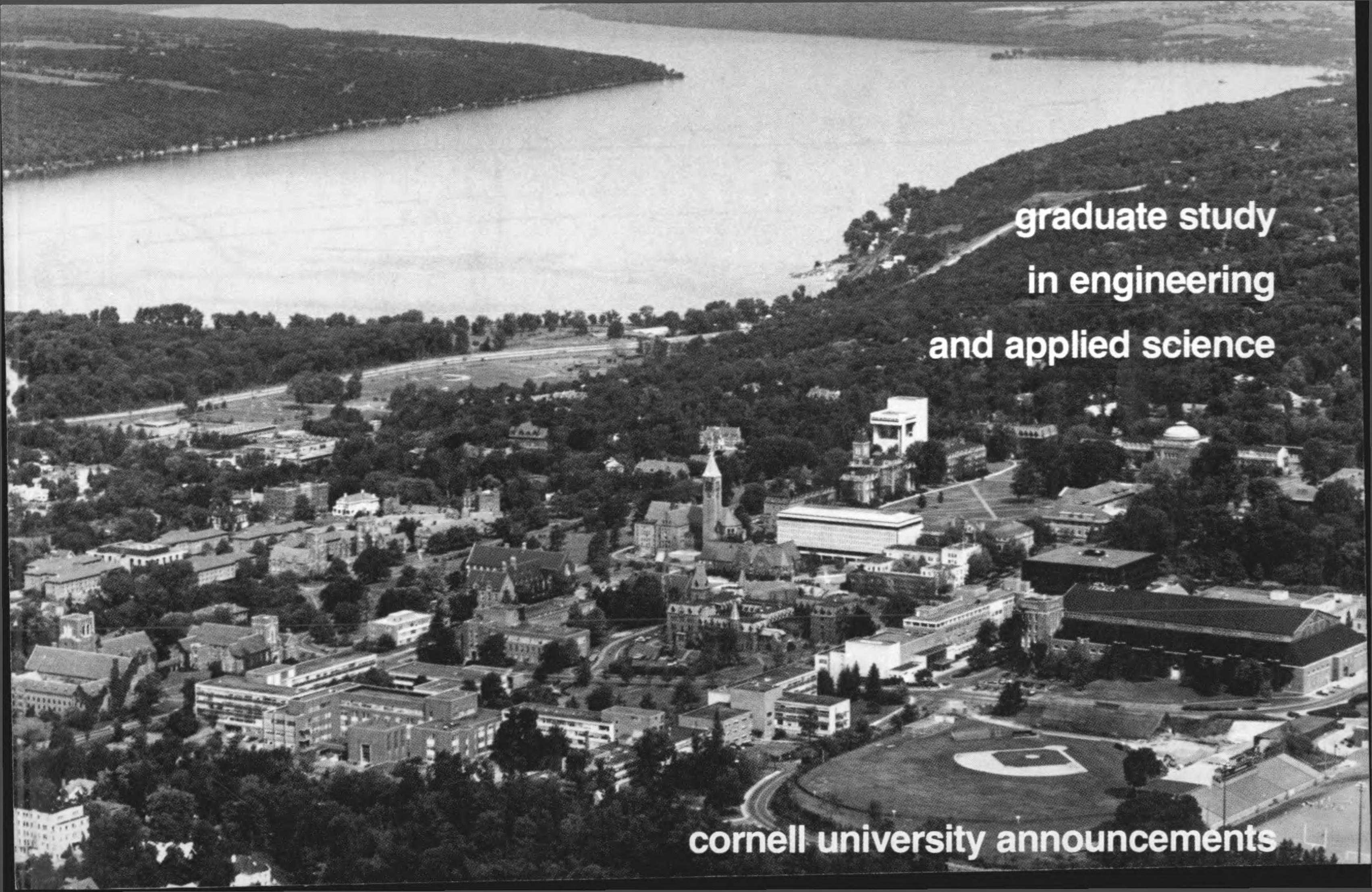
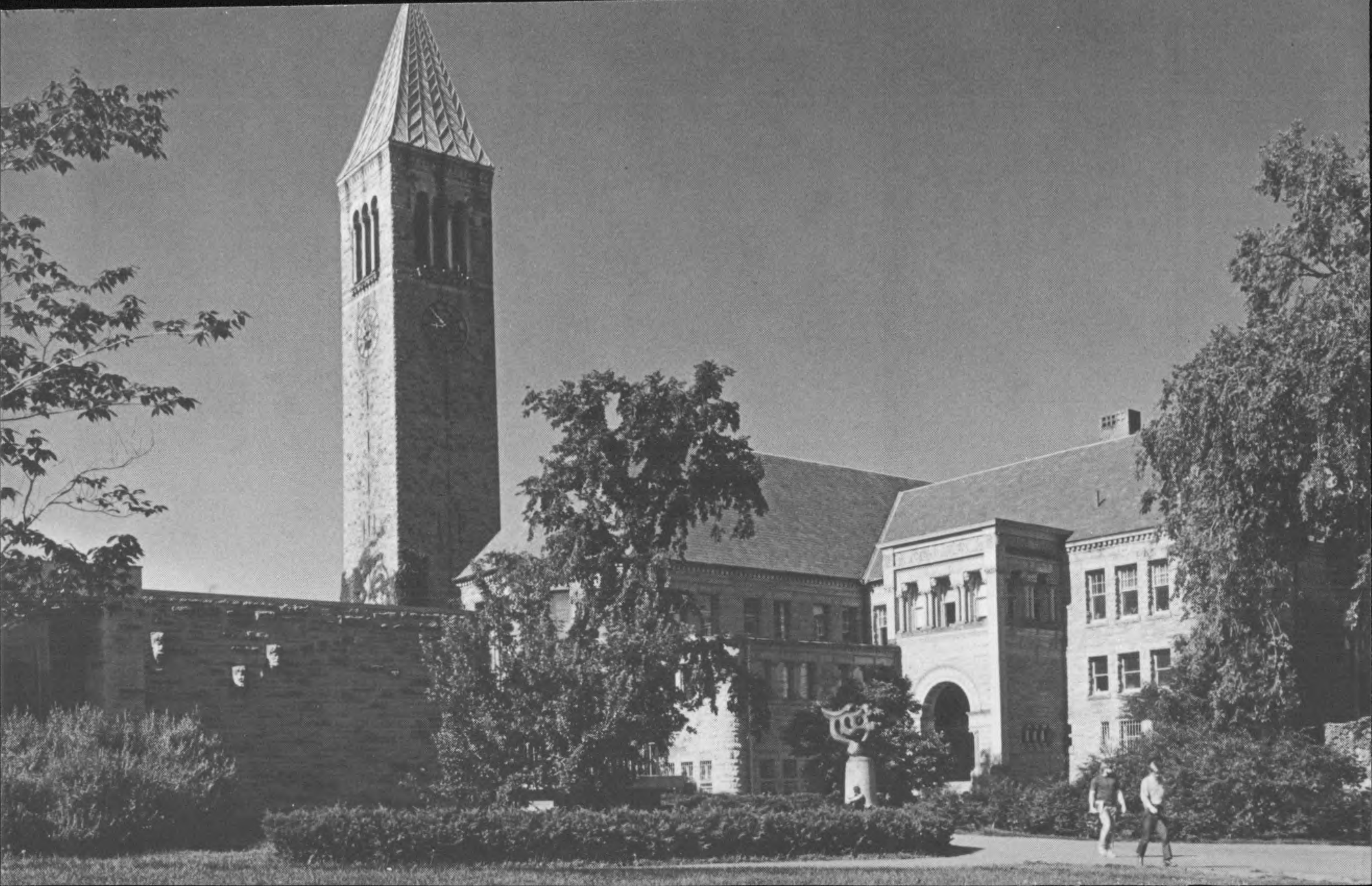


graduate study in engineering and applied science

cornell university announcements



Graduate Study in Engineering and Applied Science

Cornell University Announcements
(USPS 132-860)
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Cornell University
Ithaca, New York

Cornell University Announcements

Following is a list of *Announcements* published by Cornell University to provide information on programs, faculty, facilities, curricula, and courses of the various academic units.

Agriculture and Life Sciences
College of Architecture, Art, and Planning
College of Arts and Sciences
Graduate School of Business and Public Administration
Engineering at Cornell
Graduate Study in Engineering and Applied Science
General Information*
Graduate School
School of Hotel Administration
College of Human Ecology
School of Industrial and Labor Relations:
  ILR at Cornell
  Graduate Study at ILR
Law School
Medical College (New York City)
Graduate School of Medical Sciences (New York City)
Officer Education (ROTC)
Summer Session
New York State College of Veterinary Medicine

*The *Announcement of General Information* is designed to give prospective students pertinent information about all aspects and academic units of the University.

In addition to the *Announcements* listed above, the University publishes a master catalog of University courses, *Cornell University: Description of Courses*, and a handbook for enrolled students, *Academic Information*.

Requests for the publications listed above should be addressed to
Cornell University Announcements
Building 7, Research Park
Ithaca, New York 14850.
(The writer should include a zip code.)

Contents

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 and Doctor of Philosophy degrees and, in many cases, the professional Master of Engineering degree. Prospective students should understand the general nature of the programs leading to each of these advanced degrees, as well as the specific requirements.

All academic courses of the University are open to students of all races, religions, ethnic origins, ages, sexes, and political persuasions. No requirement, prerequisite, device, rule, or other means shall be used by any employee of the University to encourage, establish, or maintain segregation on the basis of race, religion, ethnic origin, age, sex, or political persuasion in any academic course of the University.

M.S. and Ph.D. Degrees

The prospective student who wishes to specialize in an engineering or related subject at the Master of Science or Doctor of Philosophy level 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 descriptions in this booklet of various graduate fields and their areas of activity may help the student choose a field.

The M.S. or Ph.D. candidate also selects a Special Committee, headed by the professor who will supervise the student's work and including two additional faculty members. The information in this publication may be helpful in making this selection. 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.

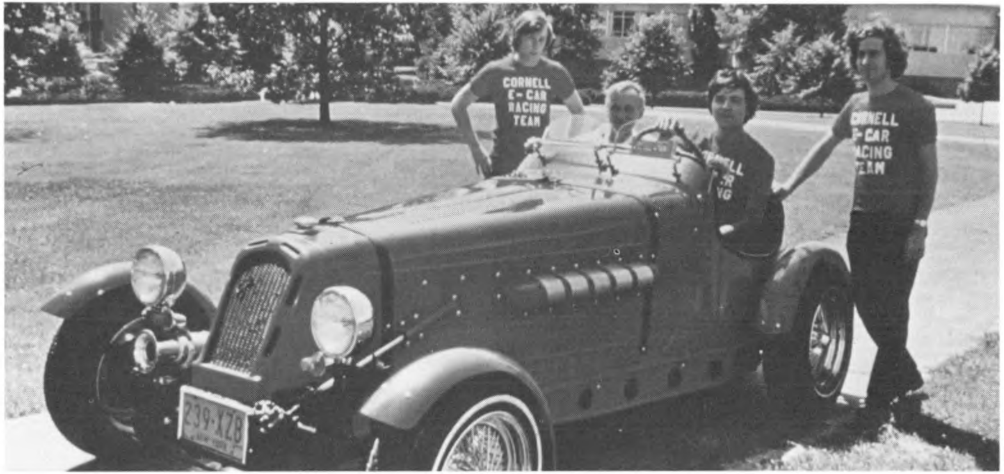
The Master of Engineering Degree Program

A one-year program leading to the professional Master of Engineering degree is offered in eleven fields of engineering and applied science. The degrees are:
M.Eng. (Aerospace)
M.Eng. (Agricultural)
M.Eng. (Chemical)
M.Eng. (Civil)
M.Eng. (Electrical)
M.Eng. (Engineering Mechanics)
M.Eng. (Engineering Physics)
M.Eng. (Materials)
M.Eng. (Mechanical)
M.Eng. (Nuclear)
M.Eng. (OR & IE)

These degrees are intended primarily for students who wish to prepare for professional careers in engineering or applied science. They 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.

The program prepares students for practice not only in the well-established engineering fields but also in new areas of technology and applied science that must be developed to serve the needs and to help solve the problems associated with a complex technology. Development of technical competence to move into such areas as water resources, energy conversion, information processing, or urban planning, for example, requires training beyond that of a four-year program. Graduate education is also needed as preparation for work in engineering areas that require significant economic, political, environmental, or social competence. The curricula stress advanced work in a particular area of application but also have broad flexibility to accommodate new combinations of course work. Every program emphasizes participation in a specific design project directed toward the development of competence and experience in the solution of a realistic or practical problem in engineering or applied science.

Many Master of Engineering degree holders enter small businesses or professional practice in industrial, government, or nonprofit organizations. An increasing number, however, are using the M.Eng. curriculum as part of a dual graduate degree program leading to both the M.Eng. and the Ph.D. degrees. 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.



Design work on models of the Cornell electric car is a continuing activity in the M.Eng. (Electrical) degree program.

Requirements for the degree include thirty credits of advanced technical work, normally completed in two semesters. Of these, a minimum of three credits must be earned by working on the design project. Financial aid is available in the form of scholarships and loans awarded on the basis of both academic merit and economic need. A limited number of teaching assistantships and fellowships are also open to M.Eng. degree candidates.

The programs of the eleven different professional engineering fields differ considerably in detail. Each is described under the appropriate subject area in the following sections.

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 help each other 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.

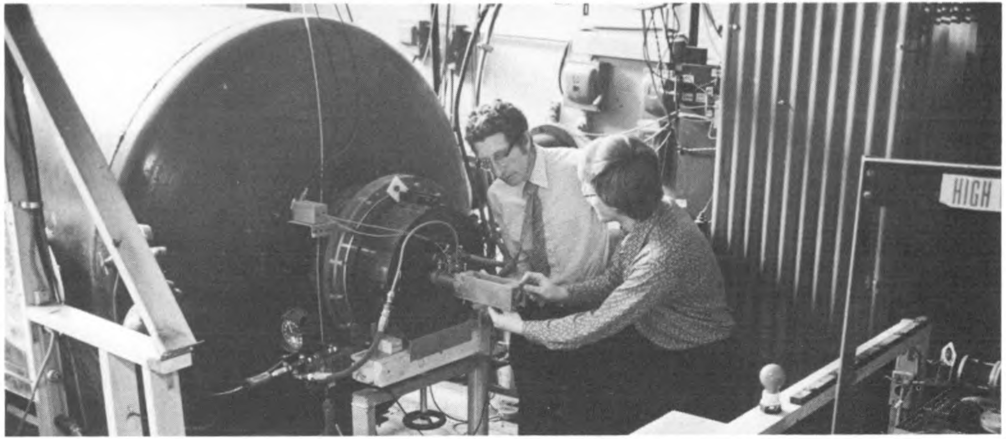
Active research topics are indicated by the following examples of recent theses (listed with the names of the supervising professors) and publications. A more complete list of publications is available upon request.

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

Caughey, D. A., and Jameson, A. 1977. Accelerated iterative calculation of transonic nacelle flowfields. *AIAA Journal* 15(10):1474.

Chen, H.-C. 1976. Applications of the finite element method to compressible flow problems. Ph.D. thesis (S.-F. Shen).

Cramer, M. S.; George, A. R.; and Seebass, A. R. 1976. Flowfield in the plane of symmetry below a delta wing. *AIAA Journal* 14(2):212.



A plasma wind tunnel is used to simulate the interaction of Earth's magnetic field with the solar wind in research directed by Professors Peter L. Auer and P. C. Tobias de Boer (who is shown at left in the photo).

Crow, J. E.; Auer, P. L.; and Allen, J. E. 1975. The expansion of a plasma into a vacuum. *Journal of Plasma Physics* 14(part 1):65.

de Boer, P. C. T., and David, T. S. 1977. Highly negative probes in a flowing continuum plasma. *AIAA Journal* 15:694.

de Boer, P. C. T., and Miller, J. A. 1976. Boundary layer effects on density measurements in shock tubes. *Journal of Chemical Physics* 64:4233.

George, A. R. 1977. Helicopter noise—state of the art. Paper no. 77-1337 read at AIAA 4th Aeroacoustics Conference, 3–5 October 1977, in Atlanta, Georgia. (To be published in *Journal of Aircraft.)*

George, A. R., and Kim, Y. N. 1977. High-frequency broadband rotor noise. *AIAA Journal* 15(4):538.

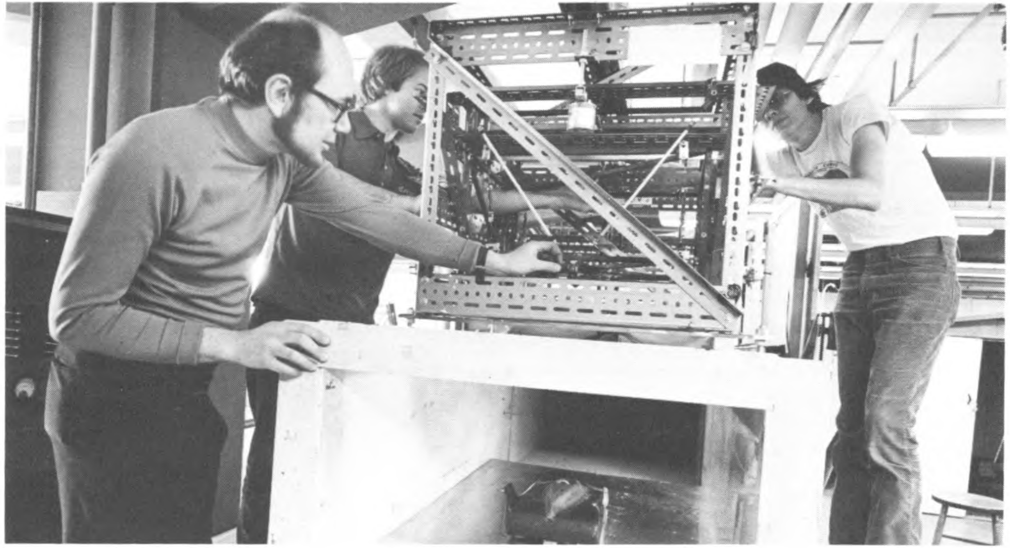
Habashi, W. 1975. A study of the finite element method for aerodynamic applications. Ph.D. thesis (S.-F. Shen).

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

Kosstrin, H. M. 1974. The reduction of nitric oxide emissions from hydrocarbon combustion sources. Ph.D. thesis (E. L. Resler, Jr.). Patent no. 4,015,161, *Anti-Pollution Spark Plug*, issued March 29, 1977, was based on this research.

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

Ludford, G. S. S. 1977. Combustion: basic equations and peculiar asymptotics. *Journal de Mécanique* 16(4):531.
Lumley, J. L. 1977a. Drag reduction in two phase and polymer flows. *Physics of Fluids Supplement* 20(10):564.
——. 1977b. Some applications of singular perturbations to problems in fluid mechanics. In *Singular perturbations and boundary layer theory,* ed. B. Gay and J. Mathieu, pp. 334–350. Berlin, Heidelberg, New York: Springer-Verlag.
Lumley, J. L., and Newman, G. R. 1977. The return to isotropy of homogeneous turbulence. *Journal of Fluid Mechanics* 82(1):161.
Nenni, J. P. 1976. An asymptotic approach to the separation of two-dimensional laminar boundary layers. Ph.D. thesis (S.-F. Shen).
Noir, D. 1975. The absorption of sound by turbulence. Ph.D. thesis (A. R. George).
Shen, S.-F. 1977. Finite-element methods in fluid mechanics. *Annual Review of Fluid Mechanics* 9:421.
Shen, S.-F., and Nenni, J. P. 1975. Asymptotic solution of the unsteady two-dimensional incompressible boundary layer and its applications on separation. In *Proceedings of the unsteady aerodynamics symposium,* ed. R. B. Kinney, pp. 245–259. Tucson: University of Arizona.
Wang, K. K.; Shen, S.-F.; Stevenson, J. F.; and Hieber, C. A. 1976. Computer-aided injection molding system. In *Proceedings of the NSF/RANN conference on production research and technology,* ed. G. Jacobi, pp. 22–28. Chicago: IIT Research Institute.
Warhaft, Z. 1976. Heat and moisture flux in the stratified boundary layer. *Quarterly Journal of the Royal Meteorological Society* 102:703.



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

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.

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 (W. J. McLean); 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).

The titles of some recent M.Eng. (Aerospace) projects and the faculty advisers are:

Automotive Efficiency Improvement System (W. J. McLean)
Design of a Two-State Burner for Combustion Studies (W. J. McLean)
Evaporation Time of Water Droplets from a Hot Plate (P. C. T. de Boer)
Visualization of Velocity Profiles in Unsteady Boundary Layers (S.-F. Shen)
Wind Tunnel Design and Calibration (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*
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, 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., Sc.D. (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*
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, 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 and empirical. 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 either the University or external 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 encouraged 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, programmable calculators, 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 utilization 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, with 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.

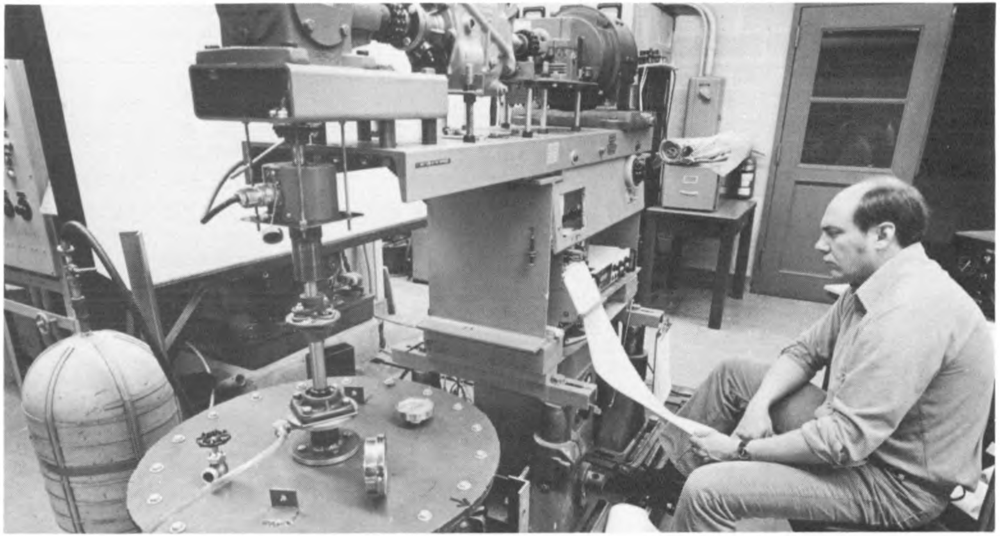
Brief descriptions of the research activity in six general areas are given in the following sections.

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

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 the use of producer gas as a petroleum substitute, solar heating and cooling of greenhouses and residences, wind-energy utilization for water heating, energy management on dairy farms, and the generation of methane gas from agricultural wastes. The National Science Foundation, the Department of Energy, and other federal, state, and industrial groups have provided funding for these projects. Most of them are multidisciplinary activities that utilize 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. A highlight of the energy work is two full-scale methane-generation reactors, designed for a family-sized farm with sixty-five cows, that are now in operation at Cornell's dairy research facility.

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

Froelich, D. P. 1976. Steady-periodic analysis of the greenhouse thermal environment. Ph.D. thesis (N. R. Scott).

Gunkel, W. W. 1978. Power sources and equipment. Chapter 12 in *Yearbook of agriculture — living on a few acres.* U.S. Department of Agriculture (in press).

Gunkel, W. W.; Price, D. R.; Lucas, G. M.; Murray, D. L.; Casler, G. L.; and Sutter, S. 1976. *Energy requirements for New York State agriculture. Part 2: Indirect energy inputs.* Agricultural Extension bulletin no. 406.

Jewell, W. J. et al. 1976. *Bioconversion of agricultural wastes for pollution control and energy conservation.* U.S. Energy Research and Development Administration (now Department of Energy) report no. TID-27164 (available through the National Technical Information Service).

Right above: A demonstration fermenter for generating methane from dairy waste is in operation at Cornell's Animal Science Teaching and Research Center at Harford, New York. This plug-flow generator was designed as part of a study sponsored by the U.S. Department of Energy.

Right: The use of solar energy for heating greenhouses is being studied by a research group including Professor Donald R. Price (at left).

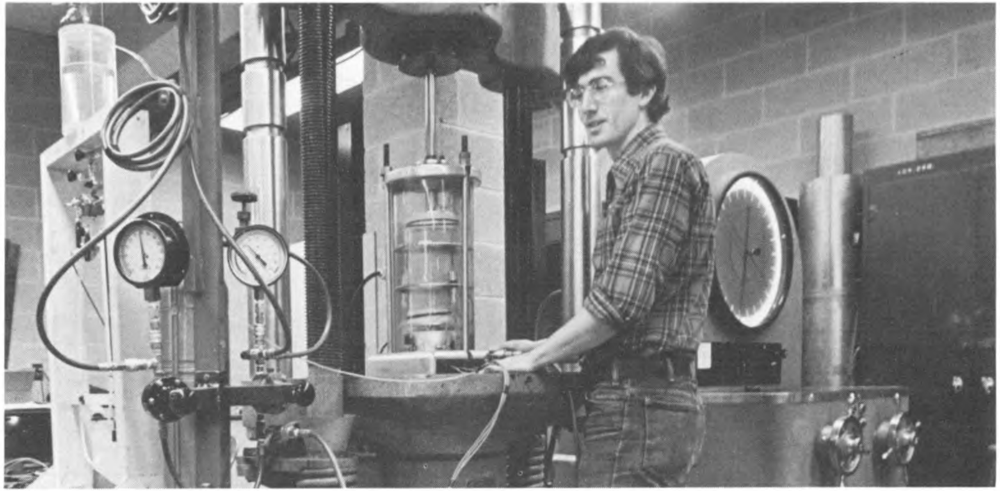
Jewell, W. J. et al. 1978. *Anaerobic fermentation of agricultural residues: potential for improvement and implementation.* U.S. Department of Energy report no. ACP/T2981-07 (available through the National Technical Information Service).

Neyeloff, S. 1976. The use of anaerobic digester's gas as a fuel for internal combustion engines: the effects of carbon dioxide dilution. M.S. thesis (W. W. Gunkel).

Price, D. R., Weeks, S. A. et al. 1976. Reduction of energy and detergent use for cleaning milk handling equipment. In *33rd annual progress report to the New York Farm Electrification Council,* pp. 24–35. Ithaca, N.Y.: Cornell University.

Williams, D. W.; McCarty, T. R.; Morris, G. R.; Gunkel, W. W.; and Price, D. R. 1976. Utilization of biogas for farm production energy. *Transactions of the ASAE* 19(6):1034.

Wilson, G. E., and Price, D. R. 1977. Increasing the effectiveness of the greenhouse as a solar collector. ASAE paper no. 77-4527, presented at the 1977 Winter Meeting of the American Society of Agricultural Engineers in Chicago, Illinois.



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

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 studies of flood control and flood-plain management, investigations of the use of soil-stabilization methods to improve marginal gravels for farm-to-market roads, and planning studies for rural areas. Some of the questions that are asked in these studies deal with the impact of part-time farmer residents on the economy and development of rural areas, the need for improved low-volume rural roads, land or landfill disposal of sewage sludge, flood control in small watershed projects, and improvements of marginal agricultural land.

Examples of publications, theses, and reports resulting from work in this area are listed below (related material is cited under Environmental Quality and Water Management):

Cowell, M. S. 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).

Gerling, J. F. 1976. An analysis of the factors influencing development in the Nanticoke Creek watershed. M.P.S. report (L. H. Irwin).

Irwin, L. H. 1976. The need for secondary roads engineering. *American Road Builder* 53(5):21.

——.1977a. Determination of pavement layer moduli from surface deflection data for pavement performance evaluation. In *Proceedings of 4th international conference on the structural design of asphalt pavements,* pp. 831–840. Ann Arbor: University of Michigan.

——.1977b. Transportation problems and research needs in the rural sector. In *Transportation research circular,* no. 187, pp. 19–22. Transportation Research Board, National Academy of Sciences.

——.1978. Use of fracture energy as a fatigue failure criterion. In *Proceedings of the Association of Asphalt Paving Technologists,* vol. 46. San Antonio, Texas (in press).

Environmental Quality and Water Management

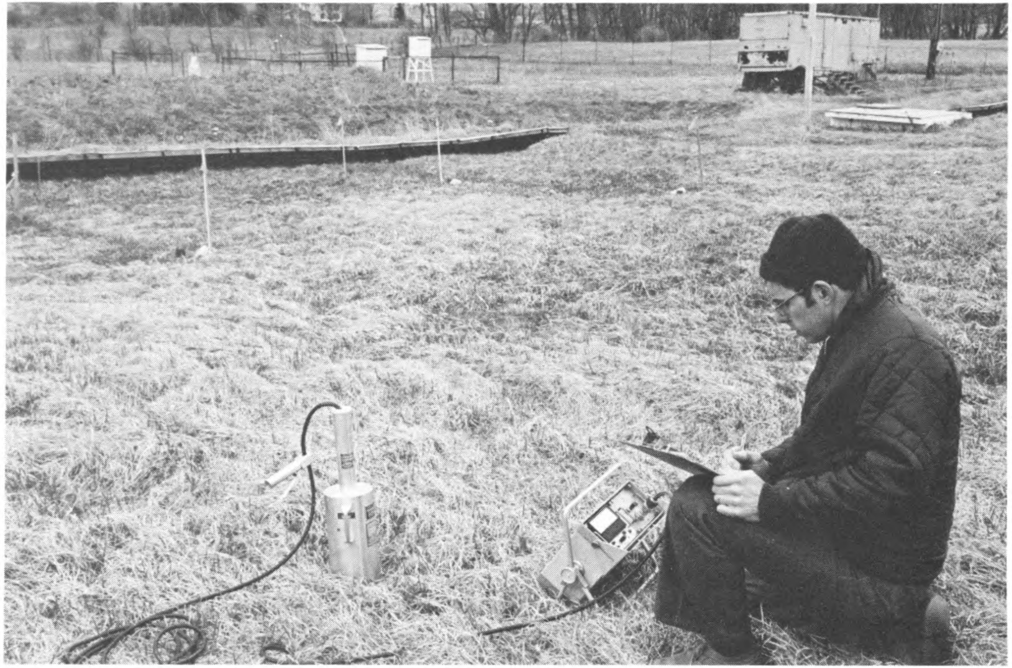
Agricultural waste residues and problems associated with the rural environment are among the greatest challenges to engineers and scientists concerned with environmental quality management. The trend toward confinement feeding of livestock, the increasing size of food-processing operations, and the high concentrations of waste, as well as the necessity to avoid water, air, and soil pollution, make imperative a successful attack on the waste, water, and soil management problems that are facing agriculture.

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 rural pollution associated with humans, animal-waste management, pollution control in food and fiber production, and land use and nutrient management to optimize environmental quality. A new additional focus of this program is the use of land for recycling and recovery of wastewater and sludges.

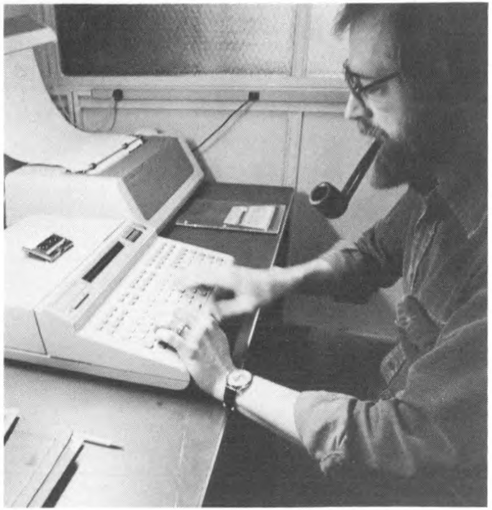
Current research efforts include projects on the treatment of animal wastes, feasible handling and treatment processes and analytical models for animal-waste management, application of municipal and agricultural wastes to land, the establishment of design parameters for agricultural-waste management systems, and projects to determine the feasibility of generating energy from agricultural wastes.

Hydrologic studies dealing with the application of engineering principles to problems in soil and water management include the design and construction of drainage systems, the evaluation of water budgets in a humid area, soil-plant-water relationships, small-watershed hydrology, and nonpoint-source pollution.



Field studies of agricultural waste runoff are conducted in controlled plots. The trailer houses data-acquisition equipment.

Other research in the area of soil and water management includes studies of the inflow component of runoff, the interaction of water movement and materials transport, groundwater recharge, and water movement in frozen soils. Related work is also under way in problems of tropical irrigation.



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

Examples of publications and theses on these subjects are:

Allee, D. J., and Walter, M. F. 1976. Implementation of non-structural flood risk management in the northeastern U.S.: a review of informational needs. In *Proceedings of conference on flood damage abatement.* Blacksburg, Va.: Virginia Water Resources Research Center, Virginia Polytechnic Institute.

Anthonisen, A. C.; Loehr, R. C.; Prakasam, T. B. S.; and Srinath, E. G. 1976. Inhibition of nitrification by ammonia and nitrous acid. *Journal of the Water Pollution Control Federation* 48(2):835.

Black, R. D.; Walter, M. F.; and Swader, F. N. 1977. Apparent effects of subsurface drainage on soil physical properties. In *Proceedings of 3rd national drainage symposium.* ASAE publication I-77. St. Joseph, Mich.: American Society of Agricultural Engineers.

Chen, Y. R., and Hashimoto, A. G. 1976. Rheological properties of aerated poultry waste slurries. *Transactions of the ASAE* 19(1):128.

Coote, D. R.; Haith, D. A.; and Zwerman, P. J. 1976. Modeling the environmental and economic effects of dairy waste management. *Transactions of the ASAE* 19(2):326.

Cummings, R. J., and Jewell, W. J. 1977. Thermophilic aerobic digestion of dairy waste. In *Food, fertilizer and agricultural residues,* ed. R. C. Loehr, pp. 639–658. Ann Arbor, Mich.: Ann Arbor Science Publishers.

Haith, D. A. 1976. Land use and water quality in New York rivers. *ASCE Journal of the Environmental Engineering Division* 102(EES):1.

Haith, D. A., and Dougherty, J. V. 1976. Nonpoint source pollution from agricultural runoff. *ASCE Journal of the Environmental Engineering Division* 102(EES):1055.

Haith, D. A.; Koenig, A.; and Loucks, D. P. 1977. Preliminary design of wastewater land application systems. *Journal of the Water Pollution Control Federation* 49(12):2371.

Jewell, W. J. et al. 1976. Control and treatment of egg breaking and processing wastes, parts 1 and 2. *Industrial Wastes* 22(2,3):26.

Jewell, W. J.; Kodukula, P. S.; and Wujik, W. J. 1978. *Limitations of land treatment of wastes in the vegetable processing industries.* Final report, Department of Agricultural Engineering, Cornell University.

Jewell, W. J., and Seabrook, B. L. 1977. *Historical review of land application as an alternative treatment process for wastewaters.* U.S.

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.

Environmental Protection Agency report no. EPA 430/9-77-008, MCD.
Loehr, R. C., ed. 1976. *Land as a waste management alternative.* Ann Arbor, Mich.: Ann Arbor Science Publishers.
Loehr, R. C., ed. 1977. *Food, fertilizer and agricultural residues* (proceedings of Cornell agricultural waste management conference). Ann Arbor, Mich.: Ann Arbor Science Publishers.
Loehr, R. C.; Jewell, W. J.; Novak, J. D.; Clarkson, W. W.; and Friedman, G. F. 1978. *Land application of wastes: an educational program.* Florence, Ky.: Van Nostrand (in press).
Ludington, D. C., and Sobel, A. T. 1977. Storability of partially dried poultry manure. In *Food, fertilizer and agricultural residues,* ed. R. C. Loehr, pp. 581–598. Ann Arbor, Mich.: Ann Arbor Science Publishers.
MacVicar, T. K. 1978. A solid state transducer for recording piezometer systems. M.S. thesis (M. F. Walter).
Martin, J. H., and Loehr, R. C. 1977. *Poultry waste management alternatives: a design and application manual.* Report no. EPA-600/2-77-204, U.S. Environmental Protection Agency. Athens, Georgia.
McCarty, T. R. 1977. The effect of bedding rate on the form and quantity of nitrogen in a solid manure system. M.S. thesis (D. C. Ludington).
Nieber, J. L.; Walter, M. F.; and Black, R. D. 1976. *A review and analysis of selected hydrologic modelling concepts.* Ithaca, N.Y.: Water Resources and Marine Sciences Center, Cornell University.
Safley, L. M. 1977. System selection and optimization models for dairy manure handling systems. Ph.D. thesis (D. R. Price).
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. *Transactions of the ASAE* (in press).

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

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

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

production, processing, and handling has also been considered. One study was concerned with the relation of human visual capacity to the monitoring of trailed vehicles and the detection of malfunctions. Another study dealt with the relationships of energy demands of the food system to the type of foods supplying the recommended dietary allowance for humans.

Examples of publications and theses in this area are:

Albright, L. D. 1976. Cooling short cylinders in air using a water spray. *Transactions of the ASAE* 19(4):762.

Balthazar, J. A. 1978. Response of the dairy cow's teat by finite element analysis. M.S. thesis (N. R. Scott).

Chapman, C. D.; Rand, R. H.; and Cooke, J. R. 1977. A hydrodynamical model of bordered pits in conifer tracheids. *Journal of Theoretical Biology* 67:11.

Cole, G. W. 1976. A model of heat transfer from the respiratory tract of a chicken. Ph.D. thesis (N. R. Scott).

Cole, G. W., and Scott, N. R. 1977. A mathematical model of the dynamic heat transfer from the respiratory tract of a chicken. *Bulletin of Mathematical Biology* 39:415.

Cooke, J. R.; De Baerdemaeker, J. G.; Rand, R. H.; and Mango, H. A. 1976. A finite element shell analysis of guard cell deformations. *Transactions of the ASAE* 19(6):1107.

Delwiche, M. J., and Cooke, J. R. 1977. An analytical model of the hydraulic aspects of stomatal dynamics. *Journal of Theoretical Biology* 67:113.

Gartland, P.; Schiavo, J.; Hall, C. E.; Foote, R. H.; and Scott, N. R. 1976. Detection of estrus in dairy cows by electrical measurements of vaginal mucus and by milk progesterone. *Journal of Dairy Science* 59(5):982.

Hillman, P. E.; Scott, N. R.; and van Tienhoven, A. 1977. Impact of centrally applied biogenic amines upon the energy balance of fowl. *American Journal of Physiology: Regulatory Integrative and Comparative Physiology* 232(5):R137.

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

Ku, A. C.; Furry, R. B.; Jordan, W. K.; and Dropkin, D. 1977. Numerical analysis of heat and mass transfer during freeze-drying. In *Proceedings of the international symposium on freeze-drying of*

A researcher enters a controlled-environment chamber used in studies of optimal storage conditions for vegetables. The low oxygen levels are insufficient to sustain human life.

biological products, pp. 207–219. Basel, Switzerland.
Mabry, C. A. 1978. Thermoregulatory responses of poultry to local heating and cooling of the spinal cord. M.S. thesis (N. R. Scott).
Moutner, D. N. 1977. A mathematical model of oxygen diffusion in potato tissue. M.S. thesis (J. R. Cooke).
Pettibone, C. A., and Scott, N. R. 1976. Relationship of temperatures in the cervical blood vessels to brain temperatures in chickens. *Transactions of the ASAE* 19(4):736.
Scott, N. R., and Reitsma, S. Y. 1978. Factors which affect milk flow rate in linerless milking systems. In *Proceedings of the international symposium on machine milking,* pp. 162–175. Washington, D.C.: National Mastitis Council.
Sooter, C. A., and Millier, W. F. 1978. The effect of pellet coatings on seedling emergence from lettuce seeds. *Transactions of the ASAE* (in press).

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. The research is interdisciplinary, with cooperative field-oriented activities involving several departments of the College of Agriculture and Life Sciences as well as such agencies as the International Rice Research Institute, the University of the Philippines, the Sino-American Joint Commission on Rural Reconstruction in Taiwan, and the Khuzestan Water and Power Authority in Iran.

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.

Professor Gilbert Levine (at center) directed a recent study of rice-field irrigation in the Philippines.

A sampling of research activities is given by these recent theses:

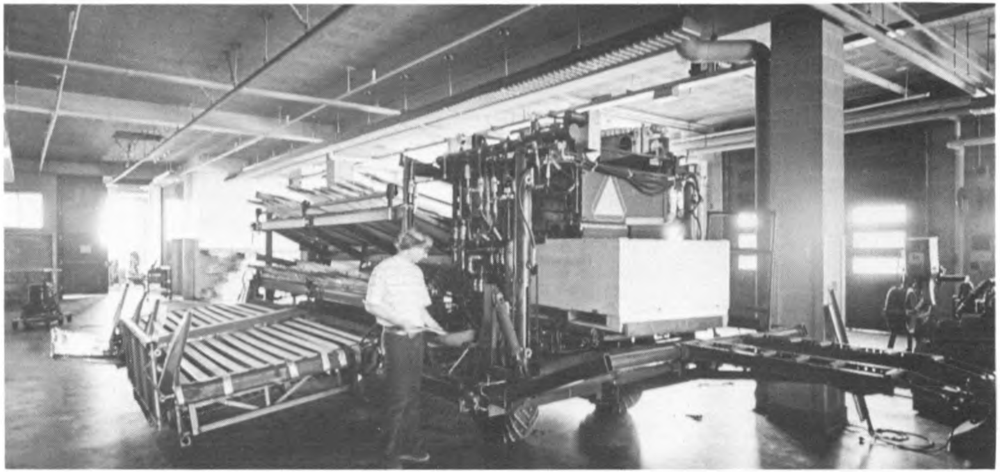
Early, A. C. 1976. The influence of water management policies on operating policies for sugar cane districts in the Philippines. Ph.D. thesis (G. Levine).
Miranda, S. M. 1975. The effects of physical water control parameters on Philippine lowland rice irrigation system performance. Ph.D. thesis (G. Levine).
Wolf, J. M. 1975. Water constraints in corn production in central Brazil. Ph.D. thesis (G. Levine).

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.



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

Right: This apple-box dumper unloading fruit onto a grading line was designed to unload from the top to reduce bruising.

Cornell research and development efforts have been directed also 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 was studied in a project involving simulation studies of tractor motion in overturns.

Examples of publications and theses in this area are:

Albright, L. D. 1976. Air flow through hinged baffle slotted inlets. *Transactions of the ASAE* 19(4):728.

Albright, L. D., and Scott, N. R. 1977. Diurnal temperature fluctuations in multi-airspaced buildings. *Transactions of the ASAE* 20(2):319.

Chowdhury, A. H.; White, R. N.; and Scott, N. R. 1977. Small scale models for reinforced concrete structures. *Transactions of the ASAE* 20(1):132.

Eiland, B. R. 1976. An apple tree response to a high frequency trunk shaking. M.S. thesis (W. F. Millier, 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.

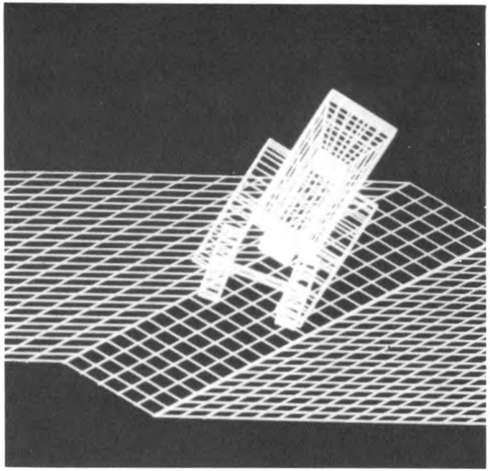
Masemore, B. J. 1978. Influence of tractor geometry and mass on side overturns. M.S. thesis (G. E. Rehkugler).

Millier, W. F.; Rehkugler, G. E.; Pellerin, R. A.; and Throop, J. A. 1977. High capacity harvesting apparatus. U.S. patent no. 4,014,440 (21 claims).

Myers, A. W. 1976. Instructional materials related to moldboard plows, plowing and plow adjustment. M.P.S. report (W. W. Gunkel).

Pellerin, R. A.; Millier, W. F.; Lakso, A. N.; Rehkugler, G. E.; Throop, J. A.; and Allport, T. E. 1978. Apple harvesting with an inertial *vs.* impulse trunk shaker on open center and central leader trees. *Transactions of the ASAE* (in press).

Rehkugler, G. E.; Atherton, P.; and Kelly, J. E. 1978. Simulating the motion of two- and four-wheel drive tractors. *Agricultural Engineering* 59(3):17.



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

Rehkugler, G. E.; Kumar, V.; and Davis, D. C. 1976. Simulation of tractor accidents and overturns. *Transactions of the ASAE* 19(4):602.

Rehkugler, G. E.; Millier, W. F.; Pellerin, R. A.; and Throop, J. A. 1976. Analysis of a reciprocating panel fruit lowering device. *Transactions of the ASAE* 19(1):30.

Scura, L. T., Jr. 1976. Mechanization of root-soil separation in bare-root harvesting of nursery stock. M.S. thesis (W. W. Gunkel).

Srivastava, A. K., and Rehkugler, G. E. 1976. Strain rate effects in similitude modeling of plastic deformation of structures subject to impact loading. *Transactions of the ASAE* 19(4):617.

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*

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*

Edward W. Foss, B.S.A. (New Hampshire), M.S.A. (Cornell): *safety engineering, community resources development, the teaching of agricultural mechanization*

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 utilization for farm use, 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*
Donald R. Price, B.S. (Purdue), M.S. (Cornell), Ph.D. (Purdue): *electric power and processing, energy utilization, systems engineering analysis*
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 utilization in the food system relative to human nutrition*
Norman R. Scott, 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*
Michael F. Walter, B.S., M.S. (Illinois), Ph.D. (Wisconsin): *water resources, water management, small-watershed hydrology, drainage*

Further Information

The publication *Department of Agricultural Engineering: The Staff and Program,* published each fall, contains summary information on current teaching, research, and extension activities of the Department of Agricultural Engineering. Another publication, *Agricultural Engineering Research,* describes new and continuing research projects, lists the faculty and staff members and graduate students involved in each project, and indicates the major cooperating units in interdisciplinary projects. 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.

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 from the various 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.

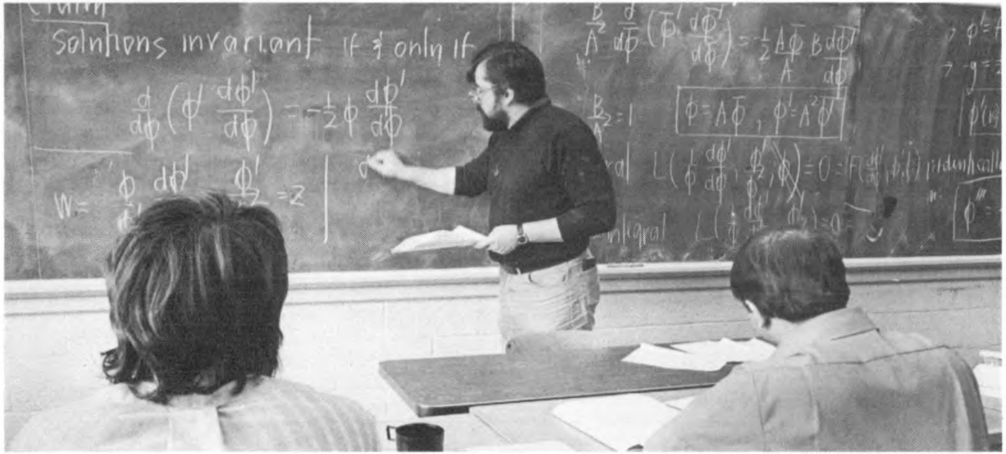
Research and study in this field are coordinated through the Center for Applied Mathematics. There are some forty core faculty members in the center, and graduate students occasionally do their thesis research under additional faculty members not formally associated with this field. The center does not offer courses itself; 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.

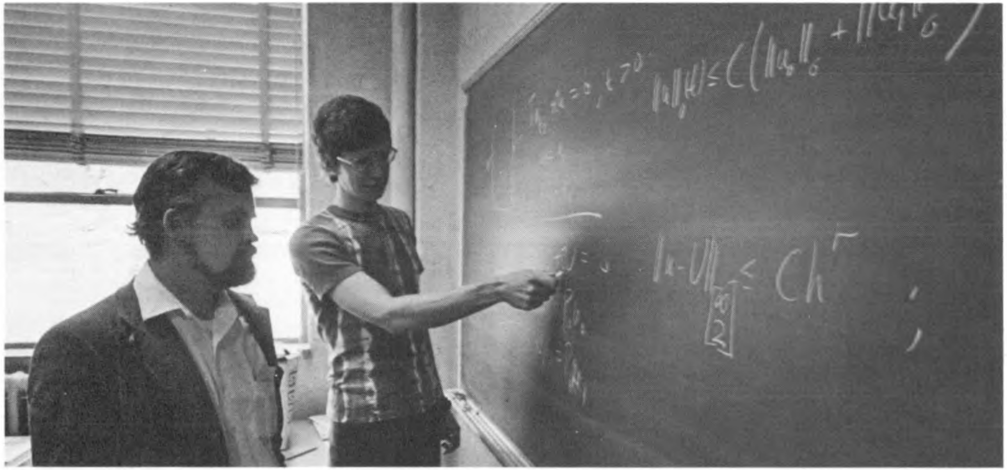
Facilities

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.





The following recent theses, listed with the supervising professors, 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 in lattice spin systems. Ph.D. thesis (M. E. Fisher).

Harlow, D. G. 1977. Probabilistic models for the tensile strength of composite materials. Ph.D. thesis (H. M. Taylor 3d).

Hastings, A. M. 1977. Some models in population biology. Ph.D. thesis (S. A. Levin).

Knopf, P. M. 1977. Weak-type multipliers. Ph.D. thesis (R. S. Strichartz).

Mansfield, P. J. 1977. On logarithmic Sobolev inequalities. Ph.D. thesis (L. Gross).

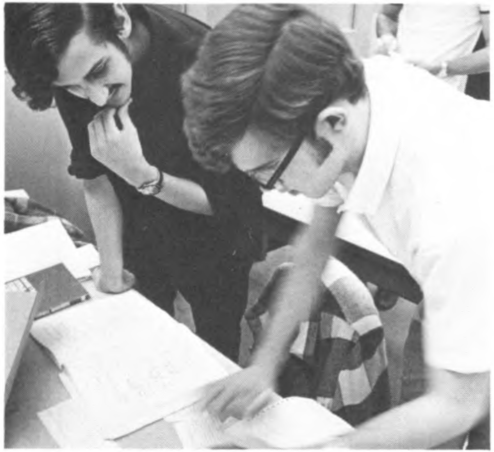
Marwil, E. S. 1978. Exploiting sparsity in Newton-like methods. Ph.D. thesis (J. E. Dennis).

Winther, R. 1977. A numerical Galerkin method for a parabolic control problem. Ph.D. thesis (J. H. Bramble).

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 (at left) and Lars B. Wahlbin discuss a problem in partial differential equations.



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*

James H. Bramble, A.B. (Brown), M.S., Ph.D.

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

(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*

John E. Dennis, B.S., M.S. (University of Miami), Ph.D. (Utah): *numerical mathematics, mathematical programming*

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. (Southhampton, England): *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*
Jack C. Kiefer, B.S., M.S. (M.I.T.), Ph.D. (Columbia): *probability and statistics*
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*
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, such as the Laboratory of Plasma Studies, the Cornell High Energy Synchrotron Source (CHESS), the Materials Science Center, and the Center for 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 techniques for electron microscopy and electron spectroscopy, for x-ray analysis and metallography, for special materials preparation, for chemical analysis, and for studies at very high or low pressures and temperatures are provided by the facilities of the University's Materials Science Center. Also, the Field of Applied Physics is closely associated with two new major research facilities at Cornell, the National Research and Resource Facility for Submicron Structures (NRRFSS) and the Cornell High Energy Synchrotron Source (CHESS).

NRRFSS was established at Cornell by the National Science Foundation (NSF) through a grant for five million dollars. Cornell's ongoing research programs in applied physics and electrical engineering were the pivotal factors in the selection of this university as the host institution. A large fraction of the research groups in the Field of Applied Physics will be associated with the submicron facility as users and contributors; programs that will contribute significantly to the work of the facility include those in surface physics, electron optics, and electron-energy-loss spectroscopy.

CHESS is a multiuser laboratory that has been established by NSF in connection with the Cornell Electron Storage Ring (CESR) now under construction (it is scheduled for completion in 1979). CESR— a facility that Cornell is very fortunate to have— will cover the single-particle energy range of from 4 to 8 GeV and will open up exciting possibilities in elementary particle physics. CHESS will make use of an important by-product of the stored high-energy particles: an enormous quantity of highly collimated x and ultraviolet radiation. This radiation can be collected and used as an experimental probe in an extraordinarily wide range of disciplines, from solid-state physics and chemistry to materials science and biology. The spectrum provided by CHESS will be unique internationally in its high-energy x-ray flux, and the center will provide experimental facilities for scientific and technological applications of these x rays. Synchrotron radiation is an exciting new tool in fundamental and applied research; facilities larger than CHESS are planned on a national scale. Cornell researchers in the Field of Applied Physics will have the remarkable opportunity to build and operate for the entire scientific community this prototype high-energy synchrotron source.

Other facilities available for applied physics research include the radar-radio observatory in Arecibo, Puerto Rico; the unique high-current relativistic electron beam facility of the Laboratory of Plasma Studies; the tunable laser facility of the Materials Science Center; the synchrotron; and semiconductor growth and processes laboratories.

In the Ward Laboratory of Nuclear Engineering students can use a fast-pulsed TRIGA neutron reactor, an x-ray irradiation cell, a low-flux nuclear critical facility, and a high-current charged-particle accelerator (Dynamitron) for energies up to 3 MeV.

Areas of Research

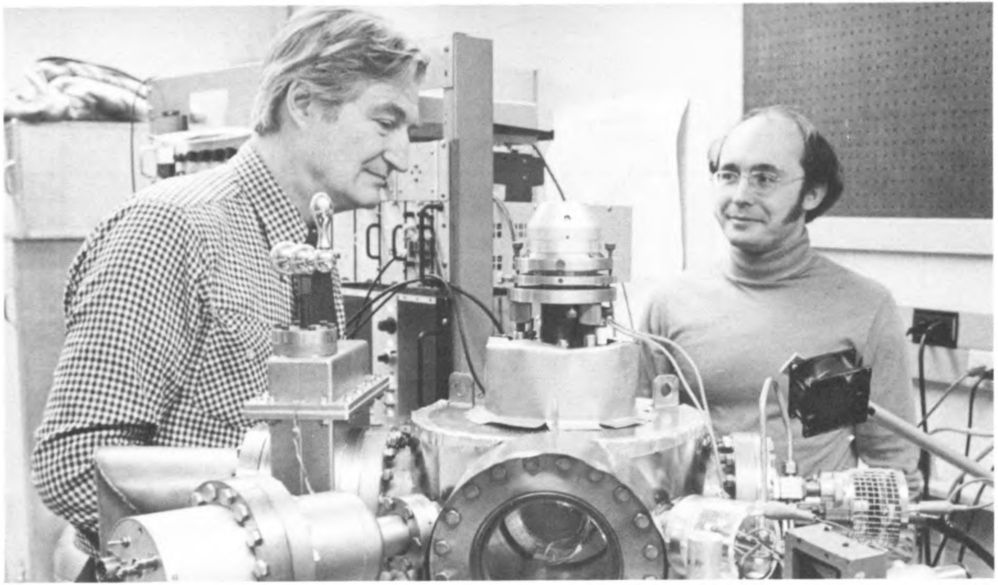
The broad applicability of the principles and techniques of physics is illustrated by the many research areas within the Field of Applied Physics. Examples of current programs are described in the nine general categories listed below; the names of professors working with specific projects are indicated in parentheses. (This material was prepared in the spring of 1978; 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 approaches, from theory to experiment. 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 ultra-sensitive 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 utilize 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 the new National Research and Resource Facility for Submicron Structures at Cornell. 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).

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

Other research in this general area concerns structure studies of phase transformations associated with high-field superconductors and with the properties of flux line lattices in Type II superconductors, where 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 principally 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 wide 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).

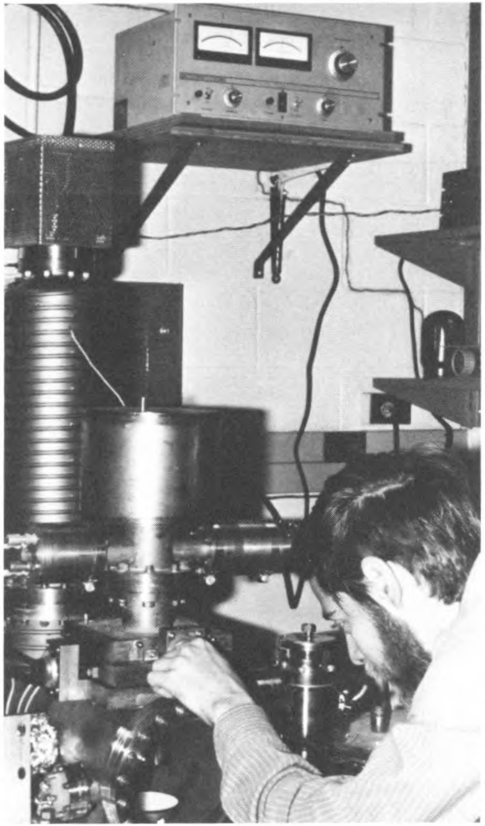
One example of limited dimensionality is the optical and electronic response of inhomogeneous materials. Of particular interest is the optical behavior of ceramic/metal (cermet) composite films. Ongoing research has shown that such materials can be adapted to be extremely viable candidates for application 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 submicron 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).

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

When electrons pass through an electron microscope specimen, inelastic scattering representing transfer of energy to the sample can occur. The modes in which the specimen can absorb this energy reflect the electronic structure and thus the chemical structure of the sample. The addition of an electron spectrometer to an electron microscope makes it possible to obtain this chemical information along with the spatial information normally accessible with an electron microscope. The angular dependence of the scattering reflects the momentum dependence with which the specimen absorbs the energy, and this in turn reflects new types of electronic structural information. Experimental work of this sort has included studies of plasmon, surface plasmon, and surface guided optical modes, and of inter- and intra-band excitations: studies of inner-core excitations are currently under way. In addition, background scattering and its temperature dependence are being investigated in order to determine ultimate limits and approaches to chemical analysis. (J. Silcox).

The generation and measurement of extremely high pressures, and the performance of experiments at these pressures, have been the subject of a substantial research effort. Pressures approaching two megabars have been achieved with the use of tiny spherical indentors made of



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.

diamond, and submicron fabrication techniques have made possible the use of interdigitated electrodes on the diamond indentors to probe matter at extreme pressures. (A. Ruoff).

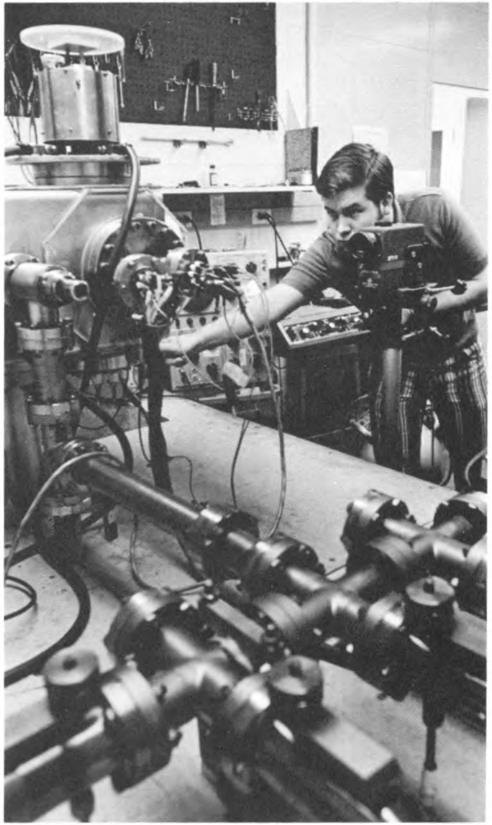
Liquid crystals display a variety of bizarre phenomena because of their unique combination of liquid and solid properties. Defect structures, transport processes, and phase transitions in smectic liquid crystals are currently under study with the help of special laser-optical techniques. Of particular 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 Laboratories and the Cornell 12-GeV synchrotron. The new Cornell High Energy Synchrotron Source (CHESS), to be completed in 1979 in conjunction with the 8-GeV storage ring, will permit an expanded program of research. (B. W. Batterman).

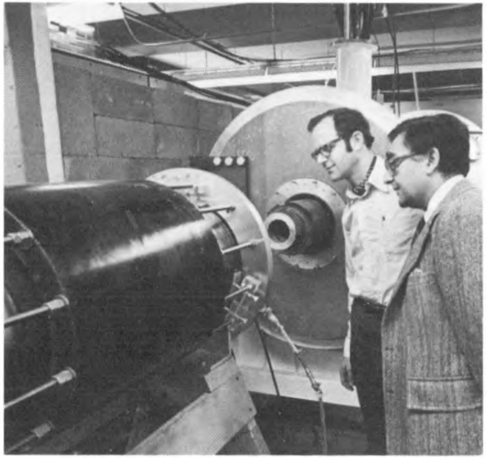
Some recent typical publications and theses (listed with the name of the supervising professor) in the area of solid-state physics are:

Agrawal, D. C.; Loomis, B. A.; and Kramer, E. J. 1976. Flux pinning by radiation damage in oxygen-doped niobium. *Philosophical Magazine* 33:343.



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

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.
Billington, R. L. 1978. Electron structure of clean and chemisorbed transition metals using field electron tunneling spectroscopy. Ph.D. thesis (T. N. Rhodin).
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.
Brucker, C. F., and Rhodin, T. N. 1977. Reaction of acetylene and ethylene on the αFe (100) clean iron surface. *Journal of Catalysis* 47:214.
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., and Buhrman, R. A. 1977. Optical properties of selectively absorbing Ni/Al_2O_3 composite films. *Applied Physics Letters* 31:423.
Jackel, L. D. 1976. Experimental study of superconducting weak links. Ph.D. thesis (R. A. Buhrman).
Kramer, E. J. 1978. Fundamental defect-fluxoid interaction in irradiated superconductors. *Journal of Nuclear Materials* 72:5.
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).
Seidman, D. N. 1978. The study of radiation damage in metals with the field-ion and atom-probe microscopes. *Surface Science* 70:532.



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

Tang, C. L.; Kreismanis, V. G.; and Ballantyne, J. M. 1977. Wide band electro-optical tuning of semiconductor lasers. *Applied Physics Letters* 30:113.
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. Much of this work is conducted at the interdepartmental Laboratory of Plasma Studies.

The principal subject of plasma research at Cornell is the confinement and heating of thermonuclear plasmas. Cornell is recognized as the leading university in the area of the technology of high-current ion beams and relativistic-electron beams and their application in thermonuclear studies. Current topics of research include magnetic configurations and instabilities and waves in plasmas, collisionless shock waves, magnetospheric and ionospheric plasma physics, plasma turbulence, kinetic theory, and astrophysical plasmas.

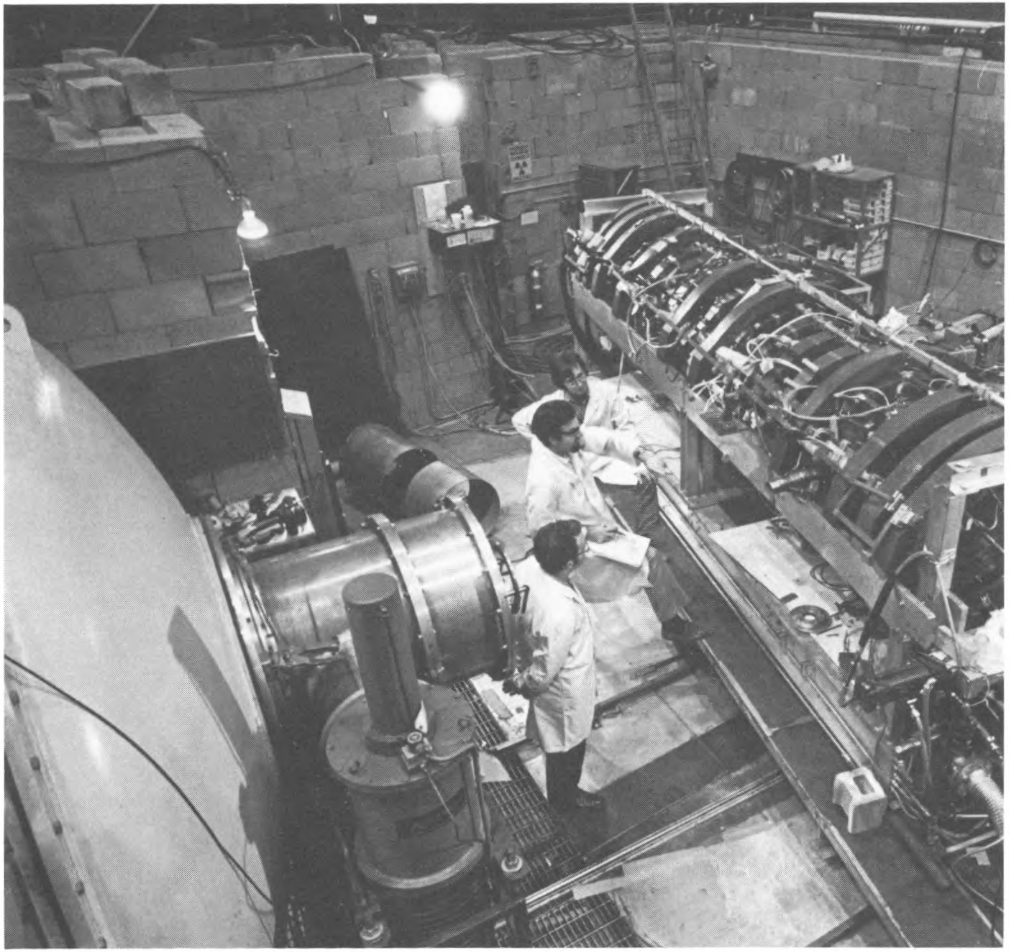
The dynamic behavior of fully ionized plasmas is being studied with the use of a plasma wind tunnel under conditions in which collective plasma effects are important but ordinary collisions between single particles are not. These studies relate to the understanding of collision-free shock formation and the nature of the Earth's bow shock in the solar wind. (P. L. Auer, P. C. T. de Boer).

Valuable experimental facilities for plasma studies include pulsed high-power Marx generators, used to generate intense ion and electron beams. Two potential applications of these beams for thermonuclear fusion 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. Fleischmann, D. Hammer, R. 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. (R. Sudan, D. Hammer, C. 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 wide 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 (R. Lovelace, E. Ott, R. Sudan), and part involves the development and use of large-scale computer programs for the simulation of plasma processes (R. Sudan). Some of the computer work utilizes the Magnetic Fusion Energy Computer facility at the Lawrence Livermore Laboratory. Also being considered are instabilities in space plasmas (E. Ott, R. Sudan), the interaction of microwaves with electron beams (P. McIsaac), shock waves in plasmas (P. Auer), kinetic theory of plasmas (R. Liboff), the theory of plasma heating in Tokamak fusion devices (E. Ott), and the dynamics of plasma in the nuclei of galaxies and quasars (R. Lovelace).

Recent, typical publications and theses in the area of plasma physics include:

Auer, P. L. 1974. Self-consistent equilibria and current limitation in relativistic electron beams. *Physics of Fluids* 17:148.



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.

de Boer, P. C. T., and Ludford, G. S. S. 1975. Spherical electric probe in a continuum gas. *Plasma Physics* 17:29.
Davis, H.; Rej, D. J.; and Fleischmann, H. H. 1977. Production of field reversing electron rings by stacking. *Physical Review Letters* 39:744.
Exdahl, C.; Greenspan, M.; Kribel, R.; Sandel, F.; Sethian, J.; and Wharton, C. 1974. Plasma heating using strong turbulence and relativistic electron beams. In *Proceedings of 5th international conference (IAEE) on plasma physics and controlled thermonuclear fusion,* CN-33/C2-2. Tokyo, Japan.
Friedman, A.; Ferch, R. L.; Sudan, R. N.; and Drobot, A. T. 1977. Numerical simulation of strong proton rings. *Plasma Physics* 19:1101.
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. 1976. Low frequency stability of high current particle rings. *Physics of Fluids* 19:723.
Ott, E.; Manheimer, W. M.; and Klein, H. H. 1974. Stimulated Compton scattering and self-focusing in the outer regions of a laser fusion plasma. *Physics of Fluids* 17:1754.

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.

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 non-thermal 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

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.

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 being studied.

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 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.

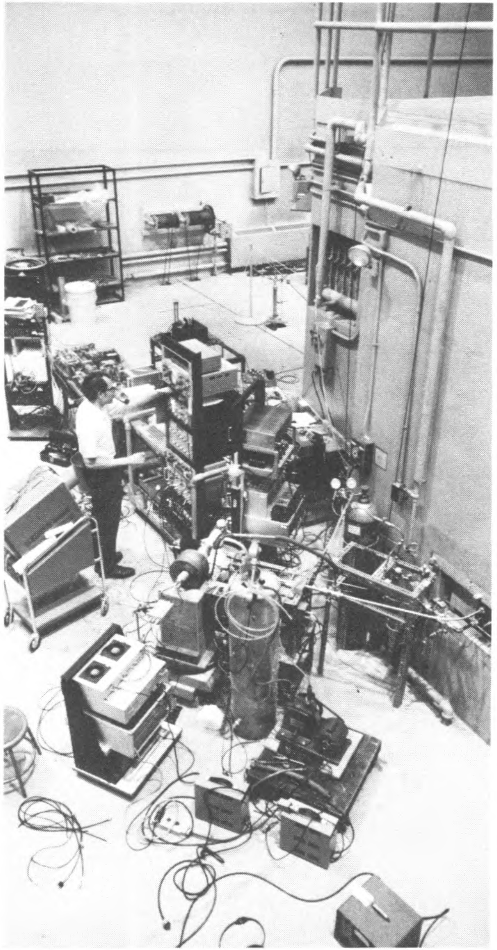
Koppel, D. E.; Axelrod, D.; Schlessinger, J.; Elson, E. L.; and Webb, W. W. 1976. Dynamics of fluorescence marker concentration as a probe of mobility. *Biophysical Journal* 16:1315.

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



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.

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.

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.

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 thousand-foot radio-radar telescope (the world's largest), has recently been upgraded to operate at much shorter wavelengths, improving radar sensitivity by a factor of two thousand; this provides exceptional research opportunities for graduate students. 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

An important facility for research in astrophysics is the National Astronomy and Ionosphere Center in Puerto Rico, which is the world's largest radio-radar telescope. This 96-foot antenna is suspended over a dish-shaped reflector 1,000 feet in diameter.

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. Sudan, E. Ott, D. Farley) and of the large-scale electric fields and currents in the magnetosphere (M. Kelley). The theory of the modes and instabilities of flat disc, self-gravitating systems is being investigated (R. Lovelace).

Representative publications and theses 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.

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 interiors 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 and by problems of earthquake prediction. (A. F. Kuckes).

Representative publications in this field are:

Billington, S., and Isacks, B. L. 1975. Identification of fault planes associated with deep earthquakes. *Geophysical Review Letters* 2:63.

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).

Kuckes, A. F. 1974. Lunar magnetometry and mantle convection. *Nature* 252:670.

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

Nekut, A.; Connerney, J. E. P.; and Kuckes, A. F. 1977. Deep crustal electrical conductivity; evidence for water in the lower crust. *Geophysical Research Letters* 4:239.

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.

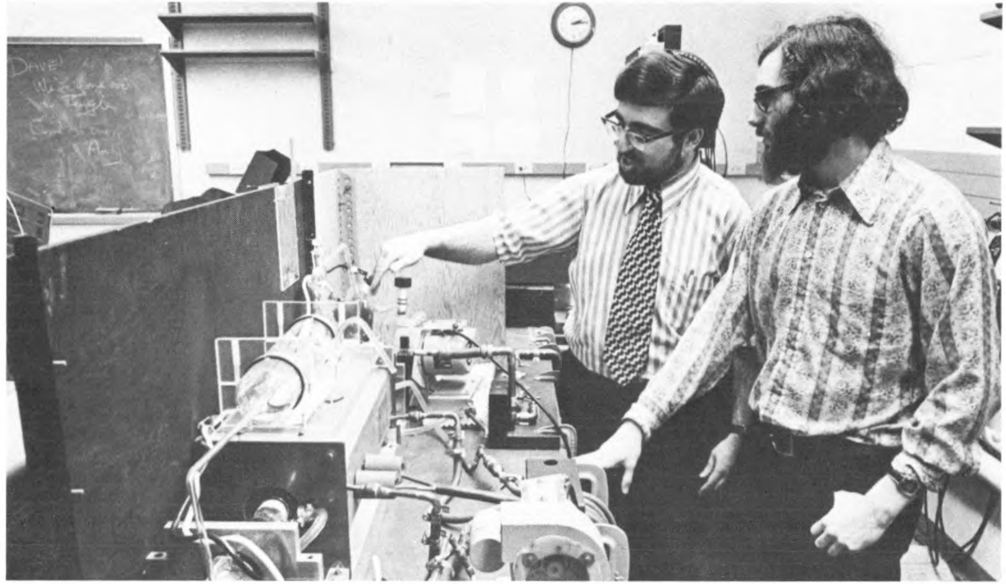
Biophysics

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).

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



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

Voltage clamping of muscle cells is performed by Bruce Land, a postdoctoral associate of Professor Miriam Salpeter (standing) in research on the biophysics of nerve-muscle interaction.

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 compartments within a cell 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).

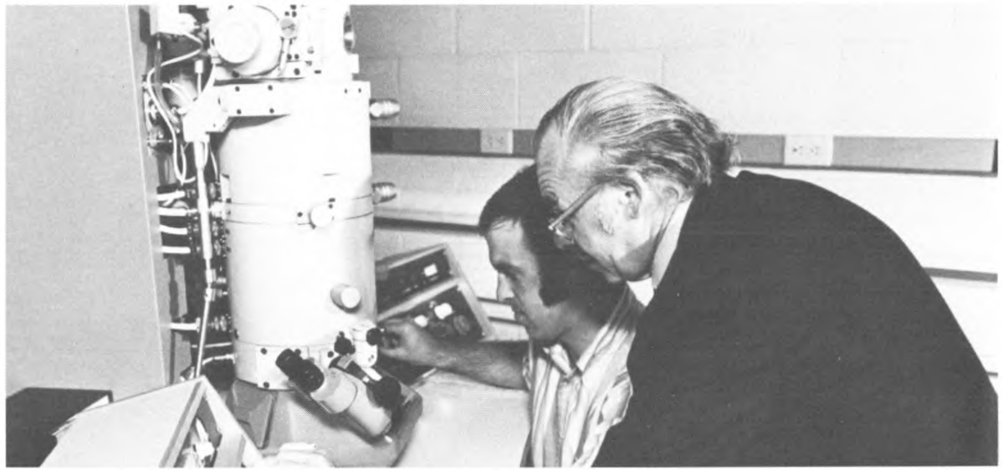
Investigations of the configuration and atomic structure of macromolecules are being pursued with the use of very-high-resolution microscopy. Nucleic acids — their configuration, association, and polymerization — and, ultimately, the direct observation of the base sequence in the polynucleotide are of particular interest in these studies. Observations on enzyme configurations, substructure, and active site locations are also being made. An electron microscope capable of achieving still higher resolution is being developed. (B. M. Siegel).

The dynamics of biophysical processes are being studied with the help of modern physical optics. Diffusion and the chemical kinetics of 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 photo-bleaching, 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 (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 our 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 are:

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

Koppel, D. E.; Axelrod, C.; Schlessinger, J.; Elson, E. L.; and Webb, W. W. 1976. Dynamics of



Above: Fluorescence correlation spectrometry is used in research directed by Professor Watt Webb (at left). Laser-induced fluorescence gives information on the kinetics of reactions in small units such as cell membranes.

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

fluorescence marker concentration as a probe of mobility. *Biophysical Journal* 16:1315.

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.

Riddle, G. H. N. 1971. Growth and properties of thin pyrolytic graphite films for electron microscopic substrates. Ph.D. thesis (B. M. Siegel).

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.

Siegel, B. M. 1971. Current and future prospects in electron microsopy for observations in biomolecular structure. *Philosophical Transactions of the Royal Society of London B* 261:5.

Spanswick, R. M. 1974. Hydrogen ion transport in giant algae cells. *Canadian Journal of Botany* 52:1029.

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.

Experiments are being carried out on inelastic collision processes (involving collision energies up to a few electron volts) in high-temperature gases. These processes include dissociation, ionization, recombination, and relaxation of vibrational and electronic excitation. Most of this work is carried out using shock tubes for the preparation of the high-temperature gas. Emphasis is given to processes that are important in environmental pollution and in work with gas lasers. (S. H. Bauer, P. C. T. de Boer, E. L. Resler, Jr.). Shock-tube techniques are also being applied to the study of droplet nucleation in the vapor phase of iron and other metals. (S. H. Bauer).

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

The interaction of atoms, molecules, and electrons with metals and semiconductors provides detailed information on the nature of atomic forces, of energy transfer, and of chemical bonding in atoms, molecules, and clusters. Investigations now under way are concerned with the quantum mechanical description of charge transfer and energy levels and with the mobility and binding of atoms involved in very localized interactions as in very small particles or on solid surfaces. Experimental measurements are made of the thermodynamics and kinetics associated with the atomistic nature of physical and chemical processes that are characteristic of chemisorption, oxidation, and related phase transformations. (T. N. Rhodin, J. M. Blakely).

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 50–100 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 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.

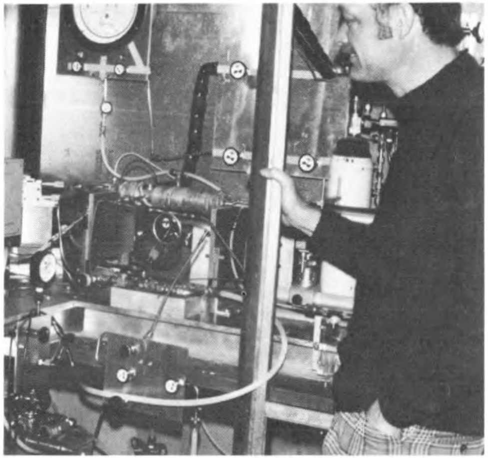
Brucker, C., and Rhodin, T. 1976. Low-energy electron-diffraction, Auger and photoemission studies of oxygen reactions on α-Fe(100) surfaces. *Surface Science* 57:523.

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.

Pirkle, R. F.; Davis, C. C.; and McFarlane, R. A. 1975. Comparative performance of CF_3I, CD_3I and CH_3I in an atomic iodine photodissociation laser. *Chemical Physics Letters* 36:305.



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

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 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, while 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 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.

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).

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.

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 ^{3}He-^{4}He mixtures. *Physical Review Letters* 34:1080.

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 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 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 hours of credit. 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, P. L. Hartman, 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 their 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*
Simon H. Bauer, B.S., Ph.D. (Chicago): *electron diffraction and shock-tube techniques, chemical lasers*
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*
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*
Keith E. Gubbins, B.S., Ph.D. (London): *statistical mechanics of liquids, liquid surfaces*
David Hammer, B.S. (California Institute of Technology), Ph.D. (Cornell): *plasma physics, thermonuclear fusion*
Paul L. Hartman, B.S. (Nevada), Ph.D. (Cornell): *optical properties of solids*
Martin O. Harwit, B.A. (Oberlin), Ph.D. (M.I.T.): *astrophysics*
James R. Houck, B.S. (Carnegie-Mellon), Ph.D. (Cornell): *astrophysics*
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* (on leave as assistant director of the National Science Foundation)

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*

Che-Yu Li, B.S.E. (Taiwan College of Engineering), Ph.D. (Cornell): *mechanical properties of materials, irradiation effects*

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*

Ross A. McFarlane, B.Sc. (McMaster), M.Sc., Ph.D. (McGill): *quantum electronics*

Paul R. McIsaac, B.E.E. (Cornell), M.S.E., Ph.D. (Michigan): *microwave electronics*

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*

Edward Ott, B.S. (Cooper Union), M.S., Ph.D. (Polytechnic Institute of Brooklyn): *plasma physics, electrophysics*

Edwin L. Resler, Jr., B.S. (Notre Dame), Ph.D. (Cornell): *high-temperature gasdynamics, magnetohydrodynamics*

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, 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 programs in interdisciplinary and developing specialties, as well as in the more traditional areas of chemical engineering. Approximately forty students are now pursuing graduate work in a variety of areas.

As in most engineering fields at Cornell, three graduate degree programs are offered in chemical engineering. Students may enter a research-oriented course of study leading to the degree of Doctor of Philosophy or Master of Science or may study for the professional degree of Master of Engineering (Chemical).

Cornell offers unusual opportunities for interdisciplinary research, and the system of graduate fields (which often cut across department lines) encourages such studies. Faculty members within the School of Chemical Engineering are involved in collaborative work with other researchers in the Materials Science Center and in academic units in chemistry, physics, mechanical engineering, applied and engineering physics, food science, microbiology, agricultural sciences, and applied mathematics. Joint seminar programs in such fields as applied mathematics, chemical physics, materials science, and biochemistry offer a forum for the discussion of research activities. Major research facilities available include an excellent library system (among the top ten in the United States), the Wilson synchrotron for high-energy and x-ray studies, the submicron facility, the DEC 11/70 computer at the School of Chemical Engineering, and the University's IBM 370/168 computer and its associated array processor.

Graduate students normally enrich their education by taking advantage of the diverse courses offered in the many distinguished schools and departments at Cornell. In addition to minors in other engineering fields, the physical sciences, the biological and agricultural sciences, and mathematics, some students select minors in such nonengineering fields as business administration, economics, and law.

The faculty is an outstanding group of professionals with a strong commitment to scholarly research and teaching. Many keep in close touch with industrial practice by serving as consultants to a wide variety of firms. Five have received the annual Tau Beta Pi – Cornell Society of Engineers Excellence in Engineering Teaching Award. Faculty publications include several hundred journal articles and four textbooks that are used in chemical engineering departments throughout the nation. These texts are:

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: thermodynamics and transport properties of fluids.* New York: McGraw-Hill.

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

Facilities

In addition to the University support facilities mentioned above, special facilities are available in Olin Hall of Chemical Engineering. This building is well equipped for modern research. It includes many small laboratories for graduate student research (many of these will be refurbished in 1978), as well as specialized laboratories for work

in such areas as polymers, unit operations, biochemical engineering, microscopy, kinetics, surface science, transport phenomena, and thermodynamics. The school maintains its own library of reference books and periodicals to supplement the larger libraries in the College of Engineering and the University.

Facilities of special interest in certain areas are described under the various areas of research.

Areas of Research

Transport phenomena, reaction kinetics, and thermodynamics are the fundamentals of chemical engineering, and projects in these areas are an important part of the total research activity of the University.

As a result of the diversity of faculty interests, projects that represent the extension of chemical engineering into other fields are also available. These fields include materials science, applied chemistry, microbiology, food science, applied mathematics, applied physics, environmental engineering, and the agricultural sciences.

Much of the school's current or projected research can be grouped into the categories listed below, although the groupings are necessarily arbitrary and there is considerable interaction among areas.

Olin Hall, the spacious headquarters of the School of Chemical Engineering, is centrally located on the Cornell campus.

Biochemical Engineering

Biological processes are important in all natural cycles and in many industrial processes. Solutions to such societal problems as energy and food production, protection of the environment, and the production of pharmaceuticals require the contribution of biochemical engineers. Specialists in this area will also have an increasingly important role in the development of a basic understanding of how biological systems function.

Because the School of Chemical Engineering at Cornell has maintained a long-term commitment to biochemical engineering, the facilities and the interdisciplinary links necessary for an effective program have been well established. A wide variety of research projects are currently in progress.

R. K. Finn's research encompasses a number of important problems. Among these is the improvement of alcohol fermentation processes, which potentially can provide the United States with a fuel derived solely from agricultural by-products, including cellulose. Current work includes the development of techniques for the rapid removal of product alcohol by vacuum distillation or solvent extraction.

Another project under Finn's supervision is the development of microbial processes to enhance the digestibility and nutritional value of cellulosic materials, such as straw, for feeding to ruminants. This project involves fundamental studies of solid-substrate fermentation and the digestion of feedstuffs in the ruminant stomach.

Many industrial wastewaters contain toxic refractory chemicals such as the moderately persistent pesticide 2,4D. The proper treatment of wastewater requires greater knowledge of the effects the chemical and physical properties of organic compounds have on their biodegradation. Finn and M. Alexander of the Department of Agronomy are leading a project to investigate the kinetics and metabolic pathways involved in the degradation of such compounds.

In addition to these specific projects, Finn has active interest in aeration and agitation, biopolymer synthesis from methanol, enzyme purification by solvent precipitation, and the kinetics of microbial growth and product formation.

M. L. Shuler's research group is examining a variety of fundamental experimental and theoretical problems involved in the utilization of waste materials, the production of nonconventional foods, and the manipulation of organisms to increase the yield of bioproducts.

One of these projects is concerned with the manipulation of the abiotic environment to enhance the formation of secondary products from suspension cultures of plant cells. Many pharmaceuticals require, as starting compounds, natural products from plants; since such compounds normally must be extracted from whole plants, a cell-culture process would offer practical benefits. In addition, information about the effects of environmental manipulation on cell differentiation might prove useful to those working in the agricultural and medical sciences.

A kinetic study of the biodegradation of pentachlorophenol is carried out by Gary Stanlake, a postdoctoral associate, with the use of a chemostat. Studies such as this are aimed at the improvement of industrial wastewater treatment.

Another project supervised by Shuler is the development and experimental verification of a computer model for the growth of individual bacterial cells. The development of such a model may allow the formation of optimal process designs for the production of biochemicals and assist in the implementation of process-control strategies for fermenters. Also, with a well-developed quantitative model, it should be possible to rapidly test the plausibility of new hypotheses for the mechanisms of bacterial growth. G. G. Cocks is jointly supervising that portion of the project requiring the use of the electron microscope.

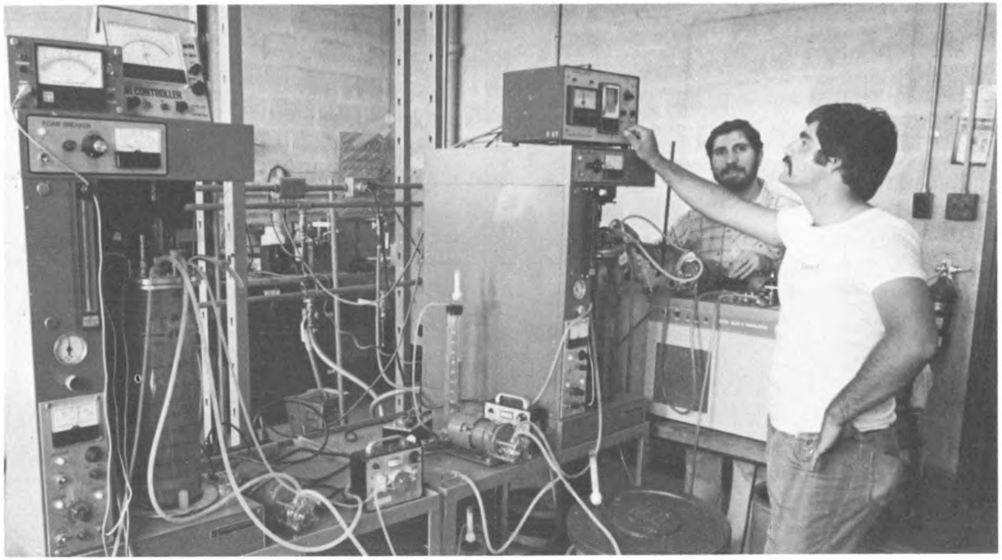
An ongoing project headed by Shuler has developed reactor systems using whole cells immobilized in hollow fiber devices that are capable of the continuous production of biochemicals. In certain cases, such schemes may simplify product recovery and result in increased yields.

Shuler is also a member of an interdisciplinary group, which includes researchers in poultry science and nutrition and in microbiology, investigating the use of controlled microbial processes to convert poultry manure into a high-protein feedstuff suitable for refeeding to hens. In addition to reducing environmental problems, such a scheme could help to increase significantly the world's ability to produce high-quality protein.

A new project planned by Shuler in collaboration with researchers at the Institute of Food Science will seek to develop fermentation techniques for the manufacture of protein-enriched and meatlike foods from nontraditional food sources. In this project, natural fermentative cultures from Asia will be manipulated to yield food products acceptable to American tastes. The large-scale production of such foods would require a thorough study of heat and mass transfer characteristics in solid-substrate fermentations and of the kinetics of growth of mixed-microbial cultures.

In Olin Hall of Chemical Engineering about 3,600 square feet of space is devoted to research projects in biochemical engineering. In addition, a 400-square-foot laboratory has been completely remodeled and equipped for a new graduate-level laboratory course, Controlled Cultivation of Microbial Cells.

The research laboratories are well equipped with fermenters, including a variety of New Brunswick bench-scale units and one 40-liter unit. There is also an excellent selection of equipment for both aseptic and nonaseptic experiments involving biological organisms. This equipment includes temperature-controlled and refrigerated shakers, and analytical devices such as a Coulter Counter,



Students Fikret Kargi (at left) and Glenn Mazzamaro are using a multistage aerobic fermentation process in research on the conversion of poultry waste into single-cell protein.

a Beckman Acta Spectrophotometer, a Beckman TOC unit, and an IEC refrigerated centrifuge.

The work of graduate students and faculty members in the area of biochemical engineering is represented by the following publications:

Finn, R. K. 1975. The prospects for fermentation alcohol from hydrolyzed cellulose. *Biotechnology and Bioengineering Symposium Series* 5:353.

Haller, H., and Finn, R. K. 1978. Kinetics of biodegradation of p-nitrobenzoic acid. *Applied and Environmental Microbiology* 35:816.

Ho, S. V., and Shuler, M. L. 1977. Predictions of cellular growth patterns by a feedback model. *Journal of Theoretical Biology* 68:415.

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

Kubeck, D. J., and Shuler, M. L. 1978. Electronic measurement of plant cell number and size in suspension culture. *Journal of Experimental Botany* 29:511.

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

Shuler, M. L. et al. 1978. A process for the aerobic conversion of poultry manure into a high protein feedstuff. *Biotechnology and Bioengineering* (in press).

Tam, K. T., and Finn, R. K. 1974. Residence time of sphere or air bubble in sheared non-Newtonian fluids. *Nature* 252:572.

——. 1977. Polysaccharide formation by a *Methylomonas*. Chapter 5 in *Extracellular microbial polysaccharides,* symposium series no. 45, ed. P. A. Sandford and A. Laskin, p. 58. Washington, D.C.: American Chemical Society.

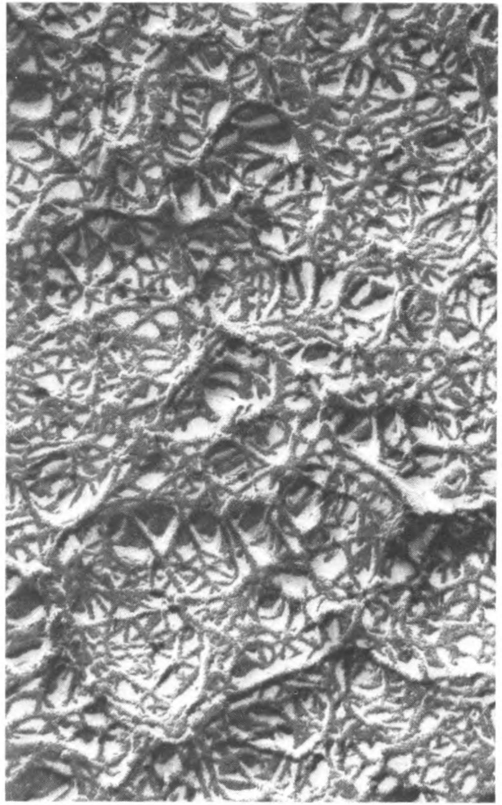
Chemical Microscopy

Chemical microscopy has been taught at Cornell since the turn of the century and is still a vital, growing field of study. In recent years many new and exciting microscopes have been developed that are now widely used in chemical and chemical engineering research. Today microscopical techniques are so far developed that one of the ultimate goals of chemical microscopy — to see individual atoms and molecules and to observe the reactions between them — may soon be realized.

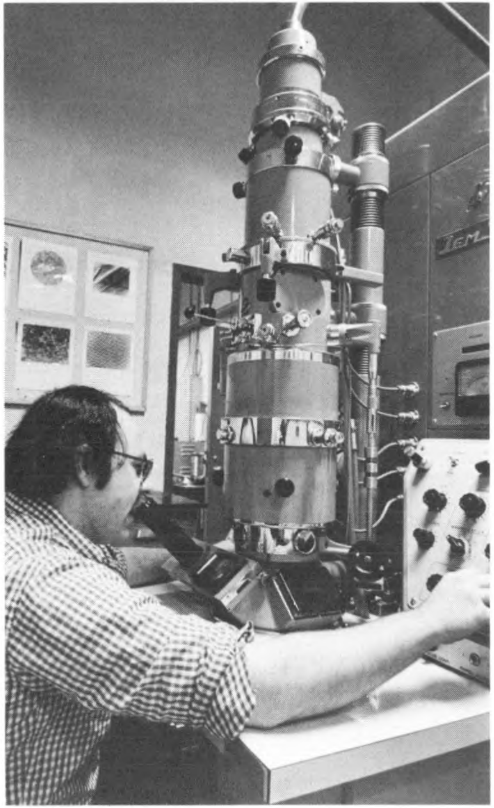
Current research programs include studies of the formation, microstructure, and physical properties of gels and other polymeric materials. This research has potential applications in medicine. Much of the current effort is devoted to studying collagen as a biomaterial that would be useful, for example, in kidney machines or for artificial blood vessels, sutures, corneal replacement, vitreous-body replacement, or drug-delivery systems. Another aspect of microscopical research is the study of the nucleation and growth of crystals. This research has applications in such areas as desalination by freezing, the engineering production of crystalline products, mineralogy, and biomedical problems such as the growth of bones, teeth, and kidney stones. Still another group of research projects is devoted to studies of the structure of biological cells such as bacteria and yeasts.

The microscopy laboratory is well provided with light and electron microscopes and auxiliary equipment for the preparation of specimens.

These facilities are under the supervision of G. G. Cocks, who, in collaboration with other faculty members, directs research projects in this field.



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.



Electron microscopes such as this one used by graduate student Rich Weissman are available for experimental work in chemical microscopy and in many other areas of chemical engineering research.

In the new minicomputer laboratory, Professor Keith Gubbins discusses a problem in the simulation of liquids with postdoctoral associates Paulette Clancy and Steve Thompson.

Representative theses and articles include:

Cluthe, C. E. 1972. A microscopical study of the structure of radiation crosslinked aqueous poly (ethyleneoxide) gels and frozen cryoprotective solutions. Ph.D. thesis (G. G. Cocks).

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

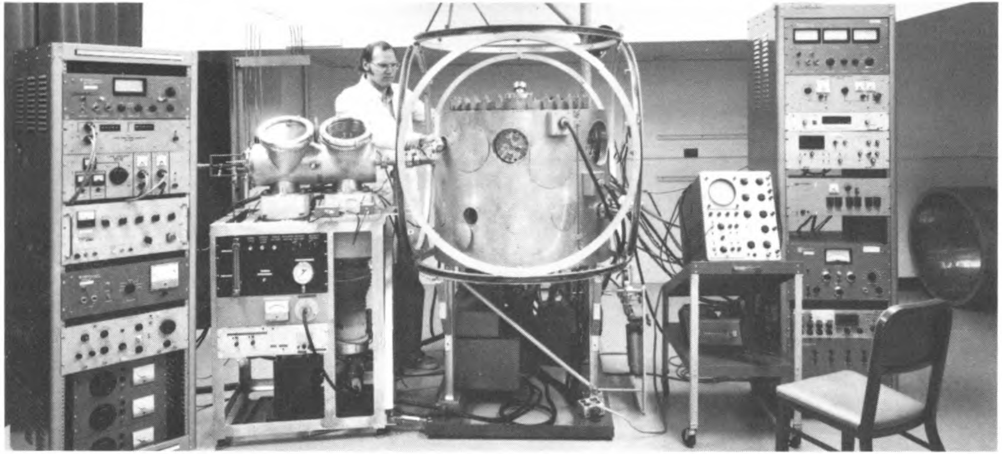
Cocks, G. G., and Cluthe, C. E. 1971. Structures formed by cryoprotective agents used in freeze-etching. In *Proceedings, Electron Microscopy Society of America*. New Orleans: Claitors.

Weissman, R. C. 1978. A microscopical study of the gelation of chemically crosslinked collagen. Ph. D. thesis (G. G. Cocks).

Computer Simulation

With recent advances in computer technology it has become possible to numerically evaluate problems that would have been unapproachable a decade ago. Much of the research in the school makes use of the computer to simulate the response of physical systems to perturbations in their environment, forming an important bridge between actual experiment and theory. Such research not only allows the solution of specific problems but also furthers the development of computer simulation techniques. Projects involving computer simulation are described in the sections on biochemical engineering, polymers and biomaterials, and thermodynamics of fluid mixtures.

Excellent facilities are available for large-scale computation. These include the school's PDP



11/70 computer, the largest of the PDP 11 series, which has 256 kb of core storage plus 28 mb of disk, and is comparable in speed to such mainframe computers as the IBM 360, the CDC 6400, and the Honeywell 6000 series. The University's Office of Computer Services also maintains a floating point array processor attached to the University's IBM 370/168 for large-scale computing. The speed of the array processor is similar to that of a CDC 7600 (about fifteen times faster than the DEC 11/70); it has at present 100 kw of memory and uses 32-bit words. A substantial amount of time on this machine is allocated for research on computer simulation of liquid mixtures that is being carried out at the School of Chemical Engineering.

Examples of recent publications are:

Haile, J. M.; Litchinsky, D.; McPherson, R.; Gray, C. G.; and Gubbins, K. E. 1976. Monte Carlo simulation of molecular fluids on a minicomputer. *Journal of Computational Physics* 21:227.

Ho, S. V., and Shuler, M. L. 1977. Predictions of cellular growth patterns by a feedback model. *Journal of Theoretical Biology* 68:415.

Streett, W. B., and Gubbins, K. E. 1977. Liquids of linear molecules: computer simulation and theory. *Annual Review of Physical Chemistry* 28:373.

Streett, W. B., and Tildesley, D. J. 1978. Computer simulations of polyatomic molecules. III. Monte Carlo studies of homonuclear and heteronuclear hard diatomics. *Journal of Chemical Physics* 68:1275.

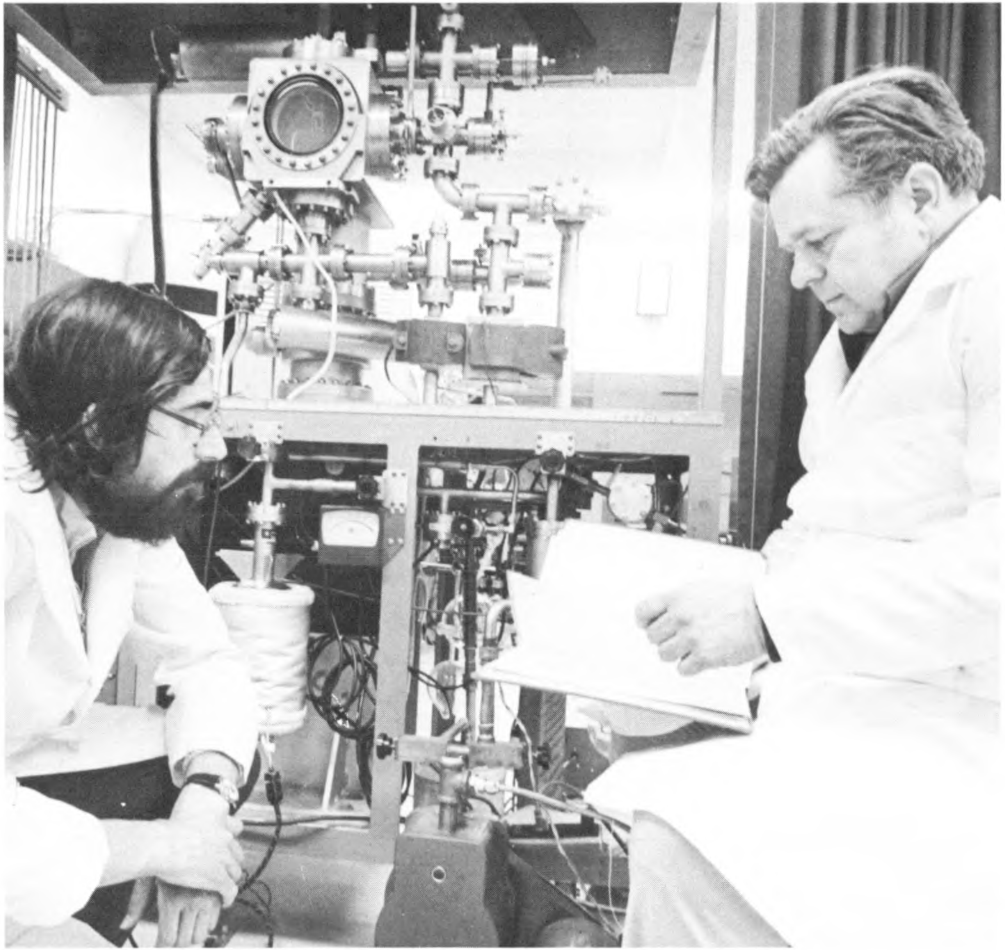
Research aide Herb Sawin adjusts low-energy electron diffraction (LEED) optics during research on iridium catalysts (used in hydrazine rocket engines).

Kinetics, Catalysis, and Surface Science

The heart of most industrial chemical processes is the reactor element, which often employs a catalyst. Although kinetics has been a vital part of chemical engineering instruction and research for many years, kinetic data are often the weakest link in the assessment of a new process. Also, the fundamental nature of reactions at the surface of a solid catalyst is poorly understood. These problem areas are the subject of research at the School of Chemical Engineering that seeks to improve the understanding of the basic mechanisms involved in chemical change. The programs in this area are strengthened by the strong interest at Cornell in surface science. Chemical engineering faculty members and students share interests and cooperative work with research groups in materials science and engineering, chemistry, physics, and applied physics.

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, 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.

One current project is concerned with the decomposition kinetics of monopropellent rocket fuel, another is a study of the reactive surface chemistry of ruthenium, and a third is an investigation of how the distribution of active metals can be controlled in the impregnation of



porous catalysts. New project work includes the development of an experiment to study the collision dynamics of oxygen atoms with solid surfaces in the NASA space shuttle and a study of the growth of epitaxial oxides on aluminum and titanium.

Catalysis by supported metals and the kinetics of gas-solid reactions are being investigated by P. Harriott. Transient and steady-state tests in a differential reactor have been used to clarify the steps in the formation of methane on Ni-SiO_2 catalysts, and the apparent changes in kinetics with temperature and particle size are now being studied. Specially prepared silver catalysts are used to measure the rate of partial oxidation of methanol to formaldehyde under conditions in which temperature and concentration gradients normally obscure the kinetics. Research continues on the regeneration of spent carbon adsorbents, using a fluidized reactor and a thermal balance to separate the steps of pyrolysis, combustion of the residue, and reaction of the adsorbent.

The effects of mass transfer on overall reaction rates and on scale-up problems are also being investigated under Harriott. Diffusion and nonequilibrium adsorption have been shown to affect the selectivity in slurry hydrogenation, and the effects of solvent properties are being examined. Work continues on fluidized beds, with current interest focused on the effect of particle properties on bubble formation and gas interchange rates.

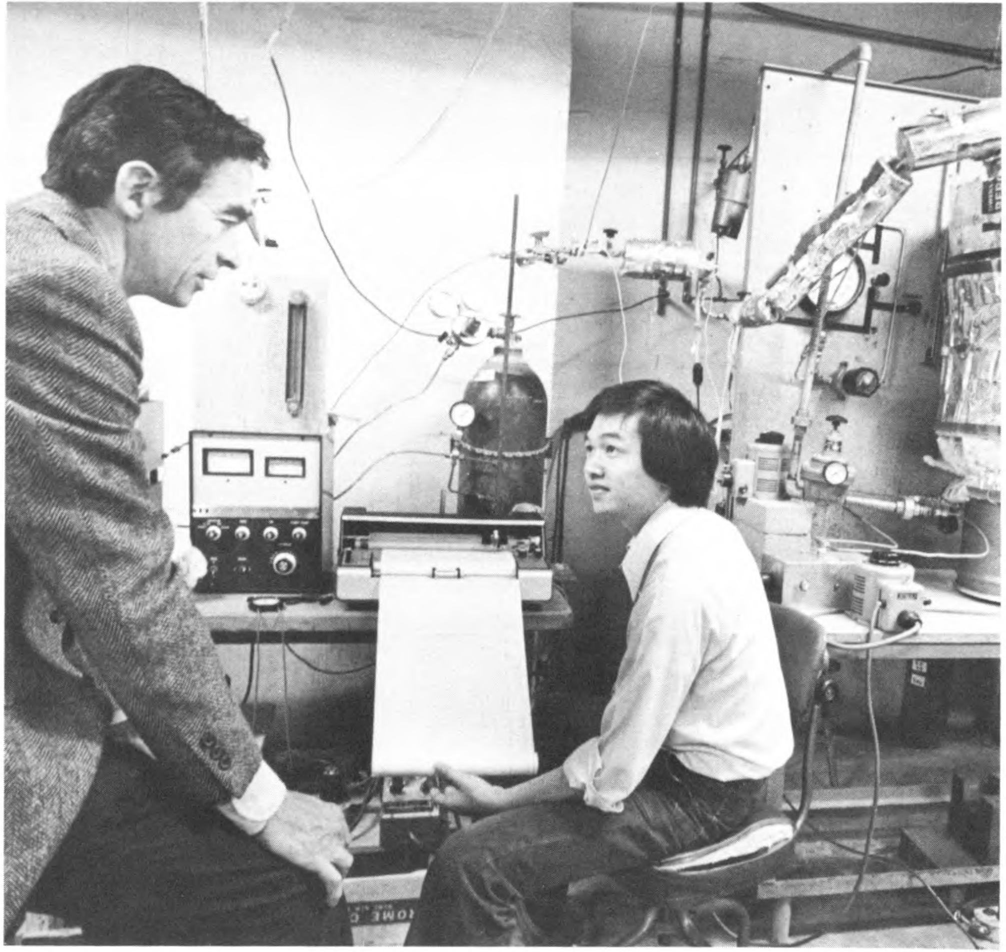
The reactive surface chemistry of ruthenium is studied by Professor Robert Merrill (at right) and graduate student Bill Arvin.

R. L. Von Berg and F. Rodriguez are available to direct theses related to the development of nuclear facilities. Nuclear reactor engineering involves many chemical engineering processes, and chemical engineers with a background in nuclear physics are uniquely qualified to handle many of the problems of this industry. Preparation for such work requires a major in chemical engineering and course work in the School of Applied and Engineering Physics, which has outstanding experimental facilities in this field. Ph.D. candidates may also work on thesis problems at the Brookhaven National Laboratory on Long Island. Another aspect of nuclear energy is the use of high-energy radiation to induce chemical reactions; at Cornell an extremely versatile gamma radiation cell is available for such work.

Facilities for research in kinetics, catalysis, and surface science also include a recently completed 3,600-square-foot "clean room" for surface chemistry research. This room houses the sophisticated high-vacuum units employed in fundamental studies. An additional 800-square-foot laboratory is used for kinetic studies and for the preparation and characterization of catalysts. A BET apparatus and an electron microscope for use in characterizing catalysts are available.

Recent publications in this area include:

Hernandez, L. A., and Harriott, P. 1976. Regeneration of powdered active carbon in a fluidized bed. *Environmental Science and Technology* 10:454.



Professor Peter Harriott and graduate student Sa Ho discuss progress in a kinetic study of methane formation from simulated coal gas.

Kiran, E., and Rodriguez, F. 1973. Effects of gamma radiation on aqueous polymer solutions — a comparative study. *Journal of Macromolecular Science–Physics B* 7:209.
Masel, R. I.; Miller, W. H.; and Merrill, R. P. 1976. Atomic scattering from a sinusoidal hard wall: comparison of approximate methods with exact quantum results. *Journal of Chemical Physics* 65(7):2690.
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* (in press).
Merrill, R. P. 1977. A molecular view of diffusion and reaction in porous catalysts. *Journal of Catalysis* 50:184.
Stoll, A. G., Jr.; Ehrhardt, J. J.; and Merrill, R. P. 1976. Helium diffraction from tungsten (112). *Journal of Chemical Physics* 64(1):34.
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* (in press).

In a graduate research project, Richard Mohring tests the mechanical properties of a new polymeric fiber.

Polymers and Biomaterials

Hundreds of industries and millions of people are involved in the production of plastics, rubbers, lacquers, rayons, and cellophanes. 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.

Polymer studies directed by F. Rodriguez center on mechanical, electrical, and optical properties of multicomponent polymer systems, including copolymers, polymer blends, filled polymers, crosslinked polymers, and polymer solutions. Also under investigation are the kinetic relationships of polymerization processes — often rapid reactions of free-radical or ionic character — and the distribution of reaction products.

Another research area in which Rodriguez is active is the study of the crosslinking of collagen and collagen-polymer mixtures by ultraviolet irradiation. This work is directed toward finding collagen-based materials with physical properties that make them suitable for such uses as artificial blood vessels, burn coverings, and cornea replacement. Studies of polyacrylamide gels are also under way in collaboration with C. Cohen; the goal is to achieve an understanding of the phase diagram and thermodynamics of these gels.

Cohen's research is concerned mainly with the thermodynamic and fluid dynamic properties of polymer solutions and bulk polymers. Theoretical results for phase separation and critical conditions have been obtained for the general case in which the important effect of volume change when polymer and solvent are mixed is taken into account. These results will be tested, extended, and used to predict and interpret the Brillouin spectra of light scattered from polymer solutions — spectra that contain information about transport processes in the solution.

A new laser light-scattering spectrophotometer in Cohen's laboratory will be used primarily for the study of relaxation and diffusion phenomena in bulk polymers. Relaxation phenomena are important in determining the bulk transport properties, which in turn determine the mechanical and engineering properties of polymeric materials; laser light scattering is used to obtain information that cannot be acquired by more standard techniques based on mechanical, dielectric, and NMR measurements. The diffusion of small molecular species through polymers will be studied in another planned project.

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 have been found to compare well with experimental results obtained in the industrial laboratories of Cincinnati Milacron and Xerox. Current efforts include an attempt to resolve the orientation of polymers in the mold and to define the various process variables that determine such orientation.

The chief research interest of G. G. Cocks is the development of various techniques, such as freeze-etching, for the preparation of specimens for electron microscopy. Current work includes a study of the structure and mechanical properties of collagen gels prepared by crosslinking the polymer solution by means of gamma radiation, ultraviolet radiation, or chemical reaction.

Some representative publications in this area of research are:

Chapman, E. W., and Rodriguez, F. 1977. Acrylic resin reinforcement of reconstituted collagen films. *Polymer Engineering and Science* 17:282.

Clark, D. B., and Rodriguez, F. 1976. A comparison of drag reduction for flows in circular tubes with flow between parallel plates. *Journal of Applied Polymer Science* 20:315.

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

Cohen, C. 1977. Thermodynamic fluctuations and light scattering in monodisperse polymer solutions. *Journal of Polymer Science* (A-2) 15:291.

Cohen, C.; Sankur, V.; and Pings, C. J. 1977. Laser correlation spectroscopy of amorphous polymethylmethacrylate. *Journal of Chemical Physics* 67:436.

Zvanut, C. W., and Rodriguez, F. 1977. Collagen as a biomaterial: modulus jump and degradation of collagen gels. *Journal of Applied Polymer Science* 20:2871.

Thermodynamics of Fluid Mixtures

The proper selection and design of chemical processing equipment require precise information on the composition of the fluid mixtures within each processing unit. The study of the thermodynamics of fluid mixtures can yield important information about the properties of each phase and the interchange of material between phases.

The research interests of K. E. Gubbins center around the understanding of phase equilibria and molecular transport processes in liquid mixtures of industrial interest. Present emphasis is on polar and hydrogen-bonded liquids, and on liquids of interest to the natural gas industry. Three approaches are used: experimental, computer simulation, and theoretical. Some current research projects are described below.

1. In computer simulation studies of liquefied methane and other constituents of liquefied natural gas, a model is proposed for the intermolecular forces, and then the motion of the molecules is simulated by the computer. The computer can determine the physical properties of the liquid for all state points in the phase diagram, the intermolecular force model can be refined by using available experimental data, and then this force model can be used to study state conditions and properties that are inaccessible in the laboratory.

2. The gas-liquid surface of a polar fluid is being studied by computer simulation, yielding many properties that cannot be determined experimentally; examples are the concentration profiles, molecular orientations, and diffusion coefficients at the surface.

3. Phase diagrams for mixtures involving polar and hydrogen-bonded components are being studied by a combination of theory, simulation, and experiment. The aim is to produce a detailed understanding of such mixtures and to develop accurate correlation methods.

Contacts, including reciprocal visits, are maintained with groups doing similar work at the University of Florida, the University of Guelph, and several universities in Europe (notably, Oxford, Kent, and Stuttgart).

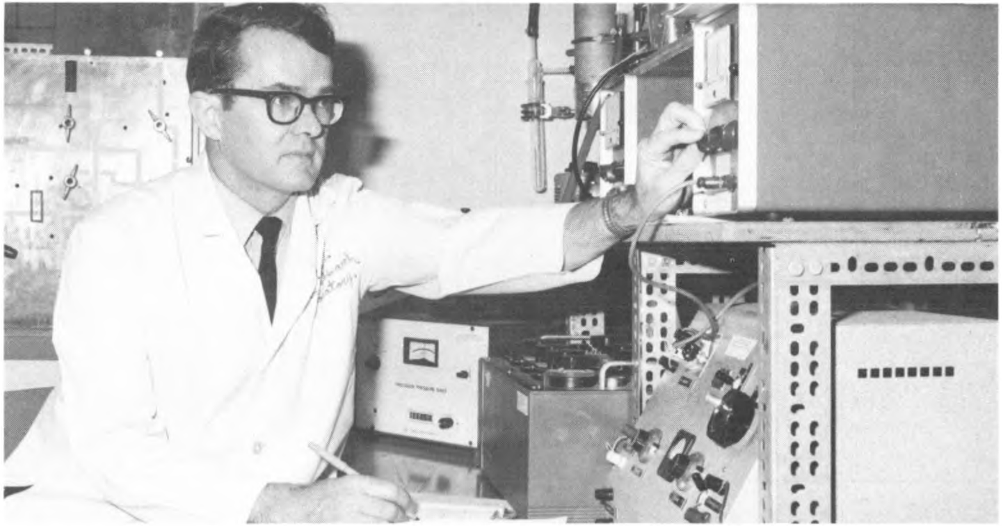
The two principal research interests of W. B. Streett are experimental studies of the physical and thermodynamic properties of pure and mixed fluids at high pressures (PVT, velocity of sound, phase equilibria, etc.), and computer simulation studies of fluids using Monte Carlo and molecular dynamics methods. The experimental studies are applied to problems of interest in petroleum refining, coal gasification, liquefaction and transportation of natural gas, and other industrial processes. Besides having chemical engineering applications, these high-pressure experiments are relevant to studies of the deep atmosphere and interior structures of the giant planets — Jupiter, Saturn, Uranus, and Neptune — which are known to be composed mainly of light gases. The computer simulation studies of fluids provide detailed information about structure and motion at the molecular level and about the often subtle relations between microscopic and macroscopic properties. In this field Streett works closely with Gubbins. Their joint research on fluids, combining the methods of theory, experiment, and computer simulation, constitutes a powerful integrated approach to the study of dense fluids. Examples of current research projects include the following:

1. Vapor-liquid equilibrium studies of binary mixtures containing hydrogen are carried out using a vapor-recirculating equilibrium system capable of reaching pressures as high as 10,000 bars. Experiments on mixtures of hydrogen with nitrogen, methane, ethane, and higher hydrocarbons are in progress.

2. PVT measurements on pure and mixed fluids at pressures as high as 4,000 bars are made by means of a gas-expansion PVT apparatus. Pressures are measured with an accuracy of 0.01 percent by a deadweight gauge, temperatures with an accuracy of 0.01° K by a platinum resistance thermometer, and densities with a precision of a few parts in ten thousand.

3. Computer simulations of model fluids consisting of highly idealized molecules are carried out using Monte Carlo and molecular dynamics methods. The former technique is based on the use of random numbers; the latter on the solution of the Newtonian equations of motion of several hundred to several thousand interacting particles. Sophisticated computer programs requiring many hours of computing time are used in this research.

C. Cohen directs his interest in thermodynamics toward the study of polymer solutions and gels, as described in the section on polymers and biomaterials.



Dr. William Streett measures the PVT behavior of a fluid mixture at high pressure.

Facilities available for the computer simulation studies of fluids include the PDP 11/70 computer at the School of Chemical Engineering and the University's array processor (described in the section on computer simulation). Experimental equipment includes apparatus for PVT and speed-of-sound measurements and for high-pressure phase equilibrium studies; facilities are available for experiments conducted over a wide temperature range, including cryogenic conditions.

Representative publications in this area include:

Cohen, C. 1977. Thermodynamic fluctuations and light scattering from monodisperse polymer solutions. *Journal of Polymer Science* (A-2) 15:291.

Cohen, C.; Gibbs, J. H.; and Fleming, P. D. 1973. Condensation and gelation: clarification of Stockmayer's analogy. *Journal of Chemical Physics* 59:5511.

Gubbins, K. E., and Gray, C. G. 1978. *Statistical mechanics of polyatomic fluids.* International series of monographs on chemistry. Oxford: Oxford University Press (in press).

Gubbins, K. E.; Gray, C. G.; and Egelstaff, P. A. 1978. Thermodynamic derivatives of correlation functions. *Molecular Physics* 35:315.

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.

Nunes da Ponte, M.; Streett, W. B.; and Staveley, L. A. K. 1978. An experimental study of the equation of state of liquid mixtures of nitrogen and methane, and the effect of pressure on the excess thermodynamic functions of this system. *Journal of Chemical Thermodynamics* 10:151.

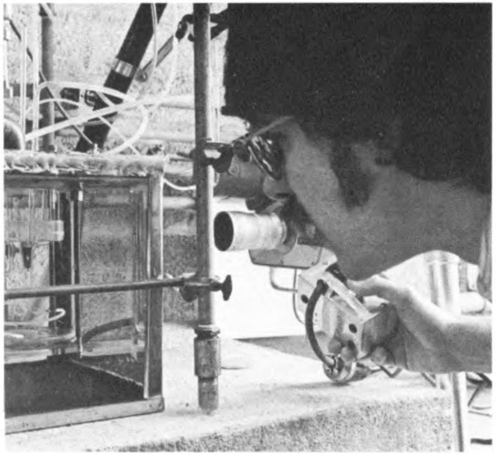
Streett, W. B., and Gubbins, K. E. 1977. Liquids of linear molecules: computer simulation and theory. *Annual Review of Physical Chemistry* 28:373.

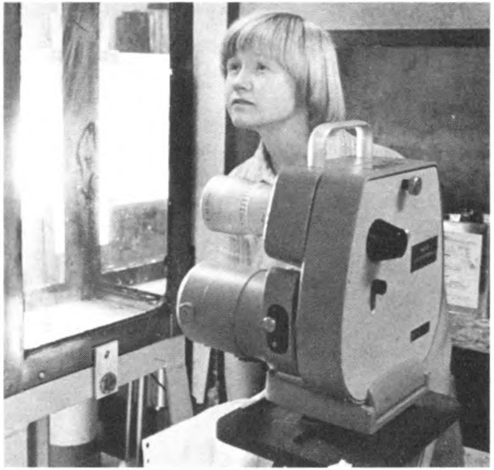
Streett, W. B., and Tildesley, D. J. 1978. Computer simulations of polyatomic molecules. III. Monte Carlo studies of homonuclear and heteronuclear hard diatomics. *Journal of Chemical Physics* 68:1275.

Transport Processes

Problems in transport processes are frequently encountered in chemical processes, yet their behavior is often poorly understood. Several faculty members have research projects oriented toward the solution of some of these problems.

G. G. Scheele is concerned primarily with the fluid mechanics of immiscible liquid-liquid systems. Most of his studies have arisen from actual industrial problems and involve both experimental and theoretical aspects. One experimental technique employed to facilitate the observation of rapidly occurring phenomena is high-speed motion-picture photography. Examples of Scheele's current research projects include studies of (1) the effect of impact velocity on the probability of coalescence of two colliding drops, (2) the interaction of rapidly moving drops with a planar liquid interface, (3) the prediction and measurement of the velocity distribution in a laminar liquid jet, and (4) the effect of relative phase motion on the formation and behavior of drops and jets in immiscible liquid-liquid systems.





Above: In this experiment high-speed motion picture photography is being used by graduate student Dave Clark to study the rapid coalescence of liquid drops. Such graduate research projects will provide a better fundamental basis for the design of liquid-liquid extraction systems.

Below: In related work, graduate student Marise Lada is using high-speed motion picture photography to study the mechanics of drop formation in liquid-liquid systems. This information will aid in the design of liquid injection systems.

J. Smith has directed several research projects on the behavior of free-flowing solids. A recent study, using a piezoelectric pickup as an impact counter, established particle frequency distributions across a stream of TCC catalyst beads issuing from openings of various shapes in hoppers of various designs. These distributions will be helpful in the development of mathematical models of the particle motion. Other areas in which Smith has research interest include aeration and mixing of non-Newtonian liquids and ternary liquid-liquid phase equilibria.

G. G. Cocks, P. Harriott, R. L. Von Berg, and H. F. Wiegandt are involved in a study of desalination by freezing, a process that utilizes secondary, immiscible, direct-contact refrigerants. This process has favorable thermodynamics and offers intriguing engineering possibilities. Overall engineering and economic evaluations are used to incorporate the results of the experimental work at Cornell and the contributions of other experimenters into a general desalination program.

Investigations of molecular transport processes in liquid mixtures, polymer solutions, and bulk polymers are directed by K. E. Gubbins and C. Cohen; these studies are described under other headings.

The following publications illustrate research on transport processes at Cornell:

Cohen, C., and Fleming, P. D. 1976. Hydrodynamics of solids. *Physical Review B* 13:500.

Cohen, C.; Fleming, P. D.; and Gibbs, J. H. 1976. Hydrodynamics of amorphous solids with application to the light scattering spectrum. *Physical Review B* 13:866.

Cohen, C., and Leal, L. G. 1978. Light scattering from rigid spheroids in shear flows. I. The orientation correlation. *Journal of Chemical Physics* 63:5348.

Haile, J.; Mo, K. C.; and Gubbins, K. E. 1976. Viscosity of cryogenic liquid mixtures, including LNG. *Advances in Cryogenic Engineering* 21:501.

Hanley, J. M.; Murad, S.; and Gubbins, K. E. 1978. A correlation of the existing viscosity and thermal conductivity data of gaseous and liquid ethane. *Journal of Physical Chemistry Reference Data* (in press).

Harriott, P. 1975. Thermal conductivity of catalyst pellets and other porous particles. *Chemical Engineering Journal* 10:65.

Mo, K. C., and Gubbins, K. E. 1976. Conformal solution theory for viscosity and thermal conductivity of mixtures. *Molecular Physics* 31:825.

An instrument useful in many projects is the spectrophotometer. Here graduate student Charles Baker uses it for research on transport through membranes.

Pendergrass, J. H., and Scheele, G. F. 1974. Rapid coalescence of liquid drops at a liquid-liquid interface. Paper read at 67th Annual Meeting of American Institute of Chemical Engineers, December 1974, in Washington, D.C.

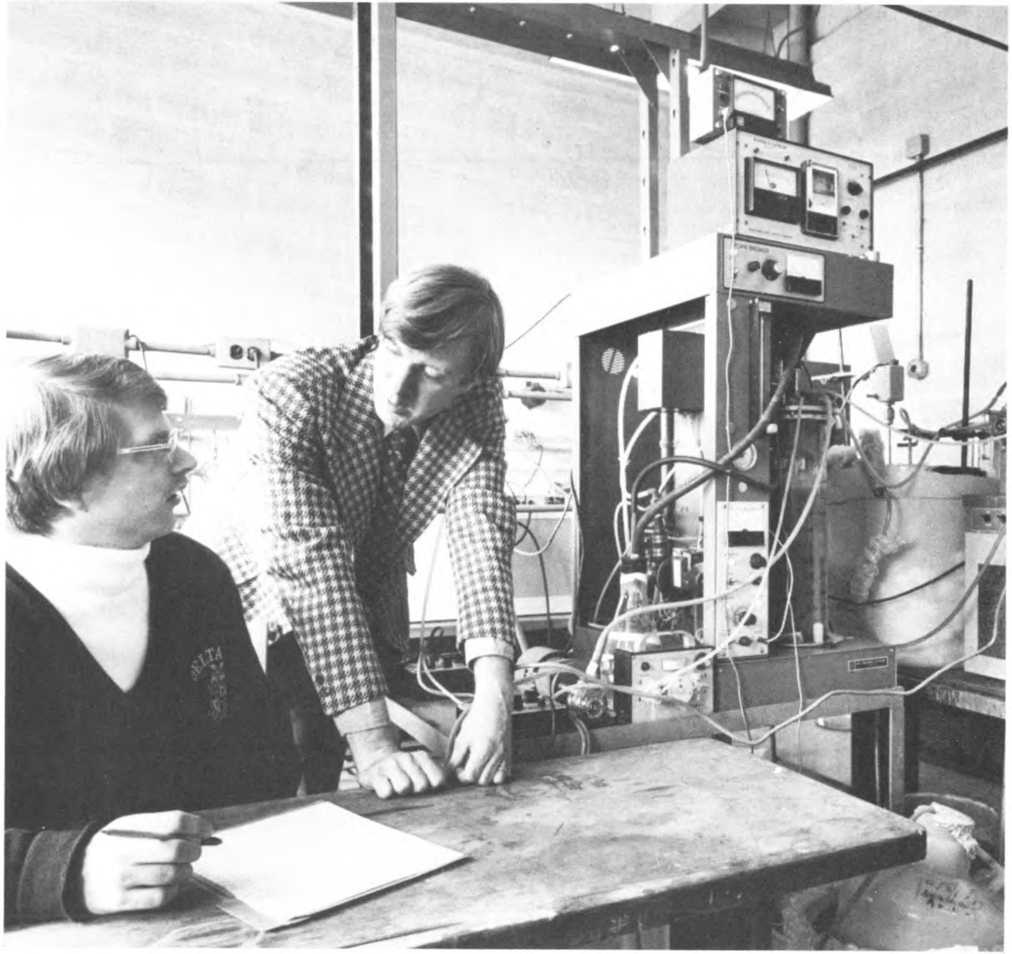
Wiegandt, H. F.; Von Berg, R. L.; and Patel, P. R. 1978. The crossflow piston bed. *Desalination* (in press).

Yu, H., and Scheele, G. F. 1975. Laminar jet contraction and velocity distribution in immiscible liquid-liquid systems. *International Journal of Multiphase Flow* 2:153.

M.Eng. (Chemical) Degree Program

The professional master's degree program in chemical engineering is intended primarily 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 somewhat in contrast to the more mathematical and theoretical course work offered for the Master of Science degree, which has an orientation toward research. Both the M.Eng. (Chemical) and the M.S. degree work may be utilized in graduate programs leading to the Ph.D. degree.

The present M.Eng. (Chemical) curriculum comprises four required courses, a design project giving three or six credits, and four or five technical elective courses to make a total of thirty credits. The required courses are Process Equipment Design, Design of Chemical Reactors, Numerical Methods, and Process Control. The technical electives may be chosen from the offerings of the School of Chemical Engineering or of other units of the College of Engineering and the University. Frequently selected chemical engineering electives are Phase Equilibria, Petroleum Refining, Development Economics, Polymeric Materials, Polymeric Materials Laboratory, Fermentation Engineering, Industrial Microorganisms, Wastewater Engineering, Advanced Thermodynamics, Synthetic Fuels, and Air Pollution Control.



Professor Michael Shuler and M.Eng. student Jan Slaby discuss the microbial conversion of poultry manure to chicken feed.

Design projects are related to the specialties of the faculty. In recent years these projects have dealt with petroleum refining, organic chemicals, petrochemicals, and monomers for plastics. Examples of recent project titles and the supervising professors are:

Coal Desulfurization by Solvent Extraction (J. C. Smith)

Magnetic Desulfurization of Coal (J. C. Smith)

Hydrofluoric Acid Slurry Process (J. C. Smith)

Conversion of Poultry Manure into High Protein Feedstuff (M. L. Shuler)

Regeneration of Spent Carbon Adsorbents in a Fluidized Bed (P. Harriott)

Design of Reactors for Improved Heat Transfer in Suspension and Emulsion Polymerization (P. Harriott)

Faculty Members and Their Research Interests

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), Ph.D. (M.I.T.): *kinetics and catalysis, coal gasification, 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*

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*

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

Julian C. Smith, Chem.E. (Cornell): *heat transfer, mixing, solids handling*

William B. Streett, B.S. (U.S. Military Academy), Ph.D. (Michigan): *properties of fluids at high pressures, computer simulation, studies of liquids*

Raymond G. Thorpe, 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): *petroleum processing, saline-water conversion* (on leave each fall term)

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.

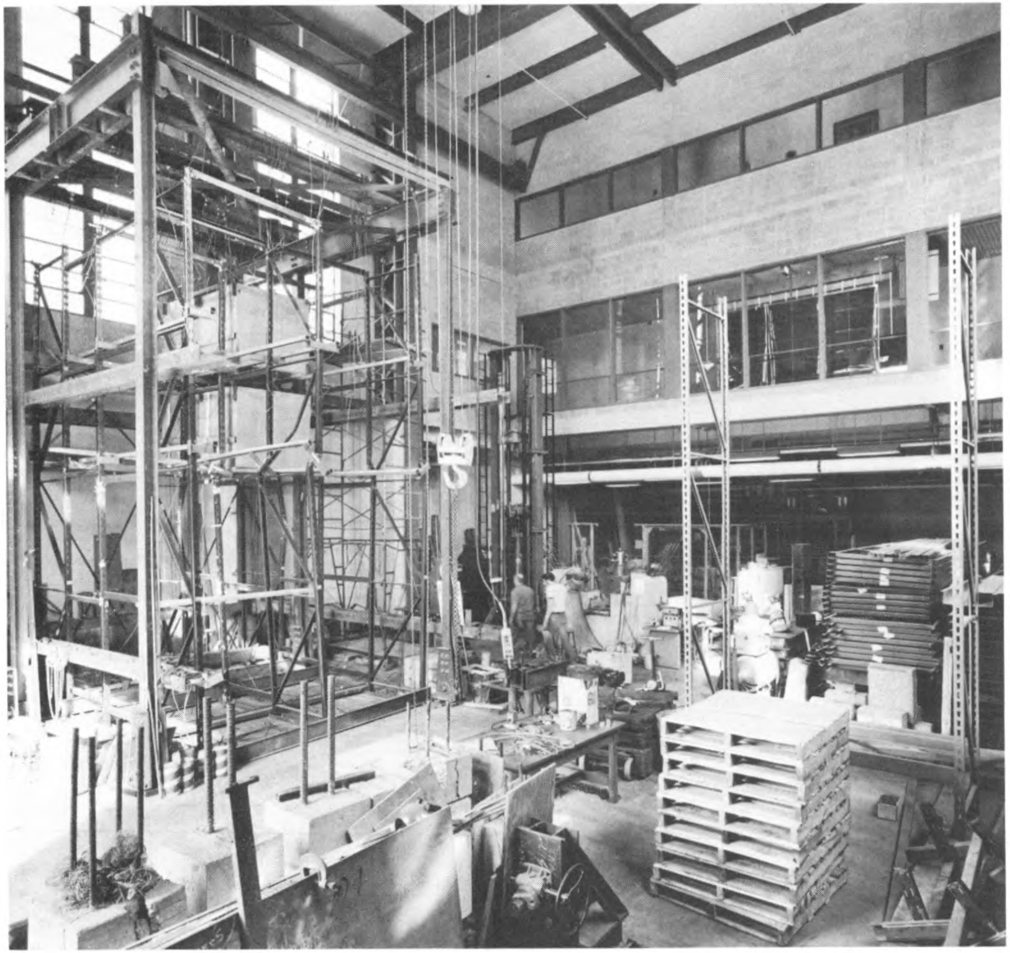
More than one hundred students are now enrolled in graduate programs at Cornell in civil and environmental engineering. These programs lead to the degrees of Doctor of Philosophy, Master of Science, and Master of Engineering (Civil). Major subject areas for Ph.D. and M.S. candidates are aerial photographic studies, 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.

In the photogrammetric area, facilities include some of the latest geodetic and photogrammetric instruments and equipment. Opportunities are provided for research on instrumentation for ground, aerial, and space surveys, geodetic control, analytic aerotriangulation, geometric aspects of various remote sensors, and problems inherent in land surveying. Airphotos and remote-sensing facilities available in the school include an extensive library of more than 600,000 airphotos of the United States and other areas of



the world.These illustrate various geographic and geomorphic features and sequential changes; many are accompanied by ground and laboratory data and other source material.

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 equipped for demonstrations in wave mechanics and rotating flows and for a variety of conventional experiments. A large wind tunnel is available for the modeling of atmospheric transfer phenomena, important in studies of hydrology and air pollution.

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

A new interactive computer graphics facility, directed by D. P. Greenberg and located in Rand Hall, is one of the finest in American universities. In engineering, this interdisciplinary system is used for research on structures, fluid mechanics, and environmental systems engineering.

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.

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 interpreting airphotos and imageries; (2) specific applications in engineering, geology, agriculture, and planning; (3) specific applications in various climatic 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:

Liang, T., contributor. 1975. *Manual of remote sensing,* ed. R. Reeves. Falls Church, Virginia: American Society of Photogrammetry.

Liang, T., and Philipson, W. R. 1977. The use of airphoto interpretation and remote sensing in soil resource inventories. In *Soil resource inventories* (Proceedings of workshop sponsored by U.S. Agency for International Development). Ithaca, New York: Cornell University.

Markham, B. L. 1978. Monitoring aquatic vegetation with aerial photography. M.S. thesis (T. Liang).

Teng, W. L. 1977. Remote sensing in monitoring leachate from landfills in central New York State. M.S. thesis (T. Liang).

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 on these subjects are:

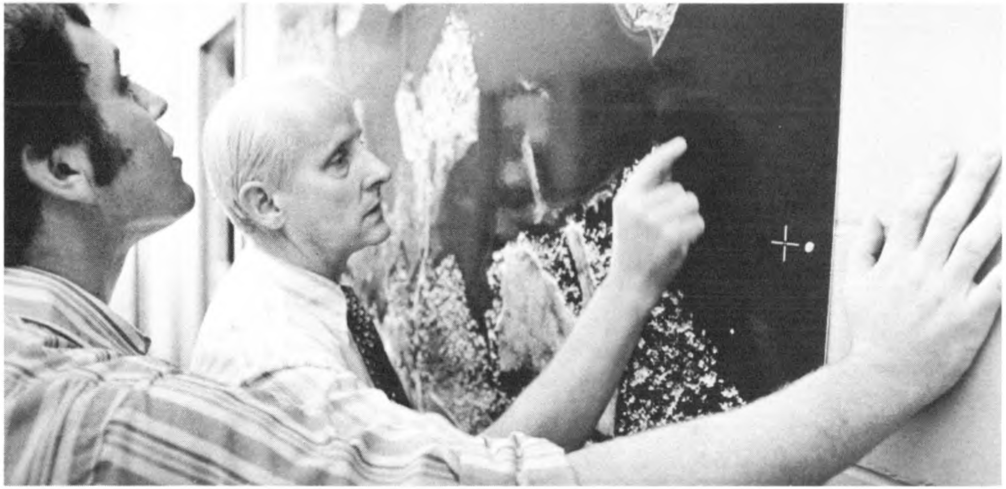
Bialas, W. F. 1975. Economic models for nonstructural flood plain planning. Ph.D. thesis (D. P. Loucks).

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

Ittig, P. T. 1974. Planning ambulatory health care delivery systems. Ph.D. thesis (G. P. Fisher).

Loucks, D. P. 1976. Surface water quality management. Surface water quantity management. Chapters 5 and 6 in *Systems approach to water management,* ed. A. K. Biswas. New York: McGraw-Hill.

Stereoscopic airphoto study is used in land-use inventory projects.



Aerial photographs such as this infrared image (examined by Professor Arthur McNair and a graduate student) are used to measure and map environmental factors.

Lynn, W. R. 1973. *Evaluation of environmental health programmes.* World Health Organization technical report series, no. 528. Geneva: World Health Organization.
Orloff, N. 1977. *The future of the Council on Environmental Quality.* Paper published by U.S. Senate Interior Committee.
Rovinsky, R. 1977. Models to evaluate the economic and environmental effects of insecticide use. Ph.D. thesis (C. A. Shoemaker).
Schuler, R. E. 1974. The interaction between local government and urban residential location. *American Economic Review* 64(4):682.
Shoemaker, C. A. 1977. Crop ecosystem models for pest management. In *Ecosystem modelling in theory and practice,* ed. C. A. Hall and J. Day. New York: Wiley-Interscience.
Stedinger, J. 1975. *Design of controls for a solar-heated building.* Report LA-5925-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

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 inventory 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.

Examples of recent publications and theses in this area are:

Coskun, B. 1976. Analytical aerial triangulation with corrections for systematic errors. Ph.D. thesis (A. J. McNair).
Hassan, M. M. 1977. Strength of figure tables for design of horizontal control networks. Ph.D. thesis (A. J. McNair).
Heinzen, M. R. 1977. Hydrographic surveys: geodetic control criteria. M. S. thesis (A. J. McNair).
McNair, A. J. 1977. Survey engineering vs. other 4-year engineering programs: Australia and United States. Graduation address at Queensland Institute of Technology, Brisbane.

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; the interaction between soil and rock structures; analytical, finite element, and probabilistic modeling; and marine and coastal geotechnique and geomechanics.

A sampling of recent papers and theses indicates some of the current research in this area:

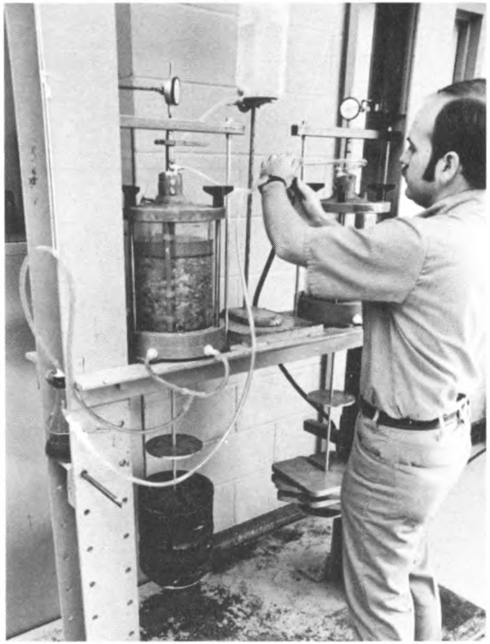
Cording, E. J., and O'Rourke, T. D. 1977. Excavation, ground movements, and their influence on buildings. Paper read at Annual Meeting of American Society of Civil Engineers, 17–21 October 1977, in San Francisco, California.

Egan, J. A., and Sangrey, D. A. 1978. Critical state model for cyclic load pore pressure. In *Proceedings of ASCE specialty conference on earthquake engineering and soil dynamics*, pp. 410–424. New York: American Society of Civil Engineers.

Ingraffea, A. R. 1978. On discrete fracture propagation in rock loaded in compression. In *Numerical methods in fracture mechanics* (Proceedings of 1st international conference), pp. 235–248. Swansea, United Kingdom: University College, Swansea.

Kulhawy, F. H. 1978. Geomechanical model for rock foundation settlement. *ASCE Journal of the Geotechnical Engineering Division* 104 (GT2):211.

O'Rourke, T. D.; Cording, E. J.; and Boscardin, M. 1977. Damage to brick-bearing wall structures caused by adjacent braced cuts and tunnels. Paper read at Conference on Large Ground Movements and Structures, 3–6 July 1977, in Cardiff, Wales.



Soil testing is involved in graduate research projects in geotechnical engineering.

Pollard, W. S. 1978. Rate and time effects in cyclic triaxial testing. Ph.D. thesis (D. A. Sangrey).

Sangrey, D. A. 1977. Marine geotechnique — state of the art. *Marine Geotechnology* 2:45.

Stewart, J. P. 1978. Uplift load-deformation behavior of drilled shaft foundations. M.S. thesis (F. H. Kulhawy).

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 resources 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 and graduate students have included studies of lake circulation, unsteady flows in channels, nearshore currents, dynamic coastline processes, evaporation from water and land surfaces, groundwater flow, and the fluid mechanics of porous materials.

A sampling of recent faculty publications and theses is given below:

Brutsaert, W., and Mawdsley, J. A. 1976. The applicability of planetary boundary layer theory to calculate regional evapotranspiration. *Water Resources Research* 12(5):852.

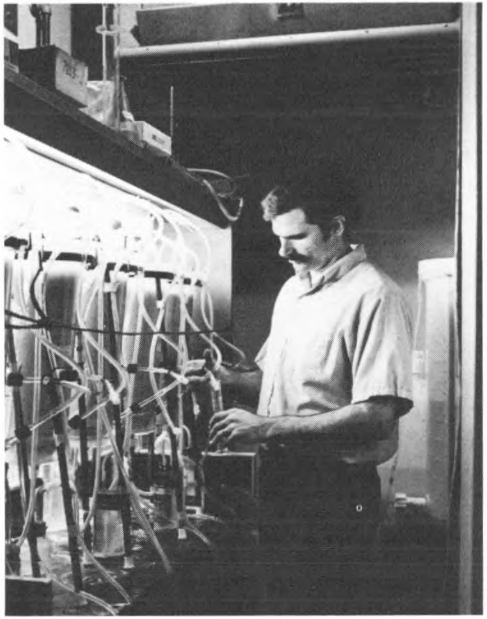
Jirka, G. et al. 1977. Transient heat releases from

offshore nuclear power plants. *ASCE Journal of the Hydraulics Division* 103(HY2):151.
Lennon, G. P. 1977. Effects of beach topography on nearshore currents. M.S. thesis (P. L.-F. Liu).
Liggett, J. A., with Young, D. L. 1977. Transient finite element shallow lake circulation. *ASCE Journal of the Hydraulics Division* 103(HY2):109.
Liu, C. C.-K. 1976. Numerical evaluation of response functions of a nonlinear rainfall-runoff model: flood hydrograph analysis in the Chemung River basin. Ph.D. thesis (W. H. Brutsaert).
Liu, P. L.-F. 1976. A perturbation solution of a nonlinear diffusion equation. *Water Resources Research* 12(6):1235.
Young, D. L. 1976. Dynamics of transient wind-driven circulation in a stably stratified basin by finite element analysis. Ph.D. thesis (J. A. Liggett).

Sanitary Engineering

Graduate study in the major subject of 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.



Recent graduate research in sanitary engineering included a study of the possible use of sulfur that has been removed from stack gases for the biological control of nitrogen levels in wastewater effluents.

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 are representative of recent research in the area:

Bisogni, J. J., Jr., and Driscoll, C. T., Jr. 1977. Denitrification using thio sulfate and sulfide. *ASCE Journal of the Environmental Engineering Division* 103:593.
Bliss, F. H. 1977. Denitrification ability of activated sludge under cyclic anaerobic and aerobic environments. M.S. thesis (J. J. Bisogni, Jr.).
Dentel, S. K. 1978. Anaerobic digestibility of chemically-coagulated organic materials. M.S. thesis (J. M. Gossett).
Dick, R. 1975. Research and the quest for clean water. (Report of the Water Pollution Control Federation Research Committee.) *Journal of the Water Pollution Control Federation* 47(2):240. Also in *Congressional Record,* 17 January 1975, p. 5947.
Gates, C. D., and Auer, P. L. 1978. *An assessment of potential environmental effects of implementing new energy technologies.* Cornell Center for Environmental Research report to New York State Energy Research and Development Authority.
Gossett, J. M. et al. 1978. Anaerobic digestion of sludge from chemical treatment. *Journal of the Water Pollution Control Federation* 50:533.
Preliminary design of a wastewater treatment plant and land disposal system in Suffolk County, New York. 1977. M.Eng. design project (C. D. Gates).

Structural Engineering

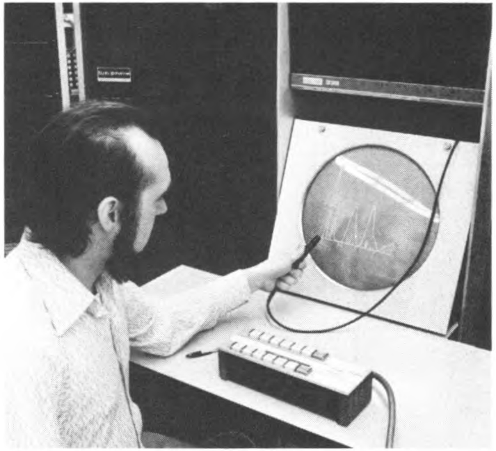
Structural engineering is one of the major branches of Cornell's program in civil and environmental engineering. Research projects involving graduate students are grouped into the following areas:

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 diaphragm effects of steel panels, stability of compression and flexural members, design criteria for compact sections, and connection behavior.

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 seismic shear transfer across cracks in nuclear containment vessels and other thick-walled structures.

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.



Above: Professor Richard White and graduate students are studying the strength of nuclear reactor containment vessels subjected to earthquake loads.

Right above: Computer graphics is an important tool in structural engineering design. For example, results of manipulations with the light pen are displayed almost instantly.

Right: Modeling is one of the methods used in the design and testing of large structures. This graduate student is working with a hyperbolic paraboloid roof model.

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 and has been applied to the pollution analysis of lakes.

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:

Alvi, A. Q. 1977. Steel fiber reinforced concrete in axial compression. Ph.D. thesis (W. McGuire).

Carino, N. 1974. The behavior of a model of plain concrete subject to compression-tension and tension-tension biaxial stresses. Ph.D. thesis (A. H. Nilson).

Desmond, T. P. 1977. The behavior and strength of thin-walled compression elements with longitudinal stiffeners. Ph.D. thesis (T. Peköz).

Gross, J. L.; Mutryn, T. A.; and McGuire, W. 1977. Computer graphics in nonlinear design problems. Paper read at Specialty Conference of Canadian Society of Civil Engineers, October 1977, in Montreal.

Kalyanaraman, V.; Peköz, T.; and Winter, G. 1977. Unstiffened compression elements. *ASCE Journal of the Structural Division* 103(ST9):1833.

Kanodia, V. 1975. Finite element elastic instability analysis of deep shells of double curvature. Ph.D. thesis (R. H. Gallagher).

Laible, J. P.; White, R. N.; and Gergely, P. 1977. *Experimental investigation of seismic shear transfer across cracks in concrete nuclear containment vessels.* ACI report no. SP-53. Detroit: American Concrete Institute.

Nilson, A. H., and Walters, D. B. 1975. Deflection of two-way floor systems by the equivalent frame method. *ACI Journal* 75:5.

Petrina, P. 1978. Safety analysis of nuclear concrete containment structures. Ph.D. thesis (R. N. White, R. G. Sexsmith).

Slate, F. O. 1974. Low-cost housing for developing nations — a new course at Cornell University. *TECHNOS* 3(1):79.

Smith, J. K. 1978. The effects of cracks on the seismic analysis of nuclear containment vessels. Ph.D. thesis (P. Gergely).

Wu, S. C.; Abel, J. F.; and Greenberg, D. P. 1975. An interactive computer graphics approach to surface representation. *Communications of the ACM* 20(10):703.

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

The major focus of study and research in this area is the application of analytical techniques to transportation problems, particularly those of urban transportation. The approach is typically multimodal. Specific interests of faculty members include demand modeling for passenger and freight movements, the development of mass-transit systems, airport planning and operation, traffic flow theory, transportation systems analysis, highway design, transportation-communication interrelationships, transportation economics, and freight transportation.

Examples of recent papers and theses in this area are:

Brazie, C. L. 1972. Simulation models of satellite airport systems. Ph.D. thesis (G. P. Fisher).

Cesario, F. 1975. A combined trip generation and distribution model. *Transportation Science* 9(1):211.

Coulter, J. W. 1978. The effect of an exogenous value-of-time variable on a logit mode-choice model for the work trip. Ph.D. thesis (A. H. Meyburg).

Fisher, G. P. 1975. Goods transportation in urban areas. In *Proceedings of the Engineering Foundation conference,* ed. G. P. Fisher. Report no. DOT-OS-60099, Federal Highway Administration, U.S. Department of Transportation.

Meyburg, A. H., with Stopher, P. R. 1975. *Urban*

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

transportation modeling and planning. Lexington, Massachusetts: Lexington Books, D.C. Heath.

Orloff, C. 1973. Routing and scheduling a fleet of vehicles: the school bus problem. Ph.D. thesis (W. R. Lynn).

Schuler, R. E., with Coulter, J. W. 1978. The influence of socio-economic factors on the value of time in commuting to work. *Transportation* (in press).

Water Resource Systems

For graduate students interested in water resources planning and management, there are numerous interdisciplinary degree programs available through the Field of Civil and Environmental Engineering. Ph.D. degree candidates who wish 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 resources 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 wish to become acquainted with some of the management and planning issues of water resources 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. Cornell's Water Resources and Marine Sciences Center offers considerable assistance in both course work and research.

The variety of research projects in this area is suggested by the following faculty publications and theses:

Dworsky, L. B., with Berger, B. B. 1977. Water pollution control. *EOS, Transactions of the American Geophysical Union* 58(1):16.

El-Sahragty, M. 1974. Methods for analyzing storm water storage and treatment systems. Ph.D. thesis (D. P. Loucks).

Haith, D. A. 1976. Land use and water quality in New York rivers. *ASCE Journal of the Environmental Engineering Division* 102 (EE2):1.

Horrigan, J. K. 1975. Urbanization and urban runoff — strategies for management. M.S. thesis (L. B. Dworsky).

Loucks, D. P., and Koenig, A. 1977. Management model for wastewater disposal on land. *ASCE Journal of the Environmental Engineering Division* 103(EE4):181.

Turgeon, A. 1975. Optimal operation of hydro-steam power systems. Ph.D. thesis (C. A. Shoemaker).

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.

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

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.

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 that included the intensive intersession work periods, listed with information about the participants, are:

Olympic Facilities (twenty-eight students; Elio D'Appolonia, 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)

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, 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 Associates, 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)

Detection of Buried River Channels in Glaciated Regions (T. Liang)

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 resources planning management and policy*

Gordon P. Fisher, P.E.; B.E., D.Eng. (Johns Hopkins): *transportation systems analysis, traffic flow theory, public systems, engineering economics, urban goods movement*

Charles D. Gates, B.A. (Williams), M.S. (Harvard): *sanitary engineering, water quality, nonpoint waste sources*

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*

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. (Hochschule fur Bodenkulter), 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), 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*

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*

Arthur J. McNair, P.E.; B.S., M.S.C.E. (Colorado): *geodesy-photogrammetry*

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*

Dwight A. Sangrey, P.E.; B.S. (Lafayette), M.S. (Massachusetts), Ph.D. (Cornell): *soil behavior, soil dynamics, marine and coastal geotechnique, soil-structure interaction, probabilistic modeling*

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*

Richard N. White, 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 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. 1973. *An introduction to programming: a structured approach using PL/I and PL/C*. Cambridge, Mass.: Winthrop.

———. 1976. *A primer on structured 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.

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.

Salton, G. 1969. *Automatic information* *organization and retrieval.* New York: McGraw-Hill.

——. 1975. *Dynamic information and library processing.* Englewood Cliffs, N.J.: Prentice-Hall.

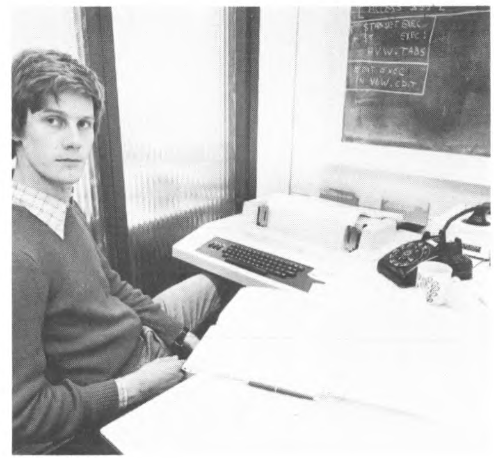
Salton, G. et al. 1971. *The SMART retrieval system: experiments in automatic document processing.* Englewood Cliffs, N.J.: Prentice-Hall.

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 digital computer, a solid background in mathematics (for example, 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).

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.

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).



Facilities

The central computing facility at Cornell is a three-megabyte IBM 370/168, 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. The 168 operates under the VM system, so that arbitrary virtual machines can be configured for various experimental purposes. The department also has a PDP-11/60 (microprogrammable) system for its own research, with a link to the IBM 370.

Areas of Research

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

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

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

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

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).

Theory of Algorithms

There is a growing belief that a relatively small number — perhaps a score — of fundamental processes dominate all computing, 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 has recently been 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:

Galil, Z. 1975. The complexity of resolution procedures for theorem proving in the propositional calculus. Ph.D. thesis (J. E. Hopcroft).

Musinski, J. A. 1973. Determining the complexity of matrix multiplication and other bilinear forms. Ph.D. thesis (J. E. Hopcroft).

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

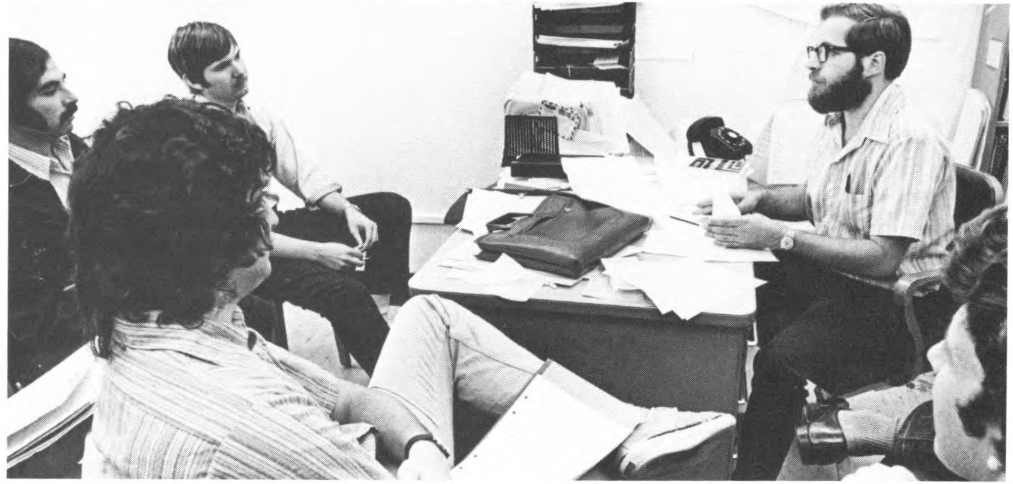
Right: Professor Robert S. Cartwright is a specialist in program verification and semantics. (He is seated in one of the carrels provided for graduate students in computer science.)

Theory of Computation

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

As a result of recent work in theoretical computer science, a unified theory of feasible computation is emerging that has strong connections to

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



recursive function theory, to formal language theory, and to the theory of algorithms. This theory and these connections are being investigated by several professors and their students.

Theses in this area include:

Hunt, H. B. 1974. On the time and tape complexity of languages. Ph.D. thesis (J. E. Hopcroft).

Kozen, D. 1977. Complexity of finitely presented algebras. Ph.D. thesis (J. Hartmanis).

Mehlhorn, K. 1974. Polynomial and abstract subrecursive classes. Ph.D. thesis (R. L. Constable).

Simon, J. 1975. On some central problems in computational complexity. Ph.D. thesis (J. Hartmanis).

Other recent work in this area concerns the computational complexity of schemata and the analysis of algorithms for manipulating them. Publications based on this research include the texts, cited above, by Hartmanis and Stearns and by Aho, Hopcroft, and Ullman, and also journal articles such as the following:

Hartmanis, J., and Baker, T. P. 1975. On simple Goedel numberings and translations. *SIAM Journal of Computing* 4(1):1.

Hartmanis, J., and Hunt, H. B., III. 1974. The LBA problem and its importance in the theory of computing. *SIAM-AMS Proceedings* 7:1.

Hopcroft, J., and Musinski, J. 1973. Duality applied to the complexity of matrix multiplication and other bilinear forms. *SIAM Journal on Computing* 2(3):159.

Compiler Construction

The PL/C compiler, a very efficient compiler for a subset of PL/I, was implemented under the leadership of R. W. Conway. The compiler is unusual in that it attempts to make plausible repairs of all errors so that every program reaches execution. It has become the standard instructional system for PL/I and is used at more than a hundred universities throughout the world. A description is available in published form:

Conway, R. W., and Wilcox, T. R. 1973. Design and implementation of a diagnostic compiler for PL/I. *Communications of the ACM* 16(3):169.

Further work on PL/C is directed toward expanding the subset of PL/I and improving both efficiency and error repair. A group at Cornell has developed an interactive version of the system.

Members of the field are also involved in the study of automatic translator writing systems and their practical application. D. Gries's book on compiler construction, cited above, reflects this work.

Program Verification and Semantics

R. S. Cartwright, R. L. Constable, J. Donahue, D. Gries, and their students are working on various aspects of program verification and of the formal semantics of programming languages. Cartwright is especially interested in the problem of designing a verifiable Lisp-like programming language with recursive data type. Constable is concerned with theoretical issues arising in this area, particularly questions about the underlying logical systems and models. He is also director of the PL/CV Verifier project. Donahue is applying theories of formal semantics to the description and design of real programming languages. Gries is working on programming methodology, new techniques for correctness proofs, and ways of teaching these approaches to programming. The experimental PL/CV Verifier, written in PL/I, was built at Cornell and is distributed with the PL/C compiler to interested research groups.

Some examples of recent work in this area are:

Cartwright, R., and Oppen, D. 1978. Unrestricted procedure calls in Hoare's logic. In *Conference record of the fifth annual ACM symposium on principles of programmers languages.* New York: Association for Computing Machinery.

Clarke, E. M., Jr. 1976. Completeness and incompleteness for Hoare-like axiom systems. Ph.D. thesis (R. L. Constable).

Constable, R. L., and Egli, H. 1976. Computability concepts for programming language semantics. *Journal of Theoretical Computer Science* 2:133.

Donahue, J. 1976. Complementary definitions of programming language semantics. In *Lecture notes in computer science 42.* Berlin, Heidelberg, and New York: Springer-Verlag.

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

Owicki, S. 1975. Axiomatic proof techniques for parallel programs. Ph.D. thesis (D. Gries).

Professor Ray Teitelbaum (second from left) is directing the implementation of a new, highly interactive version of PL/C on the department's PDP-11 minicomputer and LSI-11 microcomputer.

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

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

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 above). The participation of graduate students in this program is indicated by thesis work completed recently:

Williamson, R. E. 1974. Real time document retrieval. 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

J. E. Dennis, F. Luk, and C. Van Loan are conducting research in the areas of numerical linear algebra, solutions of nonlinear systems of equations, and nonlinear optimization. J. Bramble is primarily interested in the numerical solution of partial differential equations. Ph.D. theses have been written on approximation theory, solutions of nonlinear systems of equations, and solutions of matrix polynomial and λ-matrix problems; an example is:

Gay, D. 1975. Brown's method and some generalizations, with applications to minimization problems. Ph.D. thesis (J. E. Dennis).

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 other academic areas represented in the field are mathematics, applied mathematics, electrical engineering, theoretical and applied mechanics, and operations research and industrial engineering. The field members are listed below.

Gregory Andrews, B.S. (Stanford), Ph.D. (Washington): *operating systems*

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

Robert S. Cartwright, A.B. (Harvard), M.S., Ph.D. (Stanford): *program verification and semantics*

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*

John E. Dennis, B.S., M.S. (University of Miami), Ph.D. (Utah): *numerical analysis*

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

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

Juris Hartmanis, 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*

William L. Maxwell, B.M.E., Ph.D. (Cornell): *digital simulation, operations research*

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

Christopher Pottle, B.E. (Yale), M.S., Ph.D. (Illinois): *signal processing, systems theory*

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): *operating systems*

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

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 spectrum of interests, ranging from the desire to engage in research on basic electrical phenomena or on the processing of signals, to the 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 utilize 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 forty graduate students are enrolled in the Field of Electrical Engineering. Of these, fifty are working for their 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, as at Cornell, that encourages interaction among people working in related research areas.

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 her or his Special Committee, devises a program of courses and research tailored to the student's 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 giving access to several of the largest computing networks in existence are used in many of the research projects in both electrophysics and systems. In addition the School of Electrical Engineering has several minicomputer and microcomputer systems with extensive peripheral devices that are available to all faculty members and students for research and instructional use. One of these machines is interfaced with an analog computer to provide a hybrid facility.

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

Research in this area involves the application of electrical engineering techniques to biological and medical systems and includes studies of electrophysiological techniques, animal sound communication, sensory processing in the nervous system, and the dynamics of cancer cellular proliferation and cancer therapy.

Current efforts include studies of mechanisms and models underlying periodic electrical activity of single pacemaker nerve cells and circadian oscillation in the sea snail eye, vocal communication in frogs and toads, the encoding of complex sounds in the auditory nervous system, information coding in the multiunit response of sensory receptors, and models and design of cancer therapy.

R. R. Capranica, M. Kim, and W. J. Heetderks direct these research efforts. Examples of publications and theses or reports (listed with the name of the supervising professor) in this area are:

Capranica, R. R. 1976. The auditory system. In *Frog neurobiology,* ed. R. Llinas and W. Precht, pp. 551–575. Heidelberg: Springer-Verlag.

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.

Heetderks, W. J. 1978. Criteria for evaluating multiunit spike separation techniques. *Biological Cybernetics* 29:215.

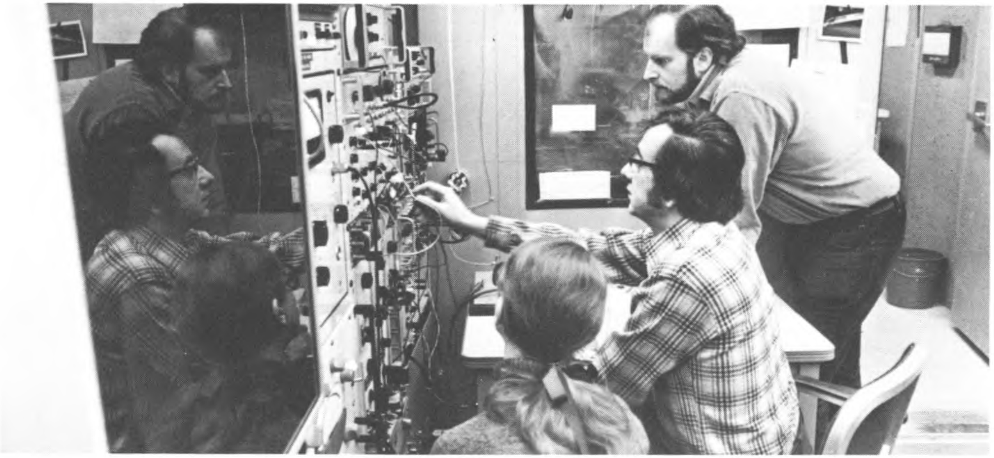
Kim, M., and Perry, S. 1977. Mathematical methods for determining cell DNA synthesis rate and age distribution utilizing flow micro-fluorometry. *Journal of Theoretical Biology* 68:27.

Kim, Y., and Kim, M. 1977. Modulation of repetitive action potentials in molluscan neurons stimulated with alternating currents. *Brain Research* 122:361.

Narins, P. M. 1976. Auditory processing of biologically meaningful sounds in the treefrog, *Eleutherodactylus coqui.* Ph.D. thesis (R. R. Capranica).

Yu, F. 1978. Microprocessor based data collection system for neurophysiological research. M.Eng. (Electrical) report (W. J. Heetderks).

Some of the graduate theses in progress are: A Neurological Control Model of the Peripheral



Above: Sounds used in behavioral studies of animal communication are generated electronically in research directed by Professor Robert R. Capranica (at center). The work also includes related neurophysiological experiments.

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).

Visual System of *Aplysia*, Pharmacological and Systems Study of Pacemaker Neurons, Sensitivity of the Eardrum Measured by Light Scattering Spectroscopy, Neural Basis for Sound Localization in Treefrogs, Sound Communication in Redwing Blackbirds, The Power of Heuristic Multi-Spike Isolation Techniques, The Role of PAD in the Type I Mechano Receptor System, and Systems Analysis and Experimental Studies in Chemical Control of Tumor Growth.

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. 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 research, experimentation, and design activities in this area.

D. W. Hammerstrom, H. C. Torng, and N. M. Vrana and their students work on these projects. Recent publications and reports include:

Bowra, J. W., and Torng, H. C. 1976. The modeling and design of multiple function unit processors. *IEEE Transactions* C25:210.

Hammerstrom, D. W., and Davidson, E. S. 1977. Information content of CPU memory referencing behavior. In *Proceedings of fourth annual symposium on computer architecture* (held 23–25 March 1977, in Washington, D.C.), p. 184. New York: IEEE Computer Society.

——. 1978. The use of second order memories to reduce addressing overhead. Submitted for publication.

Koenig, M., and Eichorn, K. 1976. A laboratory module for developing microprocessor based design projects. M.Eng. report (N. M. Vrana).

Riera, M. 1976. A microprogram module for CPU design projects. M.Eng. report (N. M. Vrana).

Torng, H. C., and Wilhelm, N. C. 1977. The optimal interconnection of circuit modules in microprocessor and digital system design. *IEEE Transactions* C26:450.

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.

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, and J. S. Thorp direct research projects in this area.

Recent reports, theses, and publications include:

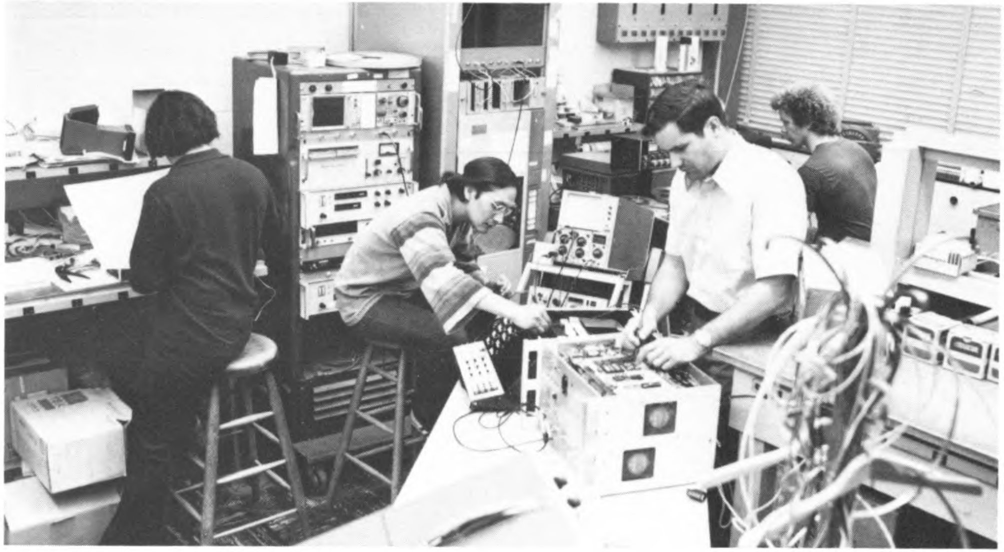
Bennett, W. 1977. A microprocessor-based controller for maximizing torque in fuel-injected engines. M.Eng. report (R. J. Thomas).

Sherkat, V. 1978. On the transient control of a power system via dynamic braking. Ph.D. thesis (J. S. Thorp).

Thomas, R. J. 1976. An efficient root-locus program for feedback control system design. *IEEE Transactions* E19:76.

Thomas, R. J.; Thorp, J. S.; and Pottle, C. 1976. A model-reference controller for stabilizing large transient swings in power systems. *IEEE Transactions* AC21:746.

Wong, T. 1977. A programming package for numerical solution of Lyapunov and Riccati equation. M.Eng. report (R. J. Thomas).



Digital Circuits and 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) and high-order ladder and lattice filter structures for speech processing and digital communications systems.

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

Left above: A Master of Engineering student works on a microprocessor-based system being designed for on-line signal analysis.

Above: Hardware units for the analysis of rocket and backscatter radar data have been designed and built by student groups. The equipment shown contains complex RF and digital circuits with microprocessors for programmable control functions.

data logging, data compression, radar control and on-line data processing, on-line experiment control, and process control. Work is also being done with sampled analog systems using charge transfer devices for real-time data analysis.

T. Berger, N. H. Bryant, D. T. Farley, T. C. Fine, W. J. Heetderks, M. C. Kelley, W. Ku, and N. M. Vrana direct research in this area.

Recent reports and publications include:

Blaine, G. M. 1977. A generalized filter using a tapped analog delay line. M.Eng. report (W. J. Heetderks).

Botsakos, M. 1976. Design of a data acquisition system for use in predicting orchard diseases. M.Eng. report (N. M. Vrana).

Gilmour, P. 1976. A software package for automatic speech parameter extraction on PDP 11/40 minicomputer system. M.Eng. report (W. Ku).

Jones, K. 1977. Controller for a synthesizer

of cricket songs: development of hardware and user programs. M.Eng. report (D. J. Aneshansley).
Ku, W. H., and Ng, S. M. 1975. Floating-point coefficient sensitivity and roundoff noise of recursive digital filters realized in ladder structures. *IEEE Transactions* CAS22:927.
Thomson, D. 1976. A data collection and processing system for an auroral radar. M.Eng. report (M. C. Kelley).

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 energies. 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 transiting charged particle 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 that occur in electromagnetic theory. A current project in this area focuses on structure symmetry as related to the propagation characteristics of periodic structures for microwave and millimeter circuits and devices; these include filters, interaction circuits for electron-beam or active semiconductor media, antenna arrays, transducers for surface-wave devices, modulators, and mode converters.

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:

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. *Reviews of Scientific Instruments* 49:507.
Maresca, N., and Liboff, R. L. 1975. Fields and radiation due to a charge incident on a conducting plane. *Journal of Mathematical Physics* 16:116.
McIsaac, P. R. 1976. Bidirectionality in gyrotropic waveguides. *IEEE Transactions* MTT24:223.

A center for collecting weather satellite data was designed and assembled in a doctoral research project.

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, M. C. Kelley, and J. L. Rosson.

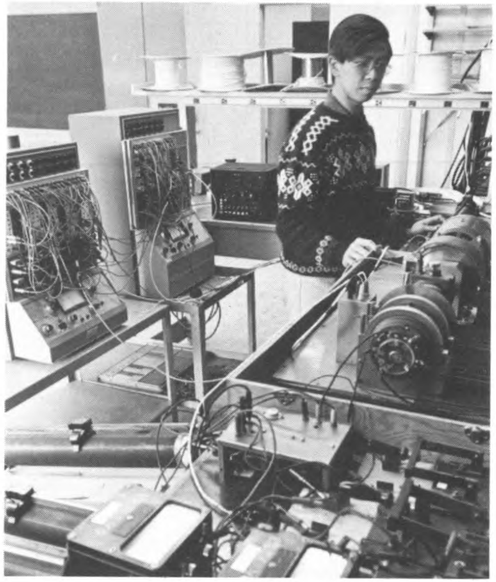
Recent theses and publications include:

Aneshansley, D., and Eisner, T. 1975. Ultraviolet-viewing with battery operated television camera. *Nature* 256(5513):150.

Minks, D. 1977. Electronic synthesis of the basic components of cricket songs. M.Eng. report (D. J. Aneshansley).

Sanik, P. S. 1978. An instrument system to measure the vertical distribution of ozone in the lower troposphere. Ph.D. thesis (N. H. Bryant).

Woodland, H. 1973. Special effects generator: combination of two video images. M.Eng. report (N. H. Bryant).



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.

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. While activities of such broad scope continue, 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 direct work in the application of solid-state devices to the implementation of control functions for electric-car development.

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 and students from the Schools of Electrical Engineering, Mechanical and Aerospace Engineering, and Civil and Environmental Engineering and University personnel responsible for planning and facilities.

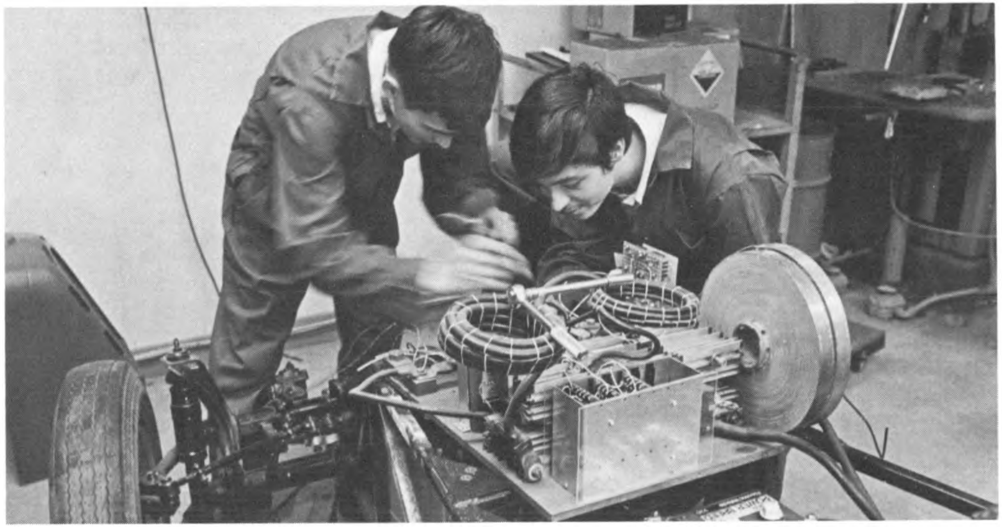
In the area of high-voltage breakdown and dielectric phenomena, research techniques and instrumentation developed in the Laboratory of Plasma Studies could be applied to investigations of insulation behavior and to studies of switching phenomena. Several impulse-power facilities, which function at voltages ranging from 0.5 million to 5 million volts with duration periods of between 50 nanoseconds and a few microseconds, are available for such studies. S. Linke, J. A. Nation, R. N. Sudan, and C. B. Wharton are interested in related research topics that overlap the subject matter of plasma physics.

Recent theses, M.Eng. reports, and publications include:

Chu, D., and Palesch, D. 1976. Design and analysis of ultra-high-voltage (UHV) electric power networks in the northeastern U.S.A. M.Eng. report (S. Linke).

Coulombe, S. A. 1975. Design of an electric vehicle for urban-suburban use. M.Eng. report (J. L. Rosson).

de Groff, A., and Amin, R. 1978. A thyristor phase-controlled converter/inverter for a model HVDC link. M.Eng. report (R. J. Thomas).



A continuing project for Master of Engineering students is the design of operating systems for the Cornell electric car.

Fong, J., and Pottle, C. 1978. Processing of power system analysis problems via simple parallel microcomputer structures. Paper F78-229-7 read at Winter Meeting of IEEE Power Engineering Society, January – February 1978, in New York.

Gallai, A. M. 1977. Comparisons of power-system-transient-stability-model complexities. M.S. thesis (R. J. Thomas).

Linke, S. 1977. Surge-impedance loading and power transmission capability revisited. Abstracted in *IEEE Transactions* PAS96 (4):1097. Full text in IEEE publication no. 77CH 1190-8-PWR.

Oey, K. K. 1976. On-line digital computer control of large-scale power system transient modes. Ph.D. thesis (R. J. Thomas).

Thomas, R. J.; Thorp, J. S.; and Pottle, C. 1976. A model-referenced controller for stabilizing large transient swings in power systems. *IEEE Transactions* AC21(5):746.

Thorp, J. S.; Phadke, A. C.; Horowitz, S. H.; and Beehler, J. E. 1978. Limits to impedance relaying. Paper F-78-219-8 read at Winter Meeting of IEEE Power Engineering Society, January – February 1978, in New York.

Information and Decision Theory

Research efforts in 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 and T. L. Fine direct research in this area. Examples of publications and theses are:

Berger, T. 1977. Explicit bounds to R(D) for a binary symmetric Markov source. *IEEE Transactions* IT23:52.

Berger, T., and Lau, J. K. 1977. On binary sliding block codes. *IEEE Transactions* IT23:343.

Chang, M. U. 1978. Rate distortion with an informed decoder and partially informed encoder. Ph.D. thesis (T. Berger).

Fine, T. L. 1973. *Theories of probability: an examination of foundations.* New York: Academic Press.

Fine, T. L., and Kaplan, M. A. 1977. Joint orders in comparative probability. *Annals of Probability* 5:161.

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

Tung, S. 1978. Multiterminal source coding. Ph.D. thesis (T. Berger).

Electron beam lithography is used for the fabrication of submicron-scale electronic devices. The microcomputer-controlled system uses a modified scanning electron microscope.

Integrated Circuits and VLSI 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 from industrial and university laboratories across the country who come to this national facility to carry out their own research.

Research programs range from the fundamental development of new machines to provide finer line definition or improve the analysis of submicrometer structures and the application of these machines to the production of advanced electronic devices, to the investigation of fundamental physical processes that are important in devices constructed on a submicrometer scale. Much of this work is done in the submicron facility 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 submicron facility.

Central to the work of the facility are programs which apply the lithographic and processing capabilities of the laboratory to the fabrication of

Equipment in the submicron facility includes a multiple-mask electron beam evaporation system for sequential deposition of patterned thin-film layers.

new components and subsystems for VLSI. One program is concerned with the physical limits to reduction in size of silicon MOSFETs and Schottky-gate MOSFETs, and studies are continuing on the properties of submicron-size devices 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 micron or smaller. Another project in this area involves the use of 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-micron 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. Frey, J. M. Ballantyne, C. A. Lee, and E. D. Wolf. Some relevant publications and theses are:

Benson, I. 1978. Theory and applications of a scanning laser microscope. M.S. thesis (J. M. Ballantyne).

Berenz, J. 1977. GaAs Read diodes. Ph.D. thesis (C. A. Lee, G. C. Dalman).

Frey, J. 1976. Effects of intervalley scattering on noise in GaAs and InP field-effect transistors. *IEEE Transactions* ED23:1298.

Frey, J., and Maloney, T. J. 1975. Frequency limits of GaAs and InP field-effect transistors. *IEEE Transactions* ED22:357.

Gurney, R. D. 1976. Fabrication technology for microwave GaAs field-effect transistors. M.S thesis (J. Frey).

Kratzer, S. 1978. Transient velocity characteristics of electrons in compound semiconductors. M.S. thesis (J. Frey).

Kwor, R. 1976. Experimental and theoretical studies of ion-implanted silicon Read IMPATT diodes. Ph.D. thesis (C. A. Lee, G. C. Dalman).

Maloney, T. J. 1976. Nonequilibrium electron transport in compound semiconductors. Ph.D. thesis (J. Frey).

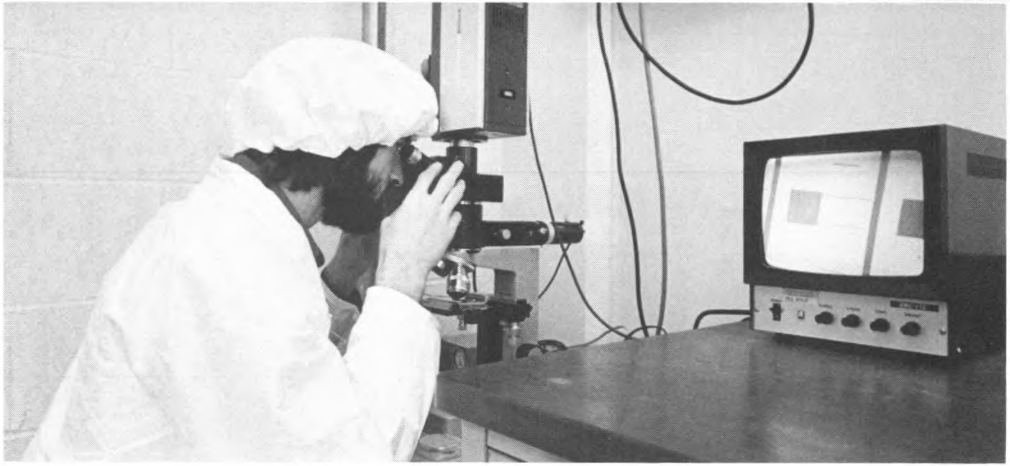
Microwave Semiconductor Devices and Circuits

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.

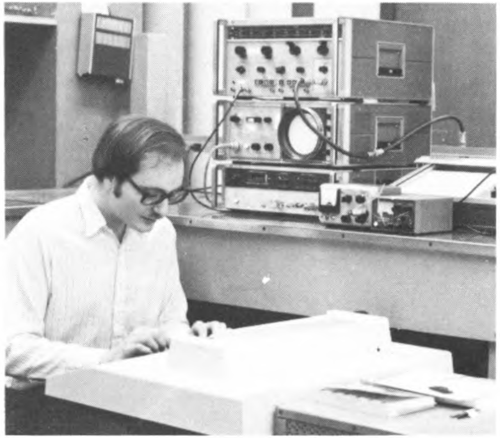
Current projects are concerned with the principles of operation and the means for improving the performance of such devices as both low-noise and high-power microwave field-effect transistors (FETs), Gunn diodes, and various types of avalanche diodes. Monolithic and hybrid microwave integrated circuits 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, by various methods, of semiconductor crystals used in studies of impurity diffusion, metallization, photolithography, and ion implantation.



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.



Right: 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.

H. J. Carlin, G. C. Dalman, L. F. Eastman, J. Frey, W. Ku, and C. A. Lee are directing this work. Representative reports, theses, and publications are:

Berenz, J. J. 1977. Small-signal characteristics of gallium arsenide Schottkey-Read IMPATT diodes. Ph.D. thesis (C. A. Lee, G. C. Dalman).

Komiak, J. J., and Carlin, H. J. 1977. Real frequency design of broadband microwave amplifiers. In *Proceedings of 6th biennial conference on active microwave semiconductor devices and circuits,* p. 65. Ithaca, N.Y.: Cornell University.

Ku, W. H. 1977. Exact synthesis of interstage matching networks for broadband microwave GaAs FET amplifiers. Paper read at IEEE International Microwave Symposium, June 1977, in San Diego, California.

Kwor, R. 1976. Experimental and theoretical studies of ion-implanted silicon Read IMPATT diode. Ph.D. thesis (C. A. Lee, G. C. Dalman).

Lawrence, D., and Eastman, L. F. 1978. Use of current controlled GaAs LPE for optimum doping profiles in LSA diodes. *Electronics Letters* 14:77.

Maloney, T. J., and Frey, J. 1976. Frequency limits of GaAs and InP field-effect transistors at 300 K and 77 K with typical active-layer doping. *IEEE Transactions* ED23:519.

Mokari-Bolhassan, M. E., and Ku, W. H. 1977. Gain-bandwidth limitations and synthesis of single-stub bandpass transmission-line structures. *IEEE Transactions* MTT25:848.

Souza, R. F. 1976. Small- and large-signal effects on IMPATT diodes. Ph.D. thesis (G. C. Dalman, C. A. Lee).

Wu, J.-S. 1978. Analytical and computer-aided design techniques for IMPATT reflection amplifiers. Ph.D. thesis (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 having 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. The methods used in this program are currently being extended to nonlinear and time-varying networks, with particular emphasis on 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 theses and publications include:

Carlin, H. J. 1977. A new approach to gain-bandwidth problems. *IEEE Transactions* CAS24:170.

Denton, G. A. 1977. Selective, constant delay wave digital filters. M.Eng. report (H. J. Carlin).

Fong, J. 1978. Large scale power system and nonlinear network simulation via simple parallel microcomputer structures. Ph.D. thesis (C. Pottle).

Ku, W. H., and Petersen, W. 1977. Synthesis of broadband matching networks for microwave transistor amplifiers. In *Proceedings of IEEE international symposium on circuits and systems,* pp. 704–707. New York: Institute of Electrical & Electronics Engineers.

Wong, Y. M., and Pottle, C. 1976. Adaptation of circuit-simulation algorithms to a simple parallel microcomputer structure. *IEEE Journal on Electronic Circuits and Systems* 1:27.

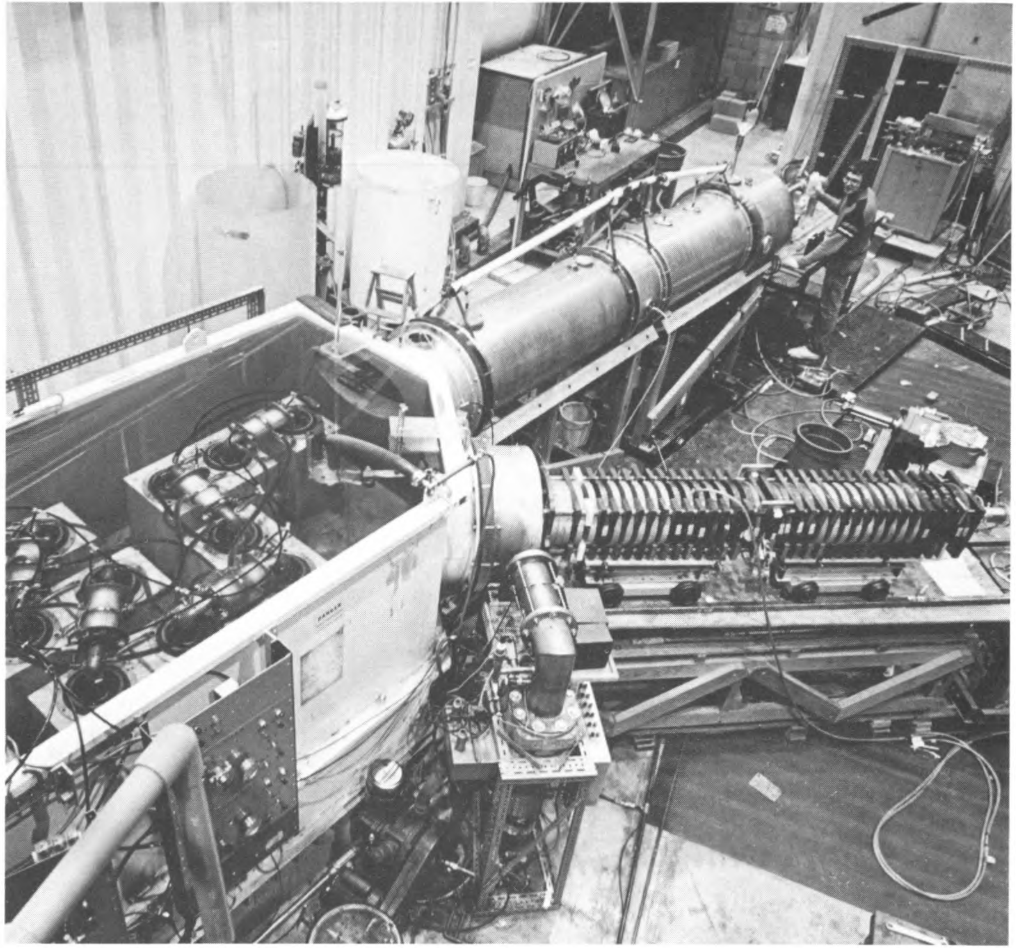
Plasma Physics and Applications

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 controlled thermonuclear power research.

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 electron and ion beam research 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 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 which 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,



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.

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.

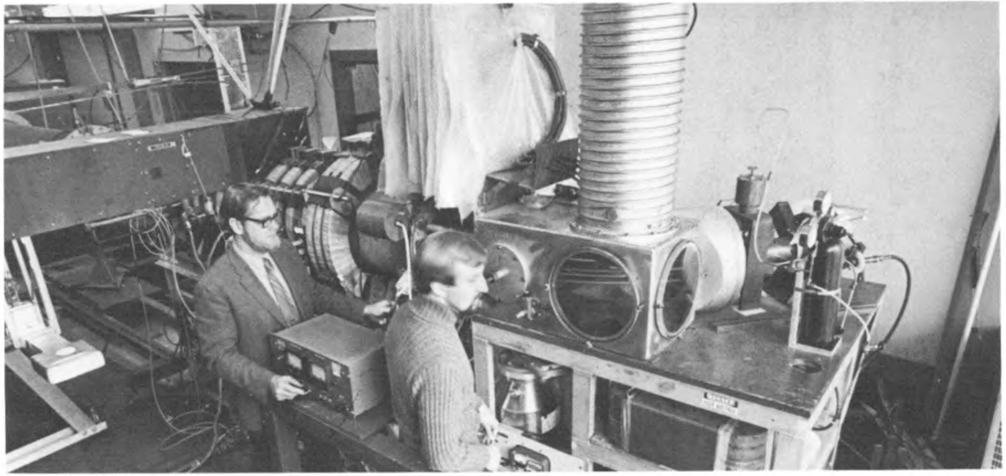
Electrical engineering faculty members directing plasma research include R. L. Liboff, J. A. Nation, E. Ott, R. N. Sudan, and C. B. Wharton. Other academic units at Cornell that participate in the Laboratory of Plasma Studies activities include those in applied and engineering physics, chemistry, mechanical and aerospace engineering, nuclear science and engineering, and physics.

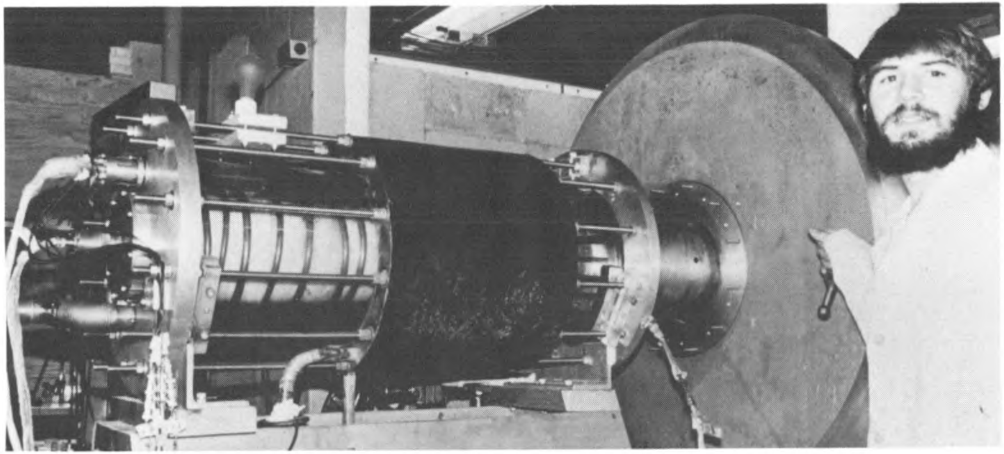
Recent theses and papers in this area include:

Carmel, Y. 1974. Application of intense relativistic electron beams to microwave generation. Ph.D. thesis (J. A. Nation). A paper based on this research was published under the same title in 1973 in *Journal of Applied Physics* 44:5268.

Greenspan, M. 1977. Experimental study of plasma heating by relativistic electron beam. Ph.D. thesis (C. B. Wharton).

Liboff, R. L., and Maresca, N. 1975. An interpolation formula for the energy radiated by a point charge passing through a hole in a plane. *Canadian Journal of Physics* 53:62.





Right above: Research on the heating of plasmas, part of a study of controlled thermonuclear processes, is supervised by Professor Charles B. Wharton (at left).

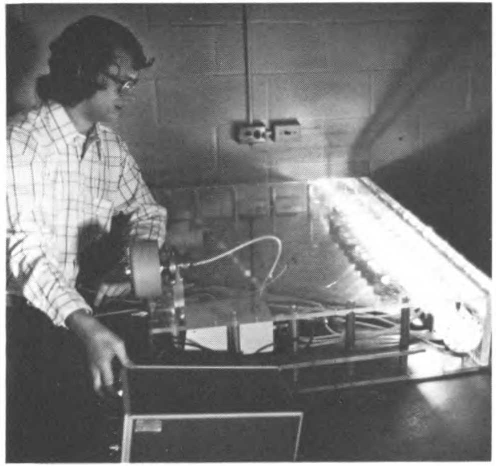
Right: Postdoctoral associate Michael Greenspan is working on a project, directed by Professor Ravindra N. Sudan, to focus high-power proton beams on a target.

Ott, E.; Manheimer, W. M.; and Klein, H. H. 1974. Stimulated Compton scattering and self-focusing in the outer regions of a laser fusion plasma. *Physics of Fluids* 17:1757.
Pereira, N. R. 1976. Theory and simulation of Langmuir solitons. Ph.D. thesis (R. N. Sudan). Papers based on this research were published in 1977 in *Physics of Fluids* 20:271; 20:936.
Sethian, J. 1976. Thomson scattering and diamagnetic studies of plasma heating. Ph.D. thesis (C. B. Wharton). A condensed version was published in 1978 in *Physical Review Letters* 40:451.

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.



Right above: The development of a very high-power laser to produce pulses in the megawatt range is a project for this graduate student working with Professor Ross A. McFarlane.

Right: A tunable semiconductor laser is being developed in research sponsored by Professors Joseph M. Ballantyne and Chung L. Tang.

Tunable infrared lasers that have planned application to tunable laser spectroscopy and laser-induced chemistry are being developed. This work is interdisciplinary, with 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. With 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 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 utilize 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. Related research on materials for active thin-film optical devices centers on electroluminescent metal-insulator-semiconductor (MIS) structures; the objectives are to obtain information on recombination mechanisms, interface states, barrier energies, and current transport and to make efficient MIS devices. Opportunities for numerous design projects arise in this and related work; for example, in the development of electrochromic films for displays.

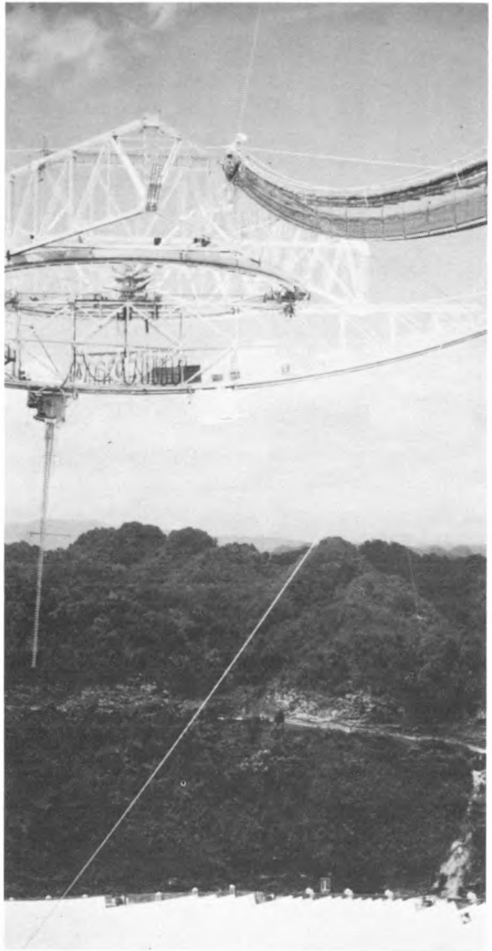
Faculty members involved in these various research efforts are J. M. Ballantyne, R. A. McFarlane, C. L. Tang, and G. J. Wolga. Among recent publications in this area are:

Davis, C. C., and McFarlane, R. A. 1977. Lineshape effects in atomic absorption spectroscopy. *Journal of Quantum Electronics* 18:151.

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.

Long, S. I.; Ballantyne, J. M.; and Eastman, L. F. 1974. Steady-state liquid epitaxial growth of GaAs. *Journal of Crystal Growth* 26:13.

Tang, C. L.; Kreismanis, V.; and Ballantyne, J. M. 1976. Wide band electro-optical tuning of semiconductor lasers. *Journal of Applied Physics* 30:113.



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.

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 utilizes 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), and other specialized measurement, control, and navigation equipment. The design and construction of such devices provides ample opportunity to develop state-of-the-art engineering expertise.

R. Bolgiano, D. T. Farley, M. C. Kelley, E. Ott, and R. N. Sudan are involved in these research efforts. Recent theses and papers in this area include:

Costa, E. 1978. Aspects of the linear and nonlinear development of equatorial spread F with applications to ionospheric scintillation. Ph.D. thesis (M. C. Kelley).

Kelley, M. C. 1978. The earth's electric field. *Engineering: Cornell Quarterly* 13(2):15.

Keskinen, M. 1978. Numerical simulation and theory of strong ionospheric gradient-drift turbulence. Ph.D. thesis (R. N. Sudan). A paper based on this research was published in 1977 in *Physical Review Letters* 38:966.

Vickrey, J. F. 1978. Incoherent scatter measurements of the motions of H^+ and O^+ in the topside ionosphere. Ph.D. thesis (D. T. Farley).

Satellites and sounding rockets, such as this Dual Hawk shown on a launch pad in India, carry Cornell instruments into the near-Earth regions of space. Research in this area is under the supervision of Professor Michael C. Kelley.

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, and a vapor-phase epitaxial station 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 or molecules are shot at a seed crystal face in a vacuum chamber, producing extremely thin layers with fine control of thickness, and very smooth layers without defects. Crystals of gallium arsenide, indium phosphide, and such alloys as aluminum gallium arsenide are grown with 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.

The semiconductor materials are tested electrically to determine electron density and mobility; other physical and chemical properties are tested by such techniques as photoluminescence measurement and secondary-ion mass spectroscopy.

The materials are processed to produce semiconductor electron devices such as microwave field-effect transistors and Gunn and avalanche devices, as well as lasers and light detectors. Equipment provided at the national submicron facility is particularly useful in projects of this kind.

Professors L. F. Eastman, J. M. Ballantyne, and C. A. Lee, and Research Associate C. Wood are principally responsible for the work carried out in this area. Among recent theses and publications are:

Ip, K. T. 1978. High purity indium phosphide for microwave electron devices. Ph.D. thesis (L. F. Eastman).

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. 1977. Electric current controlled liquid phase epitaxy of GaAs on N^+ and semi-insulating substrates: growth parameters and doping modulation. Ph.D. thesis (L. F. Eastman).

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.

Wrick, V. L.; Ip, K. T.; and Eastman, L. F. 1978. High purity LPE InP. *Journal of Electronic Materials* 7:253.

Wrick, V. L.; Scilla, G. J.; Eastman, L. F.; Henry, R. L.; and Swiggard, E. M. 1977. Effects of baking time on LPE InP: purity and morphology. In *Proceedings of 6th international symposium on gallium arsenide and related compounds*, pp. 35–40. London: Institute of Physics.

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 above: Laboratories with humidity and temperature control and filtered air are provided for work, such as crystal growth and semiconductor processing, that requires clean-room conditions.

Right: An ion implanter is used by Professor Charles A. Lee (at right) and a graduate student for processing semiconductor materials into electron devices.

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, B.S., B.S.E.E. (Utah), S.M., Ph.D. (M.I.T.): *optoelectronic materials and devices, integrated optics*

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

Ralph Bolgiano, Jr., B.S., B.E.E., M.E.E., Ph.D. (Cornell): *tropospheric radiophysics, communication theory*

Nelson M. 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.): *bioelectronics, pattern recognition*

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 techniques*

William H. Erickson, B.S., M.S. (Carnegie Institute

The annual spring picnic of the School of Electrical Engineering, held on campus in front of Phillips Hall, is attended by upperclass and graduate students and faculty and staff members.

of Technology): *power engineering, instrumentation*
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, pattern classification*
Jeffrey Frey, B.E.E. (Cornell), M.Sc., Ph.D. (California, Berkeley): *microwave solid-state devices, integrated electronics*
Daniel W. Hammerstrom, B.S. (Montana), M.S. (Stanford), Ph.D. (Illinois): *computer system performance evaluation and analysis, computer architecture*
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 Ku, B.S.E.E. (Pennsylvania), M.E.E., Ph.D. (Polytechnic Institute of Brooklyn): *active networks, digital circuits*
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): *plasma physics, electromagnetic theory*
Simpson Linke, B.S., M.E.E. (Cornell): *energy systems, high-voltage phenomena*
Ross A. McFarlane, B.Sc. (McMaster), M.Sc., Ph.D. (McGill): *lasers, atomic and molecular spectroscopy*
Henry S. McGaughan, B.S.E. (Michigan), M.E.E. (Cornell): *network and communication theory*
Paul R. McIsaac, B.E.E. (Cornell), M.S.E., Ph.D. (Michigan): *electromagnetic theory, microwave circuits and devices*
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*
Edward Ott, B.S. (Cooper Union), M.S., Ph.D. (Polytechnic Institute of Brooklyn): *plasma physics*
Christopher Pottle, B.E. (Yale), M.S., Ph.D. (Illinois): *computer-aided design, network theory*
Joseph L. Rosson, B.S. (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, electromagnetic waves*
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): *optimization and control theory applications 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*
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 physics*

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, 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.

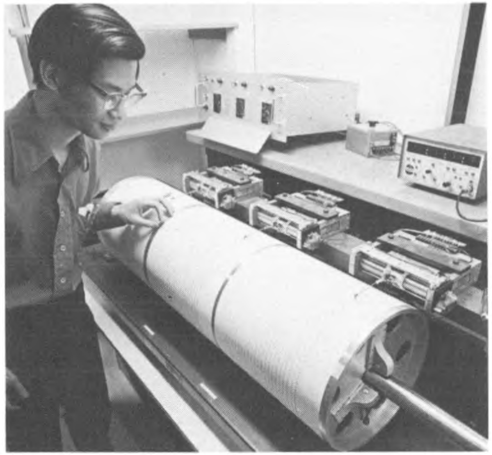
In recognition of these major new developments in geology and of the corresponding promise of this science, Cornell has been reorganizing its Department of Geological Sciences during the 1970s. The faculty has been expanded, new facilities have been made available, and a number of new programs have been developed in cooperation with other departments. Major innovations in curricula and research have been introduced.

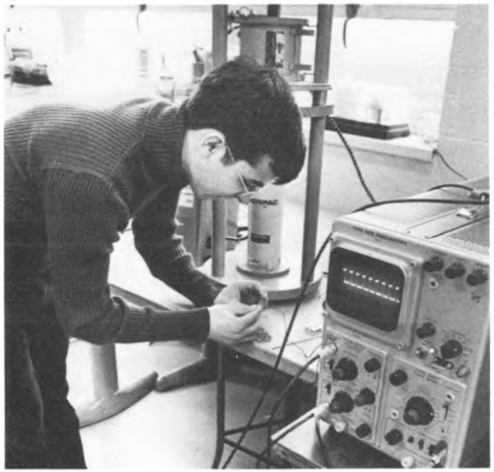
The graduate Field of Geological Sciences includes, in addition to department members, faculty members of other departments who maintain an active interest in geological problems. There are approximately forty graduate students, all of whom participate in one or more of the research activities of the 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 geology, economic geology, geochemistry, geomorphology, geophysics, geotectonics, marine geology, mineralogy, paleontology, petrology, physical geology, Pleistocene geology, rock mechanics, seismology, stratigraphy, and structural geology. 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 careers available for geologists, a broad spectrum of talents is required, and 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 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 utilize 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

Most geological sciences classrooms, laboratories, and offices are located in Kimball Hall on the Engineering Quadrangle. Here the department has outstanding collections of minerals, rocks, and fossils, and a large library of seismograms from the World Wide Standardized Seismograph Network and from other stations. Among the facilities are a geochemistry laboratory, a rock-preparation laboratory, an instrument shop, darkrooms, x-ray machines, a petrographic laboratory, and a paleontological





Basic research instrumentation available in Kimball Hall includes microscopes, a permanent seismograph station, and (at left) equipment for measuring sound velocities in core samples.

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.

Recent field projects have been carried out at a wide variety of sites, including Indonesia, the Philippines, Fiji and the New Hebrides, the Aleutian islands, Greenland, Iran, the Rhine graben, the Scottish highlands, and several 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.

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, 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 studies are: seismological investigations of the subducted lithosphere utilizing field observations; geological studies of the accretionary prism of sediments landward of trenches on a number of island arcs, integrated with seismic and drilling programs; studies of ancient melanges; petrologic studies of island arc volcanic rocks, including field and laboratory work; 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

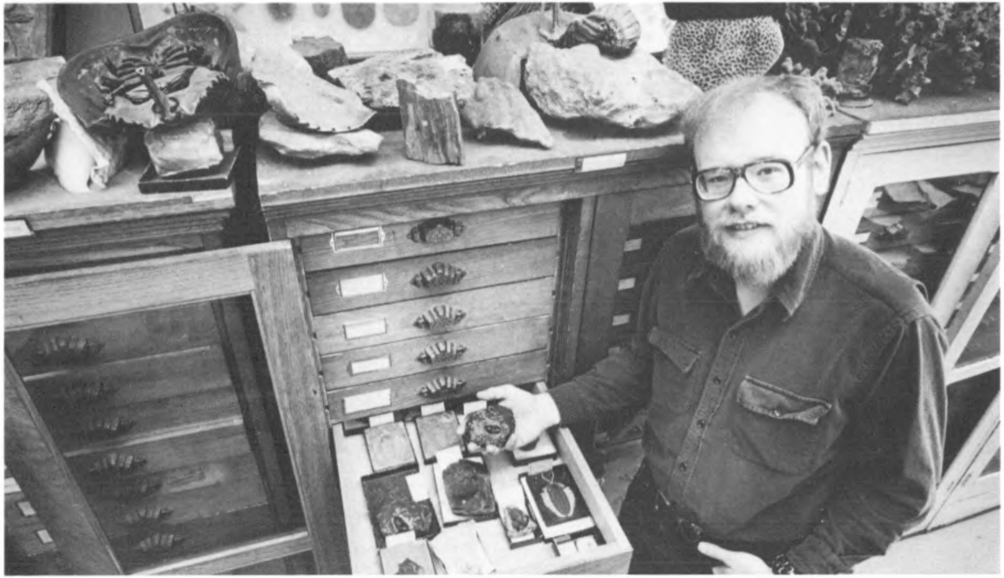
(COCORP), a major United States research project being carried out with other universities, companies, and government agencies. The object is to determine the geological structure of the continental crust using seismic reflection techniques developed by the oil industry. Graduate students have the opportunity to participate in the field work, 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.

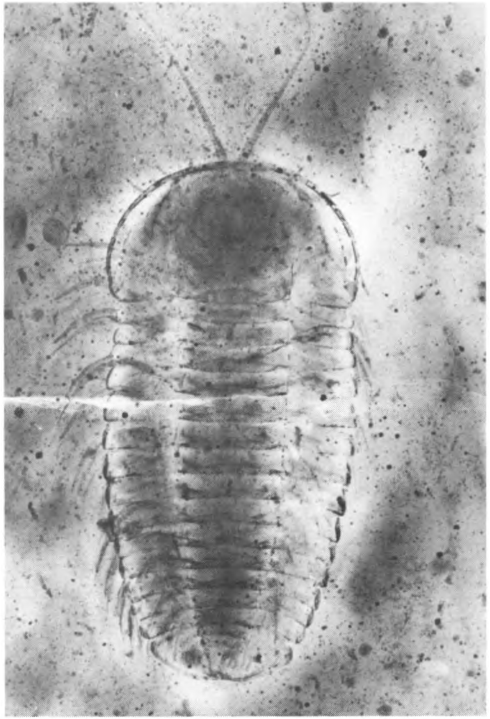
Studies are being carried out to understand the history of surface rocks that have originated in the deep crust and upper mantle. Examples are rocks associated with kimberlites, native iron deposits, and platinum-group metal deposits. There are indications, for example, that some native iron samples had a deep origin and may represent accretional material not assimilated in the core.

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.

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

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 (at right) work with Professors Jack E. Oliver and Sidney Kaufman in studies of the seismic profiles.





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.

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. High-resolution radiography was one of the techniques used to obtain the image, at right, of a pyritized specimen about 4 cm long.

An understanding of recent crustal movements is sought in a program involving analysis of leveling observations throughout the United States, and correlation of such data with seismic and geological information.

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:

Bird, J. M., and Weathers, M. S. 1977. Native iron occurrences of Disko Island, Greenland. *Journal of Geology* 85:359.

Bloom, A. L. 1978. *Geomorphology: a systematic analysis of late Cenozoic landforms.* Englewood Cliffs, N. J.: Prentice-Hall.

Brown, L. D.; Reilinger, R. E.; Holdahl, S. R.; and Balazs, E. I. 1977. Postseismic crustal uplift near Anchorage, Alaska. *Journal of Geophysical Research* 82:3369.

Cisne, J. L., and Rabe, B. D. 1978. Coenocorrelation: gradient analysis of fossil communities and its applications in stratigraphy. *Lethaia* 11:341.

Isacks, B. L., and Barazangi, M. 1977. Geometry of Benioff zones: lateral segmentation and downwards bending of the subducted lithosphere. In *Island arcs, deep sea trenches, and back-arc basins.* Maurice Ewing series, no. 1. Washington, D.C.: American Geophysical Union.

Karig, D. E.; Caldwell, J. G.; and Parmentier, E. M. 1976. Effects of accretion in the downgoing plate. *Journal of Geophysical Research* 81:6281.

Kay, R. W. 1977. Geochemical constraints on the origin of Aleutian magmas. In *Island arcs, deep sea trenches, and back-arc basins.* Maurice

Fieldwork is carried out at many locations around the world. Above: Professor Daniel E. Karig works along streams on an Indonesian island to gather data for geological mapping. Right: a 35-day western field trip course is offered by the department.

***Left:** A graduate student studies seismological data obtained in fieldwork in the New Hebrides. The project, one of a number in geophysics, is supervised by Professor Bryan L. Isacks.*

***Left below:** 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.*

***Below:** Professor Donald L. Turcotte (third from left) supervises research on convection processes in the Earth. The model was used to simulate geothermal reservoir circulations.*

***Right:** Turcotte's research also includes studies of volcanism on Earth and the other planets. This Viking image of Mars shows huge volcanoes as much as 24 kilometers high.*

Ewing series, no. 1. Washington, D.C.: American Geophysical Union.
Kohlstedt, D. L.; Geotze, C.; and Durham, W. B. 1976. Experimental deformation of olivine single crystals with application to flow in the mantle. In *The physics and chemistry of minerals and rocks,* ed. R. G. U. Strens, pp. 35–49. London: Wiley.
Oliver, J. 1978. Exploration of the continental basement by seismic reflection profiling. *Nature* 275:485.
Oliver, J. E., and Kaufman, S. 1977. Complexities of the deep basement from seismic reflection profiling. In *The Earth's crust,* ed. J. Heacock, pp. 243–253. Monograph 20. Washington, D.C.: American Geophysical Union.
Rhodes, F. H. T., and Austin, R. L. 1977. Ecologic and zoogeographic factors in the biostratigraphic utilization of conodonts. In *Concepts and methods of biostratigraphy.* New York: Halstead.
Travers, W. B. 1978. Overturned Nicola and Ashcroft strata and their relation to the Cache Creek group, southwestern Intermontane Belt, British Columbia. *Canadian Journal of Earth Sciences* 15:99.
Turcotte, D. L., and Ahern, J. L. 1978. A porous flow model for magma migration in the asthenosphere. *Journal of Geophysical Research* 83:767.
Wilburn, D. R., and Bassett, W. A. 1977. Isothermal compression of magnetite (Fe_3O_4) up to 70 kbar under hydrostatic conditions. *High Temperatures-High Pressures* 9:35.

Cornell is situated in a region especially good for studies in stratigraphy and glacial erosion. Also, the Ithaca area is one of the few places in the world where kimberlites have been found.

Faculty Members and Their Research Interests

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 diamond cells and other techniques*

John M. Bird, B.S. (Union), M.S., 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, evolutionary biology, population and community paleoecology, stratigraphy, arthropods*

Bryan L. Isacks, A.B., Ph.D. (Columbia): *seismology, tectonics, mantle earthquakes and subduction of the lithosphere, observations of surface deformation related to large shallow earthquakes, seismotectonics of island arcs of the Southwest Pacific*

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*

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*

George H. Morrison, B.A. (Brooklyn College), M.A., Ph.D. (Princeton): *analytical geochemistry, trace-element abundances, ion microprobe studies*

Jack E. Oliver, B.A., M.A., Ph.D. (Columbia): *geophysics, geotectonics, recent vertical movements, deep crustal reflection studies*

Frank H. T. Rhodes, 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 one 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*

Dwight Sangrey, B.S. (Lafayette), M.S. (Massachusetts), Ph.D. (Cornell): *soil behavior, soil dynamics, marine and coastal geotechniques, soil-structure interaction, probabilistic modeling*

William B. Travers, B.S., M.S. (Stanford), Ph.D. (Princeton): *structural geology, tectonics, petroleum geology, sedimentology*

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 undertake research and study in the area of materials to students with widely differing undergraduate backgrounds. The forty-five students now enrolled in graduate programs have undergraduate degrees in physics, applied physics, and 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. One of the purposes of the Materials Science Center is to support large central facilities that make available to every student and faculty member modern, and often very expensive, equipment. The center also provides financial assistance for graduate students through research assistantships.

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 campus, 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, Siemens 102, and AEI EM6G microscopes, as well as an AMR 900 scanning electron microscope. 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.

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

Above: *Equipment in the Materials Science Center facility in Bard Hall 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.*

Right: A radio frequency sputtering apparatus, also in Bard Hall, is used for the fabrication of thin-film metals, alloys, and ceramic materials.

years projects were started on catalysis, ceramic oxides, amorphous materials, biomaterials, 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 distributions and anharmonic vibrations in solids.

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.

Recent publications and theses (listed with the supervising professor) in the area of imperfections in solids include:

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. *Electron Microscopy in Mineralogy*, ed. H. R. Wenk, pp. 234–237. Berlin: Springer-Verlag.

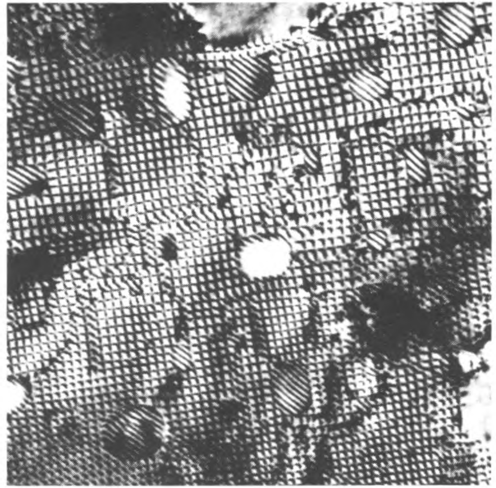
Roberto, J.; Batterman, B. W.; Kostroun, V.; and Appleton, B. R. 1975. Positive ion-induced Kossel lines in copper. *Journal of Applied Physics* 46:936.

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

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 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.



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.

Surfaces, Interfaces, and Thin Films

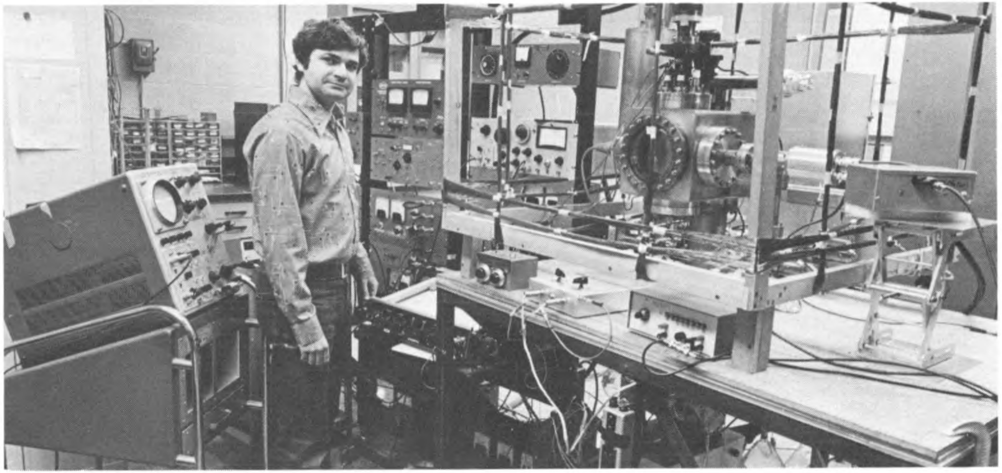
New methods to fabricate thin alloy films of controlled composition are being investigated by D. G. Ast and his students by comparing experimental output, as determined by electron microprobe analysis, with theoretical models. The structure of thin amorphous and crystalline films is being studied with the use of high-resolution electron microscopy.

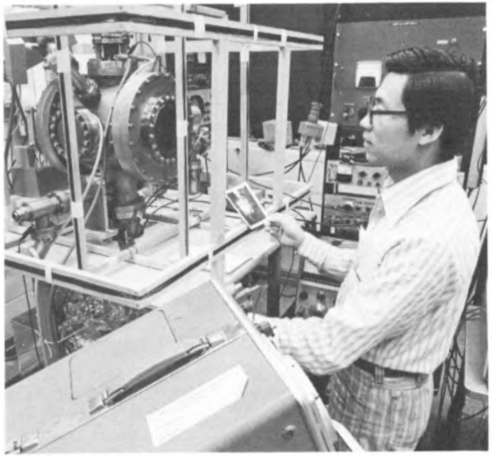
In a project directed by S. L. Sass diffraction techniques have been developed for studying the structure of grain boundaries. X-ray diffraction studies of planar grain boundaries in thin-film bicrystal specimens are being carried out in order to answer the following questions: (1) Is the boundary structure 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.





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.

Typical publications and theses 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.

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.

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 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, cross-linking, 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 annealed Ni-Fe base metallic glasses 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. 1976. Fracture toughness and yield strength of annealed Ni-Fe base metallic glasses. *Materials Science and Engineering* 23:241.

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. 1978. Temperature dependence of the flow stress and ductility of amorphous $Fe_{40}Ni_{40}P_{14}B_{6}$. *Journal of Materials Science* (in press).

Krenz, H. G.; Kramer, E. J.; and Ast, D. G. 1976. Structure of solvent crazes in polystyrene. *Journal of Materials Science* 11:2211.

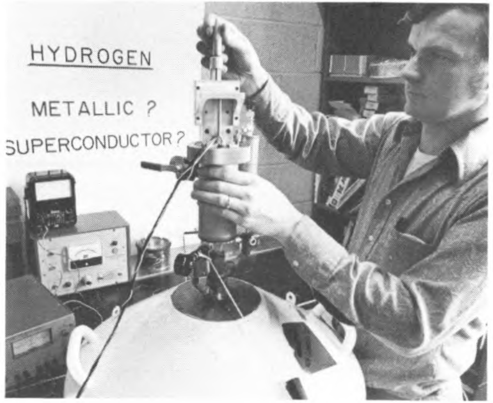
Min, B. K., and Raj, R. 1978. Hold-time effects in high temperature fatigue. *Acta Metallurgica* 26(6):1007.

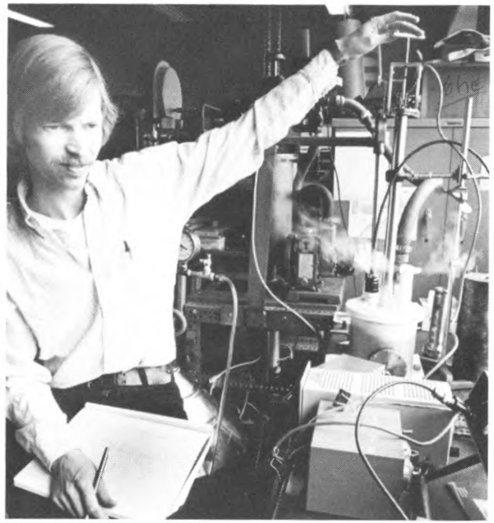
Pavinich, W., and Raj, R. 1977. Fracture at elevated temperature. *Metallurgical Transactions A* 8:1917.

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.

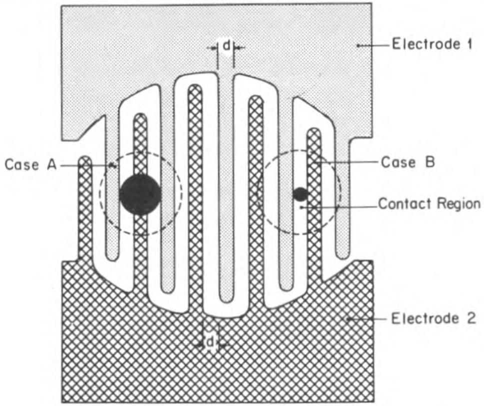
Some recent papers in this area are:

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.

Ruoff, A. L., and Chan, K. S. 1978. Transformation pressure of ZnS by a new primary pressure technique. In *Proceedings of 6th international high pressure conference* (held July 1977 at the University of Colorado, Boulder, Colorado). New York: Plenum.



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.

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 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.

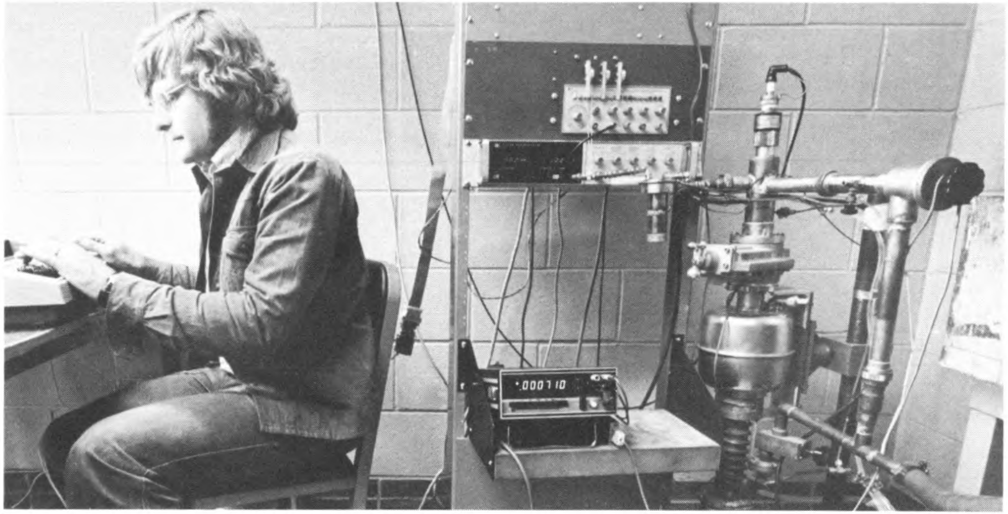
Ceramic Materials

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.

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.



A recent project involved microprocessor-controlled measurement of the AC ion conductivity of a solid electrolyte, sodium-β-alumina. This ceramic is under consideration for use in light-weight batteries.

Representative publications and theses are:

Allender, J. 1978. Hydrogen reduction of nickel-ferrite and aluminum doped nickel-ferrite. Ph.D. thesis (L. C. DeJonghe).

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, pp. 35–49. 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).

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 in this area are:

Ast, D. G. 1974. Evidence for percolation controlled conduction in amorphous As_xTe_{1-x}. *Physical Review Letters* 33:1042.
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).
Rickenback, R. 1973. Multi-layered thin film superconductors. M.S. thesis (D. G. Ast).

Electron Microscopy

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 an 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 observations of these materials by electron microscopy are now set by their high sensitivity to radiation damage from the electron beam.

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 of relevance include:

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.

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.

Electron microscope studies are among the projects available for Master of Engineering students. This instrument is a 200-keV electron microscope.

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* (in press).

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 credit hours of courses in mathematics, 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, D. Grubb, E. W. Hart, H. H. Johnson, D. L. Kohlstedt, E. J. Kramer, C.-Y. Li, R. Raj, A. L. Ruoff, S. L. Sass, and D. N. Seidman.

Examples of recent design projects, and the supervising professors, 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)

Faculty Members and Their Research Interests

Dieter G. Ast, Dipl.Phys. (Stuttgart), Ph.D. (Cornell): *amorphous materials, multilayered superconductors, biomaterials, holographic testing, metallic glasses*

Boris W. Batterman, B.S., Ph.D. (M.I.T.): *x-ray and neutron diffraction, solid-state phenomena*

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*

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, 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*

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, 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*

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 Field 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 biomechanical engineering. Candidates also choose a minor subject that is generally from some other field such as mathematics, physics, 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 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 fifty 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; a computer terminal that allows interactive and batch processing is 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 main streams of study and research are supplemented by an area which embraces both: biomechanical engineering.

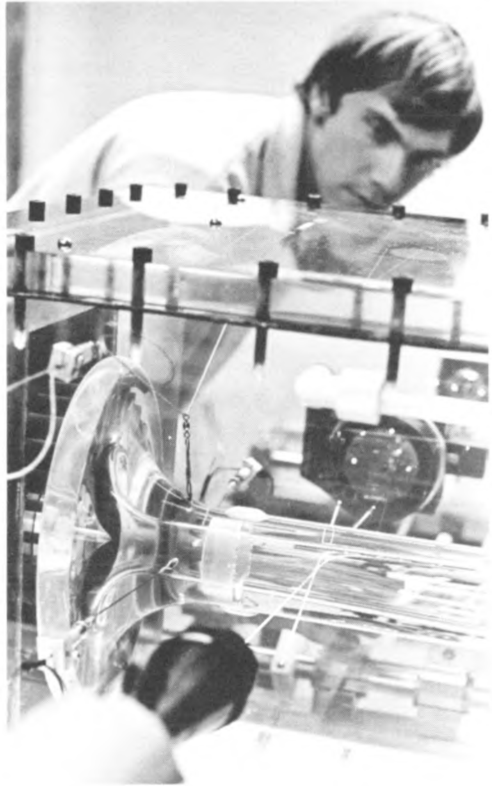
Research is also carried out in cooperation with the graduate Fields of Aerospace Engineering, Applied Mathematics, Applied Physics, Chemical Engineering, Chemistry, Operations Research, and Theoretical and Applied Mechanics.

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.

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.



A graduate student working with Professor Sidney Leibovich uses a laser-doppler anemometer to study the mechanics of vortex 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.

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.

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, Research Support Specialist Edward Jordan, and Professor John L. Lumley, the principal investigator.

Representative publications are:

Faler, J. H., and Leibovich, S. 1977. Disrupted states of vortex flow and vortex breakdown. *Physics of Fluids* 20:1385.

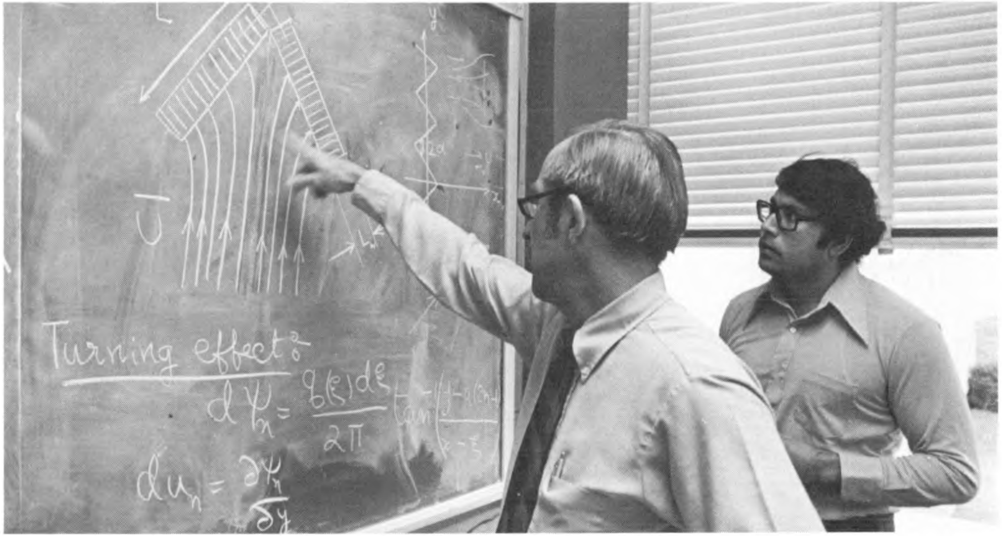
Leibovich, S. 1977. Convective instability of stably stratified water in the ocean. *Journal of Fluid Mechanics* 82:561.

Lumley, J. L. 1978. Computational modeling of turbulent flows. Chapter to appear in *Advances in applied mechanics,* vol. 18, ed. C. S. Yih. New York: Academic Press.

Lumley, J. L.; George, W.; and Buchhave, P. 1979. Turbulence measurements with the laser-doppler anemometer. To appear in *Annual reviews of fluid mechanics,* vol. 11 (in press).

Torrance, K. E. 1978. Numerical approaches to solid-state convection in planetary bodies. *Physics of the Earth and Planetary Interiors* (in press).

Warhaft, Z., and Lumley, J. L. 1978. An experimental study of the decay of temperature fluctuations in grid generated turbulence. *Journal of Fluid Mechanics* (in press).



Problems in the cooling of large power plants are studied by Professor Franklin K. Moore (at left) and his research group.

Heat Transfer

Problems of current interest are concerned with heat rejection to the environment, natural convection flows, geophysical heat transfer, and heat transfer in biological 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 esthetic impacts. An environmental wind tunnel is employed for studies of cooling-tower heat transfer.

Studies of natural convection flows using laser-holographic interferometry are under way.

Heat transfer and flow processes in porous media are being studied for both single-phase systems and two-phase, boiling systems. Geothermal reservoirs and naturally occurring hydrothermal circulations are considered.

Examples of recent publications and theses on these subjects are:

Moore, F. K. 1976. Dry cooling towers. In *Advances in heat transfer,* vol. 12, ed. T. F. Irvine, Jr., and J. P. Hartnett, pp. 1–75. New York: Academic Press.

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* (in press).

Ribando, R. J. 1977. Geothermal energy-related problems of natural convection in porous media. Ph.D. thesis (K. E. Torrance).
Torrance, K. E., and Sheu, J. P. 1978. Heat transfer from plutons undergoing hydrothermal cooling and thermal cracking. *Numerical Heat Transfer* 1:147.

Combustion

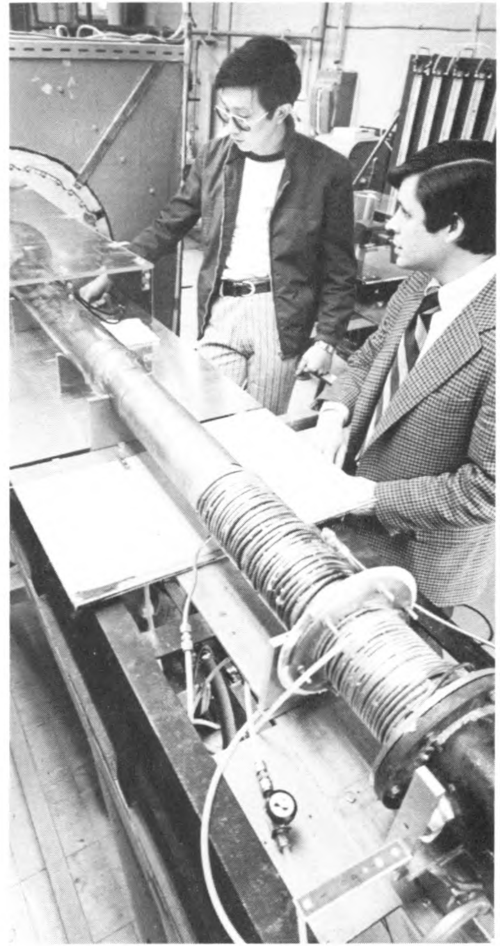
Current programs include studies of chemical kinetics, fluid mechanics, turbulence, and air-pollutant generation as they pertain to combustion processes in practical energy-conversion devices operating on conventional and alternative fuels. A large experimental program with advanced diagnostic equipment 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.

Recent papers in this area include:

Chan, T. S.; Lanewala, S.; and McLean, W. J. 1978. Experimental and analytical studies of nitric oxide production during shock-induced oxidation of hydrogen cyanide. *Combustion and Flame* (in press).
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, pp. 297–319. New York: Plenum.
Oven, M. J.; McLean, W. J.; and Gouldin, F. C. 1977. $NO-NO_2$ measurements in a methane-fueled swirl-stabilized combustor. Paper read at Spring Technical Meeting, Central States Section, The Combustion Institute, 28–30 March 1977, at NASA Lewis Research Center, Cleveland, Ohio.
Rubin, M. B., and McLean, W. J. 1978. Performance and NO_x emissions of spark ignited combustion engines using alternative fuels—quasi one-dimensional modeling. II. Methanol fueled engines. *Combustion Science and Technology* (in press).
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. New York: AIAA.



Laser-doppler velocity measurements are used to study fluid mixing processes in a swirl combustor in a project supervised by Professor Frederick C. Gouldin (at right). This research has potential applications in gas turbines.

Power and Energy Systems

In general the area of power and energy systems encompasses studies of modern methods of energy utilization 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 requiring 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 utilization 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.

Examples of recent publications in this area are:

Auer, P. L. 1977. Fusion power— its promise and prospects. *Engineering: Cornell Quarterly* 12(3):32.

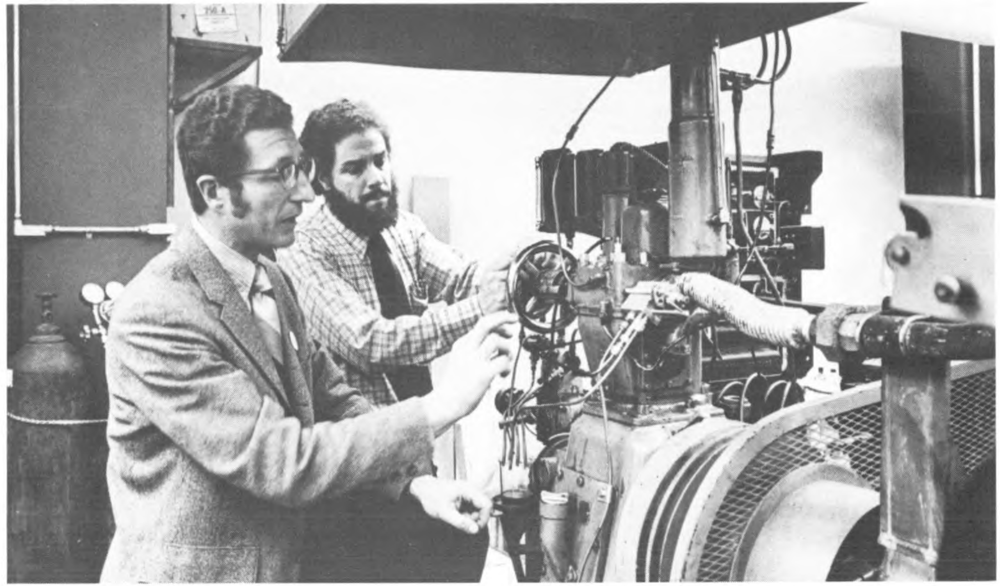
Auer, P. L., and Braun, C. 1977. Systemwide uranium feed and separative work conservation available with advanced reactors. *Annals of Nuclear Energy* 4:27.

de Boer, P. C. T.; McLean, W. J.; and Homan, H. S. 1976. Performance and emissions of hydrogen fueled internal combustion engines. *International Journal of Hydrogen Energy* 1:114.

Moore, F. K. 1976. Regional climatic effects of power plant heat rejection. *Atmospheric Environment* 10:806.

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. I, pp. 832–841. LaGrange Park, Ill.: American Nuclear Society.

Torrance, K. E., and Shum, J. S. W. 1976. Time-varying energy consumption as a factor in urban climate. *Atmospheric Environment* 10:329.



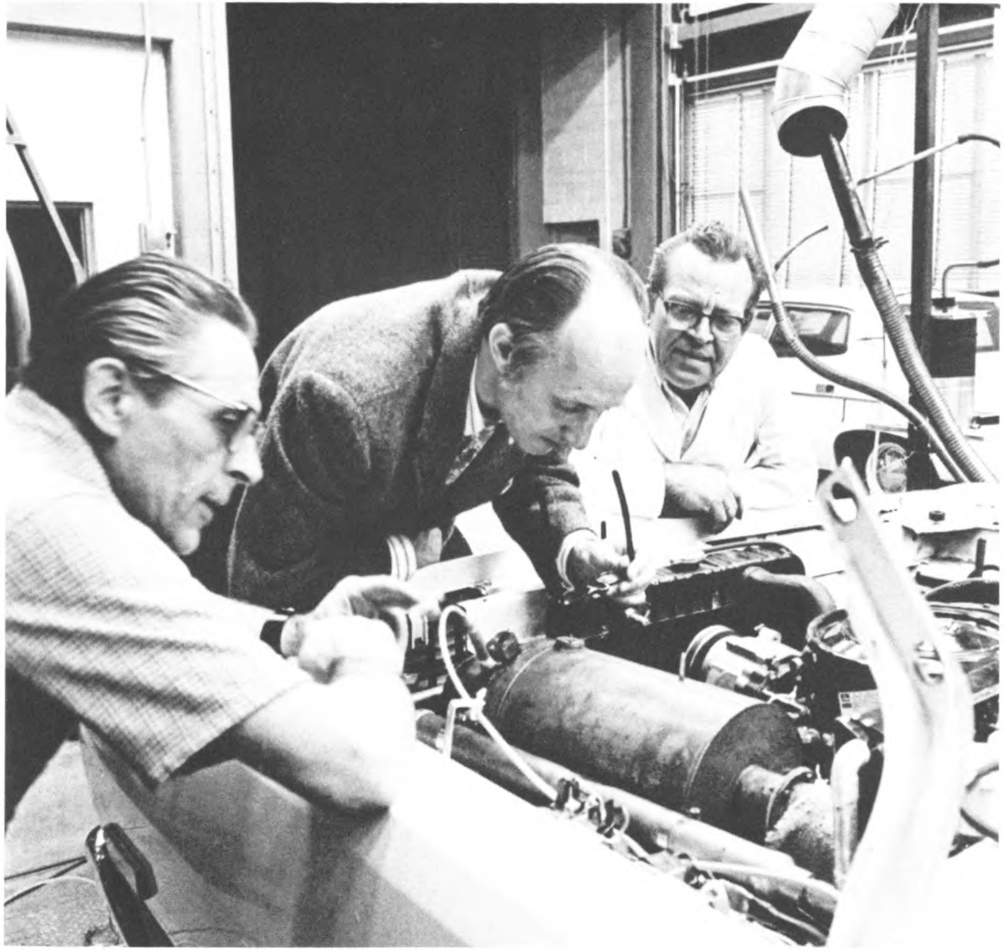
The fuel injection pump of a CFR engine modified to run on hydrogen is adjusted by Professors P. C. Tobias de Boer (at left) and William J. McLean.

Mechanical Systems and Design

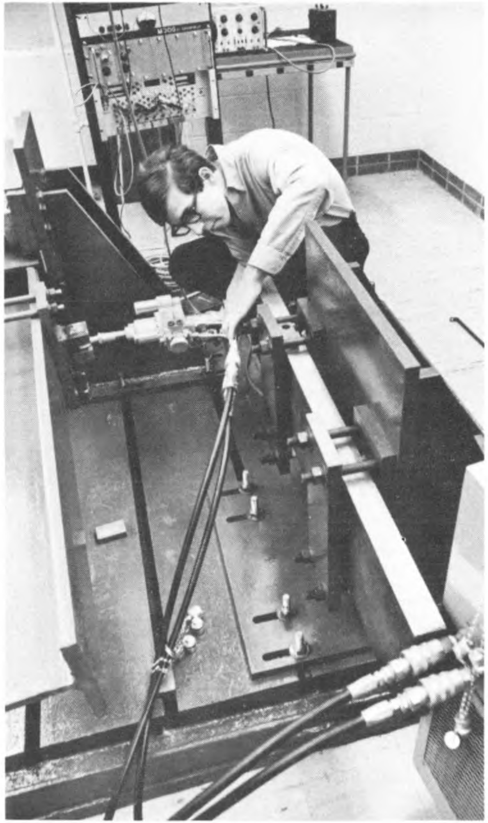
Research in this area is concerned with the design, analysis, and manufacture of devices, machines, and systems. At Cornell these terms are broadly interpreted and encompass areas such as lubrication, vibrations, mechanical reliability, controls, and dynamics. The common theme of the work is the application 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.

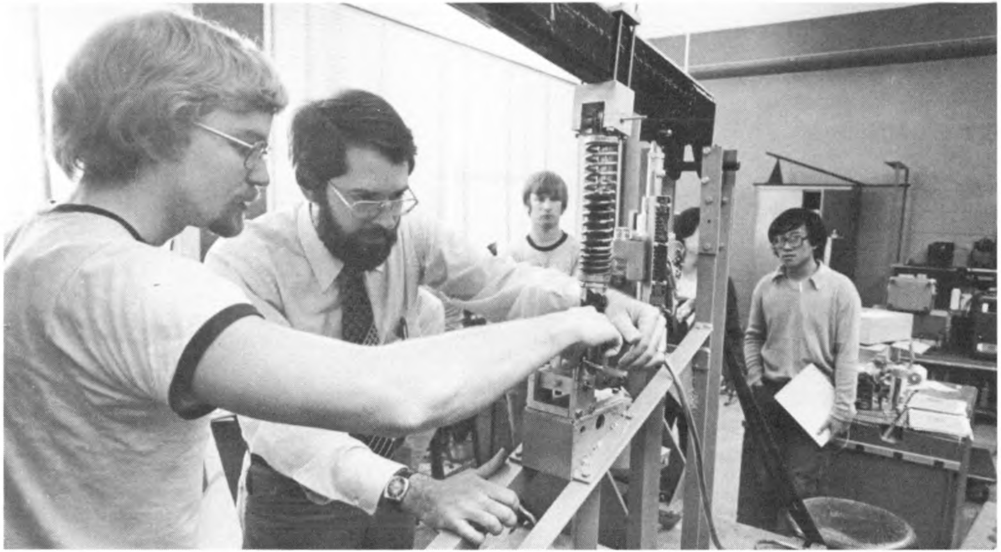
Vibration and dynamic studies have dealt with the nonlinear response of advanced-technology systems such as vehicle suspensions. In many of the projects in this area computer-based methods are used for the efficient analysis of problems; computer graphics are being used to help interpret complicated nonlinear system responses such as limit-cycle behavior.



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. (at center). This photo shows adaptations, subsequently patented, that were made in an initial phase of the work.



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.



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 in the area of mechanical systems and design include:

Booker, J. F., and Stickler, A. C. 1976. Bearing load/displacement determination for multi-cylinder reciprocating machinery. *Journal of Mechanical Design (ASME)* (in press).

Eidelberg, B. E., and Booker, J. F. 1976. Application of finite element methods to lubrication: squeeze films between porous surfaces. *Journal of Lubrication Technology (ASME)* 98:175.

Harlow, D. G., and Phoenix, S. L. 1978. The chain-of-bundles probability model for the strength of fibrous materials. I. Analysis and conjectures. *Journal of Composite Materials* 12:195.

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).

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 on Applied Mathematics* 34(2):227.
Taylor, D. L. 1975. Multi-parameter eigensystems — applications to rotor dynamics. In *Proceedings of 4th world congress on machines and mechanisms,* pp. 517–520. London: Institution of Mechanical Engineers.
——. 1976. *Effects of drawbar properties on the behavior of articulated vehicles.* ASME publication no. 76-WA/Aut-10.

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 the effect of surface quality of machined components on wear.

Representative papers in this area are:

Jahanmir, S. 1978. On the wear mechanisms and the wear equations. Paper read at International Conference on Fundamentals of Tribology, 19–22 June 1978, in Boston, Massachusetts.
Jahanmir, S., and Suh, N. P. 1977. Surface topography and integrity effects on sliding wear. *Wear* 44:87.

The design of systems for injection molding of plastics is a joint project with industry for which Professor K.-K. Wang (at right) is one of the principal investigators.

Stevenson, J. F.; Hieber, C. A.; Galskoy, A.; and Wang, K. K. 1976. An experimental study and simulation of disk filling by injection molding. In *Proceedings of 34th annual technical conference,* pp. 282–288. Greenwich, Conn.: Society of Plastics Engineers.
Wang, K. K. 1976. Research associated with industry: Cornell's injection molding project. *Engineering: Cornell Quarterly* 10(4):1.
Wang, K. K., and Ahmed, S. 1976. Ultrasonic detection of weld strength for dissimilar-metal friction welds. In *Proceedings of 4th North American metalworking research conference,* ed. T. Altan, pp. 384–389. Columbus, Ohio: Battelle Laboratory.

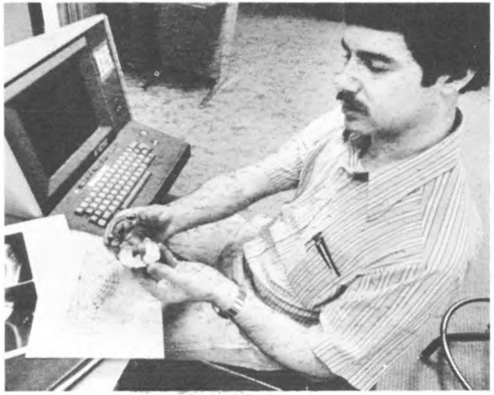
Biomechanical Engineering

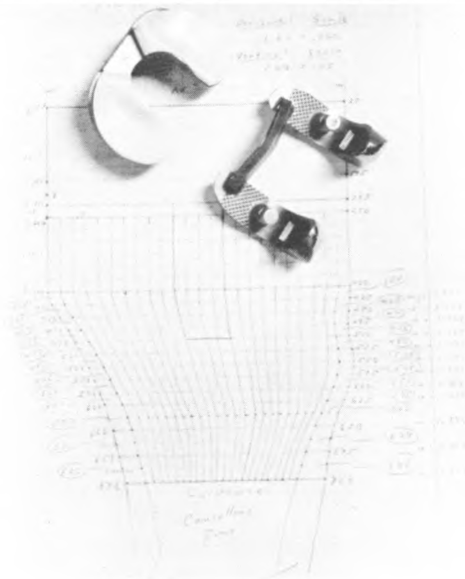
Research in the area of biomechanics is concerned with the analysis and design of biomechanical systems encountered in orthopedic surgery and rehabilitation medicine. The overall goal is to understand the structure and function of normal, impaired, and reconstructed components of the musculoskeletal 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.

Research in the area of biological mass and heat transfer is concerned with the low temperature

***Below:* A graduate researcher examines plastic and metal parts designed for a knee prosthesis in a project directed by Professor Donald L. Bartel.**

***Right:* A stress distribution obtained by computer-aided analysis is used in specifying materials and dimensions.**





preservation of biological cells, tissues, and organs. A cryomicroscope is used to videotape the formation of intracellular ice and to characterize cell viability as a function of freezing and thawing rates. Cells and tissues being studied include cancer and heart cells, sperm and embryos, and plant cells. Complementary theoretical analyses of ice nucleation and mass and heat transfer in tissues are being carried out.

Examples of recent publications and theses are:

Bartel, D. L.; Marshall, J. L.; Schieck, R. A.; and Wang, J. B. 1977. Surgical repositioning of the medial collateral ligament — an anatomical and mechanical analysis. *Journal of Bone and Joint Surgery* 59-A(1):107.

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* (in press).

Desormeaux, S. G. 1976. The effect of cross-sectional geometry of fixation stems on stresses in bone-implant systems. M.S. thesis (D. L. Bartel).

Levin, R. L. 1978. The water permeability of yeast cells at subzero temperatures. *Journal of Membrane Biology* (in press).

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., the M.S., and the 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 requirements 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 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.

The construction of a racing bicycle for an attempt at a speed record was a project for M.Eng. (Mechanical) students. The design included a racing canopy of transparent plastic over the framework shown.

Titles of 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 Construction of a Wear Tester (S. Jahanmir)
- Design and Evaluation of a Two-Stage Combustor for Emission Control (F. C. Gouldin)
- Design of a Cryogenic Chamber for Freezing Biological Materials (R. L. Levin)
- 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)
- Determination of Optimal Freeze-Thaw Protocols for Biological Materials (R. L. Levin)
- 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)
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*
Donald L. Bartel, B.S., M.S. (Illinois), Ph.D. (Iowa): *design optimization and reliability, computer-aided design, biomechanical engineering*
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*
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, 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*
Said Jahanmir, B.S. (Washington), S.M., Ph.D. (M.I.T.): *manufacturing engineering, mechanical behavior of engineering materials, friction and wear*
Sidney Leibovich, B.S. (California Institute of Technology), Ph.D. (Cornell): *fluid dynamics, wave propagation, air-sea interactions*
Ronald L. Levin, S.B., S.M., Sc.D. (M.I.T.): *thermodynamics, biological mass and heat transfer*
John L. Lumley, B.A. (Harvard), M.S.E., Ph.D. (Johns Hopkins): *fluid dynamics, turbulence and turbulence modeling, geophysical turbulence, stochastic processes*
William J. McLean, B.S., M.S., Ph.D. (California, Berkeley): *thermodynamics, pollution control, combustion*
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*
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 design, design of components*

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), 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 reactors 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 with 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 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: the *Announcement of the Graduate School* and *Cornell University: Description of Courses*. 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, with a 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

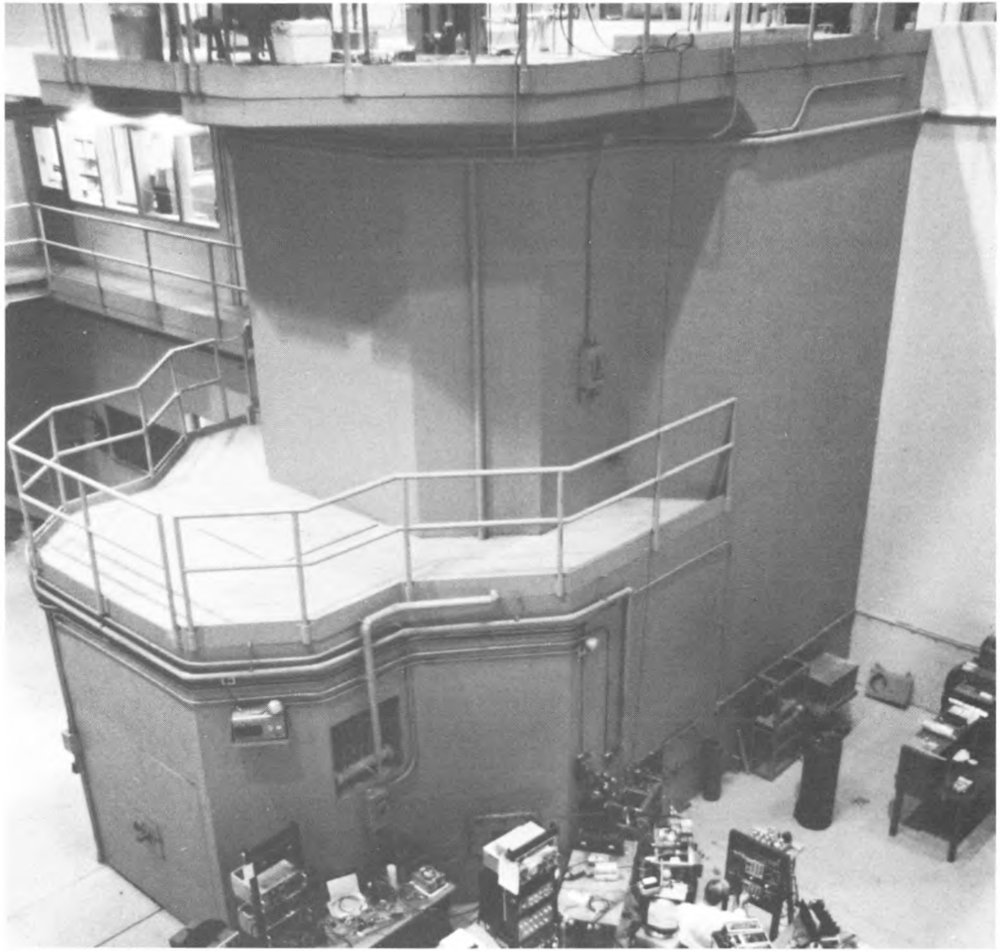
The Ward Laboratory of Nuclear Engineering is the major facility at Cornell for graduate research and teaching in reactor physics and engineering, low-energy nuclear structure physics, and nuclear and radiation chemistry. The following primary facilities are housed in the laboratory.

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.

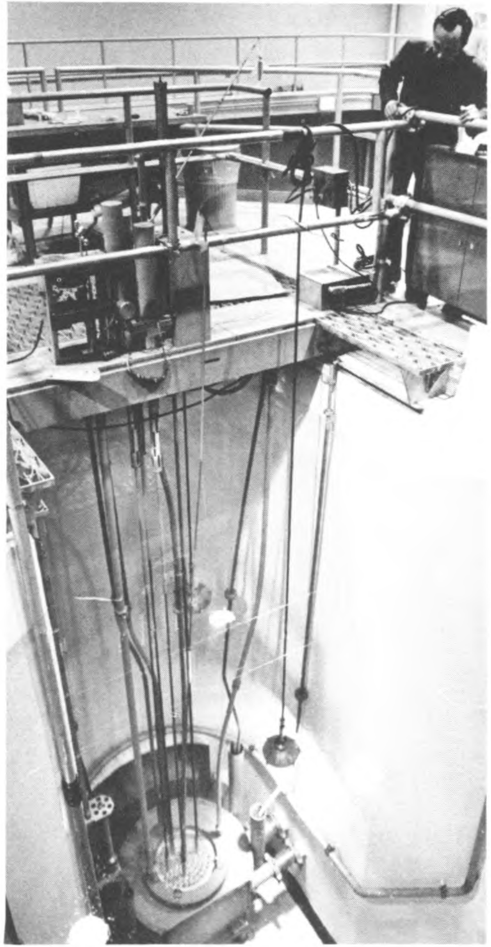
A critical facility, or "zero-power" reactor, of versatile design. This facility, unique to Cornell University, is used for basic studies in reactor physics and dynamics. Auxiliary equipment includes a pulsed 14-MeV neutron generator used for studies of reactor transients.

A shielded gamma cell with a 4,000-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 up to 2.5-mA beam current. This is used for studies of atomic and nuclear structure and



Cornell's TRIGA reactor, a source of neutrons and gamma rays, is located in the Ward Laboratory of Nuclear Engineering.



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 two in-house minicomputers. In addition, facilities of other departments are available. The general resources of the University include a computing system with a central machine, several satellite stations, and a number of teletypewriter terminals.

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*. Some of the current projects are described below.

The core of the TRIGA is twenty-five feet under water.

Nuclear Reactor Engineering

A current research project is to develop fast-reactor plant models and computer codes for the analysis of nuclear-plant transients and accidents. Another project involves probabilistic safety analysis of nuclear systems.

Graduate research is represented by the following theses, listed with the supervising professor:

Pavlenco, G. 1976. Primary loop transients and accidents in a liquid-metal-cooled fast breeder reactor. Ph.D. thesis (K. B. Cady).

Khatib-Rahbar, M. 1978. System modeling for transient analysis of loop-type liquid-metal-cooled fast breeder reactors. Ph.D. thesis (K. B. Cady).

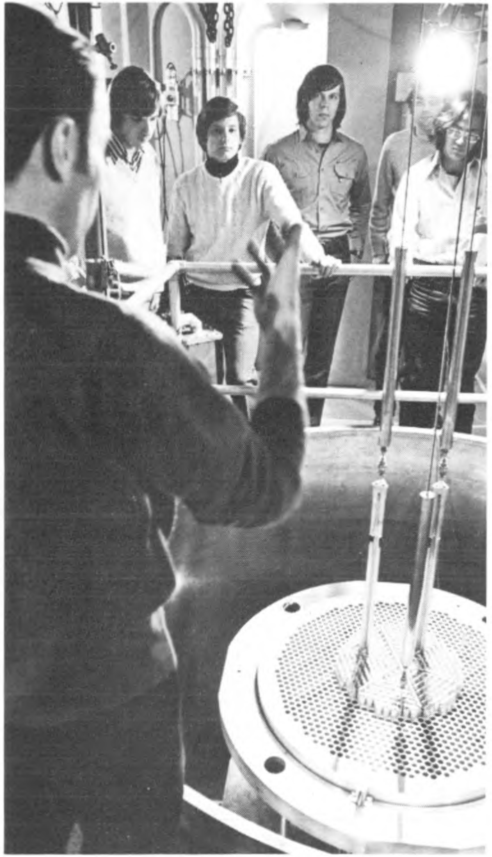
Mitra, S. 1978. Reliability techniques applicable to nuclear systems. Ph.D. thesis (K. B. Cady).

Fission Reactor Physics

Basic research in the kinetics of the neutron chain reaction is carried out in conjunction with the work on reactor plant dynamics discussed above. The Cornell critical facility is the main experimental facility for 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 the operational understanding of nuclear reactor cores.

An example of journal publications in this field is:

Greenspan, E., and Cady, K. B. 1970. The measurement of neutron importance functions. *Journal of Nuclear Energy* 24:529.



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 the phenomena of radiation-induced swelling and creep. An example of Cornell research in this area 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 predicts behavior at high doses.

Two publications based on this research are:

Mansur, L. K.; Okamoto, P. R.; Taylor, A.; and Li, C.-Y. 1976. *Surface-reaction-limited void growth.* ASTM special technical publication no. 570.

Mancuso, J. F.; Huang, F. H.; and Li, C.-Y. 1975. Fundamental aspects of radiation damage in metals. In *Proceedings of the international conference* (held October 1975, in Gatlinburg, Tennessee).

Low-Energy Nuclear Physics

Among projects now under way in this area is an experimental study of isomeric (metastable) excited states in nuclei. The energies, spins, parities, lifetimes, and other parameters of these levels can be compared with predictions from theoretical models and thus can provide checks on the validity of these models. Several high-spin isomers have been discovered at Cornell with use of the TRIGA reactor and the fast-transfer system.

Isomeric states frequently decay by internal conversion, producing vacancies in the inner electron shells of the atom, which results in x-ray emission. A new method for determining properties of isomeric levels solely by observation of these x rays has been developed in the course of research on ^{182}Ta. The method is applicable to other nuclides.

The discovery of spontaneously fissioning isomers and recent theoretical research at various laboratories have led to the hypothesis of a new type of isomerism called shape isomerism, described in an article in *Physics Today*

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.

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.

(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 with use of neutrons from the TRIGA reactor.

A new type of detector — the inner-shell vacancy (ISV) detector — was recently conceived and developed at Cornell in order to make feasible a key series of shape-isomer experiments using reactor neutron beams.

Examples of recent publications in this area 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 3rd 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.

Interaction of Radiation and Matter

The interaction of energetic photons and matter is being investigated with synchrotron radiation emitted by electrons accelerated by the 8-GeV Cornell electron storage ring (CESR). The intense synchrotron radiation, which is continuous in photon energy (3–300 keV), collimated (10 seconds of arc), and polarized, is being used in a variety of experiments to probe the structure of atomic aggregates and the consequences of local (on an atomic scale) energy deposition. Experiments using synchrotron radiation include a study of the excitative and de-excitative processes in atoms and molecules following creation of specific inner-shell vacancies by the photoeffect; a study of the immediate environment of an atom or molecule in substances of solid-state and biological interest (via the extended absorption edge fine structure); the determination of photon interaction cross sections as a function of photon energy; a study of photon transport as a function of photon energy, shielding material, and configuration; the quantitative determination of the elements (phosphorus to americium) in substances by x-ray absorption spectrometry and x-ray fluorescence; and x-ray interferometry.

The following two publications based on Ph.D. theses are representative of research in this area:

Kostroun, V. O., and Baptista, G. B. 1976. *K-MM* radiative-Auger transition rates for argon. *Physical Review A* 14:363.

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

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.

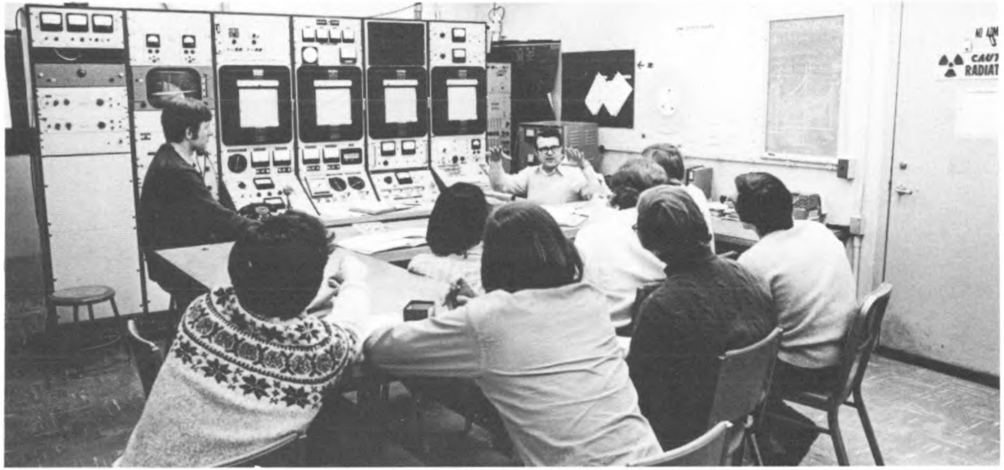
Examples of recent papers in this area are:

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. 1057–1066.

——. 1978a. Multielement analysis of lake sediments by neutron activation analysis. *Analytica Chimica Acta* (in press).

——. 1978b. Use of standard reference materials as multielement irradiation standards in neutron activation analysis. *Journal of Radioanalytical Chemistry* (in press).



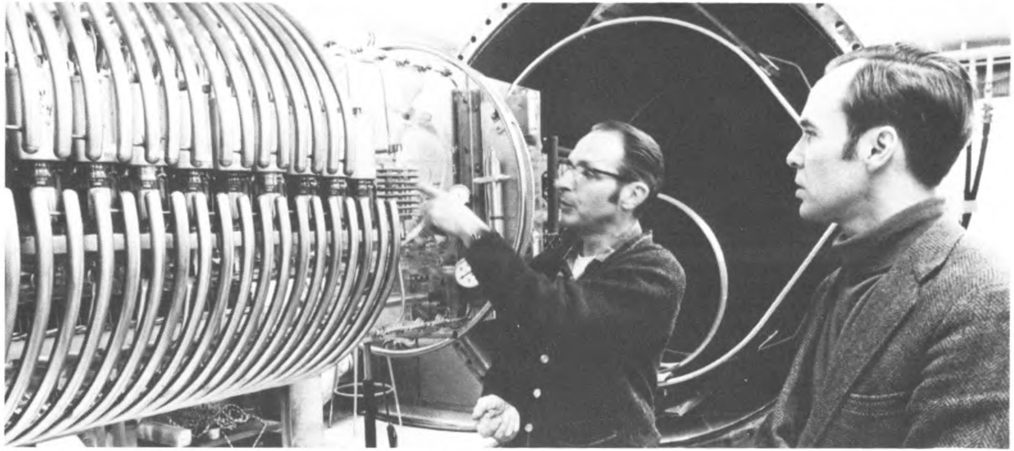
Above: A class listens to an explanation of the zero-power reactor. Professor Vaclav O. Kostroun is at left.
Right: Students work in the control room.

Fusion Physics and Technology

The scientific feasibility of fusion power is likely to be demonstrated within the next few years; at Cornell a program in fusion technology that will complement the existing strong plasma physics program is being started.

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 (as described by H. H. Fleischmann in the May 1975 issue of *Physics Today*). 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. This work is directed by 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.



A 3-MeV dynamitron, a low-energy, high-current ion accelerator, is used in studies of nuclear structure and radiation damage. Professor K. Bingham Cady is at right.

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.

The following papers are among those recently published in the area of fusion-related plasma physics:

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.

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 departmental 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*

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): *nuclear structure physics, interaction of atomic and nuclear processes, atomic 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

The graduate Field of Operations Research offers Ph.D. and M.S. degree programs in operations research, with four areas of concentration: applied probability and statistics, industrial and systems engineering, information processing, and mathematical programming.

Also offered, under the auspices of the School of Operations Research and Industrial Engineering, is a one-year program leading to the professional degree of Master of Engineering (OR & IE).

More than sixty-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 four areas of concentration are given below.

Applied Probability and Statistics

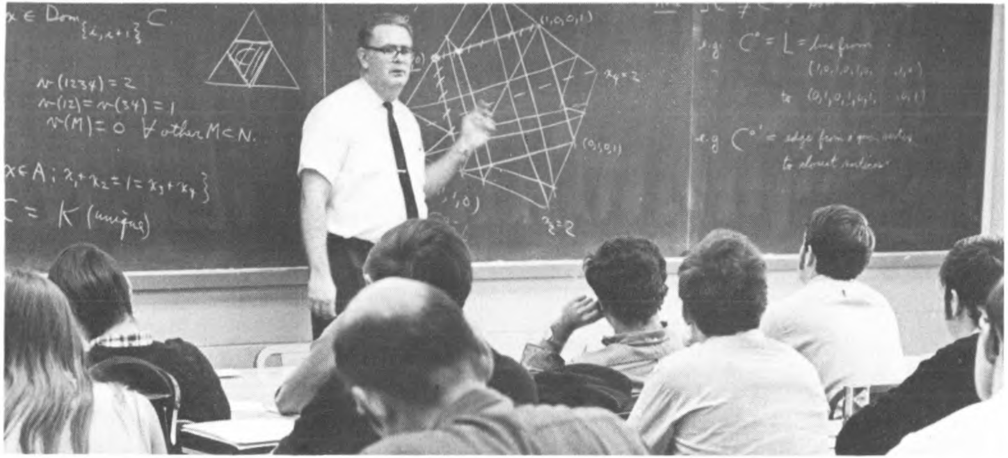
This area of study and research is appropriate for students whose primary interest is in the techniques and associated underlying theory of probability and statistics, particularly as applied to problems arising in science and engineering. The techniques emphasized are those associated with applied stochastic 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 corrected 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.

Information Processing

Information processing deals with the analysis and design of systems that record, transmit, store, and process information. Emphasis is on the application and integration of equipment rather than on the design of machines. Areas of interest include systems for information retrieval, manufacturing control, and traffic control. This subject also includes such underlying theoretical topics as data structure, operating system organization, and computing language structure.

The principal campus computing facility is an IBM 370/168, with on-line operation from many campus locations. A satellite computer, directly connected to the 370/168, is located in Upson Hall, where the School of Operations Research and Industrial Engineering is housed. Teletypewriter terminals are also available.

Mathematical Programming

Work in mathematical programming traditionally consists of linear, nonlinear, integer, and combinatorial programming (including network flows and scheduling theory). Research in these

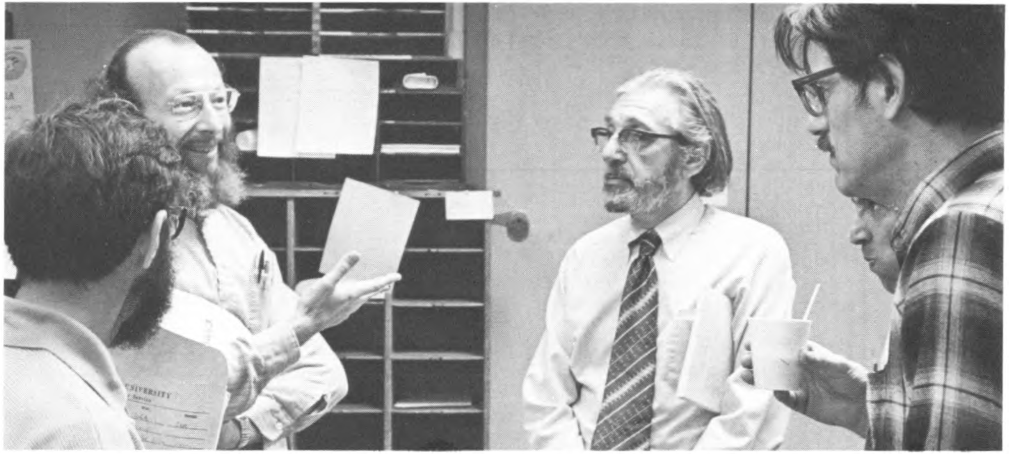
***Left above:* Professor William Lucas lectures on game theory.**

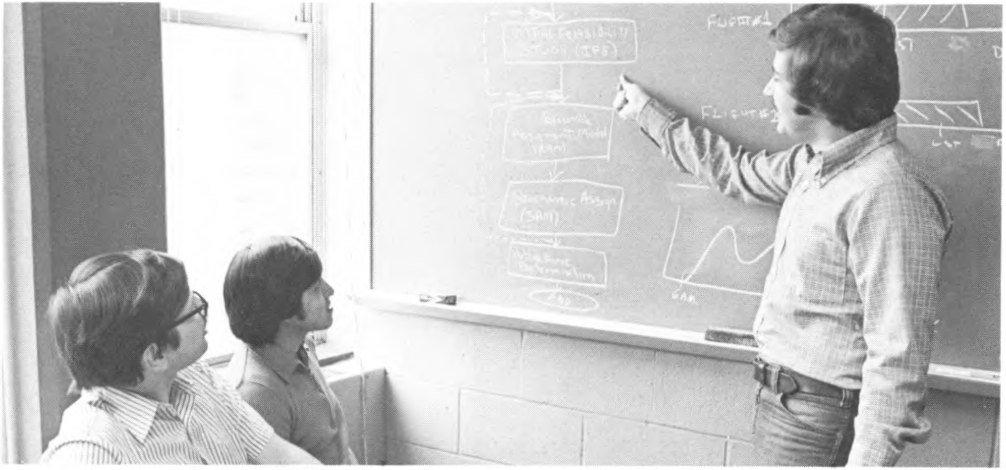
***Left below:* Graduate students discuss class problems with Professor Howard Taylor 3d.**

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 considerations of the properties of solutions and applications in 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).





Right above: An informal gathering precedes the regular colloquium of the Field of Operations Research. At the center of this group are Professors Jack Kiefer (at left) and Robert Bechhofer.

Right below: Graduate students discuss their project work with Professor John Muckstadt (at left).

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 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:

Applied Stochastic Processes (sponsored by the National Science Foundation)

Approximating Nonparametric Problems by Parametric Problems with No Loss of Asymptotic Efficiency (sponsored by the National Science Foundation)

Component Management (sponsored by the Office of Naval Research)

The Cooperative Theory of Behavior and Its Applications (sponsored by the Office of Naval Research)

Initialization Bias in Simulation Experiments (sponsored by the National Science Foundation)

Investigations in Discrete Optimization (sponsored by the National Science Foundation)

Multiple Decision Selection and Ranking Procedures (sponsored by the Army Research Office, Durham)

PL/C Compiler Development (sponsored by the IBM Corporation and Siemens Corporation)

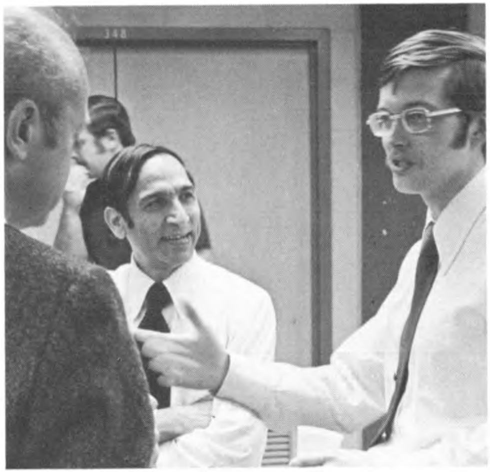
Privacy and Security in Information Systems (sponsored by the National Science Foundation)

Probability Models in Engineering Structures and Materials (sponsored by the National Science Foundation)

Problems in Complementarity Theory (sponsored by the National Science Foundation)

Research on *n*-Person Games (sponsored by the National Science Foundation)

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 (at center) frequently speak at colloquia. At right is Cornell Professor Thomas Santner.

Statistical Engineering (sponsored by the Office of Naval Research)

Statistical Methods for Environmental Health Studies (sponsored by the National Institute of Environmental Health Sciences)

Statistical Procedures for Analyzing Data from Reliability and Life Testing of Engineering Systems (sponsored by the National Science Foundation)

Some books and recent research papers by faculty members are:

Bechhofer, R. E.; Kiefer, J.; and Sobel, M. 1968. *Sequential identification and ranking procedures*. Chicago: University of Chicago Press.

Billera, L. J.; Heath, D. C.; and Raanan, J. 1978. Internal telephone billing rates — a novel application of non-atomic game theory. *Operations Research* 26 (in press).

Billera, L. J., and Provan, J. S. 1978. A decomposition property for simplicial complexes and its relation to diameters and shellings. *Annals of the New York Academy of Sciences* (in press).

Conway, R. W., and Gries, D. 1975. *An introduction to programming: a structured approach using PL/1 and PL/C-7,* 2d ed. Cambridge, Mass.: Winthrop.

Karlin, S., and Taylor, H. M. 1975. *A first course in stochastic processes,* 2d ed. New York: Academic Press.

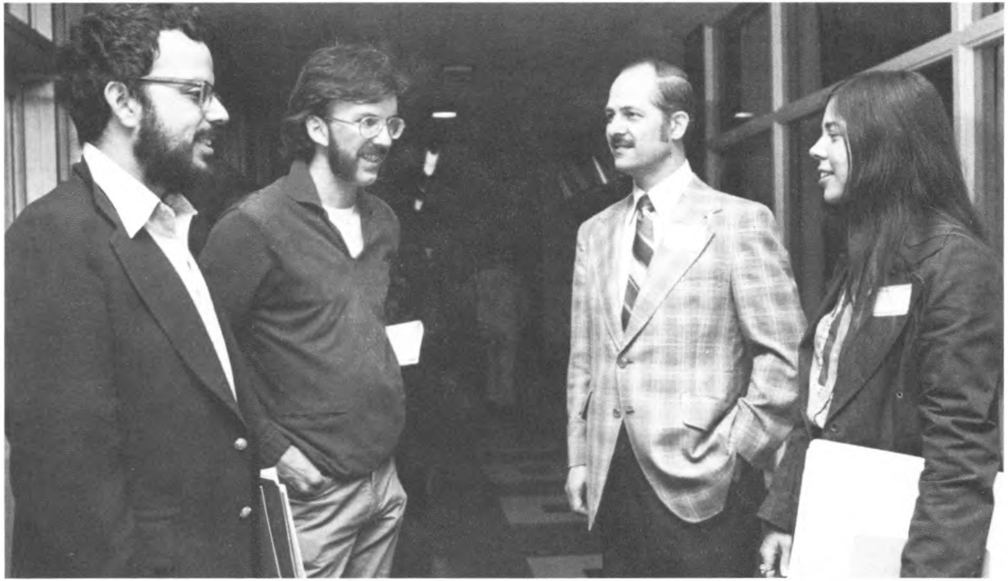
Lucas, W. F. 1977. Game Theory. In *Encyclopedia of computer science and technology,* vol. 8, ed. J. Belzer, A. G. Holtzman, and A. Kent, pp. 363–392. New York: Marcel Dekker.

Maxwell, W. L.; Miller, L. W.; and Ginsberg, A. S. 1975. An experimental investigation of priority dispatching in a simple assembly shop. *Logistics* 1:125.

Muckstadt, J. A. 1973. A model for a multi-item, multi-echelon, multi-indenture inventory system. *Management Science* 20(4):472.

Nemhauser, G. L.; Cornuejols, G.; and Fisher, M. 1977. Location of bank accounts to optimize float: an analytic study of exact and approximate algorithms. *Management Science* 23(8):789.

Nemhauser, G. L., and Garfinkel, R. 1972. *Integer programming*. New York: Wiley.



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.

Prabhu, N. U. 1965. *Queues and inventories*. New York: Wiley.

Santner, T. J., and Rinott, Y. 1977. An inequality for multivariate normal probabilities with application to a design problem. *Annals of Statistics* 5:1228.

Spitzer, F. L. 1964. *Principles of random walk*. Princeton: Van Nostrand.

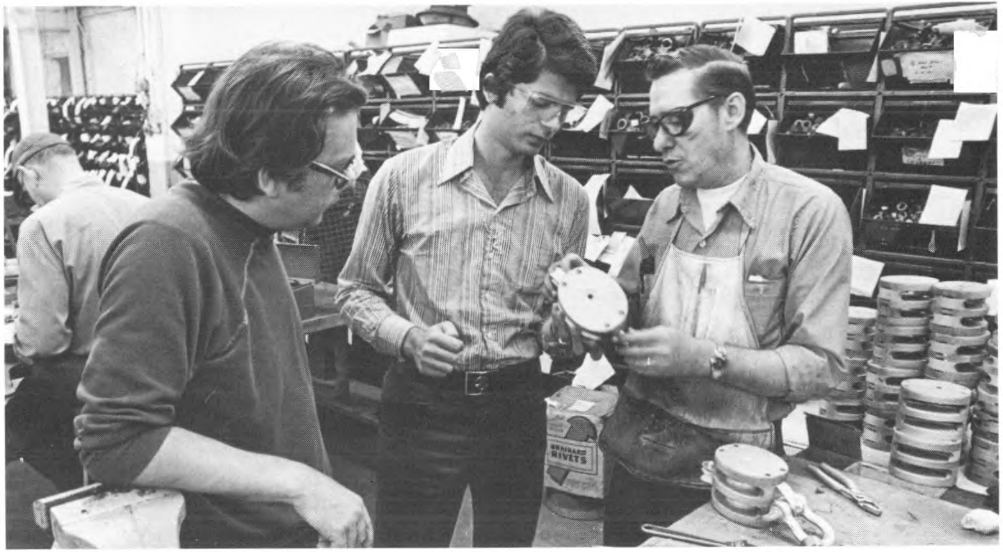
Taqqu, M. S. 1977. Law of the iterated logarithm for sums of non-linear functions of Gaussian variables that exhibit a long range dependence. *Z. Wahrscheinlichkeitstheorie und Verwandte Gebiete* 40:203.

Todd, M. J. 1976. *The computation of fixed points and applications*. Berlin-Heidelberg: Springer-Verlag.

Trotter, L. 1975. A class of facet producing graphs for vertex packing polyhedra. *Discrete Mathematics* 12:373.

Turnbull, B. 1976. The empirical distribution function with arbitrarily grouped censored and truncated data. *Journal of the Royal Statistical Society* B38:290.

Weiss, L. 1977. Sequential tests on a multinomial distribution and a Markov chain. *Stochastic Processes and Their Applications* 6(1):1.



A group project for M.Eng. (OR&IE) students was to work with engineers from a nearby parts manufacturing company to set up a new process for the manufacture of blocks. Here Professor William Maxwell (at left) and a student confer with an assembly worker.

An idea of the specific research conducted by graduate students, and also of the kind of jobs they assume 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.

Russell Barton: Mathematica, Princeton, New Jersey. Regression models for grouped censored survival data with an application to exoffender post release performance evaluation (B. Turnbull).

Robert Blau: Chase Manhattan Bank, New York. The problem of scheduling independent jobs with simultaneous multiple resource requirements (W. L. Maxwell).

Wagner Borges: Instituto de Matematica e Estatistica, Universidade de Sao Paulo, Brazil. Extreme value theory in triangular arrays with applications to the stability of fibrous materials (H. M. Taylor).

Bharat T. Doshi: Department of Statistics, Rutgers University. Continuous time control of Markov processes on an arbitrary state space (N. U. Prabhu).

Peter H. Farquhar: Graduate School of Business, Harvard University. Fractional hypercube decompositions of multiattribute utility functions (W. F. Lucas).

James R. Fergusson: Bureau of Management Consulting, Supply and Services, Ottawa, Canada. Enumerative algorithms for separable non-convex programming problems: methodology for a short-term flood control model (G. L. Nemhauser).

Richard Gelber: School of Public Health, Harvard University. A sequential goodness-of-fit test for composite hypotheses involving unknown scale and location parameters (L. Weiss).

Jeffrey Hooper: Bell Laboratories. Selection procedures for ordered families of distributions (T. J. Santner).

Joseph Raanan: Bell Laboratories. The value of the non-atomic game arising from a rate-setting application and related problems (L. J. Billera).

Ajitkumar Tamhane: Department of Industrial Engineering and Management Sciences, Northwestern University. On minimax multistage elimination type rules for selecting the largest normal mean (R. E. Bechhofer).

Robert J. Weber: School of Organization and Management, Yale University. Bargaining solutions and stationary sets for *n*-person games (W. F. Lucas).

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 he or she can 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.

Faculty members of the School of Operations Research and Industrial Engineering who are available to supervise M.Eng. (OR & IE) projects are R. E. Bechhofer, J. Bloom, T. O. Boucher, D. C. Heath, W. L. Maxwell, J. A. Muckstadt, G. L. Nemhauser, N. U. Prabhu, T. J. Santner, L. W. Schruben, A. Schultz, L. E. Trotter, B. W. Turnbull, and L. I. Weiss.

The following list of recent and current project titles, with the supervising professors, is

Graduate students in operations research hold an annual picnic at a nearby state park.

representative of the M.Eng. work undertaken in this field:

Analysis of Subjective Data Using Multidimensional Scaling and Conjoint Measurement (B. W. Turnbull, T. J. Santner)

Data Sensitivity Study for a Linear Programming Refinery Model (L. E. Trotter)

Forecasting Price Changes of Spare Parts for Maintenance Materials (A. Schultz)

An Investigation of Operations Characteristics of a Material Flow System (W. L. Maxwell)

Stress Analysis for Print Characters (D. C. Heath)

A Study of Xerox Spare Parts Logistics at the Branch–Technical Representative–Customer Interfaces (J. A. Muckstadt)

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. (Columbia): *engineering and industrial economics*

Richard W. Conway, B.M.E., Ph.D. (Cornell): *information processing systems*

John E. Dennis, B.S., M.S. (University of Miami), Ph.D. (Utah): *numerical optimization*

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*

Jack C. Kiefer, B.S., M.S. (M.I.T.), Ph.D. (Columbia): *statistical decision theory, optimal experimental design*

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, 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*

Byron W. Saunders, B.S. (Rhode Island State), M.S. (Stevens): *industrial systems, economic analysis*

Lee W. Schruben, B.S. (Cornell), M.S. (North Carolina), Ph.D. (Yale): *applied operations research, health systems*

Andrew Schultz, Jr., B.S., Ph.D. (Cornell): *systems analysis*

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, by mathematical analysis and experimental observation, of the motion and deformation of solids and fluids. Although its historical roots are deep, it is a particularly modern subject because it is basic to so many areas of modern technology.

Graduates of the Cornell programs in theoretical and applied mechanics, having acquired a solid background in fundamentals, 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 graduate Field of Theoretical and Applied Mechanics is sponsored by the faculty of the department of the same name. Its programs offer 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. As can be seen from the areas of research below, topics that have been selected recently are quite diverse.

The principal areas of teaching and research are solid mechanics, fluid mechanics, dynamics and space mechanics, biomechanics, mechanics of materials, and related mathematical methods. All students majoring in the field are required to minor in another field of the Graduate School, chosen according to their research interests and needs. Minors frequently chosen are aerospace engineering, applied mathematics, applied physics, astronomy, electrical engineering, geophysics, 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 the student's major and minor advisers.

The field has maintained a steady number of graduate students (about twenty-five), who come from a variety of academic and geographic backgrounds. The normal residence period for a student entering with a bachelor's degree is one and one-half years for the M.S. and four years for the Ph.D.; most study for the doctoral degree. Almost all students are supported either by teaching and research assistantships (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 somewhat more limited basis.

Teaching assistants are asked to lead problem sessions (classes of about twenty students) of various undergraduate courses in mechanics and engineering mathematics or to assist in the laboratories of strength of materials and dynamics. As a result they usually have a sounder understanding of basics and are better prepared to present technical subjects orally than those who do not have such experience.

Research assistants work under the direction of one or more professors on projects sponsored by government agencies or industry. Currently the subjects of sponsored projects are creep and relaxation of metals at high temperatures; 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); mechanics of composite materials; mathematical analysis of combustion; magnetohydrodynamic duct flow; and dynamical studies of the early evolution of the solar system.

Students who wish to prepare for professional engineering careers generally seek the degree of Master of Engineering (Engineering Mechanics). This degree program requires a minimum of thirty credit hours of graduate-level work in engineering mechanics, including an engineering design project. Courses are in such subjects as elasticity, plasticity, advanced dynamics, waves and vibrations, fluid mechanics, and engineering mathematics. The program is generally completed in one year.

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 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 departmental analog computers and minicomputers. In addition the department has a PDP 11/40 computer system 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 biomechanics, dynamics, fluid mechanics, and solid mechanics 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 professors have also been elected to the faculties of other graduate fields. They are J. A. Burns (astronomy and space sciences), J. T. Jenkins (applied mathematics), P. J. Holmes (applied mathematics), G. S. S. Ludford (aerospace engineering, applied mathematics), and R. H. Rand (agricultural engineering, applied mathematics). Some of their research constitutes contributions to these other disciplines as well as to theoretical mechanics.

Biomechanics, Biomathematics, Bionics, and Robots

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 improve 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, tendons, and contact lenses. Principles of mechanics and applied mathematics are being used to help understand how leaves breathe and why stomata open and close.

Examples of publications in this area are:

Block, H. D.; Lewis, D. C.; and Rand, R. H. 1977. Visual perception, invariants, neural nets. In *IEEE international symposium on information theory,* p. 85. New York: Institute of Electrical & Electronics Engineers, and Union Radio Scientifique Internationale.

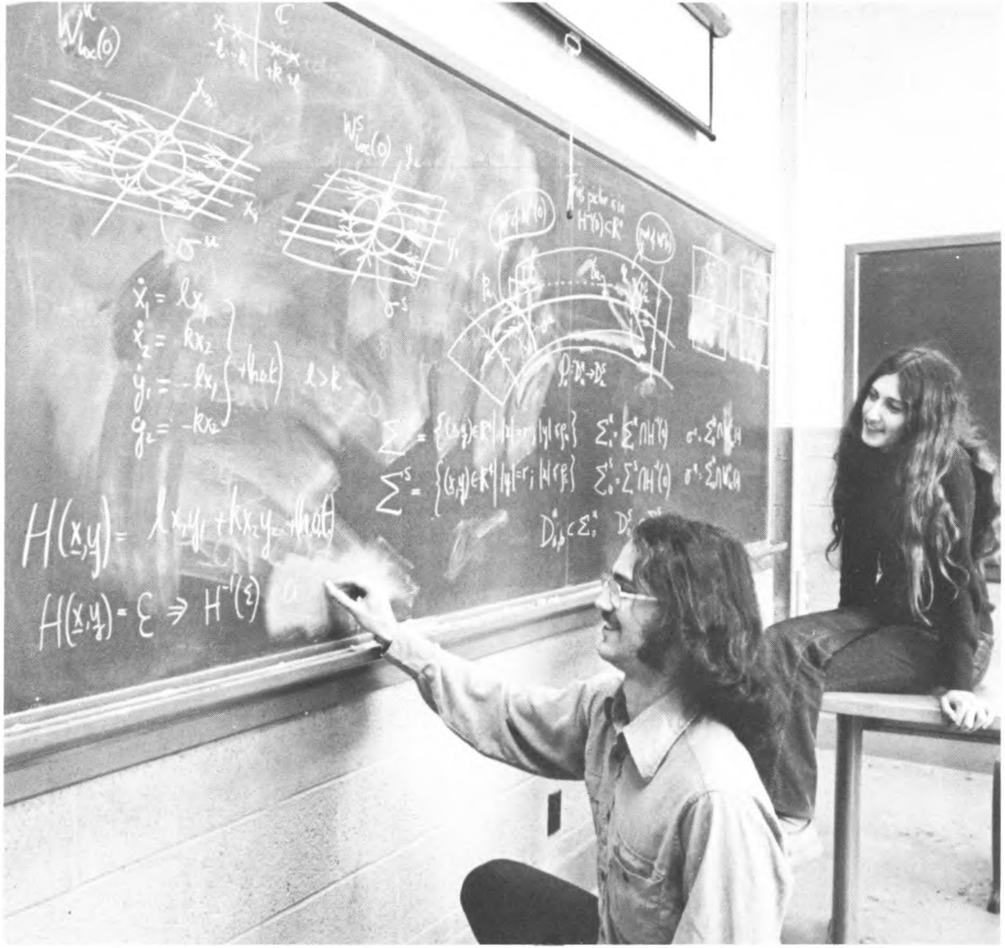
Jenkins, J. T. 1977. Static equilibrium configurations of the red blood cell. *Journal of Mathematical Biology* 4:149.

Rand, R. H. 1978. A theoretical analysis of CO_2 absorption in sun versus shade leaves. *Journal of Biomechanical Engineering* 20:100.

Dynamics and Space Mechanics

Dynamics lies at the center of mechanics. Studies in dynamics often require a deep understanding of physical phenomena and also can involve sophisticated modern mathematics. Both of these aspects are evident in research at Cornell, 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 the area of space mechanics is concerned with the long-term evolution of the solar system, the rotation of celestial bodies, including planets, asteroids, natural satellites, and pulsars, and the



deformation of the crust of the Earth and other planets. Also, in the tradition of rational mechanics, physical problems continue to stimulate exciting mathematical analyses; 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):

Burns, J. A. 1977. Orbital evolution. In *Planetary satellites*, ed. J. A. Burns. Tucson: University of Arizona Press.

Burns, J. A.; Lamy, P. L.; and Soter, S. 1978. Radiation forces acting on small particles in the solar system. *Icarus: International Journal of Solar System Studies* (in press).

Holmes, P. J. 1977. Bifurcations to divergence and flutter in flow-induced oscillations. *Journal of Sound and Vibration* 53:471.

Johnson, T. 1978. An application of the calculus of variations to the existence of periodic motions in a class of nonlinear dynamical systems. Ph.D. thesis (R. H. Rand).

Month, L. A., and Rand, R. H. 1977. The stability of bifurcating periodic solutions in a two-degree-of-freedom nonlinear system. *Journal of Applied Mechanics* 44:782.

Two graduate students, Peter Carruthers and Leslie Month, discuss the geometric representation of a dynamical systems problem.

Professors Francis C. Moon (left) and Joseph A. Burns inspect a model of a magnetically levitated train.

Fluid Mechanics

In the area of fluid mechanics several research projects with significant applications are under way. For example, magnetohydrodynamic studies of the flow of electrically conducting fluids in ducts are relevant to both the fast-breeder reactor and proposed fusion reactors. Other projects with potential applications are concerned with the mechanics of magnetic fluids, the theory of rotating flows (in particular, vortex breakdown), and combustion.

Representative publications and theses on these subjects are:

Jenkins, J. T. 1978. Flows of nematic liquid crystals. *Annual Review of Fluid Mechanics* 10:197.

Ludford, G. S. S. 1978. Current status of MHD duct flow. In *Proceedings of 2nd Bat-Sheva international seminar on MHD flows and turbulence* (held in March 1978, Beersheva, Israel). Wiley-Israel University Press (in press).

Matalon, M.; Ludford, G. S. S.; and Buckmaster, J. D. 1978. Diffusion flames in a chamber. *Acta Astronautica* (in press).

Normandia, M. J. 1978. Mathematical theory of liquid fuel drops and monopropellants utilizing the Clausius-Clapeyron relation. Ph.D. thesis (G. S. S. Ludford).

Solid Mechanics

Research is being conducted on a variety of newly developing aspects of solid mechanics. Fundamental work on the theory of elasticity, plasticity, continuum mechanics, stress-wave propagation, magnetoelastic interactions, and dynamic instability of structures has been carried out at Cornell for many years.

Currently there is active research on the scattering of elastic waves by inhomogeneities in solids (cavities and solid or fluid inserts); 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. The results are of great importance in quantitative nondestructive testing of materials.

Another active research program is concerned with the time-dependent inelastic behavior of metals, polymers, and ceramics at elevated temperatures. Included is the analysis of creep, relaxation, thermal stresses, and residual stresses in the major structural components of nuclear reactors. Experimental investigations are carried out in conjunction with members of the Department of Materials Science and Engineering.

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.

A graduate student analyzes data on the scattering of elastic waves by an obstacle.

The statics and dynamics of composite materials are also under investigation. 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 recently established laboratory has cryogenic facilities and large, charge storage banks. This research has direct application to the magnetic forming of nonferrous materials, magnetic levitation of vehicles, and the design of superconducting coils for fusion reactors.

Other current studies, involving both experiment and theory, are concerned with the mechanics of structured continua and liquid crystals, nonlinear vibrations of plates and beams, dynamic stresses in thick-walled vessels for the containment of nuclear reactors, lubrication of elastic bearings, acoustoelastic stress analysis, and acoustic emission.

Recent publications and theses based on work in these projects include:

Chian, C. 1978. Magnetically induced cylindrical stress waves in a thermoelastic conductor. Ph.D. thesis (F. C. Moon).

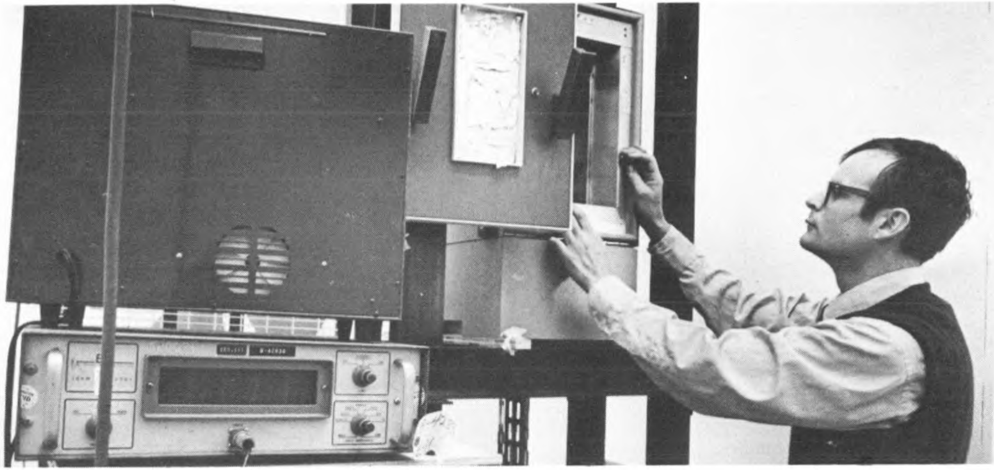
Dashner, P. A. 1978. A finite strain work-hardening theory for rate-independent elasto-plasticity. *International Journal of Solids and Structures* (in press).

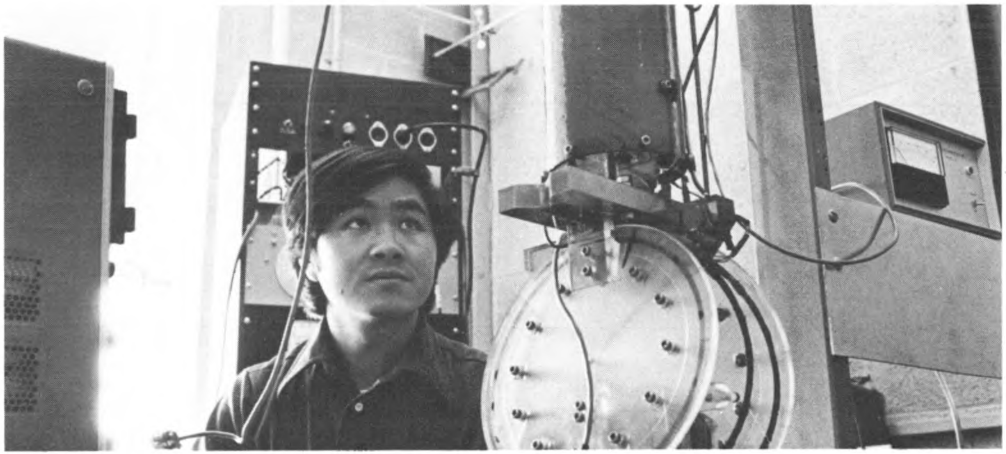
Gajewski, R. R. 1978. Transient response of a layered elastic solid to uniform pressure on a spherical cavity. Ph.D. thesis (Y.-H. Pao).

Hart, E. W. 1977. Constitutive relations for non-elastic deformation. *Nuclear Engineering and Design* 46:179.

Kumar, V. 1977. Time-dependent inelastic analysis of metallic media using constitutive relations with state variables. Ph.D. thesis (S. Mukherjee).

Kumar, V., and Mukherjee, S. 1977. A boundary-integral equation formulation for time-dependent inelastic deformation in metals. *International Journal of Mechanical Sciences* 19:713.





Right above: The stress-strain relation for a metal sample is determined in a temperature-controlled environment.

Right: Investigation of the structural stability of superconducting coils is part of a research program in magnetoelastic interactions.

Lee, L.-C. 1978. Stress analysis for a unidirectional composite reinforced with a doubly periodic array of identical inclusions. Ph.D. thesis (H. D. Conway).
Lo, K. H., and Conway, H. D. 1976. Thermal stresses in multi-layered curved bars. *Fibre Science and Technology* 9:135.
Moon, F. C. 1977. Problems in magneto-solid mechanics. In *Mechanics today,* ed. S. Nemat-Masser, p. 307. New York: Pergamon.
Pao, Y.-H., and Varatharajulu, V. 1976. Huygen's principle, radiation conditions, and integral formulas for the scattering of elastic waves. *Journal of the Acoustical Society of America* 59:1361.
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* (in press).
Sancar, S. 1977. Arrival time and spectral analysis of elastic pulses scattered from two fluid-filled cylindrical cavities in a solid. Ph.D. thesis (W. H. Sachse).
Waung, Y. C. 1977. Creep bending of beams and plates using a state variable approach. Ph.D. thesis (R. H. Lance).
Yamagishi, K. 1978. Contact problems for the radial tire. Ph.D. thesis (J. T. Jenkins).

An M.Eng. (Engineering Mechanics) student tests the strength of friction welds with ultrasonic equipment as part of his project work.

M.Eng. (Engineering Mechanics) Degree Program

A professional master's degree program in engineering mechanics has been instituted within the past few years by the faculty of the Department of Theoretical and Applied Mechanics, which is concerned almost entirely with graduate education. This M.Eng. program allows the student to master advanced subjects in mechanics and, at the same time, to develop facility in applying fundamental concepts of mechanics to modern engineering problems.

Course requirements include six credits in mathematics or applied mathematics, a design project, and sufficient graduate-level courses, selected in consultation with a department adviser, to meet the degree requirement of thirty credits.

The titles of some projects recently undertaken by M.Eng. (Engineering Mechanics) students, and the supervising professors, are:

Shear-Wave Reflectometry Measurements of Viscoelastic Fluids (W. H. Sachse)
Simulation of Solar Sailing Trajectories (J. A. Burns)

Faculty Members and Their Research Interests

Joseph A. Burns, B.S. (Webb), Ph.D. (Cornell): *planetary dynamics, celestial mechanics, natural satellite studies*

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*

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*

Herbert H. Johnson, B.S., M.S., Ph.D. (Case): *fracture, dislocation mechanics, fatigue*

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, magnetohydro-dynamics, combustion, related mathematics*

Francis C. Moon, 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*

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

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 centers: P. J. Holmes, J. T. Jenkins, G. S. S. Ludford, and R. H. Rand work with the Center for Applied Mathematics; H. H. Johnson, 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.

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 that are of great significance in many applied science and engineering projects. These are of interest to students in the various graduate fields in that their research efforts might be closely identified with those of a center or program or their research activities might be conducted in associated laboratories. These interdisciplinary units 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 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

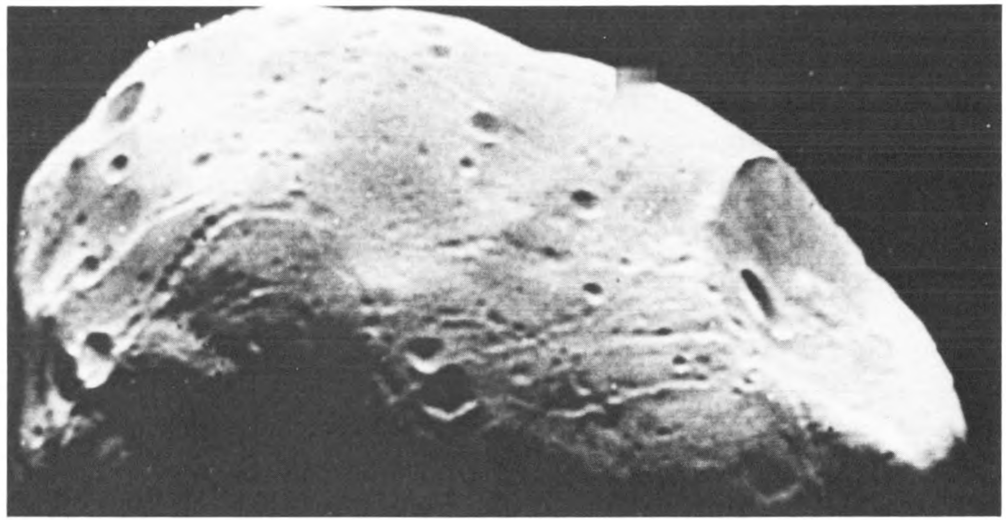
The major role of the Center for International Studies is to support and coordinate Cornell's teaching and research programs in international and comparative studies. The flexibility of degree requirements permits students considerable latitude in the selection of subjects, and appropriate courses may 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 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; and Western societies. The center also sponsors the Field of International Development, a program of graduate studies leading to a professional master's degree.

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.

A photointerpretive study of the natural satellites of Mars was undertaken recently for a doctoral thesis in geological sciences, conducted at the Center for Radiophysics and Space Research. Viking Orbiter images such as this one of Phobos, the larger of the two tiny satellites, were analyzed.



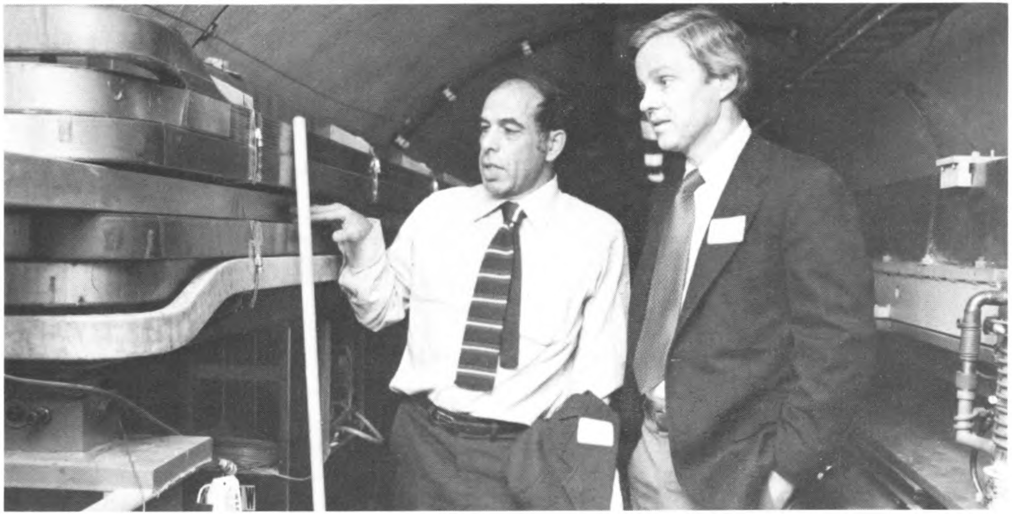
Center for Radiophysics and Space Research

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 Graduate School admission 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 extensive collections of spacecraft lunar and planetary photography. Work in optical astronomy involving occultations is in progress. Facilities for research in radio-radar astronomy are available through the National Astronomy and Ionosphere Center, operated by Cornell (see 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 (at left), director of the Cornell High Energy Synchrotron Source, explains how the facility will operate to National Science Foundation director Richard C. Atkinson during a visit to the University's Wilson synchrotron.

Cornell High Energy Synchrotron Source

The National Science Foundation has approved a one-million-dollar grant for the construction of a synchrotron radiation laboratory, to be known as the Cornell High Energy Synchrotron Source (CHESS), that is expected to be in operation by the summer of 1979. The synchrotron x radiation will be generated by the Cornell Electron Storage Ring (CESR), now under construction. As an intense source of high-energy x rays, CHESS will be unique — unmatched by any other existing or planned facility in the United States.

Synchrotron radiation, at one time considered a nuisance by high-energy physicists, has become recognized as a very powerful tool for physicists, materials scientists, chemists, crystallographers, and medical researchers studying the properties of materials that have both technological and biological importance. At Cornell, researchers in virtually all fields of physical science are expected to make use of CHESS. Particularly promising at Cornell is the use of synchrotron radiation in x-ray lithography applied to the fabrication of submicron structures.

CHESS will be available to scientists from industrial and university laboratories all over the United States. It will complement the National Synchrotron Light Source being built at Brookhaven (with an estimated completion date in 1982) and the smaller synchrotron facility at the University of Wisconsin. CHESS will be the East Coast counterpart of the Synchrotron Radiation Laboratory at Stanford, which provides x rays and ultraviolet radiation as a by-product of research devoted primarily to high-energy physics, but it will have greater capacity to generate high-energy x rays.

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

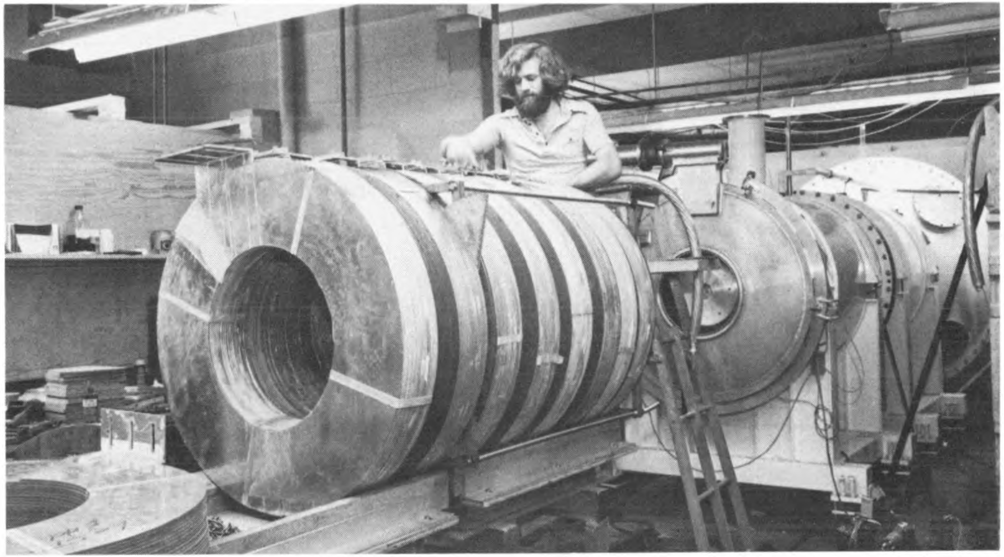
Although there is no separate graduate field or organized interdisciplinary program or center in energy studies at Cornell, there is a great amount of activity in this area in the various graduate fields, and programs directed toward fundamental or applied energy-related study and research can be arranged.

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 utilization in agricultural production. Other examples can be found in the descriptions of the various graduate fields.

Laboratory of Plasma Studies

The Laboratory of Plasma Studies was established as an interdisciplinary center for research in plasma physics and lasers. Active areas of research include controlled fusion, intense beams of relativistic electrons, intense ion beams, plasma confinement and heating experiments, basic plasma physics, theory of high-temperature plasmas, molecular lasers, chemical lasers, and laser-produced plasmas. 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 and 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 eleven years of existence, its research projects have led to the completion of seventy-one Ph.D. and fourteen M.S. theses.



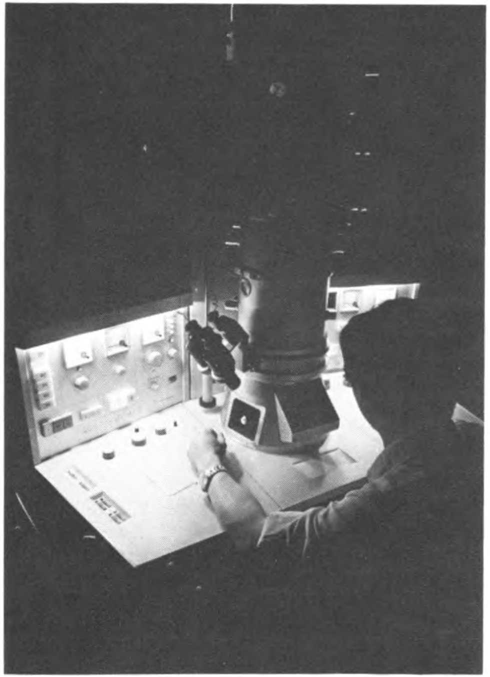
In the Laboratory of Plasma Studies, researchers are assembling magnetic field coils for an experiment to trap ion rings.

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.

***Right:* Equipment available at the Materials Science Center includes this scanning electron microscope, useful in studies of the surfaces of materials and for biological applications.**

***Below:* Electron microscopes are among the extensive facilities of the interdisciplinary center.**



Materials Science Center

The Materials Science Center facilitates graduate research and training in many phases 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, chemistry, electrical engineering, 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 staffed with trained technicians, so that researchers receive expert guidance and assistance. Extensive multiuser computer facilities 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 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.

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

The national radio-radar telescope observatory at Arecibo, Puerto Rico, is operated by Cornell.

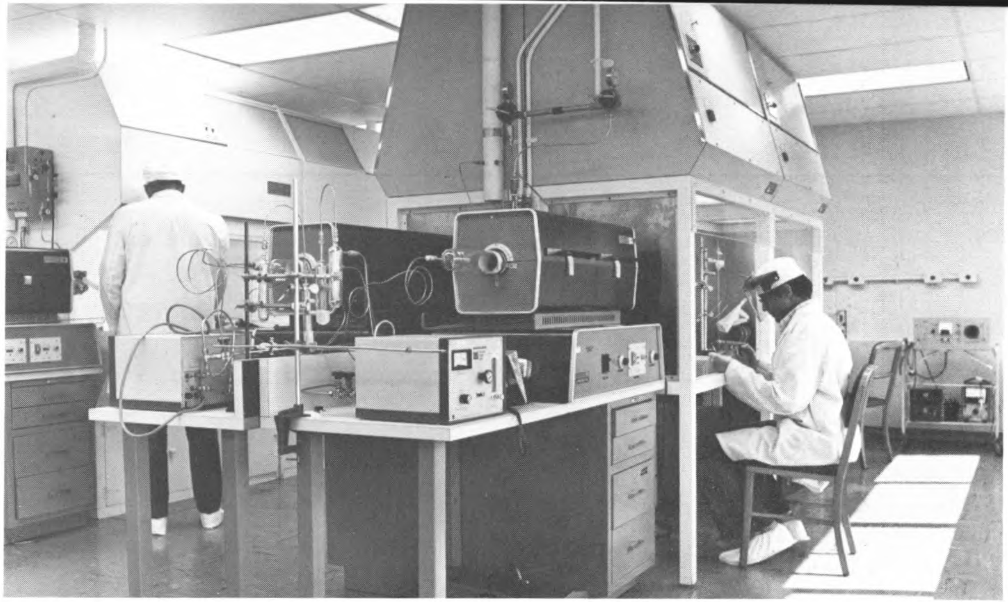
Earth's ionosphere. In recent years controlled studies of the ionosphere have been made from Arecibo by the artificial heating of preselected ionospheric layers.

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

A new national center for research on submicrometer structures was established recently by the National Science Foundation at Cornell, where a strong program in this area was already under way. 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 the National Research and Resource Facility for Submicron Structures (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. Sophisticated electronic equipment is available, and graduate students have a unique opportunity to participate in research projects utilizing these resources. Such work is arranged through professors from a number of graduate fields who are members of the facility.



A laboratory for growing semiconductor crystals is part of the clean-room area available for work at the National Research and Resource Facility for Submicron Structures.

A wide 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 utilization of both input and output devices.

The laboratory 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 printer plotters. Photographic equipment for filmmaking, videotapes, and single-image documentation is available. The multiuser system operates on several interconnected minicomputers.

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 with 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.

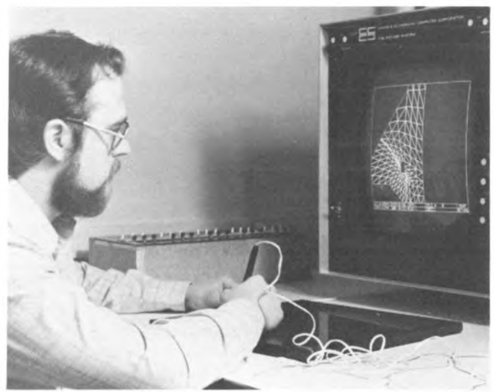
Program on Science, Technology, and Society

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, 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 our society and others. 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, and appropriate requests for support by students beyond the introductory level of graduate study will be considered.

Further information may be obtained by contacting the Program on Science, Technology, and Society, Cornell University, Clark Hall, Ithaca, New York 14853.



A graduate student in structural engineering employs facilities of the Program of Computer Graphics in a research project combining interactive computer graphics and structural mechanics. The graphic display is of a finite element mesh for the cross section of a concrete dam with a crack. This mesh is created and edited rapidly through the use of interactive graphic techniques.

General Information

Cornell is an internationally known university consisting of fourteen colleges and schools that enroll about 18,000 students, including 3,500 in the Graduate School. A unique feature of the University is the combination of privately financed and state-supported units, a circumstance that fosters Cornell's century-old concept of education in all subjects for all qualified students. The individual student is afforded an unusually rich and diverse background of academic life.

The College of Engineering has a faculty of more than two hundred. About 2,270 undergraduate and 700 graduate students are enrolled in engineering programs.

Facilities

Cornell University maintains more than ninety 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.

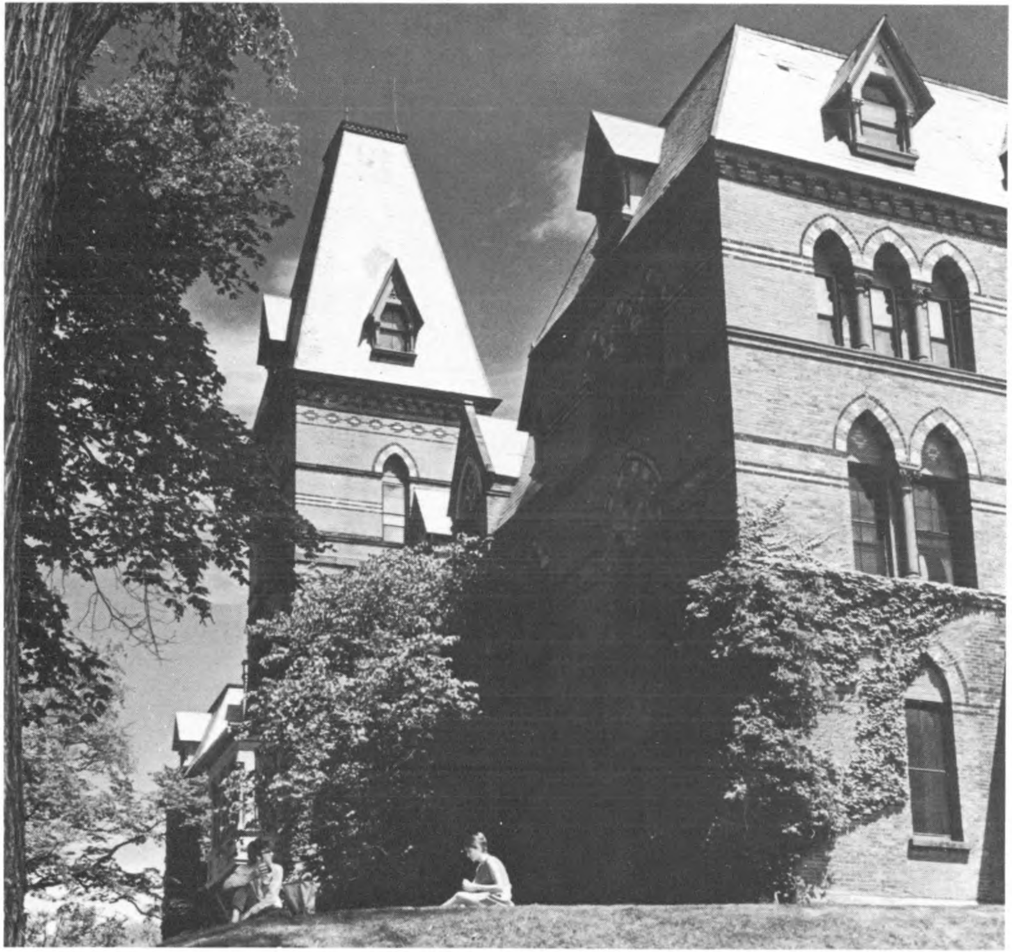
Of special importance to many graduate students is the University's computing facility. At the present time this consists of a multiprocessor complex of IBM 370 systems, including a central 370/168 system and satellite computers at various campus locations. The College of Engineering is served through two of these satellite stations, as well as by a number of slow-speed terminals.

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 Allegheny Airlines and the Greyhound Bus Lines.

Admission

Application for enrollment in any field of graduate study at Cornell is made through the Graduate School of the University; acceptance is determined by the faculties of graduate fields. Application materials for the Graduate School, 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, Upson 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 Examination 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.

Cornell University is committed to assisting those handicapped students who have special needs. A brochure describing services for the handicapped student may be obtained by writing to the Office of the Dean of Students, Cornell University, 103 Barnes 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.

An applicant for admission to an M.S. or Ph.D. degree program will receive detailed information about available financial aid along with application materials and should indicate a request for aid on the application form. A prospective student in one of the M.Eng. degree programs should file a separate application for financial aid along with the admission application.

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.

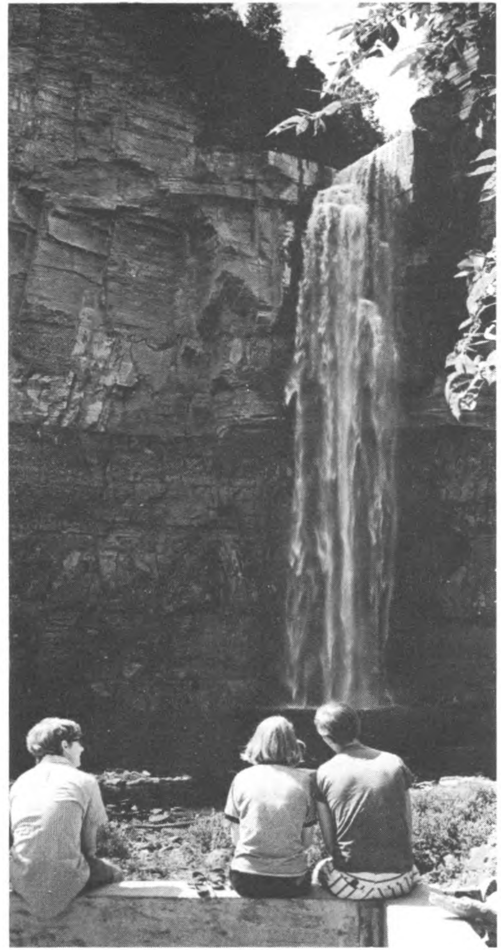
Part-time employment is sometimes available to graduate students through their own departments, and a part-time employment service is maintained by the Office of Financial Aid. Spouses of students may find employment at Cornell through the University's personnel office, or with local businesses or industries, 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.

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.

The Sage Graduate Center 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.

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 Graduate Center that is available to all graduate students and faculty members.

Further Information

The *Announcement of the Graduate School* and the *Announcement of General Information* 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 *Cornell University: Description of Courses.* Copies of these publications may be obtained by writing to Cornell University Announcements, Building 7, Research Park, Ithaca, New York 14853.

Opposite: The Engineering Quadrangle is adjacent to Cascadilla Gorge on the Cornell campus. Sage Graduate Center is at left center.