. It has two phases. One is to determine properties of yrast bands in near-magic even-even neutron-rich unstable nuclides to complement existing systematics for proton-rich nuclides. The other is to measure delayed neutron energy spectra in the range of 1 to 100 keV. The experiments are conducted at the high flux beam reactor with the mass separator TRISTAN, which provides on-line sources of fission products from ^{235}U. Yrast bands are deduced from gamma, beta-gamma, and gamma-gamma data taken with Ge(Li) and plastic detectors. Neutron data are obtained from time-of-flight measurements using plastic beta and ^{6}Li glass neutron detectors with high resolution over a path of 50 to 100 centimeters. The band experiments are expected to result in improvements in microscopic models, such as one for the variable moment of inertia. The neutron experiments provide energy spectra and neutron emission probabilities in an almost unexplored energy region; these results can be useful in reactor kinetics calculations. Neutron widths will be obtained in some cases; these will be used to deduce cross sections for the inverse process of keV neutron capture on

Students work in the control room of the zero-power reactor.

unstable neutron-rich nuclides. These cross sections, which are of considerable interest in astrophysics, are impossible to measure by direct methods.

Examples of recent publications in the area of low-energy nuclear physics are:

Clark, D. D.; Boyce, J. R.; Cassel, E. T.; and McGuire, S. C. 1979. Low-lying levels of ^{236}U from investigation of the two-quasineutron isomer in neutron capture experiments. In *Proceedings of 3d international symposium on neutron capture gamma-ray spectroscopy and related topics* (held September 1978, at Brookhaven National Laboratory).

Clark, D. D.; Kostroun, V. O.; and Siems, N. E. 1975. Identification of an isomer in Ag-110 at 1-keV excitation energy. *Physical Review C* 12:595.

Clark, D. D.; McGuire, S. C.; and Cassel, E. T. 1979. Anomalous features of the $K^{\pi} = 0^{-}$ band in ^{236}U. *Bulletin of the American Physical Society* 24:686.

Atomic Processes in Controlled Thermonuclear Fusion

Atomic and molecular processes relevant to fusion can be categorized broadly as those essential to the operation of a fusion device and those pertinent to diagnostics. Examples in the first category include those processes related to energy and particle losses from plasmas, introduction and elimination of impurities, damage to confining chambers and recycling of contaminants, heating of plasma by energy feedback mechanisms, and refueling of the plasma. Processes in the second category are those necessary for the interpretation of particle probe and spectroscopic data.

Many of the processes are difficult to investigate experimentally because they involve highly ionized ions, and suitable sources of such ions (apart from the plasma itself) are not available generally. A program to investigate fundamental atomic processes of interest in astrophysical and laboratory plasmas has recently been initiated. An electron beam ion source (EBIS) will be used to generate ions with multiple charges by successive electron bombardment of ions trapped in the space charge potential of an intense (100 ampere/cm^2) magnetically confined (2–10 keV) electron beam. The source currently under construction will generate ions of the light elements in all stages of ionization, including bare nuclei, at kinetic energies of the order of 1 keV per nucleon or less. Crossed-beam experiments in conjunction with soft x-ray, electron, and charge spectroscopy will be used to deduce electron ionization and charge transfer cross sections, dielectronic recombination rates, and other quantities.

Nuclear Geochemistry and Activation Analysis

Research in multielement trace analysis of geological, metallurgical, solid-state, biological, and environmental materials by neutron activation techniques is carried out with the TRIGA reactor. Other analytical methods such as ion microprobe techniques, spark-source mass spectrometry, and atomic spectroscopy are also employed.

Examples of papers in this area are:

Morrison, G. H. 1978. Mass spectrometric methods for trace elements in biological materials. In *Proceedings of international symposium on nuclear activation techniques in the life sciences*. Vienna: International Atomic Energy Agency.

Nadkarni, R. A., and Morrison, G. H. 1976. Neutron activation determination of noble metals using a selective group separation scheme. In *Modern trends in activation analysis, proceedings of 5th international conference* (Munich), vol. II, pp. 1057.

——. 1978. Multielement analysis of lake sediments by neutron activation analysis.

Analytica Chimica Acta 99:133.
——. 1978. Use of standard reference materials as multielement irradiation standards in neutron activation analysis. *Journal of Radioanalytical Chemistry* 43:347.

Fusion Physics and Technology

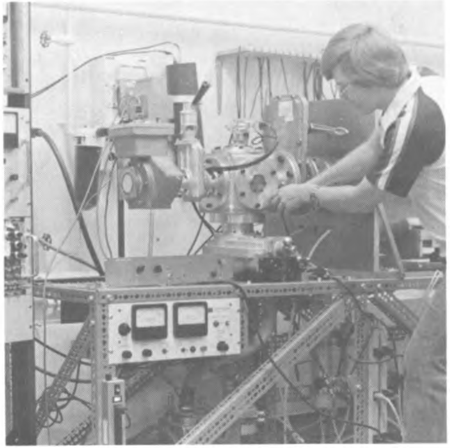
The scientific feasibility of fusion power is likely to be demonstrated within the next few years; at Cornell there is a program in fusion technology that complements the strong plasma physics program.

Most of the plasma physics research at Cornell is conducted through the Laboratory of Plasma Studies, which coordinates and facilitates the work of faculty members from several graduate fields, including Applied Physics, Electrical Engineering, Mechanical Engineering, Aerospace Engineering, and Nuclear Science and Engineering. Ongoing research related to controlled fusion includes both theoretical and experimental work in plasma confinement and heating, particularly with the use of relativistic electron beams and ion beams. Cornell is recognized as the leading university in the production and application of these beams to controlled fusion. Specific projects now under way are concerned with the production of magnetic-field configurations particularly suited for plasma confinement by electron and ion beams, and the use of ion beams for inertial confinement fusion. Members of the graduate Field of Nuclear Science and Engineering who direct work in this area are H. H. Fleischmann and D. A. Hammer.

Fusion technology combines conventional nuclear engineering with knowledge about plasma physics and with other technologies, such as that of superconducting magnet systems, that may be required for the development of fusion reactors. For example, design features based on such standard nuclear engineering considerations as neutron transport and radiation-induced material damage must be incorporated into a fusion-reactor design in such a way as to be compatible with the physics of the reacting plasma.

The reduction of impurities resulting from plasma-surface interactions is another important research area in fusion technology. At Cornell's Ward Laboratory, researchers led by V. O. Kostroun are investigating interactions of low-energy charged and neutral hydrogen isotopes with surfaces of candidate first-wall materials. Processes such as backscattering, sputtering, and the release of trapped hydrogen from surfaces are being studied under conditions that duplicate as closely as possible those occurring in actual devices. A low-energy particle accelerator combined with a unique angle-resolved time-of-flight mass spectrometer permits the acquisition of real-time data.

Among the facilities available for research in fusion physics and technology are the nuclear reactors and radiation sources previously described, as well as a variety of magnetic-confinement systems and intense-particle-beam generators. The latter category includes pulsed-power generators with powers from 10^{10} to 5×10^{11} watts for pulse durations of 10^{-7} seconds. Electron beams of 10^{11} watts and proton beams in excess of 10^{10} watts are routinely produced by these generators.



A low-energy particle accelerator, developed for first-wall studies in fusion reactors, provides the basis for a doctoral thesis project under the direction of Professor Vaclav O. Kostroun.

The following papers are among those recently published in the area:

Book, D. L.; Hammer, D. A.; and Turchi, P. J. 1978. Theoretical studies of the formation and adiabatic compression of reversed-field configurations in imploding liners. *Nuclear Fusion* 18:159.
Davis, H. A.; Rej, D. J.; and Fleischmann, H. H. 1977. Production of field reversing electron rings by ring stacking. *Physical Review Letters* 39:744.

Fleischmann, H. H., and Kammash, T. 1975. The ion ring compressor approach to fusion. *Nuclear Fusion* 15:1143.

Hammer, D. A., and Papadopoulos, K. 1975. Tokamak heating by relativistic electron beams. *Nuclear Fusion* 15:977.

Kostroun, V. O.; Janson, S. W.; and Hammer, D. A. 1979. A low energy neutral beam first-wall interaction experiment. In *IEEE proceedings of 8th symposium on engineering problems of fusion research*, p. 1850.

Faculty Members and Their Research Interests

Faculty members in a number of University departments are engaged in research programs that place a major emphasis on nuclear science and engineering. The following list of faculty members in the graduate Field of Nuclear Science and Engineering, their department or other University affiliations (in parentheses), and their areas of interest related to this field indicates the scope of research that can be undertaken:

K. Bingham Cady (Nuclear Science and Engineering, and Applied and Engineering Physics), B.S., Ph.D. (M.I.T.): *nuclear engineering, nuclear environmental engineering, nuclear reactor physics*

Alison P. Casarett (Physical Biology), B.S. (St. Lawrence), M.S., Ph.D. (Rochester): *radiation biology, physical biology*

David D. Clark (Nuclear Science and Engineering, and Applied and Engineering Physics), A.B., Ph.D. (California, Berkeley): *nuclear structure physics, nuclear instrumentation, radiation measurement*

Hans H. Fleischmann (Applied and Engineering Physics), Dipl.Phys., Dr.rer.nat. (Technical University, Munich): *thermonuclear power, plasma physics*

Charles D. Gates (Civil and Environmental Engineering), B.A. (Williams), M.S. (Harvard): *nuclear environmental engineering*

David A. Hammer (Nuclear Science and Engineering), B.S. (California Institute of Technology), Ph.D. (Cornell): *plasma physics and controlled fusion*

Bryan L. Isacks (Geological Sciences), A.B., Ph.D. (Columbia): *seismological aspects of nuclear power siting*

Vaclav O. Kostroun (Nuclear Science and Engineering, and Applied and Engineering Physics), B.Sc., M.Sc. (Washington), Ph.D. (Oregon): *interaction of radiation and matter, atomic physics, nuclear structure physics*

Che-Yu Li (Materials Science and Engineering), B.S.E. (Taiwan College of Engineering), Ph.D. (Cornell): *nuclear materials, fast-neutron damage*

Simpson Linke (Electrical Engineering), B.S., M.E.E. (Cornell): *energy conversion and transmission*

Franklin K. Moore (Mechanical and Aerospace Engineering), B.S., Ph.D. (Cornell): *thermal engineering, energy conversion*

George H. Morrison (Chemistry), B.A. (Brooklyn College), M.A., Ph.D. (Princeton): *nuclear geochemistry and cosmochemistry, activation analysis*

Mark Nelkin (Applied and Engineering Physics), B.S. (M.I.T.), Ph.D. (Cornell): *neutron scattering and transport*

James S. Thorp (Electrical Engineering), B.E.E., M.S., Ph.D. (Cornell): *systems engineering, controls*

Robert L. Von Berg (Chemical Engineering), B.S., M.S. (Washington), Sc.D. (M.I.T.): *radiation chemistry*

Additional faculty members available as advisers for M.Eng.(Nuclear) projects are:

Peter Gergely (Structural Engineering), P.E.; B.Eng. (McGill), M.S., Ph.D. (Illinois): *seismic engineering*

John C. Thompson, Jr. (Physical Biology), B.S., M.S. (Virginia Polytechnic Institute), Ph.D. (Cornell): *radiation biology, physical biology*

Richard N. White (Structural Engineering), P.E.; B.S., M.S., Ph.D. (Wisconsin): *nuclear structural engineering*

Further Information

Further information about the M.S. and Ph.D. degree programs may be obtained by writing to the Graduate Faculty Representative, Nuclear Science and Engineering, Cornell University, Ward Laboratory of Nuclear Engineering, Ithaca, New York 14853. Requests for further information about the M.Eng.(Nuclear) degree program may be addressed to the Faculty Representative, Master of Engineering (Nuclear), at the above address.

Operations Research

Three graduate degree programs in operations research are offered at Cornell: Ph.D. and M.S. programs in operations research, which allow concentration in the areas of applied probability and statistics, industrial and systems engineering, and optimization; and a one-year program leading to the professional degree of Master of Engineering (OR&IE). These are distinct programs, each tailored to specific career needs as well as to the overall preparation of the students.

About seventy-five full-time graduate students, including thirty from foreign countries, are currently registered in these programs. Approximately one-third of the students hold undergraduate degrees in mathematics; the others majored in engineering or other sciences.

In the Ph.D. and M.S. programs the problem areas and techniques of operations research are approached from a highly analytical viewpoint. Theories and techniques from mathematical programming (linear, nonlinear, dynamic, and probabilistic), combinatorics, the theory of games, stochastic processes (queuing and inventory), scheduling, and simulation are developed and used extensively. Consideration is given to the construction of appropriate mathematical models to represent various real-life operational systems and to the development of techniques for analyzing the performance of these models. Each student pursues a course of study and research that emphasizes the use of the mathematical, probabilistic, statistical, and computational sciences. The ultimate goal may range from making a fundamental contribution to the techniques of operations research to applying techniques to problems in diverse fields.

Detailed descriptions of the three areas of concentration are given below.

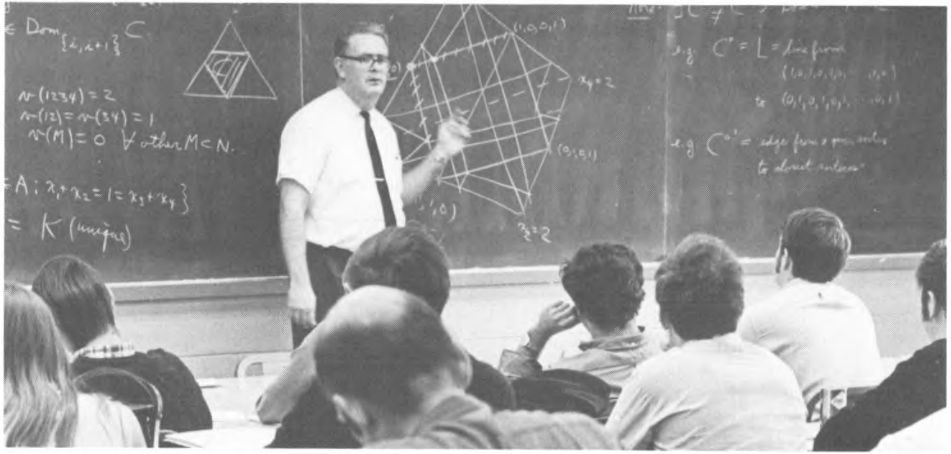
Applied Probability and Statistics

This area of study and research is appropriate for students whose primary interest is in the techniques and associated underlying theory of probability and statistics, particularly as applied to problems arising in science and engineering. The techniques emphasized are those associated with applied stochastic processes (for example, queuing theory, traffic theory, and inventory theory) and statistics (including statistical decision theory; the statistical aspects of the design, analysis, and interpretation of experiments and of ranking and selection theory; reliability theory; and analysis of life data).

Those who elect to work in this area are expected to acquire considerable knowledge of the theory of probability and statistics. All students who major in applied probability and statistics are required to have the equivalent of a minor in mathematics.

Industrial and Systems Engineering

The analysis and design of complex operational systems are the central concerns in this area. Problems occurring throughout modern society are considered. These include manufacturing problems, such as the design of integrated production, the establishment of inventory and distribution systems, plant



design, and economic analysis of engineering processes. Problems connected with government, banking, and public-service administration are also major subjects of study and research.

Students who specialize in this area are expected to have the ability to use modern analytical techniques in the design and analysis of systems; they need to acquire an understanding of inventory theory, scheduling theory, queuing theory, mathematical programming, computer science, and computer simulation. Research activity may involve the development of new methodology or the synthesis of existing knowledge.

Optimization

Work in optimization traditionally consists of linear, nonlinear, integer, and combinatorial programming (including network flows and scheduling theory). Research in these areas ranges from the development and application of computational algorithms (exact and approximate) to the associated studies of duality theory, convex analysis, fixed-point techniques, polyhedra, combinatorics, and graph theory. Another aspect is game theory — the general study of conflict and cooperation — which includes consideration of the properties of solutions and applications in

***Left above:* Professor William Lucas lectures on game theory.**

***Left below:* Graduate students discuss class problems with Professor Howard Taylor.**

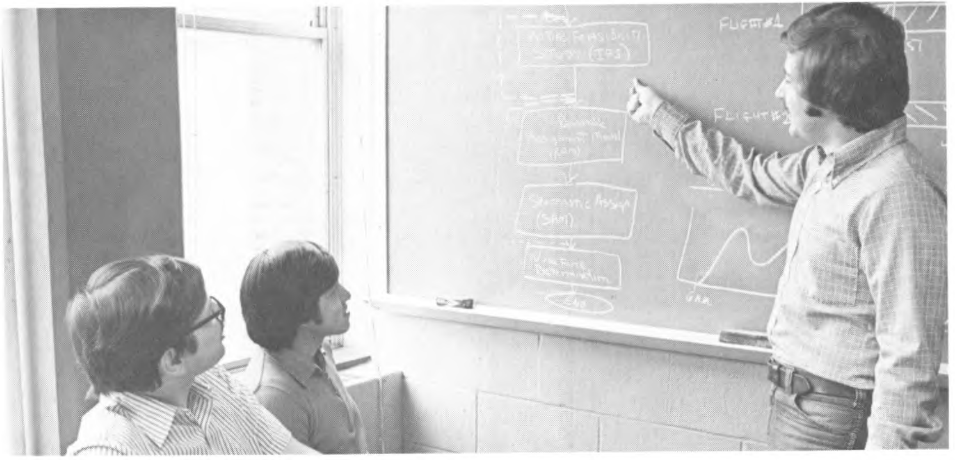
economic market theory, bidding and auctions, cost-allocation schemes, and voting procedures.

Minor Subject Areas

In addition to choosing a major subject, a candidate for the M.S. or Ph.D. degree selects a minor, which may be in operations research or in a subject offered by another field of the Graduate School. Appropriate minors that have been chosen most frequently in recent years (listed with the departments or schools that offer these courses of study) are computer science (Computer Science), econometrics and economic statistics (Economics), public systems planning and analysis (Civil and Environmental Engineering), managerial economics (Business and Public Administration), mathematics (Mathematics), and planning theory and systems analysis (City and Regional Planning).

Areas of Research

A research project is an important part of the program for all M.S. and Ph.D. degree candidates. Because the research is begun at an early stage, candidates who plan to seek



Right above: **Graduate students indicate for Professor George Nemhauser *(center)* the results of a computing project using the graphic display feature of the OR&IE microcomputer.**

Right below: **Graduate students discuss their project work with Professor John Muckstadt *(left)*.**

the doctorate are encouraged to apply for a Ph.D. program at the outset.

The range of research opportunities is suggested by the projects currently under way (sponsoring institutions are in parentheses):

An Analysis of an Inventory System for Interchangeable Recoverable Items (Air Force)

Automated Factory Control (National Science Foundation)

Component Management (Office of Naval Research)

The Cooperative Theory of Behavior and Its Applications (Office of Naval Research)

Investigations in Discrete Optimization (National Science Foundation)

Multiperson Cooperative Game Theory (National Science Foundation)

Multiple-Decision Ranking and Selection (Army Research Office)

Non-Gaussian Self-similar Processes (National Science Foundation)

RDF and Hydro Power Programs (New York State Electric and Gas)

Reliability of Load-sharing Structural and Material Systems (National Science Foundation)

Special Structure in Simplicial Algorithms (National Science Foundation)

Statistical Analysis of Life Data from Engineering and Related Systems (National Science Foundation)

Statistical Engineering (Office of Naval Research)

Statistical Methods for Environmental Health Studies (National Institute of Environmental Health Sciences)

Above: **Professors Michael Todd, Leslie Trotter, and Louis Billera *(left to right)* discuss a research project in their specialty area of combinatorial optimization.**

Right: **Visiting specialists such as Professor S. S. Gupta from Purdue *(center)* frequently speak at colloquia. At the right is Cornell professor Thomas Santner.**

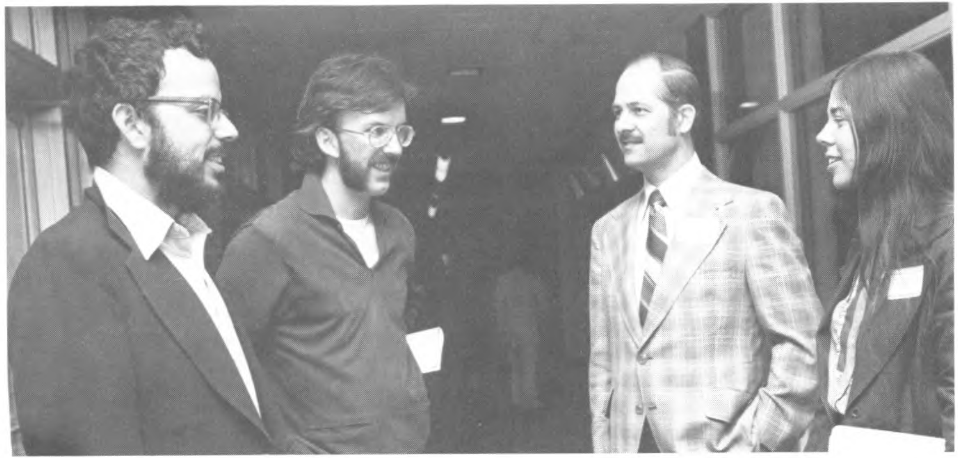
Studies in Linear Programming (National Science Foundation)

Topics in Combinatorial Optimization and Its Applications (National Science Foundation)

Some books and recent research papers by faculty members are:

Bechhofer, R. E., and Tamhane, A. C. 1981. Incomplete block designs for comparing

treatments with a control: General theory. *Technometrics* (in press).
Billera, L. J., and Lee, C. W. 1980. Sufficiency of McMullen's conditions for f-vectors of simplicial polytopes. *Bulletin of the American Mathematical Society* (new series) 2(1):181.
Bland, R. G., and Las Vergnas, M. 1979. Minty colorings and orientations of matroids. *Annals of the New York Academy of Sciences* 319:86.
Cornuejols, G.; Fisher, M.; and Nemhauser, G. L. 1977. Location of bank accounts to optimize float: An analytic study of exact and approximate algorithms. *Management Science* 23(8):789.
Dantzig, G. B., and Jackson, P. L. 1980. Pricing underemployed capacity in a linear economic model. In *Variational inequalities and complementarity problems: Theory and applications,* ed. R. W. Cottle, F. Giannessi, and J.-L. Lions, p. 127. Chichester, Great Britain: Wiley.
Garfinkel, R., and Nemhauser, G. L. 1972. *Integer programming.* New York: Wiley.
Giles, F. R.; Oyama, T.; and Trotter, L. E., Jr. 1980. Related necessary conditions for completing partial latin squares. *Journal of Combinatorial Theory (A)* 29(1):20.
Heath, D. C. 1978. On finitely additive priors, coherence, and extended admissibility. *Annals of Statistics* 6:333.
Karlin, S., and Taylor, H. M. 1980. *A second course in stochastic processes.* New York: Academic Press.
Lucas, W. F. 1977. Game theory. In *Encyclopedia of computer science and technology,* vol. 8, ed. J. Belzer, A. G. Holtzman, and A. Kent, p. 363. New York: Marcel Dekker.
Maxwell, W. L., and Wilson, R. C. 1980. Dynamic network flow modelling of fixed path material handling systems. *AIIE Transactions* (in press).



Nearly half of Cornell's Ph.D. alumni in operations research attended a recent anniversary reunion and conference on campus. Among those present were *(left to right)* Robert Rovinsky, a mathematical analyst with the U.S. Department of Agriculture; Stephen Kennedy, faculty member at San José College; William Costello of the Sidney Farber Cancer Center, a coordinator of multiclinic cancer trials; and Ellen Cherniavsky, an energy analyst at the Brookhaven National Laboratories.

Muckstadt, J. A., and Thomas, L. J. 1980. Are multi-echelon inventory methods worth implementing in systems with low-demand-rate items? *Management Times* 26(5):483.
Prabhu, N. U. 1980. *Stochastic storage processes.* New York: Springer-Verlag.
Santner, T. J., and Snell, M. K. 1980. Small sample confidence intervals for $p_1 - p_2$ and p_1/p_2 in 2 × 2 contingency tables. *Journal of the American Statistical Association* 75:386.
Schruben, L. W. 1980. Control of initialization bias in multivariate simulation response. *Communications of the Association for Computing Machinery* (in press).
Taqqu, M. S. 1979. Convergence of integrated processes of arbitrary Hermite rank. *Zeitschrift fur Wahrscheinlichkeitstheorie und verwandte Gebiete* 50(1):53.

Todd, M. J. 1976. *The computation of fixed points and applications.* Berlin-Heidelberg: Springer-Verlag.
Todd, M. J. 1980. Traversing large pieces of linearity in algorithms that solve equations by following piecewise-linear paths. *Mathematics of Operations Research* 5(2):242.
Turnbull, B. W., and Mitchell, T. J. 1979. Log-linear models in the analysis of disease prevalence data from survival/sacrifice experiments. *Biometrics* 35:221.
Wade-Smith, J.; Richmond, M.; and Taylor, H. M. 1980. Hormonal and gestational evidence for delayed implantation in the striped skunk, *Mephitis mephitis*. *General and Comparative Endocrinology* (in press).
Weiss, L. I. 1980. The asymptotic sufficiency of sparse order statistics in tests of fit with nuisance parameters. *Naval Research Logistics Quarterly* 27(3):397.

An idea of the research conducted by graduate students, and of their employment after receiving their degrees, may be obtained from the following list of recent Ph.D. recipients. The place of employment, the thesis topic, and the supervising professor are given for each graduate.

R. R. Barton: Mathtech, Mathematica, Inc., Princeton, N. J. Regression models for grouped censored survival data with an application to exoffender post release performance evaluation (B. W. Turnbull).

G. Cornuejols: Graduate School of Industrial Administration, Carnegie-Mellon University, Pittsburgh, Pa. Analysis of algorithms for a class of location problems (G. L. Nemhauser).

Frank H. T. Rhodes *(right)*, president of Cornell, and Charles W. Lake, Jr. *(center)*, a member of the Engineering College Council, congratulate Professor Andy Schultz *(left)* on the Andrew Schultz, Jr., Professorship of Industrial Engineering, newly established in his honor.

C. Diegert: Sandia Labs, Albuquerque, N. Mex. The probability of survival of redundant systems under a static load (H. M. Taylor).

R. Engelbrecht-Wiggans: Cowles Foundation, New Haven, Conn. On the fair and efficient allocations of indivisible commodities (W. F. Lucas).

J. Hooper: Bell Labs, Holmdel, N.J. Selection procedures for ordered families of distributions (T. J. Santner).

R. Kannan: Department of Mathematics, Massachusetts Institute of Technology, Cambridge, Mass. The size of numbers in the analysis of certain algorithms (L. E. Trotter, Jr.).

R. Kelley: Bell Labs, Holmdel, N.J. Further examination and a local load-sharing extension of Coleman's time to failure model for fiber bundles (H. M. Taylor).

P. Knepell: U.S. Air Force, Travis Air Force Base, Calif. An analysis of recoverable item inventory systems with service facilities subject to breakdown (J. A. Muckstadt).

V. G. Kulkarni: College of Industrial Management, Georgia Institute of

Technology, Atlanta, Ga. Ladder processes for Markov and semi-Markov chains (N. U. Prabhu).

J. S. Provan: Department of Applied Math and Statistics, State University of New York at Stony Brook, Stony Brook, N.Y. Decompositions, shellings, and diameters of simplicial complexes and convex polyhedra (L. J. Billera).

P. Rosenfeld: IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. Scheduling policies for a machine with load dependent service rates (L. E. Trotter, Jr.).

H. Singer: Bell Labs, Holmdel, N.J. An analysis of one-warehouse, n-retailer production inventory systems (J. A. Muckstadt).

M. Snell: Sandia Labs, Albuquerque, N. Mex. The application of regression methods to the initial transient problem in computer simulations (L. W. Schruben).

A. Vardi: NASA, Langley Research Center, Hampton, Va. Trust region strategies for unconstrained and constrained minimization (M. J. Todd).

M.Eng.(OR&IE) Degree Program

The main objectives of the program leading to the professional degree of Master of Engineering (OR&IE) are to give each student greater breadth and depth of technical knowledge and to provide an environment in which to synthesize the material studied in the course work. The emphasis is on mathematical modeling and on the application of quantitative techniques associated with optimization, probability, and statistics to the design and operation of systems.

Students are required to complete an engineering project in which they have the opportunity to work closely with practicing engineers or analysts as well as with Cornell faculty members. The projects are usually provided and sponsored by industrial or government organizations. Students are expected to perform all aspects of the project work, from problem formulation to communication of the results.

The following list of recent and current project titles, with the supervising professors, is representative of the M.Eng. work undertaken in this field:

Methods for Formulating Mold Repair Policies (L. W. Schruben)

Economic Feasibility of the Hydroelectric Potential of Sites along the Keuka Lake Outlet (J. Bloom)

A group project for M.Eng.(OR&IE) students involved work with engineers from a nearby parts manufacturing company to set up a new process for the manufacture of blocks. Here, Professor William Maxwell *(left)* and a student confer with an assembly worker.

Scheduling Multiproduct Process Facilities (G. L. Nemhauser)
Analysis of the Xerox de Mexico Logistics System (J. A. Muckstadt)
Analysis of Space Utilization and an Information System for a Unit Load Warehouse (W. L. Maxwell)
Economic and Legal Feasibility of Multiunit Wind Energy Conversion System (J. Bloom)

The following list of the places of employment of some recent M.Eng. program graduates indicates the job opportunities available to recipients of the M.Eng. degree:

Exxon Corporation (L. M. Blume)
E. I. du Pont de Nemours and Company (J. F. Faccenda)
Eastman Kodak (S. B. Han)
Bell Laboratories (D. R. Lukacs, H. Rostoker)
Theodore Barry Associates (R. E. Turner)
Pacific Electric and Gas (A. S. Westbom)

Faculty Members and Their Research Interests

Robert E. Bechhofer, A.B., Ph.D. (Columbia): *ranking and selection procedures, design of experiments, medical statistics*
Louis J. Billera, B.S. (Rensselaer), M.A., Ph.D. (City University of New York): *game theory, combinatorics*
Robert Bland, B.S., M.S., Ph.D. (Cornell): *network flows, graph theory, mathematical programming*
Jeremy Bloom, B.S. (Carnegie-Mellon), S.M., Ph.D. (M.I.T.): *systems engineering, energy economics*
Thomas O. Boucher, B.S. (Rhode Island), M.B.A. (Northwestern), M.Phil., Ph.D. (Columbia): *engineering and industrial economics*
Eugene B. Dynkin, Cand.Sci., D.Sc. (Moscow): *probability theory, mathematical economics*
David C. Heath, A.B. (Kalamazoo), M.A., Ph.D. (Illinois): *applied probability*
Peter L. Jackson, B.A. (Western Ontario), M.S., Ph.D. (Stanford): *stochastic models, finance*
William F. Lucas, B.S., M.A. (Detroit), M.S., Ph.D. (Michigan): *game theory, combinatorics*
Walter R. Lynn, B.S.C.E. (University of Miami), M.S.C.E. (North Carolina), Ph.D. (Northwestern): *environmental systems*
William L. Maxwell, B.M.E., Ph.D. (Cornell): *scheduling, materials handling, simulation*
John A. Muckstadt, A.B. (Rochester), M.S., M.A., Ph.D. (Michigan): *inventory and logistics control*
George L. Nemhauser (Director of the School of Operations Research and Industrial Engineering), B.Ch.E. (City College of New York), M.S., Ph.D. (Northwestern): *mathematical programming*
Narahari U. Prabhu, B.A. (Madras), M.A. (Bombay), M.Sc. (Manchester): *stochastic processes, queuing and storage theory*
Thomas J. Santner, B.S. (Dayton), M.S., Ph.D. (Purdue): *statistics*
Lee W. Schruben, B.S. (Cornell), M.S. (North Carolina), Ph.D. (Yale): *applied operations research, health systems*
Frank L. Spitzer, B.A., M.A., Ph.D. (Michigan): *probability theory*
Murad S. Taqqu, B.A. (Lausanne), M.A., Ph.D. (Columbia): *applied probability and statistics*
Howard M. Taylor 3d, B.M.E., M.I.E. (Cornell), Ph.D. (Stanford): *applied probability*
Michael J. Todd, B.A. (Cambridge), Ph.D. (Yale): *mathematical programming*
Leslie E. Trotter, Jr., A.B. (Princeton), M.S. (Georgia Institute of Technology), Ph.D. (Cornell): *mathematical programming*
Bruce W. Turnbull, B.A. (Cambridge), M.S., Ph.D. (Cornell): *biomedical statistics, quality control, reliability theory*
Lionel I. Weiss, B.A., M.A., Ph.D. (Columbia): *statistical decision theory, nonparametric statistics*

Further Information

Inquiries about graduate programs in the Field of Operations Research may be addressed to the Graduate Faculty Representative, Operations Research, Cornell University, Upson Hall, Ithaca, New York 14853. Inquiries about the professional-degree program may be addressed to the Faculty Representative, Master of Engineering (OR&IE), at the same address.

Theoretical and Applied Mechanics

Mechanics is the study of the motion and deformation of solids and fluids using mathematical analysis, modeling, and experimental observation. Although its historical roots are deep, mechanics is a particularly modern subject because it is basic to so many areas of contemporary technology.

The graduate Field of Theoretical and Applied Mechanics at Cornell offers students a broad education in the mechanics of rigid and deformable bodies (solids and fluids), applied mathematics at an advanced level, and modern experimental techniques. After a certain amount of course work, usually one year for M.S. candidates and two years for Ph.D. candidates, a student is supervised by one or more faculty members in thesis research. Recent thesis topics, examples of which are listed in the section on areas of research, have been quite diverse.

By acquiring a strong background in fundamentals, graduates of the program are able to carry out analytical or experimental research of high quality and are prepared to handle many modern engineering problems of an interdisciplinary nature.

The principal areas of teaching and research are solid mechanics, fluid mechanics, dynamics and space mechanics, mechanics of materials, biomechanics, and related mathematical methods. All students majoring in the field are required to minor in at least one other field of the Graduate School, chosen according to their research interests and needs. Minors frequently selected include aerospace engineering, applied mathematics, applied physics, astronomy, electrical engineering, geophysics, mathematics, mechanical engineering, physics, and structural engineering. The Field of Theoretical and Applied Mechanics has no rigid course requirements, so that highly individual programs can be planned by a student, together with his or her major and minor advisers.

The field has between twenty-five and thirty graduate students, who have a variety of academic and geographic backgrounds. The normal residence period for a student entering with a bachelor's degree is two years for the M.S. degree and four years for the Ph.D. degree; most study for the doctoral degree. Virtually all students are supported by teaching assistantships or research assistantships (which are of about equal financial value) administered by the Department of Theoretical and Applied Mechanics, or by University fellowships awarded by the Graduate School. Summer support is available on a slightly more limited basis.

Teaching assistants lead problem sessions (classes of about twenty students) for various undergraduate courses in mechanics and engineering mathematics, or they assist in laboratory sections on dynamics and strength of materials. As a result, they usually have a sounder understanding of basic concepts and are better prepared to present technical subjects orally than those who have not had such experience.

Research assistants work under the direction of one or more professors on projects sponsored by government agencies or industry. Current subjects of sponsored projects include creep and relaxation of metals at high temperatures; fracture; acoustic emission, propagation and scattering of ultrasonic waves, and nondestructive testing of materials; interaction of electromagnetic fields with the deformations of insulators, conductors, and superconductors (in connection with fusion reactor design and magnetically suspended vehicles); qualitative investigations of dynamical systems; problems of contact-lens design; mathematical analysis of combustion; magnetohydrodynamic duct flow; and dynamical studies of the early evolution of the solar system.

Facilities

The Department of Theoretical and Applied Mechanics has laboratories well equipped for experimental work in stress analysis, vibrations, ultrasonics, magnetoelastic interactions, and inelastic deformation of materials. Various facilities for materials processing, available through the Materials Science Center, can be used by students interested in aspects of the mechanics of materials, such as fracture, creep and relaxation, cyclic loading and fatigue, and deformation at high temperatures or pressures.

The University's extensive computer facilities are available to all students. They are supplemented by department analog computers and minicomputers. In addition, the department has computer systems based on the PDP 11/40 and the LSI-11 for on-line analysis of experimental data and for numerical analysis of medium-sized research problems.

Areas of Research

Examples of research projects in the areas of solid mechanics, fluid mechanics, dynamics and space mechanics, and biomechanics and biomathematics are described briefly below. In addition, interdisciplinary studies are being actively pursued in cooperation with other fields of the Graduate School. Examples are the dynamics of fruit harvesting (agricultural engineering), studies of fiber-reinforced materials (civil and environmental engineering, materials science and engineering), and work on the origin and dynamical evolution of the solar system (astronomy and space sciences, geological sciences).

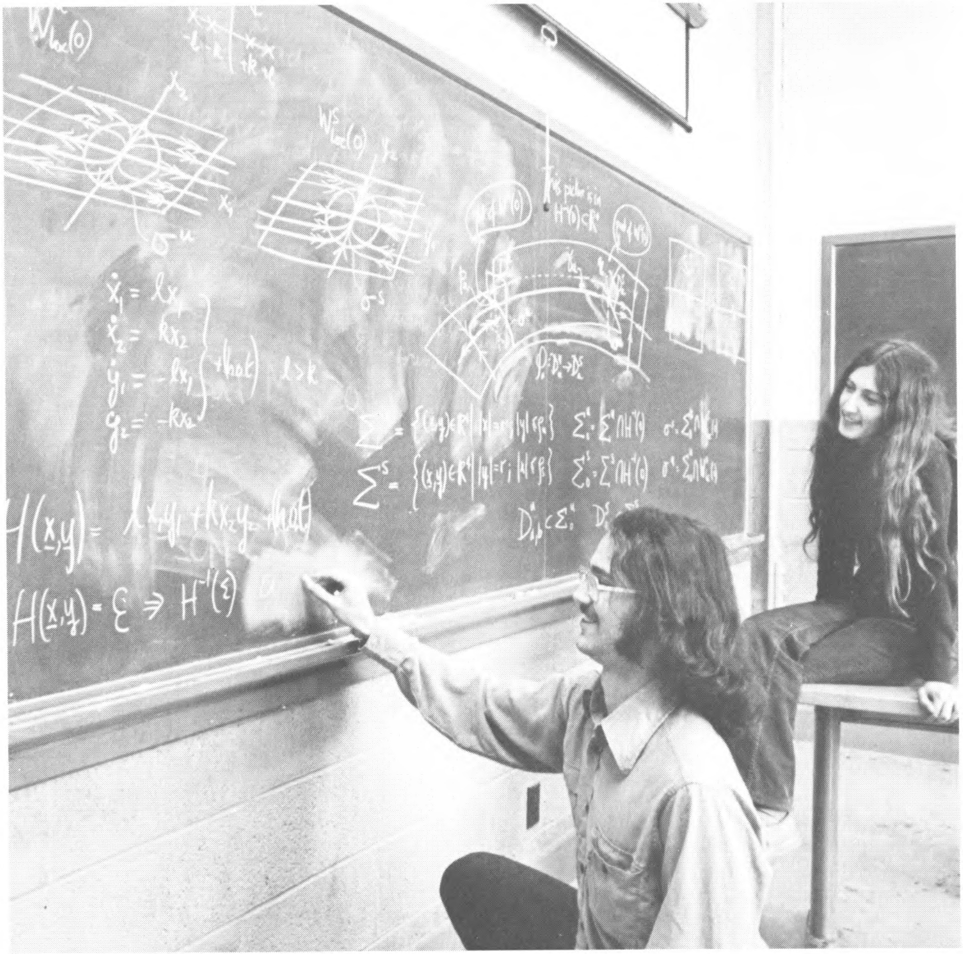
Several members of the graduate Field of Theoretical and Applied Mechanics have also been elected to the faculties of other graduate fields. These professors and fields are J. A. Burns (astronomy and space sciences), P. A. Dashner (applied mathematics), E. W. Hart (materials science and engineering), P. J. Holmes (applied mathematics), J. T. Jenkins (applied mathematics), G. S. S. Ludford (aerospace engineering, applied mathematics), and R. H. Rand (agricultural engineering, applied mathematics). Some of the research of these faculty members contributes to these other disciplines as well as to theoretical and applied mechanics.

Solid Mechanics

Research is being conducted on a variety of newly developing aspects of solid mechanics, adding to the fundamental work on elasticity, plasticity, continuum mechanics, stress-wave propagation, magnetoelastic interactions, and dynamic instability of structures that has been carried out at Cornell for many years.

The scattering of elastic waves by inhomogeneities in solids (cavities and solid or fluid inserts) is currently under study; experimental techniques of ultrasonics are combined with the analysis of single or multiple scattering of waves in solids to detect the size and material properties of the inhomogeneity. Ultrasonic wave measurements can also ascertain nondestructively the internal stresses in solids. These results are of great importance in the quantitative nondestructive testing of materials. In addition, passive ultrasonic techniques can be used to study fundamental features of acoustic emission sources, propagating structures, and detecting sensors.

A major area of investigation is the time-dependent inelastic behavior of metals and ceramics. Research is concerned both with the specification of advanced constitutive relations through theory and experiment and with the development of efficient computational tools to solve structural problems using realistic constitutive equations. The latter solutions include analytical and numerical methods, specifically, boundary-element and finite-element techniques. These studies have important implications for the design of structural components for aircraft,



nuclear reactors, high-temperature engine parts, and other energy-related systems. There is a vital interaction of this program with work in the Department of Materials Science and Engineering.

Research activity is growing in the area of fracture mechanics. New ideas for the description of crack propagation are under theoretical investigation, and analytical and numerical techniques for solving crack problems are being developed.

The statics and dynamics of composite materials are also under study. Topics include the determination of anisotropic properties, wave propagation in layered composites, and the inelastic failure mechanism of fiber-reinforced materials. Measurements of dynamic properties of new composites and other anisotropic materials are made in the ultrasonic laboratory.

A new program on the interaction of magnetic fields with elastic structures involves the theoretical study of electromagnetic forces in solids, the dynamic stability of structures, and the interactions of superconducting coils with self-generated magnetic fields. The well-equipped laboratory has cryogenic facilities, an infrared camera, and large charge-storage banks. This research has direct application to the magnetic forming of nonferrous materials, the magnetic levitation of vehicles, and the design of superconducting coils for fusion reactors.

Two graduate students, Peter Carruthers and Leslie Month, discuss the geometric representation of a dynamical systems problem.

As part of an investigation into the stability of magnetically levitated trains, a graduate student adjusts a model on a moving track.

Other current studies, involving both experiment and theory, are concerned with the mechanics of structured continua, nonlinear vibrations of plates and beams, dynamic stresses in thick-walled vessels for the containment of nuclear reactors, lubrication of elastic bearings, and a state-variable description of polymers.

Recent publications and theses (listed with the supervising professor) based on work in these projects include:

Ceranoglu, A. N. 1979. Acoustic emission and propagation of elastic pulses in a plate. Ph.D. thesis (Y. -H. Pao).

Chang, K. J.; Lance, R. H.; and Mukherjee, S. 1979. Inelastic bending of beams under time-varying moments—a state variable approach. *ASME Journal of Pressure Vessel Technology* 101:305.

Dashner, P. A. 1979. A finite strain work-hardening theory for rate independent elasto-plasticity. *International Journal of Solids and Structures* 15:159.

Hart, E. W. 1980. A theory for stable crack extension rates in ductile materials. *International Journal of Solids and Structures* 16:807.

Lenox, T. A., and Conway, H. D. 1980. An exact, closed form solution for the flexural vibrations of a thin circular plate having a parabolic thickness variation. *Journal of Sound and Vibration* 68:231.

Mak, W. C., and Conway, H. D. 1980. A summary of certain oil and bearing variables affecting the elastohydrodynamic lubrication of journal bearings. *Journal of Lubrication Technology* (in press).

Moon, F. C. 1980. Experiments on magneto-elastic buckling in a superconducting torus. *Journal of Applied Mechanics* 46:145.

Morjaria, M., and Mukherjee, S. 1980. Numerical analysis of planar, time-dependent inelastic deformation of plates with cracks by the boundary element method. *International Journal of Solids and Structures* (in press).

Morjaria, M.; Sarihan, V.; and Mukherjee, S. 1980. Comparison of boundary element and finite element methods in two-dimensional inelastic analysis. *Res Mechanica* 1:3.

Sachse, W. H., and Hsu, N. H. 1979. Ultrasonic transducers for materials testing and their characterization. In *Physical acoustics,* vol. 14, ed. W. P. Mason and R. N. Thurston. New York: Academic Press.

Sachse, W. H., and Pao, Y. -H. 1978. On the determination of phase and group velocities of dispersive waves in solids. *Journal of Applied Physics* 48:4320.

Van Arsdale, W. E.; Hart, E. W.; and Jenkins, J. T. 1980. Elongation upon torsion in a theory for the inelastic behavior of metals. *Journal of Applied Physics* 51:953.

Weaver, R. L., and Pao, Y. -H. 1979. Application of a transition matrix to a ribbon-shaped scatterer. *Journal of the Acoustical Society of America* 66:1199.

Yamagishi, K. 1978. Contact problems for the radial tire. Ph.D. thesis (J. T. Jenkins).

Fluid Mechanics

In the area of fluid mechanics, several research projects with significant applications are under way. For example, a study of the flow of a mixture of reacting gases is relevant to combustion in all its aspects, an important part of today's energy technology.

Additional research in fluid mechanics involves the modeling of the viscoelastic behavior of polymer solutions and melts. Here attention is focused on the evolution of the tangled molecular structure and the elasticity associated with it. Similar continuum microstructural theories are being applied to flowing granular materials and to flow through porous solids. Other projects with potential applications are concerned with the

Above: **Professor Wolfgang Sachse uses a minicomputer to analyze ultrasonic signals as part of a research program in nondestructive testing and materials characterization.**

Left: **One facet of research in the nondestructive testing of materials is the use of ultrasonic waves to measure stresses in metal specimens under uniaxial loading.**

mechanics of magnetic fluids, the theory of rotating flows (in particular, vortex breakdown), and magnetohydrodynamics.

Representative publications and theses (listed with the supervising professor) on these subjects are:

Buckmaster, J., and Ludford, G. S. S. 1981. *Theory of laminar flames.* Cambridge University Press Monographs on Mechanics and Applied Mathematics (in press).

Dashner, P. A. 1980. A phenomenological theory for elastic fluids. *Journal of Non-Newtonian Fluid Mechanics* (in press).

Jenkins, J. T. 1980. Static equilibrium of a fluid-saturated porous solid. *Journal of Applied Mechanics* 47:493.

Ludford, G. S. S., and Walker, J. S. 1980. Current status of MHD duct flow. In *Proceedings of 2nd Bat-Sheva international seminar on MHD flows and turbulence.* Wiley–Israel University Press.

Sen, A. K. 1979. Asymptotic analysis of near-stoichiometric flame propagation. Ph.D. thesis (G. S. S. Ludford).

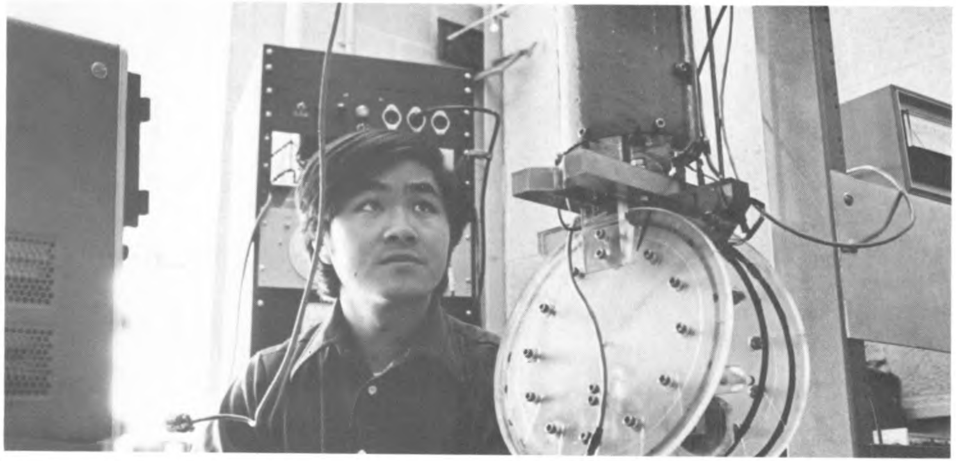
Dynamics and Space Mechanics

Dynamics is at the center of mechanics. Studies in dynamics often require a deep understanding of physical phenomena, but they can also involve sophisticated modern mathematics. Both of these aspects are evident in the Cornell research, which emphasizes applications related to space research and investigations of nonlinear processes.

The study of dynamics originated in investigations of the solar system; the modern counterpart is space mechanics, which has gained particular significance in light of the achievements of the national space program. Cornell research in space mechanics is concerned with the long-term evolution of the solar system, the dynamics of planetary rings, and the rotation of celestial bodies, including planets, asteroids, natural satellites, and comets.

Physical problems also stimulate exciting mathematical analyses, in the tradition of rational mechanics. For example, recent studies at Cornell show that instabilities occurring in magnetically levitated vehicles can be explained in terms of the nonperiodic orbit structures now known to exist for a wide class of differential equations. In other work, a new understanding of nonlinear dynamical systems is emerging from studies of the topology of solution surfaces.

Problems under study are indicated by the following recent publications and theses (listed with the supervising professor):



Investigation of the structural stability of superconducting coils is part of a research program in magnetoelastic interactions.

Burns, J. A.; Hamill, P.; Cuzzi, J. N.; and Durisen, R. H. 1979. On the "thickness" of Saturn's rings caused by satellite and solar perturbations, and by planetary precession. *The Astronomical Journal* 84:1783.

Burns, J. A.; Lamy, P. L.; and Soter, S. 1979. Radiation forces on small particles in the solar system. *Icarus: International Journal of Solar System Studies* 40:1.

Holmes, P. J. 1980. Averaging and chaotic motions in forced oscillations. *SIAM: Journal of Applied Mathematics* 38:65.

Johnson, T. L., and Rand, R. H. 1979. On the existence and bifurcation of minimal normal modes. *International Journal of Nonlinear Mechanics* 14:1.

Month, L. A. 1979. On approximate first integrals of Hamiltonian systems with an application to nonlinear normal modes in a two-degree of freedom nonlinear oscillator. Ph.D. thesis (R. H. Rand).

Moon, F. C. 1980. Experiments on chaotic motions of a forced nonlinear oscillator: strange attractors. *Journal of Applied Mechanics* 47:638.

Rand, R. H., and Holmes, P. J. 1980. Bifurcation of periodic motions in two weakly coupled van der Pol oscillators. *International Journal of Nonlinear Mechanics* (in press).

Students confer during a graduate laboratory in acoustics.

Biomechanics and Biomathematics

Research in this area has two goals. One is to study biological systems and their organization in order to devise improved engineering systems. The other is to use analytical engineering techniques to increase the understanding of biology and the interactions of biological systems. An active area of research involves the modeling of biologically important materials such as blood cells and tendons. The motion of a soft contact lens across the surface of the eye is another mechanics problem under study. Principles of mechanics and applied mathematics are being applied to develop an understanding of how leaves breathe and why stomata open and close. Researchers in theoretical and applied mechanics are collaborating with neurobiologists to investigate coupled oscillators in the nervous system of primitive fish in order to learn how such organisms swim.

Examples of publications in this area are:

Jenkins, J. T. 1980. Mechanical properties of tendon. *Orthopaedic bioengineering,* vol. 1, ed. V. C. Mow and J. L. Katz. New York: Marcel Dekker.

Sinclair, T. R., and Rand, R. H. 1979. Mathematical analysis of cell CO_2 exchange under high CO_2 concentrations. *Photosynthetica* 13:239.

Faculty Members and Their Research Interests

Joseph A. Burns, B.S. (Webb), Ph.D. (Cornell): *dynamics of the solar system, celestial mechanics, planetary satellites*

Harry D. Conway, B.S., Ph.D. (London), Sc.D. (Cambridge): *isotropic and anisotropic elasticity, plates and shells, impact, lubrication*

Peter A. Dashner, B.S., M.S., Ph.D. (SUNY, Buffalo): *continuum mechanics, inelastic behavior of materials*

Edward W. Hart, B.S. (City College of New York), Ph.D. (California, Berkeley): *nonelastic deformation, thermodynamics of inhomogeneous systems, fracture*

Philip J. Holmes, B.A. (Oxford), Ph.D. (Southampton): *nonlinear mechanics, dynamic systems, bifurcation theory*

James T. Jenkins, B.S. (Northwestern), Ph.D. (Johns Hopkins): *continuum mechanics, biomechanics*

Richard H. Lance, B.S. (Illinois), M.S. (Illinois Institute of Technology), Ph.D. (Brown): *engineering plasticity, numerical methods, inelastic behavior of solids*

Geoffrey S. S. Ludford, B.A., M.A., Ph.D., Sc.D. (Cambridge): *fluid mechanics, combustion, magnetohydrodynamics, related applied mathematics*

Francis C. Moon (Chairman of the Department of Theoretical and Applied Mechanics), B.S. (Pratt), M.S., Ph.D. (Cornell): *dynamics of solids and structures, magnetoelasticity, mechanics of superconducting systems*

Subrata Mukherjee, B.S. (Indian Institute of Technology), M.S. (Rochester), Ph.D.

(Stanford): *viscoelasticity, plasticity, creep, fracture*

Yih-Hsing Pao, B.S. (National Taiwan), M.S. (Rensselaer), Ph.D. (Columbia): *wave propagation in solids, magnetoelasticity, vibrations, earthquake engineering*

Richard H. Rand, B.E. (Cooper Union), M.S., Sc.D. (Columbia): *dynamical systems, biomechanics*

Andy L. Ruina, Sc.B., M.S., Ph.D. (Brown): *friction laws and instabilities, geomechanics*

Wolfgang H. Sachse, B.S. (Pennsylvania State), M.S., Ph.D. (Johns Hopkins): *mechanics of materials, nondestructive testing techniques, wave propagation and physical acoustics*

Many of these professors are also members of University research centers: P. A. Dashner, P. J. Holmes, J. T. Jenkins, G. S. S. Ludford, and R. H. Rand work with the Center for Applied Mathematics; H. D. Conway, Y.-H. Pao, and W. H. Sachse are active in the Materials Science Center; J. A. Burns is a member of the Center for Radiophysics and Space Research; and F. C. Moon is in the Laboratory for Plasma Studies.

Further Information

Further information may be obtained by writing to the Graduate Faculty Representative, Theoretical and Applied Mechanics, Cornell University, Thurston Hall, Ithaca, New York 14853.

Interdisciplinary Activities

Cornell University maintains several interdisciplinary research centers and programs and a number of special facilities that are of great significance in many applied science and engineering projects. These are of interest to students in the various graduate fields because their research efforts might be closely identified with those of a center or program, or their research activities might be conducted in one of the special laboratories. Some of the facilities and programs with interdisciplinary interest are described here.

The interdisciplinary centers and programs do not formally admit graduate students; a person interested in an area encompassed by an interdisciplinary center or activity should apply for graduate admission through a related graduate field and work with the interdisciplinary group through his or her supervising professors.

Center for Applied Mathematics

Coordination of graduate study and research efforts in applied mathematics is provided by Cornell's Center for Applied Mathematics. About forty-five faculty members from various departments of the University and some twenty-five graduate students are currently associated with the center. The students are enrolled in the graduate Field of Applied Mathematics.

Further information may be obtained by writing to the Director, Center for Applied Mathematics, Cornell University, Olin Hall, Ithaca, New York 14853.

Center for Environmental Research

The Center for Environmental Research provides an interdisciplinary research focus for those interested in issues pertaining to control of the environment. Because it has become increasingly evident that programs and projects with limited objectives are insufficient to cope with the complexities of existing and anticipated problems involving the environment, there is a need for approaches that involve workers in many fields. The center is designed to facilitate such approaches. Involved in the various programs sponsored or supported by the center are faculty members and graduate students in the sciences, engineering, agriculture, law, economics, government, regional planning, and public health. The center is also the water resources research institute for New York State under federal legislation.

Examples of topics studied by research groups associated with the center include water resources planning, development, and management; the effects of acid precipitation; the assessment of environmental impact statements; the interrelationships between people and their resources; environmental benefit-cost analysis; the impact of environmental legislation on economic development; and epidemiology and the environment. Reports on these subjects and other materials are available in a reading room maintained by the center for student and staff use.

The center does not offer courses; prospective students must apply to the Graduate School for admission. The two major graduate fields most closely related to the interests of the center are Civil and Environmental Engineering and Agricultural Engineering. In addition there are two relevant minor graduate fields: Water Resources and Environmental Quality.

More detailed information may be obtained by writing to the Director, Center for Environmental Research, Cornell University, Hollister Hall, Ithaca, New York 14853.

Center for International Studies

The major role of the Center for International Studies is to support and coordinate Cornell's teaching and research programs in international and comparative studies. The flexibility of degree requirements permits students considerable latitude in the selection of subjects, and appropriate courses may be chosen from the regular offerings of the various schools and colleges of the University.

The center functions through a structured network of faculty committees that are organized on a multidisciplinary basis and clustered in area studies programs, professional programs, and problem-solving programs. The area studies programs are those on China-Japan, Latin America, South Asia, Southeast Asia, and the Soviet Union. Professional programs include those on international agriculture, international education, international legal studies, international studies in planning, and international and comparative labor relations. Problem-solving programs, which examine substantive policy issues cutting across area and professional concerns, include those on international population; international nutrition; participation and labor-managed systems; peace studies; rural development; science, technology, and development; international political economy; and Western societies. The center also sponsors the Field of International Development, a program of graduate studies leading to a professional master's degree. The editorial offices of the journal *International Organization* are located at the center.

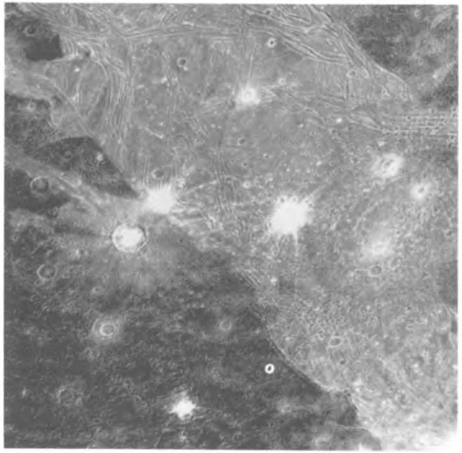
Students concerned with the international dimension of applied science and engineering as these pertain to international regulation, security, and development are encouraged to investigate the research opportunities and teaching activities of the Peace Studies Program, the Rural Development Committee, and the Science, Technology, and Development Committee.

Further information about the center and its associated programs may be obtained from the Center for International Studies, Cornell University, 170 Uris Hall, Ithaca, New York 14853.

Center for Radiophysics and Space Research

The Center for Radiophysics and Space Research provides facilities for research in astronomy and the space sciences carried out by several departments in the University and facilitates contact and cooperation among the various disciplines. Those interested in space science research may apply for admission to the Graduate School through a number of graduate fields of study. Fields of engineering and applied science that draw on the resources of the center are aerospace engineering, applied physics, electrical engineering, and geological sciences.

The center's facilities on the Cornell campus include a laboratory for infrared astronomy, a laboratory for lunar and geophysical studies, and a laboratory for planetary studies that has



The unusual grooved appearance of the terrain shown in this Voyager 2 photograph of the surface of Ganymede, Jupiter's largest moon, is probably due to internal geologic activity. A study is currently under way to investigate the structure and origin of geologic features on Ganymede and other icy satellites.

extensive collections of spacecraft lunar and planetary photography. Work in optical astronomy is also possible. Facilities for research in radio-radar astronomy are available through the National Astronomy and Ionosphere Center, operated by Cornell (see the description below).

Financial assistance in the form of graduate research assistantships is available through the center.

Further information may be obtained by writing to the Secretary, Center for Radiophysics and Space Research, Cornell University, Space Sciences Building, Ithaca, New York 14853.

Boris W. Batterman *(left)*, director of the Cornell High Energy Synchrotron Source, explained the operation of the facility to National Science Foundation director Richard C. Atkinson during a visit to the University's Wilson synchrotron.

Cornell High Energy Synchrotron Source

The Cornell High Energy Synchrotron Source (CHESS), a synchrotron radiation laboratory, provides a wide spectrum of high-energy x rays for experiments in many scientific fields. The facility, which became operational in the spring of 1980, was made possible by a $1 million grant from the National Science Foundation and is available to scientists from industrial and university laboratories throughout the United States. At Cornell, researchers in virtually every area of physical science are making use of CHESS.

The radiation is generated by the Cornell Electron Storage Ring (CESR), which was constructed primarily for high-energy physics studies. At one time considered a nuisance by high-energy physicists, synchrotron radiation has become recognized as a very powerful tool for physicists, material scientists, chemists, crystallographers, and medical researchers studying the properties of materials that have technological or biological importance. The spectrum of high-energy radiation provided by CHESS is unique, unequaled by any other synchrotron source in this country. CHESS complements the National Synchrotron Light Source, which is being constructed at Brookhaven, and is an East Coast counterpart of the synchrotron radiation laboratory at Stanford University.

Additional information may be obtained by writing to the Director, Cornell High Energy Synchrotron Source, Cornell University, Clark Hall, Ithaca, New York 14853.

Energy-Related Activities

Although there is no separate graduate field or organized interdisciplinary program or center in energy studies at Cornell, there is a great amount of activity in this area in the various graduate fields, and programs directed toward fundamental or applied energy-related study and research can be arranged.

Combustion research, for example, is being conducted by graduate students in mechanical engineering. Control of pollutant emissions by vehicles is a subject of research in aerospace engineering. Hydrogen as a fuel is being studied in mechanical engineering. Processes for liquefying and gasifying coal are being investigated in chemical engineering. Projects concerned with electric-power transmission and power-system control are under way in electrical engineering. Students and faculty members in physics and applied physics are conducting research in solar energy. Theoretical and experimental work concerned with controlled thermonuclear fusion processes is being conducted in the Laboratory of Plasma Studies. Agricultural engineering researchers are studying energy use in agricultural production. Other examples can be found in the descriptions of the various graduate fields.

In the Laboratory of Plasma Studies, researchers are assembling magnetic field coils for an experiment to trap ion rings.

Laboratory of Plasma Studies

The Laboratory of Plasma Studies is an interdisciplinary center for research in plasma physics. Active areas of research include controlled fusion, intense beams of relativistic electrons, intense ion beams, collective ion acceleration, plasma confinement and heating, basic plasma physics, theory of high-temperature plasmas, space and solar plasma physics, molecular lasers, and chemical lasers. A variety of both large and conventional laboratory-scale facilities is provided.

Faculty members associated with the laboratory represent several graduate fields, among which are applied physics, chemistry, electrical engineering, mechanical engineering, aerospace engineering, and physics. Graduate students normally become affiliated with the laboratory by choosing to do research with a faculty member engaged in a project at the laboratory. During the laboratory's first fourteen years of existence, its research projects have led to the completion of eighty-two Ph.D. and sixteen M.S. theses.

Financial assistance in the form of graduate research assistantships, available in limited quantity, is obtained directly from the laboratory; fellowships are available through the normal Graduate School channels.

Further information may be obtained by writing to the Director, Laboratory of Plasma Studies, Cornell University, Upson Hall, Ithaca, New York 14853.

Materials Science Center

The Materials Science Center facilitates graduate research and training in many aspects of the science of materials. It provides a number of special laboratories containing highly sophisticated equipment that is made available to researchers in many areas, including applied physics, chemical engineering, chemistry, electrical engineering,

geological sciences, materials science and engineering, mechanics, metallurgy, and physics. In some cases new equipment needed for specific thesis research projects and the assistance of technicians can be provided. The center is also able to provide financial assistance in the form of research assistantships.

The laboratories at the center are for materials preparation, metallography, x-ray diffraction, electron microscopy, electronics, low-temperature work, nonmetallic crystal growth, and laser development. Each of these laboratories is under the direction of a faculty member and is staffed with trained technicians, so that researchers receive expert guidance and assistance. Computing facilities in a central, multiuser environment are available for the research groups.

Most of the Materials Science Center facilities are located in Clark Hall of Science, the University's center for solid-state and applied physics, and in Bard Hall, the Department of Materials Science and Engineering building.

Additional information may be obtained by writing to the Director, Materials Science Center, Cornell University, Clark Hall, Ithaca, New York 14853.

Left above: **Equipment available at the Materials Science Center includes this scanning electron microscope, useful in studies of the surfaces of materials and for biological applications.**

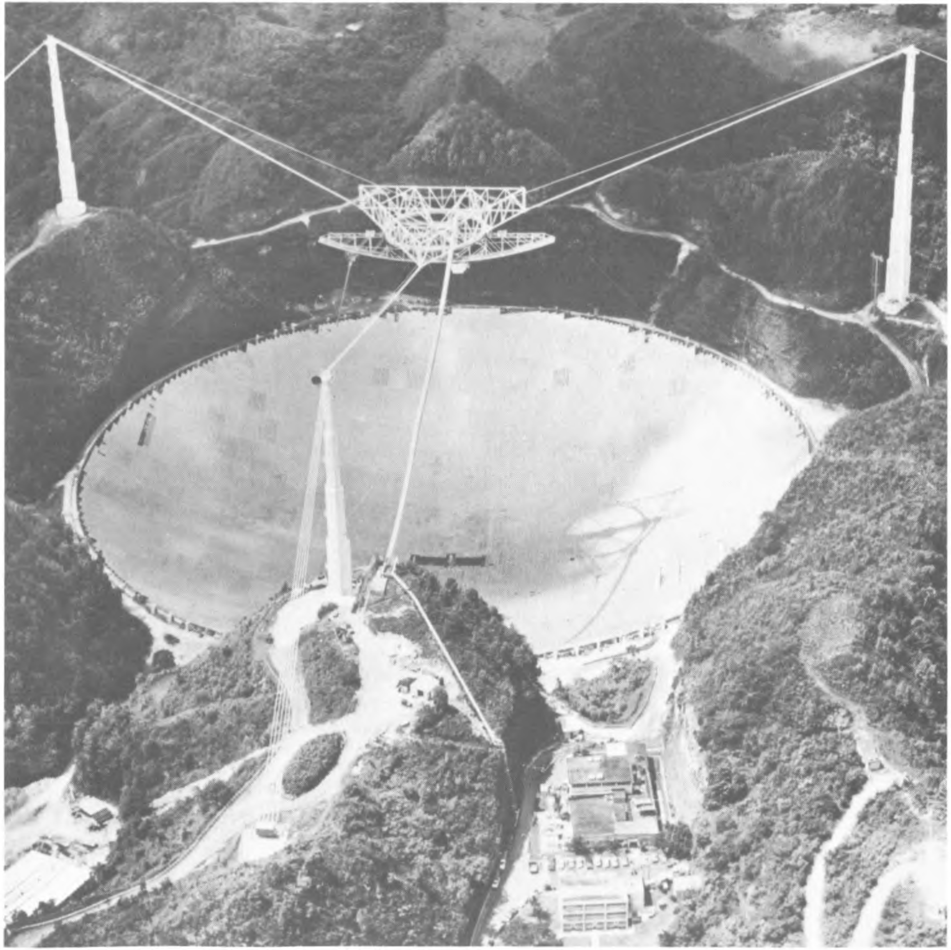
Left: **Electron microscopes are among the extensive facilities of the interdisciplinary center.**

National Astronomy and Ionosphere Center

The National Astronomy and Ionosphere Center, which has the world's largest radio-radar telescope, is operated by Cornell University for the National Science Foundation and is available for graduate research by students at Cornell and other universities in fields such as electrical engineering and astronomy. The facility is located in the mountains of northern Puerto Rico, near the coastal city of Arecibo.

The diameter of this spherical telescope is 1,000 feet, and its collecting area is 19.8 acres. A white steel platform some 500 feet above the dish is a support structure for the equipment that receives and amplifies the radio signals. Radio signals from space can be detected by this telescope in the frequency range of 10 to 7,000 MHz. The observatory also has four radar transmitters in this frequency range. The largest antenna is 96 feet in length and weighs nearly 10,000 pounds.

Through the use of radar techniques, important discoveries on the periods of rotation of the planets and their surface characteristics have been made with the Arecibo telescope. Accurate radio observations made with the instrument have contributed to the understanding of pulsars and to radio astronomical studies of the interstellar medium, radio galaxies, and quasars. The telescope has also been used to provide information, not otherwise obtainable, about the earth's ionosphere. In recent years controlled studies of the ionosphere have been



made from Arecibo by the artificial heating of preselected ionospheric layers.

Further information may be obtained by writing to the Director, National Astronomy and Ionosphere Center, Cornell University, Space Sciences Building, Ithaca, New York 14853.

National Research and Resource Facility for Submicron Structures

The National Science Foundation has established the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell, which has a strong program in this area. Faculty members and graduate students in a number of disciplines, especially applied physics, electrical engineering, and materials science and engineering, are active users of the facility, along with researchers from academic and other institutions across the country.

The chief purpose of NRRFSS is to promote and carry out research to advance the science and art of microstructure fabrication technology, which will make possible the manufacture of a new generation of ultrasmall devices and circuits for inexpensive electronic equipment, and to facilitate basic and applied research in related areas. The facility is also intended to serve as a training ground for specialists in microstructure technology.

The national radio-radar telescope observatory at Arecibo, Puerto Rico, is operated by Cornell.

Professor John Silcox discusses the finer points of the scanning transmission electron microscope (STEM) with visiting IBM scientist Dr. Phil Batson and postdoctoral appointee Peter Fejes. Using STEM, the limits of electron beam nanolithography and materials characterization are studied at the facility.

Sophisticated electronic equipment is available, and graduate students have a unique opportunity to participate in research projects using these resources. Such work is arranged through professors from a number of graduate fields who are members of the facility.

A variety of projects involving the theory, design, fabrication, testing, and application of structures with submicrometer dimensions are under way. Examples are studies of electron-beam, ion-beam, and x-ray lithography; electron and ion sources; synchrotron radiation; superconductor physics and devices; semiconductor growth and devices for integrated optics; microwave devices and circuits; the physics and chemistry of semiconductor interfaces; electronic structure; polymer resists; lasers and laser annealing; holography; amorphous metals; strain and displacement in solids; and ultrapressure.

Further information may be obtained by writing to the Director, National Research and Resource Facility for Submicron Structures, Cornell University, Phillips Hall, Ithaca, New York 14853.

Program of Computer Graphics

The Program of Computer Graphics provides an interdisciplinary center for the development of graphics techniques and the use of computer graphics in research applications. A substantial number of staff members and researchers implement these efforts.

In addition to research on computer graphics (the major focus of the program), current work includes projects in the fields of architecture, structural engineering, pollution analysis, water resources, geological sciences, medicine and bioengineering, animation, astronomy, agricultural engineering, and energy conservation. All of the work in specific disciplines relies heavily on interactive graphics. Emphasis is placed on the use of both input and output devices.

The laboratory, which is located in Rand Hall, has facilities for generating static or dynamic black and white wire-line drawings of perspective images of two- or three-dimensional objects. Full-color static displays of two- or three-dimensional images can also be produced. Interactive graphical input equipment includes digitizing tablets, light pens, and optical scanning devices; hard-copy plotted output can be obtained with the use of printers and plotters. Photographic equipment for filmmaking, videotapes, and single-image documentation is available. The multiuser system operates on several interconnected minicomputers.

A closely related program, recently established by the College of Engineering and located in Hollister Hall, is the Computer-Aided Design Instructional Facility (CADIF). Its objective is to introduce new techniques in instruction and bring sophisticated computer-graphic and computer-aided design tools into the classroom.

Both the computer graphics laboratory and CADIF use VAX/780 systems as their central processing units. The major vector graphic components are the Evans and Sutherland picture systems, which are used for the dynamic displays, and the Tektronix 4014 storage tubes, which are used for the static displays. Full-color images are generated on frame buffers using high-quality raster display monitors as output.

At the present time the most feasible way to arrange a program of study and research in computer graphics is to enter the Master of Science program and take a major in architectural science and a minor in computer science. Those students who wish to study the relationship of computer graphics to a field of application such as architecture or engineering may choose a minor in that subject area. The laboratory is also available to Ph.D. engineering students who are interested in computer-aided design and are working on associated research projects.

Program on Science, Technology, and Society

The purpose of the Program on Science, Technology, and Society is to stimulate and initiate teaching and research on the interaction of science and technology with society. The program draws its students, faculty members, and researchers from all areas of the University, including the physical, biological, and social sciences; the humanities; engineering; business and public administration; and law.

Topics of special concern to the program include biomedical ethics, defense policies and arms control, environmental ethics and toxicology, citizen participation in the nuclear debate, science policy, and technology assessment. These and other subjects are studied through courses, graduate and faculty seminars, workshops, and individual research programs. In cooperation with University departments and centers, the program has participated in the development of more than two dozen interdisciplinary courses at both the graduate and undergraduate levels. Courses developed by the program are designed to both synthesize and contrast the perspectives of the several academic disciplines used in the analysis of relationships among science, technology, and the needs, values, and institutions of society. The program also participates in the graduate minor Field of Public Policy, offering a science policy "stream" within this minor field.

Limited funding may be available for interdisciplinary thesis research on the interaction of science and technology with society. Students beyond the introductory level of graduate study may apply for such support.

Further information may be obtained by contacting the Program on Science, Technology, and Society, Cornell University, Clark Hall, Ithaca, New York 14853.

Ward Laboratory of Nuclear Engineering

Graduate students in several fields use the facilities of the Ward Laboratory of Nuclear Engineering for research and project work in reactor physics and engineering, the physics of low-energy nuclear structures, and nuclear and radiation chemistry. The laboratory is located in a separate building on the Engineering Quadrangle.

One of the major facilities is the TRIGA reactor, a source of neutrons and gamma rays. It has a steady-state power of 500 kilowatts and a pulsing capability of up to 1,000 megawatts. An apparatus unique to Cornell among universities is the low-flux critical facility, or "zero-power" reactor, equipped with a 14-MeV neutron generator. A charged-particle accelerator (Dynamitron) with energies of up to 3 MeV provides currents of up to 2.5 mA.

Further information may be obtained by contacting the Director, Ward Laboratory of Nuclear Engineering, Cornell University, Ward Laboratory, Ithaca, New York 14853.

General Information

Graduate Study at Cornell

Of the University's total enrollment of about 18,000 students, some 3,500 are in the Graduate School; of these, about 700 are enrolled in engineering and applied science programs. The College of Engineering, one of thirteen schools and colleges in the University system, has a faculty of about 200 that is the nucleus of the graduate faculty in engineering and applied science.

Master of Science and Doctor of Philosophy degree programs are organized within graduate fields. Each student accepted into a field selects a special committee, headed by the professor who will supervise the thesis research, and including two additional faculty members. The special committee has an unusually important position in graduate education at Cornell, for it is wholly responsible for overseeing the student's course of study and progress and for deciding when the student is ready to receive his or her degree. This committee is usually chosen toward the beginning of the student's residency. Those whose interests change as they progress in their studies, however, may modify their committees at some later time.

Although the Graduate School sets no course, credit, or grade requirements, leaving these matters to the discretion of each special committee, the Graduate Faculty has established general requirements, including a minimum term of residence, an oral examination, and submission of a thesis based on supervised research.

In addition to the M.S. and Ph.D. degree programs, a one-year curriculum leading to the Master of Engineering degree is offered in most of the engineering and applied science areas. These degrees are intended primarily for students who wish to prepare for professional engineering careers, but an M.Eng. curriculum can also be used as part of a graduate program culminating in the Ph.D. degree. Such a program can be designed to encompass two different areas of study or to allow for doctoral work in depth in a more specialized aspect of the M.Eng. discipline.

Required for an M.Eng. degree are thirty credits of advanced technical work, including a design project that is an essential part of the program. These degrees are often pursued by Cornell students who begin an integrated three-year curriculum in the junior year of undergraduate study, but they are open to graduates of other four-year engineering schools.

University Facilities

Cornell University maintains more than three hundred major buildings on its 740-acre Ithaca campus. The College of Engineering is centered in ten modern buildings in the area known as the Engineering Quadrangle, although some of its activities are carried out at other campus locations, such as Clark Hall, which is the University's center for solid-state and applied physics.

Cornell's outstanding library system comprises two large central facilities supplemented by a number of specialized libraries in buildings throughout the campus. The entire collection, including more than four million volumes, is available to all students. The College of Engineering library and the physical sciences and mathematics libraries are especially useful to engineering and applied sciences graduate students.

Of special importance to many graduate students is the University's computing facility. At the present time this consists of a complex of IBM and DEC computing equipment, including a central 370/168 IBM system, a DEC system 2060, satellite computers, and interactive terminals. A satellite station convenient for many engineering graduate students, for example, is located in Upson Hall on the Engineering Quadrangle; its facilities include Terak microcomputers. Many research groups also have minicomputers available for project work.

Applying for Admission

Application materials for admission to a graduate field program, including financial aid information and request forms, may be obtained from the Graduate School, Cornell University, Sage Graduate Center, Ithaca, New York 14853. These materials can also be obtained from the graduate faculty representative of a particular graduate field. Admission and financial aid application forms for the Master of Engineering degree programs may be obtained by writing to Graduate Professional Engineering Programs, Cornell University, 109 Hollister Hall, Ithaca, New York 14853.

It may be helpful for applicants, especially those who intend to apply for fellowships and scholarships, to take the Graduate Record Examinations aptitude test (verbal and quantitative) and an appropriate advanced test and have scores sent to the Graduate School. Information about these tests may be obtained from the Educational Testing Service, Princeton, New Jersey 08540.

It is the policy of Cornell University actively to support equality of educational and employment opportunity. No person shall be denied admission to any educational program or activity or be denied employment on the basis of any legally prohibited discrimination involving, but not limited to, such factors as race, color, creed, religion, national or ethnic origin, sex, age, or handicap. The University is committed to the maintenance of affirmative action programs which will assure the continuation of such equality of opportunity.

A brochure describing services for the handicapped student may be obtained from the Office of Equal Opportunity, Cornell University, 217 Day Hall, Ithaca, New York 14853. Other questions or requests for special assistance may also be directed to that office.

Financial Aid and Employment

Financial aid in the form of teaching, research, or residence hall assistantships, fellowships, scholarships, and loans is available to graduate students.

Applicants for admission will receive detailed information about available financial aid along with application materials.

Fellowships and scholarships are also offered by state and national government agencies, by foundations, and by private parties. The Cornell University Career Development Center maintains a collection of pertinent reference materials on such sources of financial aid.

Part-time employment is sometimes available to graduate students through their own departments, and a part-time employment service is maintained by the Office of Financial Aid. Spouses of students may find employment at Cornell through the University's personnel office, or with local businesses or industries, professional offices, schools or colleges, public agencies, or the hospital. A New York State employment office is located in Ithaca.

The amount, time, and manner of payment of tuition, fees, or other charges may be changed at any time without notice.

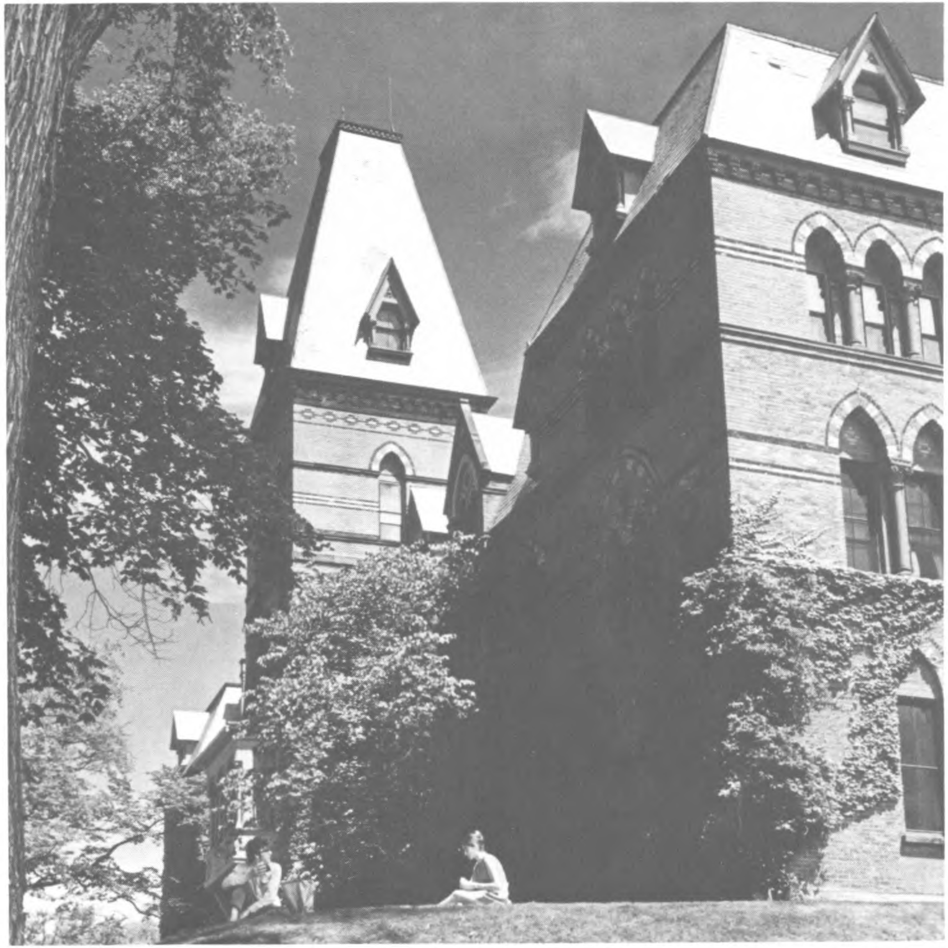
Location

Most of the schools and colleges of the University are located in Ithaca, at the southern end of the Finger Lakes region of upstate New York. The population of the greater Ithaca area, including students, is about 40,000. Public transportation to Ithaca is provided by USAir and several commuter airlines and by the Greyhound bus lines.

Housing and Dining

Graduate dormitory housing and apartments for married students are available on campus, and help in obtaining off-campus housing is offered. Detailed information about housing is sent along with requested application materials.

The University has no dining requirements but does provide a number of dining facilities on campus and offers some optional arrangements. Among these facilities is a dining service at Sage Hall that is available to all graduate students and other members of the Cornell community.



Sage Hall provides housing, dining facilities, and administrative services for Cornell graduate students.

Extracurricular Activities

Cornell offers a variety of cultural events, including lectures, special programs and conferences, and music, drama, and film presentations. Ithaca residents also have the opportunity to attend theatrical and musical events at Ithaca College.

Programs in religious affairs at the University include information, counseling, and referral services as well as ministries. The Centre for Religion, Ethics, and Social Policy is a nondenominational educational unit.

Sage Hall supplements the three student unions at Cornell in providing opportunity for social and recreational activities. Graduate students are also welcome to join undergraduates in student activities such as intramural sports, drama, and the production of campus publications. The various University musical groups and many of the more than one hundred organizations on campus are open to graduate students. Wives of male graduate students are frequently active in their own special organizations. There is also an organization for foreign students and their families.

Extensive recreational facilities, including those for swimming, ice skating, golf, bowling, and tennis, are available on campus. Graduate students are also eligible for all intramural and informal sports at the University. Additional opportunities for outdoor sports and recreation are available in the surrounding area.

Further Information

The *Announcement of the Graduate School* and *Introducing Cornell* are useful to prospective Cornell graduate students and should be consulted for additional information on admission, financial aid, and degree requirements. Information about facilities, programs, and courses available in the various schools and departments of the College of Engineering is included in *Courses of Study*. Copies of these publications may be obtained by writing to Cornell University Announcements, Building 7, Research Park, Ithaca, New York 14850.