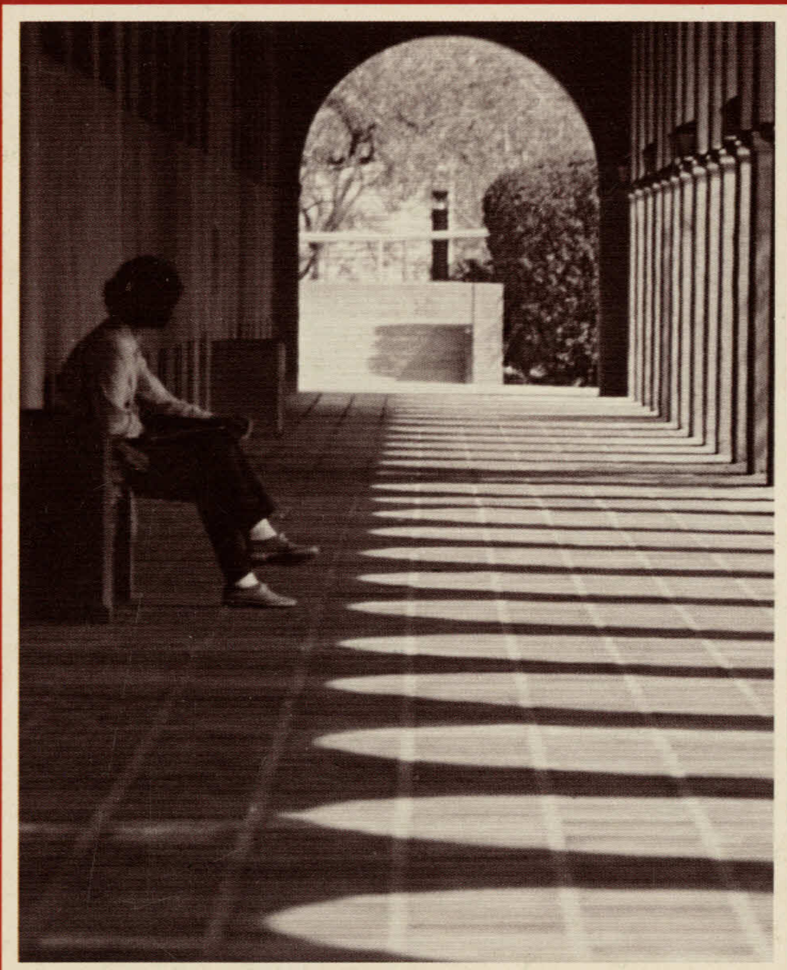
1981-82 PRESIDENT'S REPORT

CALIFORNIA INSTITUTE OF TECHNOLOGY



1981-82 PRESIDENT'S REPORT

DECEMBER 1983

CALIFORNIA INSTITUTE OF TECHNOLOGY
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On the cover:
This arcade runs along the side of the William G. Kerckhoff Laboratories of the Biological Sciences

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Report of the President

Marvin L. Goldberger, President

How's Caltech? This is a question frequently addressed to me by trustees, faculty, students, visitors, and interested friends. The general answer is, I believe, quite all right, thank you. Our research programs are strong and well supported for the most part by federal funding agencies; our educational programs are judged by our power to be merely great in some areas and truly outstanding in others; and thanks to alumni, friends, industry, and foundations we have had a highly successful fund-raising year. Notwithstanding the above, we do have problems, both immediate and long range, which we must solve if we are to insure for the future the unique position the Institute now enjoys.

Among the most pressing money-type needs, in no particular order, are the following: Financial aid for undergraduates in both low-cost loan funds and scholarships; graduate fellowships; an expanding program of elite postdoctoral fellowships; substantial new funds for instrumentation and rehabilitation of laboratory and office space; endowed professorships; an endowed research fund providing unrestricted support for the divisions on an annual basis; a major fund for innovation as areas and opportunities arise; a growing interaction with industry in pursuing generic basic research areas of mutual interest.

It is obvious that these needs are ones felt by all universities, particularly private universities. Caltech has some special characteristics that create both problems and, more importantly, great opportunities. We are small and intend to stay that way, which means that we must change without growing substantially. We cannot afford to become complacent over our current excellence and must be continuously alert to new opportunities in developing areas of research. There must necessarily be hard choices ahead as we move into new fields and out of old ones. We have made these changes in the past, and our small size has allowed us to move quickly when necessary. Given the financial resources, we shall meet these challenges in the future.

One peculiarly Caltech resource is the Jet Propulsion Laboratory. This great, primarily NASA-funded installation has a truly outstanding record of achievement. The collaboration between scientists and engineers on the campus and at the Lab has increased substantially over the past few years. As the amount of near-earth-orbit space science at JPL grows we look forward to even greater cooperative endeavors. There is in addition a substantial joint effort in the areas of microelectronics and computer science.

Graduate Education

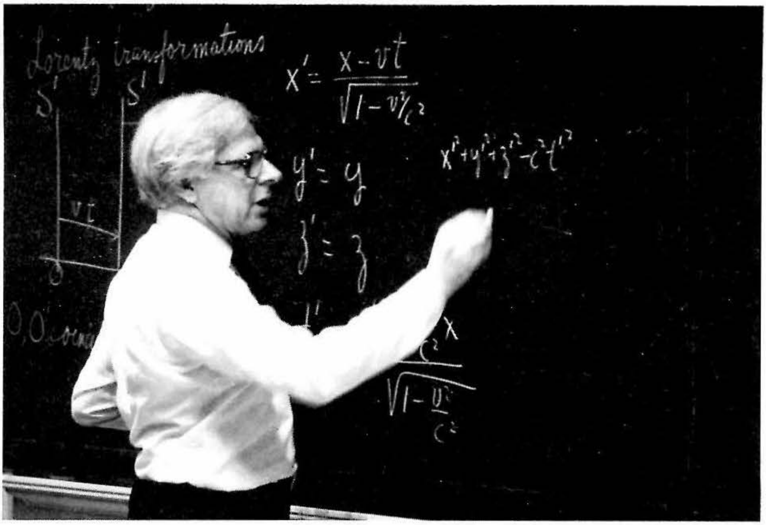
The scholarly quality of the faculty in Caltech's graduate programs in biological sciences, chemistry, physics, geosciences, chemical engineering, civil engineering, and mechanical engineering was given the highest award, "distinguished," in the 1982 series of reports released by a branch of the National Academy of Sciences. Four programs—biological sciences, chemistry, geosciences, and physics—were ranked first nationwide.

Graduate enrollment in the fall of 1982 was at an all-time high: 955. This represents an increase of 36 percent over the past 10 years.

The growth in graduate enrollment has made it necessary for Caltech to look at ways of providing more graduate student housing. Accordingly, the Institute plans to construct apartments for 156 graduate students on Caltech-owned property on Catalina Avenue south of Del Mar Boulevard. Caltech currently houses 167 of its graduate students on campus while another 195 live in Caltech-owned housing near the campus. Others must find space in Pasadena or nearby communities, where rising rents have become an increasing burden.

Undergraduates

At the undergraduate level, morale seems high, thanks in no small part to the efforts of Professor Sunney Chan, Master of Student Houses, James Morgan, Vice President for Student Affairs, and David Wales, Dean of Students. The second faculty-student conference in recent years, this time a one-day program, was held in February 1982. Although not as dramatic as the two-day conference in 1980, the session produced much helpful discussion as participants tackled seven topics: core courses and curriculum; humanities and social sciences;



President Goldberger takes a turn at teaching Physics 1 to Caltech's freshman class.

feedback, advisers, and teaching assistants; the honor system; student-body size; health and athletic facilities; and undergraduate research. Core courses drew praise for substantial improvements since the 1980 conference.

Mechanical Universe

One of those core courses—Physics 1—played a major role in the development at Caltech of a physics course for educational television. Professor of Physics and Applied Physics David Goodstein, who developed Physics 1 in a new format for the 1979 academic year, is the project director and star of the show. The series is being created with a grant from the Corporation for Public Broadcasting/Annenberg School of Communications and will be completed by the fall of 1985. The programs involve animation, shooting at a variety of locations, and a full range of special effects. We believe the series is particularly important because students in the U.S. today are so poorly served by the science educations available to them and because the programs can make a contribution to meeting this need. The project involves the production of two textbooks, one directly connected to the course and one advanced text.

SURF

We are proud of our continuing capacity to offer Summer Undergraduate Research Fellowships (SURF) to more than 70 Caltech students each year. In 1982, 72 sophomores, juniors, and seniors spent 40 hours and more weekly working on research projects that they initiated in conjunction with their faculty sponsors, and these efforts frequently result in publications. SURF, which began in 1979, is the brainchild of two Institute faculty members, Professors Fredrick H. Shair and Harold Zirin, and was initially funded by an anonymous donor. Funding and number of participants (originally 18) have increased steadily each year, thanks to the support of The Associates and a number of corporations.

The Braun and Watson Laboratories

Two major new facilities have been completed and welcomed to campus through formal dedication ceremonies. The opening of the Thomas J. Watson, Sr., Laboratories of Applied Physics was celebrated on May 5, 1982. On the northern end of campus, the structure provides expanded facilities for Caltech's programs in applied physics, especially in optical communication and plasma physics. It houses 80 faculty members, research fellows, graduate students, and support staff.

The Braun Laboratories in Memory of Carl F and Winifred H Braun were dedicated December 13, 1982. The $15-million, four-level, tile-roofed building houses 180 researchers and support staff in the divisions of Biology and Chemistry and Chemical Engineering. Eight research groups in the lab—four each from biology and chemistry—will carry out research in molecular biology, immunology, and cell-surface chemistry in the 85,000-foot structure. In their work, the scientists use the newly developed biotechnologies of recombinant DNA, monoclonal antibodies, and microchemical instrumentation.

Campus Beautification

Another spot on campus, the mall between Wilson Avenue and Millikan Library, has been transformed into a park-like area with small patios, garden spots, and benches. Five 30- to 40-foot coast live oaks were transplanted to the mall, and beds of roses were planted. At the west end, eight jacaranda trees form a grove. The mall has been named the Bechtel Mall for Stephen D. Bechtel, Jr., a member of the Board of Trustees since 1967, and chairman for many years of its Buildings and Grounds Committee.

Refurbishing Bechtel Mall has been only one aspect of a campus beautification program that has involved the upgrading of other malls and of pathways and athletic grounds.

Financial Aid

With respect to financial aid, Caltech—like other educational institutions—has continued to face the prospect of substantial cutbacks at the federal level. For 1982-83, the federal government proposed a budget that reduced or eliminated every federal student aid program. Students joined with college presidents, financial aid officers, and others in higher education to protest, and many of the cuts were restored.

Caltech has continued to accept students on the basis of merit, irrespective of financial ability. But as proposed cuts have received nationwide media attention, the Financial Aid Office has observed a shift in the income level of students applying for admission. Fewer families at the lower end of the income spectrum are applying. The average family income of freshmen entering in 1982 was $34,000 compared with $28,000 for the previous year's freshman class.

Transition at the Jet Propulsion Laboratory (JPL)

For JPL, 1981-82 was a time of transition as Bruce Murray stepped down as director and Lew Allen Jr. was appointed vice president of Caltech and director of JPL on October 1, 1982. Planetary exploration will continue as the principal activity at JPL and the unifying theme of its program, although, for a time, the future of planetary exploration was in doubt. NASA has a new program of planetary missions, in collaboration with JPL, that will be simpler than the previous one, and that will involve lower-cost spacecraft. The Galileo mission—in jeopardy for a time—was spared, and continues as the major ongoing project at the Lab. It involves a return trip to Jupiter and its satellites for studies and measurements much more detailed and complex than those of Voyager. On its visit, Galileo will go into orbit around Jupiter and launch a probe into its atmosphere.

Research

Research projects and news of scientific discoveries will be found in the divisional reports that follow. I do, however, want to highlight a few here.

Halley's Comet

Halley's Comet, the object of a worldwide search by astronomers, was detected for the first time on its current approach to the sun by Caltech astronomers. Graduate student David C. Jewitt and staff member G. Edward Danielson first found the comet on October 16, 1982, using the 200-inch Hale Telescope at Caltech's Palomar Observatory. Enhancing their search was an advanced electronic detector developed for the Space Telescope. The comet was found in the constellation Canis Minor.

Acid Fog

As concern has grown over the damaging effects of acid rain, environmental engineers at Caltech have provided evidence that acid fog may be even more harmful. Conducting the first detailed study of the composition of fog water in polluted areas, they found it to be a concentrated solution of chemicals acidic enough to corrode metal, damage vegetation, and perhaps threaten human health. The researchers believe that the role of fog in air pollution chemistry has been neglected. Based on previous studies, they note that acid rain is about 100 times less acidic than acid fog. Thus, the researchers are convinced that acid fog may prove to be the more damaging of the two.

The environmental engineers reported on measures of the pH and chemical composition of fog from three sites in Los Angeles and Bakersfield, California. They found the fog to be laden with high concentrations of pollutants such as sulfates, nitrates, ammonia, lead, copper, nickel, iron, manganese, and organic chemicals. (The pH scale is a logarithmic measure of alkalinity. A pH of 7 is neutral; higher than 7 is alkaline.) The fog water samples possessed pH's from 2.2 to 4.0, meaning that they were highly acidic.

The researchers were Associate Professor of Environmental Engineering Science Richard C. Flagan, Professor of Environmental Engineering Science James J. Morgan, and Associate Professor of Environmental Engineering Science Michael R. Hoffmann, graduate student Jed M. Waldman, graduate student Daniel J. Jacob, and staff engineer J. William Munger.

Gravity Wave Detector

Construction of a gravity wave detector to detect gravity waves from outer space is proceeding well. Already operational, the device will continue to be refined in sensitivity.

The research effort is headed by Professor of Physics Ronald W. P. Drever with Assistant Professor of Physics Stanley E. Whitcomb and Robert E. Spero, a member of the professional staff. Kip Thorne, the William R. Kenan, Jr. Professor and professor of theoretical physics, is the leading theoretician for the Caltech gravity-wave detection effort.

The detection of gravity waves would be a milestone in the history of astronomy. Gravity waves—unlike electromagnetic radiation such as the light now used by astronomers to study the universe—are ripples in space-time that undulate through space. Scientists theorize that they arise from such exotic objects as the collapse of dying stars, colliding black holes, and "starquakes" on superdense neutron stars. Light from the gravity waves is either obscured by dust or trapped by their immense gravity. Thus they have remained sources of mystery in astronomy.

How Nerve Cells Behave in Networks
A new technique to study how nerve cells behave in networks has been developed by Professor of Physics Jerome Pine. The experimental method involves growing small networks of nerve cells in a special culture dish whose bottom has been fitted with an array of microelectronic electrodes. The electrodes can be used to sense the electrical signals traveling through specific cells in the network, or to stimulate selected neurons with electrical pulses.

While physiologists have long used electrodes to study the properties of single nerve cells, until now they have been unable to experimentally investigate networks of cells. Such studies are vital, because nervous systems in humans and other animals consist of millions of individual neurons, operating as a complex system. In such systems, the summed effects of hundreds of neurons, both excitatory and inhibitory, determine whether a particular neuron finally fires a neural pulse. Most neurophysiologists believe that such properties as learning and memory stem from the architecture and operation of such arrays.

Pine is working with applied physicists and neurophysiologists at Caltech to further develop the microcircuit culture dish. In it he will grow single-layer cultures of neurons from the brain, peripheral nervous system, and junctions between nerves and muscles. Such tissue cultures tend to form themselves spontaneously into small networks, which scientists believe should exhibit some of the same basic principles as networks in living creatures.

Solar Astronomy Microwave Receiver
In solar astronomy, Caltech scientists have developed a unique microwave receiver with an information-gathering capacity 86 times greater than anything available in the past.

Gordon Hurford, a member of the professional staff in solar astronomy, and his research team designed and built two radio receivers that are part of a "frequency agile interferometer." The receivers are mounted on two twin 90-foot radio telescopes at Caltech's Owens Valley Radio Observatory. There they gather information, in highly precise unison, in the frequency field between 1 and 18 gigahertz. (Precise unison, in this instance, is equivalent to having two radio dials a million miles long that can be tuned in 1/20 of a second to within a hair's breadth.)

The receivers can detect radio waves from the sun at up to 20 different frequencies a second, as well as measure their polarization (or the right- or left-handed "twist" of the plane of the radio waves) and pinpoint the position of the source of the radio waves with an accuracy of about 1/2,000 of the solar diameter. Previously, to obtain such data, observers would have had to operate a host of separate antennas tuned to many different frequencies.

How Oceans Mix

In the stormy Drake Passage between South America and Antarctica, the waters of the Atlantic and Pacific oceans are sucked into the great Antarctic Circumpolar Current, a clockwise swirl of water that moves around the continent of Antarctica. In the past, scientists had no quantitative way of determining what happens when these bodies of water merge.

But two Caltech scientists, Donald J. Piepgras, a graduate student, and Gerald J. Wasserburg, the John D. MacArthur Professor of Geology and Geophysics, have developed a method of obtaining an isotopic signature that distinguishes Atlantic from Pacific ocean water.

In 1979, the scientists discovered that the waters of the Atlantic and Pacific are distinctly different in measures of the ratios of two isotopes of the element neodymium—those with atomic weights of 143 and 144. The key to the difference lies in the kinds of terrain through which the feedwaters of the oceans flow. Ancient continental terrains such as those of the Atlantic are characterized by lower abundances of neodymium-143 than are younger volcanic terrains, such as those surrounding the Pacific. Some 70 percent of world continental drainage flows into the Atlantic, and its waters extract material from older geological formations than do the waters of the Pacific. Thus, the ratio of neodymium-143 to neodymium-144 is lower in Atlantic than in Pacific waters. The scientists measured isotopic composition of the samples using a mass spectrometer.

Transitions

Administrative changes include a new Provost and three new division chairmen. John D. Roberts has returned to teaching and research, and Rochus E. Vogt replaces him as Vice President and Provost. Professor Vogt, who has been at the Institute for twenty years, was chairman of the Physics, Mathematics and Astronomy division, prior to which he had been Chief Scientist at JPL and Chairman of the Faculty. His replacement as division chairman is Professor of Physics Edward Stone. Peter J. Wyllie joined the Institute in July 1983 as the new chairman of the Division of Geological and Planetary Sciences, coming from the University of Chicago. Barclay Kamb, professor of geology and geophysics, will return to teaching and research. In the Division of the Humanities and Social Sciences, David M. Grether, professor of economics, stepped to the helm, succeeding Roger G. Noll, Institute Professor of Social Sciences.

Six faculty members were named to endowed professorships for distinguished service to the Institute: Eric H. Davidson, Norman Chandler Professor of Cell Biology; Norman Davidson, Norman Chandler Professor of Chemical Biology; Roger G. Noll, Institute Professor of Social Sciences; Hugh P. Taylor, Jr., Robert P. Sharp Professor of Geology; Rochus E. Vogt, R. Stanton Avery Distinguished Service Professor; and Gerald J. Wasserburg, John D. MacArthur Professor of Geology and Geophysics.

Two new Trustees were welcomed to our Board, William F. Kieschnick and Ralph Landau.

Four professors were appointed professor emeritus in 1982, stepping into this role with the respect and admiration of their colleagues: Robert P. Dilworth, professor of mathematics, emeritus; William A. Fowler, Institute Professor of Physics, emeritus; Norman H. Horowitz, professor of biology, emeritus; and R. D. Wayne, associate professor of German, emeritus.

In Memoriam

It was with deep sadness that the Caltech community received news of the death on August 21, 1982, of William H. Corcoran, the Institute Professor of Chemical Engineering. Dr. Corcoran, who earned his BS, MS, and PhD degrees at the Institute, had been associated with Caltech for 46 years. He served the Institute as executive officer for chemical engineering and as Vice President for Institute Relations. During his career he rose to the top in his profession and won many honors. He also won the deep respect and affection of those who knew him, including that of the many students whom he guided toward their own careers.

During 1982 we were grieved to lose two members of the Board of Trustees. Herbert L. Hahn, Pasadena's "dean of attorneys," joined the Board in 1955 and became a Life Trustee in 1970; he was a valued friend of the Institute. William M. Keck, who joined the Board in 1961, also gave Caltech many years of devoted service. Both of these gentlemen will be sorely missed.

Division of Biology

Leroy E. Hood, Chairman

Faculty retirements and impending completion of the Braun Laboratories in Memory of Carl F and Winifred H Braun have brought the biology division into an exciting period of new faculty recruitment. This year we welcome two new assistant professors: Barbara Wold and Ellen Rothenberg.

Wold is returning to our division, where she completed her Ph.D. work with Chandler Professor Eric Davidson in 1978. In the interim she was a postdoctoral fellow at Columbia University. Her research will use modern molecular biological techniques to gain an understanding of the function of cell-surface receptor proteins. Initially this approach will be focused on a well-known receptor, found on mammalian cells, called the low-density lipoprotein receptor.

Rothenberg, who received her Ph.D. in molecular biology at MIT, explored immunology at the Sloan-Kettering Cancer Center in New York and then at the Salk Institute in La Jolla. Interested in cellular immunology both for its own sake and as a model system for understanding developmental control mechanisms, she is currently studying the immune system of mice, examining the changes in gene expression that occur in T lymphocytes during their functional maturation, and the role of hormones and cell-cell contacts in regulating these changes.

Some highlights of current research in the division are described in the following paragraphs.

Exploiting the Gene Cloning Revolution

A desire to understand in molecular terms the factors that control the expression of genes and the events that occur during the development of an organism motivates the research efforts of a number of the biology faculty. The recently developed methods of gene cloning and of nucleotide sequence determination have made possible advances in this area at a pace that would have been inconceivable a few years ago. It is now possible to isolate a specific gene, to sequence it, and to study its expression during development. Ultimately, an important goal is to be able to introduce a gene, perhaps after manipulation *in vitro,* back into an organism and have it function in a normal manner. Such a goal is not only important to our understanding of living systems but could lead to correction of genetic defects.

Eric Davidson and his colleagues are studying the fertilized eggs and developing embryos of sea urchins as a model system. The organization of the genome of this organism, the expression of this genome during development, and the conservation of DNA sequence among sea urchin populations or among different species of sea urchins is under active study. Specific genes that are developmentally regulated, such as the multigene family of actin genes, have been selected and studied. This group has recently found that DNA sequences related to mitochondrial DNA are present in the genome of sea urchins, which is important for our understanding of the transposition of DNA sequences that have occurred during the evolution of organisms. The recently developed facilities for carrying developing embryos through to maturity will allow studies of gene expression after transforming eggs with cloned DNA.

Assistant Professor Elliot Meyerowitz and his group work with two model systems. One is the fruit fly, *Drosophila melanogaster;* the second is a green plant, *Arabidopsis thaliana.* The fly work centers around the expression of a specific chromosomal locus that is active in the third instar salivary gland. The activity of this locus is hormonally controlled, and Meyerowitz and his colleagues wish to determine how the RNAs transcribed from this locus are coordinately controlled. The green plant studies are aimed at understanding gene expression in plants, a subject that has received too little attention by molecular biologists to date.

Assistant Professor Barbara Wold is studying the expression of a mammalian, cell-surface, low-density lipoprotein receptor, which is important for cholesterol utilization. Abnormalities in this receptor lead to severe metabolic consequences and several human disease syndromes. This group, attempting to isolate the gene for this receptor and for other genes involved in cholesterol metabolism, also uses somatic cell genetics to study the molecular biology of the expression of this set of genes. An important goal is to transform cells defective in this receptor with the normal receptor gene in order to restore function.

Professor Giuseppe Attardi and his group are interested in the gene organization and control of expression in the human mitochondrion. This important organelle, which is responsible for production of energy in cells, contains its own genetic system (although its function is also highly dependent on the expression of nuclear genes). The mitochondrial genome has been shown to be extraordinarily compact, requiring a highly evolved mode of expression. Attardi has proposed that transfer RNAs are used as punctuation in polycistronic RNAs transcribed from the mitochondrial genome and that processing of these transfer RNAs by specific endonucleases is an intermediate step in the maturation of the RNA transcripts.

Associate Professor James Strauss and his group are interested in a family of animal viruses called alphaviruses, many of which are important human or veterinary pathogens. By comparing the nucleotide sequences of a number of these viruses, control sequences involved in virus replication have been identified, evolutionary relationships among the viruses deduced, and the replication strategy of this group of viruses clarified. These studies, in addition to their interest as a study of the molecular biology of a living system, may ultimately help in controlling virus infection and developing antiviral vaccines.

Bowles Professor Leroy Hood and his collaborators are interested in multigene families that encode and regulate various aspects of the vertebrate immune response, of which the antibody gene families and the families encoded by the major histocompatibility complex are leading examples. Using mice as a model system, the organization and differentiation of these systems during organismal development is under active study. Differentiation of antibody genes involves two kinds of DNA rearrangement. In the first type, different gene segments are juxtaposed to generate contiguous coding regions for antibody chains. In the second type, subsequent rearrangements occur whereby one region of the antibody gene is replaced by a second region in a programmed pattern of development. In addition, alternative patterns of RNA splicing are responsible for producing either membrane bound or secreted forms of antibodies.

In all of these studies, the ability to isolate a gene by cloning it, to determine the organization of that gene and, if desired, to establish the exact nucleotide sequence of the DNA, and the developing abilities to transform cells or organisms with cloned genes, has made rapid progress possible. There can be no doubt that not only scientific curiosity but also human health will be well served by these studies.

A Ubiquitous Regulatory Mechanism

Several years ago, the action of the hormone insulin on its target cells was shown to involve a compound called cyclic adenosine monophosphate, or cAMP. cAMP acts as an "intracellular hormone" to communicate information that an insulin molecule has landed on the cell membrane to enzymes within the cell. In subsequent years, many other cell processes have been found to be controlled by cAMP. In all of these cases, cAMP appears to act by turning on an enzyme called "cAMP-dependent protein kinase" that adds phosphate groups to cellular proteins, causing an alteration in their function. Many research groups in the biology division have now found that understanding this regulatory system is necessary in studying a variety of systems.

Professor Charles Brokaw's research group studies the movement of the tails, or flagella, that propel spermatozoa. In some species, the movements of spermatozoa are turned off while the spermatozoa are stored in the male, and this regulation involves cAMP. One of these species is the marine tunicate, Ciona. Brokaw's group has shown that this regulation controls the machinery within the Ciona sperm flagellum. Sperm taken directly from storage in the male, stripped of their covering membranes, and exposed to ATP, which is the normal fuel for their motility, show no motility unless they are also exposed to cAMP. However, if the spermatozoa are activated to start swimming before their membranes are removed, they then swim in the presence of ATP, without a requirement for cAMP. It is also possible to activate movements by exposing the demembranated sperm flagella to a commercial preparation of protein kinase. Brokaw's group is exploiting this possibility to identify the components that are regulated by phosphorylation, in order to better understand the roles of the particular molecular components of the flagellum that are required for motility. They have already found that the principal ATP-utilizing enzyme of the flagellum is one of the proteins that becomes phosphorylated in response to cAMP.

The research group of Associate Professor Elias Lazarides studies intermediate filament proteins that form a skeleton inside of cells. Some of these intermediate filament proteins interact with the contractile proteins, actin and myosin, to form the contractile apparatus of muscle cells. In the Lazarides laboratory, graduate student David Gard found evidence that these intermediate filament proteins are phosphorylated in response to cAMP at specific times in the development of muscle cells, implying that the cAMP regulatory system may in this case be playing an important role in controlling the development of the muscle cell structures.

Regulatory mechanisms involving cAMP have also been found in the nervous system, and are thought to be particularly important for understanding long-term alterations in the behavior of nerve cells, such as memory storage and learning. Professor Felix Strumwasser's research group studies the function of the nervous system in the marine slug, Aplysia. One interesting situation involves a group of neurons called the peptidergic bag cells. A few seconds of synaptic input causes these nerve cells to generate impulses for periods of about 30 minutes. The Strumwasser group has shown that this change in properties of the nerve cells is associated with an increase in the concentration of cAMP in the cells and the phosphorylation of specific proteins. Further analysis of this system is being carried out in collaboration with Professor Henry Lester and Senior Research Fellow Jeanne Nerbonne, who are developing new chemical tools for probing such systems. They have synthesized an analog of cAMP that becomes biologically active only after being exposed to light. This chemical can be added to the cells in the dark, and then a light pulse is used to cause formation of the active analog within the cell at a precisely defined time, so that the time course of the cell's electrical activity can be related to the internal cAMP concentration. The Lester group is also using this compound to study the regulation of the contraction of heart muscle cells. They have found that in response to cAMP formed by a light pulse, there is an increase in the current of calcium ions entering the cells. This suggests that the membrane channels that allow calcium ions to flow through the cell membrane are regulated by phosphorylation.

The cAMP regulatory system has been implicated in controlling learning in the fruit fly, Drosophila, by experimenters in Professor Seymor Benzer's group. Several years ago, a mutant called "dunce," having defective learning behavior, was identified. Graduate student Sandra Shotwell and Research Fellow Lawrence Kauvar have now obtained definitive evidence that the dunce mutant is a mutation in the structural gene for an enzyme called phosphodiesterase, which degrades cAMP after it is released within a cell. This system may also be involved in the plasticity of the mammalian brain. It is known that the visual system can be permanently disrupted by abnormal sensory experience, such as blocking vision through one eye for a brief period in a young animal. Previous studies by Senior Research Associate Takuji Kasamatsu, currently working in Associate Professor John Allman's group, has indicated that this visual plasticity is blocked by the drug 6-hydroxydopamine. His more recent experiments suggest that a cAMP analog restores visual plasticity to a brain previously treated with 6-hydroxydopamine. Thus, the prospect that the cAMP regulatory system plays a major role in a variety of long-term changes in advanced nervous systems, including our own, further encourages the detailed exploration of simpler systems such as Aplysia and Drosophila, where biochemical experimentation is easier.

Motion Perception

It is a commonplace observation that we attend more to moving objects than to stationary features of our visual world. Thus, a moving fly is generally more of a nuisance than one at rest. More impressive than the simple detection of motion, though, is our remarkable capacity for determining the trajectory of a moving object. For example, the rapid and accurate assessment of the flight of a ball is a crucial component of an athlete's ability to catch it or to strike a target. How does our brain carry out such complex calculations, especially when the eyes, head, and body may themselves be in rapid motion? Experiments on the primate visual system in two laboratories at Caltech have shed light on this problem.

The visual cortex of monkeys (and presumably also of humans) is divided into a large number of distinct areas—a dozen or more in some species—which contain separate representations of the visual field, and which are thought to carry out different aspects of visual function. One of these areas, the middle temporal area (MT for short) appears to be highly specialized for the analysis of motion. Allman's group

Associate Professor David Van Essen shows some results of his studies of nerve cells in the visual cortex with this segmented model of a frog's brain.

has studied area MT in a nocturnal New World monkey, the owl monkey. Graduate student John Maunsell, working in Associate Professor David Van Essen's group, has studied the same visual area in a diurnal Old World monkey, the macaque. Despite the rather different ecological niches occupied by the owl monkey and the macaque, there are remarkable similarities in the functional properties of nerve cells in MT of the two species.

Nerve cells in area MT respond well to moving objects in the visual field, with each cell being selective for several parameters of motion. Any given cell is responsive to stimulation of only a particular region of the visual field and only for motion in a particular direction, such as upward or to the left. Moreover, these cells care not only about the direction in which an object is moving, but also about how fast it is going. Within the overall population there are cells selective for all possible directions of movement and for a wide range of speeds. Yet another feature encoded by cells in MT is the distance of an object from the animal. Thus, some cells respond only to objects close to the eyes, others only to objects far away. It appears, therefore, that area MT is eminently well suited for analyzing the three-dimensional trajectories of objects moving in the visual field. This emphasis on motion is accentuated by the fact that cells in MT generally respond well to objects of any size, shape, or hue, and hence do not discriminate on the basis of form or color.

Area MT may also play a role in stabilizing our perception of the visual world during eye movements. As our eyes move about during normal vision, we perceive the world as stable despite the fact that images are moving rapidly across the retina. Allman's group has found that most cells in MT do not respond well to movements of large patterned backgrounds, even though the same cells respond well to a small moving object on a stationary background. Thus, these cells may provide a neural substrate for perceptual stability during eye or head movements. This example serves to illustrate the ways in which neurophysiological studies of the brain provide valuable insights concerning our own perceptions of the world around us.

Division of Chemistry and Chemical Engineering

Harry B. Gray, Chairman

Institute Professor William H. Corcoran died on August 21, 1982, while on vacation in Hawaii. These words by John Seinfeld, executive officer for chemical engineering and Louis E. Nohl Professor, were delivered at the Caltech memorial service. They include Professor Corcoran's own summary, written shortly before his death, of his career as a chemical engineer. We share with you this tribute to Bill Corcoran and to his scientific achievements.

To describe the accomplishments and contributions of Bill Corcoran to chemical engineering, engineering education, and to his friends and colleagues would require many, many pages. During his life, Bill attained virtually every honor and recognition available to an engineering educator, while, at the same time, truly touching the hearts and minds of all those with whom he came in contact. Perhaps no other individual had more influence on the course of engineering education in the United States over the last 20 years than he did. And throughout his long and distinguished career at Caltech, and through his continued leadership in the American Society for Engineering Education and the American Institute of Chemical Engineers, Bill Corcoran maintained a vigorous program of teaching and research. One of his proudest moments was when he received a teaching excellence award from the Associated Students of Caltech.

Two weeks before his death, Bill was asked to prepare a short essay for the AIChE entitled "My Career as a Chemical Engineer" for a series of articles to appear next year. I can think of no better summary of his career than what Bill himself wrote.

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The late Institute Professor William H. Corcoran, who received most of the honors and awards that can be won by an engineering educator, ranked his award for teaching excellence from the Associated Students of Caltech at the top of the list.

MY CAREER AS A CHEMICAL ENGINEER

William H. Corcoran

August 1982

My professional work began before World War II as an employee of Cutter Laboratories in Berkeley, California. Here my interest in pharmaceuticals and biomedical engineering was sharpened and never left me. In World War II, I was involved with a very excellent group of people at the California Institute of Technology. We were responsible for the work on processing of double-base propellant and interior ballistics of all rocket motors used by the Navy. One year of that program also concurrently dealt with ordnance work on the atomic bomb. The rocket program was very successful, and in my very biased opinion it contributed in a major way to the quality of our munitions program in World War II.

Subsequent to World War II, I went back to graduate school, courtesy of the National Research Council. I have never forgotten the fellowships they afforded me, and today I have an association with the National Research Council by way of its commission on engineering and technical systems. That is a pleasure and allows me to partially pay back the debt I owe them. After receiving my Ph.D. degree in 1948, I returned to Cutter Laboratories in Berkeley where for four years I was director of technical development. The work included process development on pharmaceuticals and biologicals, including fermentation studies on penicillin and deep-culture growth of useful organisms for manufacture of vaccines. In addition we did significant work on disposable medical equipment and mass parenteral solutions. My interest in biomedical and bioengineering was further intensified by that experience.

In 1952 I returned to the California Institute of Technology as an associate professor of chemical engineering and, except for a two-year period from 1957 to 1959, I have been associated with the California Institute of Technology ever since. In the period of 1957-1959 I was vice president and scientific director for Don Baxter Incorporated, a subsidiary of the American Hospital Supply Corporation. Here my biomedical work continued.

My work at Caltech in research has related to studies of nitric acid-nitrogen dioxide-water systems, pyrolysis of hydrocarbons, flow systems, including work on artificial heart valves, and desulfurization and supercritical extraction of coal.

Teaching has been a major interest during my professional career, and I have especially enjoyed the teaching of my senior design course entitled "Optimal Design of Chemical Systems." I have learned so much in the teaching of the course that I can hardly believe what has happened, and I do have some hopes that the students learned at the same time. In terms of breadth of opportunity for a professor I can't think of a course more designed for a professor's development.

In other professional activities I spent ten years as vice president for Institute relations at the California Institute of Technology while still maintaining my program of teaching and research. In 1978 I had the privilege of being president of AIChE. Currently, I have the pleasure of working with the accreditation board for engineering and technology and will be the president for a two-year term ending in 1984.

Along the way I have had the great fortune to act as a consultant for the American Hospital Supply Corporation and the Bechtel Corporation and as a director of Superior Farming, the KTI Corporation, and Phytogen, Incorporated, a genetic engineering firm. There has not been one dull second. If I had my life to relive, I would do exactly what I had done previously and probably would make the same mistakes. Hopefully not. It has been a great life with thanks to all the people with whom I have associated, but with special thanks to my wife Martha who understood from time zero the nature of the profession and has been a very interested observer and participant in my professional activities.

Continuing Research

Bill Corcoran left behind an active research program, which is being continued by his graduate students. His research interests were in applied chemical kinetics and biomedical engineering. In the former area he concentrated on coal processing and beneficiation, whereas in biomedical engineering his focus was on understanding the behavior of artificial heart valves and blood flow in general.

In the area of coal research, William S. Kalema is studying, over wide ranges of temperature and pressures, changes in the volume of coal and the mild oxidation of coal by nitrogen dioxide. Karl Chang is investigating the effectiveness of sulfur emission control by calcium exchange of coal prior to combustion. He is studying the kinetics and mechanism of calcium exchange of coal to maximize the effectiveness of calcium exchange while minimizing the loss in heating value of the coal. Murray Gray is investigating the effect of the composition of wood on its pyrolysis reactions. His objective is to manipulate the presence of water and minerals, which has a significant effect on the thermal reactions of wood, to better understand the formation of gas and chemicals from wood. Puvin Pichaichanarong is using supercritical extraction as a route to obtain liquid fuels from coal. He is conducting a series of experiments to relate extraction yields to the properties of the solvents used.

Bill's research interest in fluid dynamics involves the efforts of several students. Dan Hanle is investigating the flows of fluids in and near prosthetic heart valves. He seeks to understand the three-dimensional nature of the turbulent flow shear fields generated by these valves in order to correlate observed failures of implanted valves. David Suobank is investigating the sounds produced by artificial heart valves to gain knowledge of the relationships between the sound and either the physical properties of the valve or the flow of blood in and around the valve. His objective is to advance the use of noninvasive phonocardiography. Samir Barudi's research is on the mass and momentum transfer in a model of an artery bifurcation. His objective is to understand why areas of artery bifurcations are more susceptible to the formation of atherosclerotic plaques. Phil Hookham is investigating the flow behavior of suspensions, particularly simulated blood, in a rectangular channel. He is working with models in an effort to understand the phenomena associated with flows through channels.

It is fitting that Bill Corcoran's vigorous and varied research interests continue being studied by graduate students who were the recipients of his wise guidance. The faculty members who have now become their advisers will carry on a distinguished tradition.

Division of Engineering and Applied Science

Roy W. Gould, Chairman

Dedication of the newly completed Thomas J. Watson, Sr., Laboratories of Applied Physics took place on May 5, 1982. The 40,000-square-foot building will provide expanded facilities for the division's programs in integrated optics, optoelectronics, semiconductor materials, semiconductor devices, and plasma physics. We are deeply grateful to the Watson family for making possible this handsome addition to our research and teaching facilities.

Basic studies that help maintain America's competitive edge in high technology will be supported by a new grant from the Rockwell International Corporation Charitable Trust, totaling $500,000 over five years. Studies of the structure of turbulence in fluids and how it affects flow and transport of material will be undertaken by Professor Anatol Roshko and Associate Professor Paul Dimotakis. Turbulence affects aircraft control, combustion efficiency, and the design of after-burners and of high-power chemical lasers. Studies leading to new optoelectronic devices and their integration with high speed transistors to form new devices for optical communications systems will be carried out by Myers Professor Amnon Yariv and his colleagues as part of this new grant. We are vigorously seeking other ways to work with industry in meeting the technological challenge facing the United States.

We have instituted a new program to familiarize our undergraduate students with the tools for computer-aided design, guided by Professor Fred Culick and Associate Professors David Welch and Paul Dimotakis. The aim of this program is to make available "hands on" experience with interactive graphics systems used as design aids. About 50 undergraduates received three to five hours of dual "hands on" experience with the COMPUTERVISION system as part of our introductory design course. Sixty students in the basic graphics course received demonstrations of the system and of our computer-controlled milling machine. Next year we plan to expand our offerings into other areas employing the Structural Dynamics Research Corporation software using two new VAX computers.

Student interest in engineering and applied science continued strong with a slight increase in enrollment over the previous year. About two-thirds of the undergraduate students in the division are studying electrical engineering, computer science, or applied physics.

Since it is impossible to do justice to the many, varied accomplishments in the division during the past year, only a few highlights will be presented. A more complete account of the division's activities is to be found in the division's annual report, which is available on request.

Fluid Mechanics of Volcano Eruptions

The processes in volcanoes by which, upon violent eruption, magma transforms to a particulate-laden gas are poorly understood and are not amenable to direct observation. Professor Bradford Sturtevant and Visiting Professor Susan Kieffer of the Division of Geological and Planetary Sciences, together with undergraduate student Matt Swass, have carried out a series of preliminary experiments to study analogues of explosive magmatic eruptions in the laboratory at greatly reduced scale, in simplified geometries, and with simple model materials. Fluids are used in which the highly compressed and superheated state of volcanic magmas can be simulated at greatly reduced pressures and temperatures. Cryogens such as Freons are convenient liquids. Near room temperature they are superheated above their boiling points, as are water and other low-vapor-pressure constituents of magma, at conditions that are thought to be representative of the source region of the Mt. St. Helens blast.

Emphasis is placed on the jet and blast fields emanating from explosive eruptions in which the directed kinetic energy of the fluid is large and on determining the internal reservoir conditions that produce the flow fields of interest. The development of the flow field is recorded by high-speed shadow and Schlieren photography. Interesting features that have been observed include disturbance wave fields that are pushed out into the ambient atmosphere by the expanding jet, diamond shock patterns in the jet that are indicative of supersonic flow, indications that explosively depressurized liquids form jets containing a finely dispersed aerosol, and extremely strong flaring and pluming of the jet at its base.

Model Testing of Large Engineering Structures

In geotechnical practice involving soils or rock, the dimensions of structures in the field are so large as to preclude full-scale tests to realistic load levels produced by the forces of nature. Many examples of this kind exist in civil engineering, including offshore oil production platforms, large buildings, nuclear power plant structures, earth dams, and large liquefied natural gas tanks. In each case the performance and safety of the structure depends upon its interaction with the foundation soil.

A way of circumventing the testing difficulty lies in the use of a centrifuge to test a scale model and its foundation soil. Forces must be proportionally higher, 100 times gravity for a 1/100 scale model, in order to predict the correct prototype behavior. The advantages of such an experimental arrangement are, of course, the correct scaling that ensues, the cheapness of model construction, and the accessibility of the system for instrumentation. Large enough loads can even be applied to the model at the end of a test sequence to destroy it. Disadvantages are mainly related to the difficulty of conducting tests at very high g-levels, and to the problems of instrumenting small models.

Caltech has one of the few geotechnical centrifuges in the United States, operated by Professor Ronald F. Scott and his students since 1975. It can subject an approximately 100-pound payload at a radius of about one meter to accelerations up to 175g. In the past few years it has been used for investigations of pile (both normal and large) behavior under static and dynamic conditions, anchor pull-out forces, soil faulting mechanisms, and retaining wall deflections during simulated earthquakes and other studies. These tests have led to improvements in our understanding of structure-soil interactions. One investigation indicated a progressive degradation of certain soils under cyclic axial pile loading, important to an offshore site. A second showed that current methods of designing retaining walls for earthquake motions are not conservative below peak accelerations of 0.2 to 0.25 g and are too conservative above that level. A third led to a change in the method of analysis for calculating anchor pull-out forces in connection with some designs of offshore oil platforms.

Particle Formation from Gases

Vapor condensation and gas phase chemical reactions contribute to particle formation and growth in the atmosphere, combustion systems, and industrial processes. Particle concentration, size, and chemical composition are all influenced by the formation and growth mechanisms, and all determine the aerosol's environmental consequences, ease of separation from the gas, and tendency to foul or erode heat exchangers and other devices.

The common theme of Associate Professor Richard Flagan's research is understanding the factors that govern the formation and evolution of aerosols produced from gases. Very small (submicron) ash particles are formed in pulverized-coal combustion when volatilized ash condenses homogeneously. Rapid cooling of combustion gases produces such high levels of supersaturation that at least some of the vapors nucleate even though existing particles present a large surface area on which the vapors could condense. The size distribution of the ash fume is well described by assuming that the ash nuclei are generated early in the combustion process and grow primarily by coagulation.

The factors governing ash volatilization are not well understood because the chemistry of coal ash is complex and highly variable. In order to understand the mechanisms of vaporization of various ash constituents, Flagan and graduate student Connie Senior have developed a synthetic char with controlled porosity to which well characterized inorganic materials can be added. The influence of the char structure and ash chemistry on ash vaporization is being studied by burning this char under well controlled conditions in a laminar flow reactor. An understanding of the fundamental processes controlling ash volatilization will be useful in developing models describing submicron ash particle formation and in designing combustion modifications to control fine particle formation.

Application to Industrial Processes

Studies of particle formation and growth in combustion systems and in the atmosphere have added greatly to our understanding of the competition between aerosol growth and new particle formation. Flagan, working with graduate student M. K. Alam, is applying this knowledge to the development of aerosol reactors for production of high purity silicon and other industrial materials. Because of the large surface area presented by an aerosol, gas deposition rates in aerosol reactors can be many orders of magnitude larger than is possible for chemical vapor deposition on macroscopic substrates.

Uncontrolled production of low vapor pressure species such as silicon by gas phase reactions, e.g., silane pyrolysis, leads to the formation of very large numbers of small particles that are difficult to collect and are readily contaminated. By first generating seed particles by homogeneous nucleation, diluting the seed aerosol with additional reactant, and then controlling the rate of reaction, Flagan has succeeded in preventing new particle formation while growing the seed aerosol. Particles larger than 10 microns, to be separated from the gas by sedimentation, have been generated in preliminary experiments. The gaseous reactant (silane) is essentially completely converted to a readily collectable aerosol product (silicon) in a flow reactor with a residence time much less than one minute, substantially reducing the energy losses and reactor size for polycrystalline silicon production.

Air Pollution Control

Light scattering and absorption by fine particles suspended in the atmosphere are responsible for severe visibility problems in cities around the world. The ability to control fine aerosol concentrations also governs whether or not the spectacular visual range present in national parks in the southwestern United States will be retained. Some of the most difficult visibility problems to control arise when the particle loadings responsible are formed in the atmosphere from the products of gaseous photochemical reactions. In those cases, it is not at all obvious which emission sources should be controlled in order to reduce aerosol production.

During the past year, doctoral student Armistead Russell, working with senior research engineer Gregory J. McRae and Assistant Professor Glen Cass, has developed a computer-based model that describes the formation and transport of ammonium nitrate aerosol, a key component of the visibility problem observed in many locations, including Riverside, California. Emissions of reactive hydrocarbons and oxides of nitrogen from motor vehicles and industry are tracked as they react chemically in the atmosphere to eventually form nitric acid. Nitric acid then reacts with ambient ammonia to form nitrate-containing particles out of gas phase precursors. This modeling procedure is now being used to study the effect of emission control strategies that could be used to engineer a deliberate reduction in urban ammonium nitrate and nitric acid concentrations.

Metallic Glasses

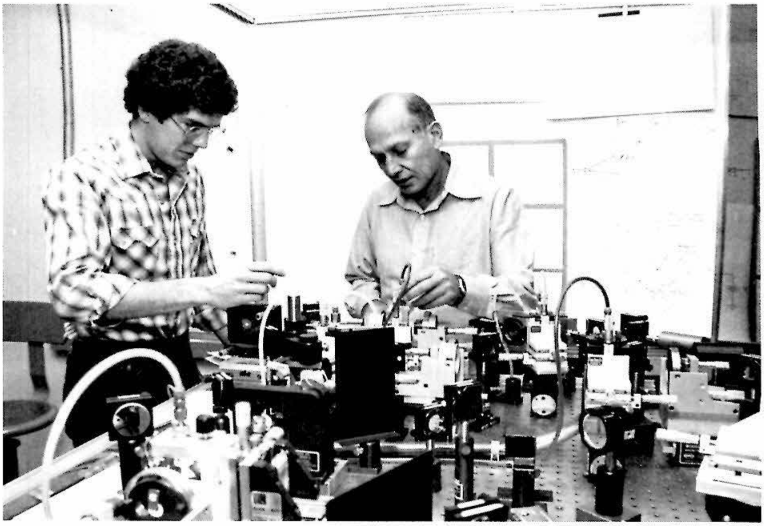
The formation of non-crystalline atomic arrangements ("glasses") is common among non-metallic solids. On the other hand, metallic solids form such phases only when extreme conditions exist during synthesis. For instance, very rapid cooling of some liquid alloys is known to result in metallic glass formation. Recent research carried out by the group of Associate Professor William L. Johnson has revealed that metallic glasses may also form under rather unexpected conditions. They have found that solid state reactions between two crystalline metals or between crystalline compounds and gases can result in the formation of metallic glasses. This novel synthesis route provides a means of synthesizing bulk quantities of metallic glass by reaction of metal powders and promises to bring these materials closer to technological applications. The reactions themselves are of considerable scientific interest and involve such phenomena as the fast anomalous diffusion of one metallic atom through another metallic material. A number of unusual experimental techniques have been developed and are being applied to understand these phenomena. The methods, which include a novel in-lab spectrometer for the study of x-ray absorption fine structure, permit the study of the location and atomic environment of the fast diffusing atom. Such information cannot be obtained by more conventional methods and is essential to understanding the novel reactions by which these glasses form.

Stable Solar Cell Contacts

Reliable metallic contacts to solar cells are of interest to the photovoltaic industry. Advanced processing steps subject completed silicon solar cells to temperatures as high as 600° C, a treatment that conventional metallizations do not withstand. Prolonged operation at modest temperatures with concentrators also shortens the useful life of cells. Interdiffusion and metallurgical reactions take place at the metal-semiconductor interface and degrade the cell's efficiency. To alleviate these problems, researchers in Professor Marc-Aurele Nicolet's group have applied the concept of a diffusion barrier to solar cell metallization schemes. By interposing a thin layer of titanium nitride between the silicon and the titanium-silver contact, the undesirable interaction can be suppressed while retaining the desirable electrical and mechanical properties. The ability of titanium nitride films to perform as diffusion barriers at high temperatures has been demonstrated. Electrical measurements on silicon solar cells show no degradation after annealing at 600° C for ten minutes.

Elimination of Optical Distortion with Phase Conjugate Optics

The principles of optical phase conjugation, a branch of nonlinear optics that had its origin at Caltech, were applied by Weizmann Research Fellow Baruch Fischer, graduate students Mark Cronin-Golomb and Jeff White, and Professor Amnon Yariv to the problem of imaging in the presence of severe distortion. In their experiment, one laser beam (A) passed first through a transparency to be imaged. A second laser beam (B)



Professor Amnon Yariv (right) and graduate student Joel Paslaski conduct research in optoelectronics, the integration of semiconductors and lasers for high-speed communication over optical fibers.

passed in the opposite direction through the distortion (a totally opaque piece of ground glass). These two beams and a third reference beam (C), which carries no information but is fundamental to the atomic process, are made to intersect inside a nonlinear optical crystal, barium titanate. The crystal mixes the three waves, giving rise to a new fourth wave, which contains both the pictorial information present in wave A and the distortion present in wave B. Because of the phase conjugation inherent in the nonlinear process, the distortion present in this new wave is reversed, and when it proceeds through the distortion and emerges, the distortion is canceled and the picture that it conveys is perfectly restored. This is just one demonstration of the many image processing applications of phase conjugation.

Scientific Computing on a New Scale

As powerful and pervasive as computers have become, they are far from equal to many computationally demanding problems in science and engineering. One way to achieve major advances in computer performance with VLSI technology is to use an ensemble of many computing elements that operate concurrently. This class of "ensemble architectures" has been investigated over the past several years by Charles Seitz, associate professor of computer science, working with graduate students Bart Locanthi, Dick Lang, Erik

DeBenedictis, Chris Lutz, Doug Whiting, Bill Athas, and Charles Ng. The characteristics of ensemble architectures that make them such an excellent fit to VLSI technology are that replication is exploited extensively, and that small computing elements allow researchers to take full advantage of future advances in microcircuit technology.

Prototypes of two ensemble machines are being constructed, one using commercially available integrated circuits, the other using VLSI chips designed at Caltech. The first is a 64-processor "homogeneous machine" that will achieve about one quarter the performance of a Cray-1 supercomputer, but at a cost 100 times less. This machine is an ensemble of microprocessor-based nodes that communicate with each other by message passing on a set of communication links structured as a 6-dimensional hypercube. A 4-processor prototype homogeneous machine is running concurrent programs written by researchers in computer science and by Professor of Theoretical Physics Geoffrey Fox and graduate students Eugene Brooks and Steve Otto. Efficient concurrent algorithms for matrix and signal processing computations have been devised by Lennart Johnsson, senior research associate in computer science.

These ensemble machines can be scaled to very large numbers of elements with an almost linear increase in performance, provided that the computational task can be suitably decomposed into smaller parts. Fortunately, such decompositions are virtually a characteristic of large and demanding computations. The prospect of using concurrent computers and algorithms to attack fundamental but computationally extremely challenging problems in physics, chemistry, geophysics, applied mathematics, computer-aided design, and many other disciplines has led to the formation of a scientific computation group. Plans and funding for a novel interdisciplinary effort in scientific computing, including construction of machines of 1000-processor scale, are well under way.

Testing of MOS Digital with Models

Most of the integrated circuit chips used in today's microprocessors, video games, and automobiles are designed in metal oxide semiconductor (MOS) technology. Recent chips designed by computer science researchers at Caltech and other universities contain up to 40,000 transistors, while commercial chips contain as many as 450,000 transistors. In designing such large and complex systems, it becomes difficult to avoid errors, and hence computers are used to verify the correctness of a design before it is ever fabricated. Logic simulation allows one such form of verification. A logic simulator is a computer program that provides a simplified model of the behavior of a chip based on a specification of its structure. The designer then simulates the operation of the chip for many input patterns to verify that the chip will function correctly.

Assistant Professor Randal Bryant has developed an abstract model for MOS digital systems in which each transistor is represented by a switch, and voltages are represented by logic levels 0, 1, and X (for indeterminate). This model can capture the wide variety of circuit designs used in MOS digital systems while retaining the simplicity and high level of abstraction required for efficient logic simulation. Bryant, along with Visiting Associate Mike Schuster and graduate student Doug Whiting, has recently implemented the logic simulator MOSSIM II based on this switch-level model. It has been used to verify a number of chip designs at Caltech, as well as at other universities and companies. The program runs fast enough to permit, for example, thousands of instructions to be executed by a microprocessor design in simulation before the chip ever exists.

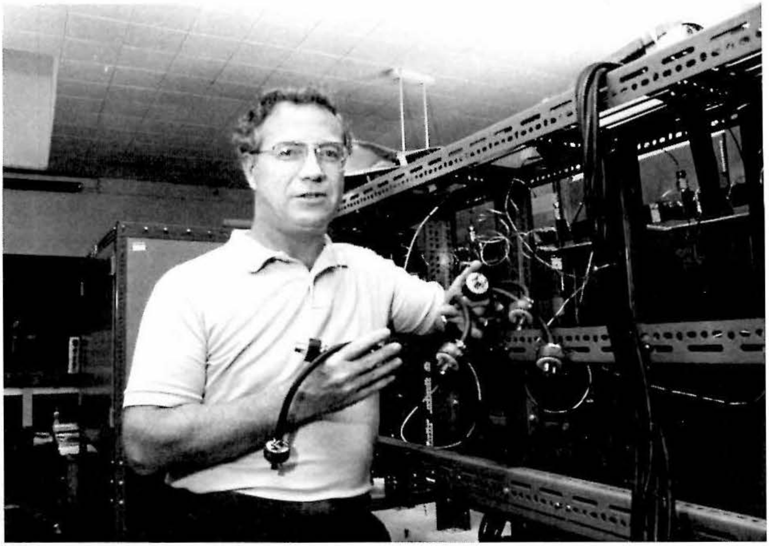
Division of Geological and Planetary Sciences

Barclay Kamb, Chairman

After a stimulating ten years as division chairman, I felt it was a good time to pass this responsibility on, and in September 1982, President Goldberger announced that a new chairman had been chosen: Dr. Peter J. Wyllie, of the University of Chicago, taking up the position in July 1983.

Dr. Wyllie is an internationally known experimental petrologist, and he will bring to the division outstanding additional strength in a field which the division entered strongly four years ago with the appointment of Professor Edward M. Stolper. Combined with the strength in analytical and field petrology and mineralogy (Professors Arden Albee, George Rossman, Leon Silver, and Hugh Taylor), the division will have one of the leading teams nationally and internationally in the petrology of crystalline rocks.

Dr. Wyllie earned two B.Sc.s, one in physics and geology and one in geology, and a Ph.D. in geology (1958) from the University of St. Andrews in Scotland. He did field work in Greenland and was glaciologist with the British West Greenland Expedition and geologist with the British North Greenland Expedition, in consequence of which, in 1954, he was awarded the Polar Medal by H. M. Queen Elizabeth. He came to the United States in 1956, to the Pennsylvania State University, where he was assistant professor of geochemistry and after two years at the University of Leeds in England, associate professor of petrology. He joined the University of Chicago in 1965 as professor of petrology and geochemistry, and in 1978 was named the Homer J. Livingston Professor. A year later he became chairman of the department of geophysical sciences.



Peter J. Wyllie waits to plug in his research equipment at Caltech where he has been appointed division chairman.

The new chairman has served as president of the Mineralogical Society of America, vice president of the International Mineralogical Association, and chairman of the Earth Science Division Advisory Committee of the National Science Foundation. He holds the Mineralogical Society of America Award and the Quantrell Award, received in 1979 for excellence in undergraduate teaching. In 1981 he was elected a Foreign Associate of the National Academy of Sciences, and in 1982 received the Wollaston Medal, the highest honor of the Geological Society of London, the oldest geological society. He is editor of the Journal of Geology, editor-in-chief of the Springer-Verlag monograph series"Minerals and Rocks," and editor of Wiley and Sons' series in intermediate geology.

Dr. Wyllie's special research interest is in the role of volatile components (particularly H_2O and CO_2) in the function of igneous and metamorphic rocks and in the melting relations of silicates at high temperatures and pressures. This interest dovetails nicely with the work of Stolper, who has recently developed a new experimental and theoretical approach to measuring the solubility of water in igneous magmas at high pressure and interpreting the solubility in terms of the speciation of the dissolved water as molecular H_2O and hydroxyl ion. Dr. Wyllie is currently investigating the difficult problem of the nature of volatile components in the earth's mantle and their relation to the origin of carbonatites and kimberlites, rocks believed to be derived from the mantle, and sometimes hosting diamonds. He is author or co-author of approximately two hundred scientific papers and three books.

Division of the Humanities and Social Sciences

David Grether, Chairman

Surveying the activities and accomplishments of the faculty and students of this division over the last year, two features are clearly foremost: diversity of activity and the exceptional quality of the programs being followed. The disciplines covered in the division include literature, economics, history, fine arts, philosophy, political science, law, and anthropology. Activities range from the more traditional academic pursuits to publishing a literary magazine and operating an art gallery. In all fields, summaries of accomplishments tend to sound like advertising—a virtually unending list of awards, grants, prizes, and publications.

History

Fellowships and grants played a major role this year in the work of Caltech's historians. Professor of History Daniel J. Kevles held a National Endowment for the Humanities Senior Fellowship for 1981-82, which permitted him to work as a fellow of the Charles Warren Center at Harvard. Kevles is preparing a book, *Genetics and Society,* on eugenics, human genetics, and related subjects in the United States and the United Kingdom from the 1890s to the present. He is continuing his work this year with the assistance of a Guggenheim Fellowship and a Sloan Foundation Officer Grant.

Professor of History Robert A. Rosenstone also held an NEH Senior Fellowship to support his work on Americans in Japan in the Meiji era. He spent most of the year at the East-West Center in Honolulu, with a two-month research trip to Japan in the spring. The appearance of the movie *Reds,* for which Rosenstone acted as historical consultant, created renewed interest in his book, *Romantic Revolutionary: A Biography of John Reed,* which was published in London and in translation in Paris in 1982. Rosenstone's critique of the film, "Reds as History," appeared in English, Italian, French, and Spanish.

History's third NEH Senior Fellow was Professor of History Eleanor M. Searle, who spent part of the year as a visiting fellow at Clare Hall, Cambridge University, working on a study that shows the importance of women in the transmission of property and power in medieval England and Normandy. During her stay in England, Searle was elected a fellow of the Royal Historical Society.

Professor of History and Social Science J. Morgan Kousser was a visiting professor at Harvard University in the fall of 1981. His study, "Separate But Equal: A Social History of School Racial Discrimination Law in the Nineteenth Century," is supported by a two-year grant from the NEH. A three-year grant from the NEH supports the preparation of a computerized edition of the charters of the Courts of Champagne in the second half of the 12th century by John F. Benton, professor of history and executive officer for the humanities.

Assistant Professor of History Nicholas B. Dirks spent most of the year in India working on the history and ethnography of the "little kingdom" of Pudukkottai with the aid of a Senior Research Fellowship from the American Institute of Indian Studies. In the summer of 1982 Assistant Professor of History Philip T. Hoffman was in France with an American Council of Learned Societies grant to work on urban investment in agriculture in early modern Europe, while James Lee, instructor in history, was a visiting scholar at Beijing University and two provincial universities in the People's Republic of China.

Literature

The academic year 1981-82 was also distinguished by the number of books the literature faculty either submitted for publication or had accepted. Professor of Literature Kent Clark's much anticipated biography of Goodwin Wharton was accepted by Oxford University Press and will appear soon. The same is true of Faculty Associate in Literature David Sundelson's *Shakespeare's Restorations of the Father* (Rutgers University Press). Associate Professor of French Annette J. Smith's monumental study on Gobineau was accepted by Droz (Paris), and her translation—produced with Clayton Eshleman, lecturer in creative writing—of the poetry of Aimé Cesaire was accepted by the University of California Press. Our new faculty member, Associate Professor of Literature Ronald Bush, has had his book on T. S. Eliot accepted by Oxford University

Press, and Associate Professor of Literature George W. Pigman was commissioned by Yale University Press to do a book on Virgil for a new series dealing with the major classical authors. Finally, Jerome J. McGann, Dreyfuss Professor of the Humanities, had two books accepted by the University of Chicago Press, and two new books of verse are currently in production. Volume III of McGann's continuing edition of *The Complete Poetical Works of Lord Byron* was also published this year by Oxford. The most prolific author this year was Professor of Literature Oscar Mandel, who published four books.

The faculty also published or had accepted for publication in 1981-82 a number of major scholarly articles—one each by Professor of Philosophy W. T. Jones, Associate Professor of Psychology and the Humanities Louis Breger, Associate Professor of Literature Jenijoy La Belle, Pigman, Smith, and Sundelson; and two by Paul Mann, Mellon Postdoctoral Instructor; three by Bush; and eight by McGann. Special notice has to be taken, however, of the continuing work in translation by Eshleman and Smith. Both have been active in promoting the work of Cesaire by publishing, in various journals, translations of his poetry.

Also worthy of mention is the literary magazine *Sulfur,* edited by Clayton Eshleman. Begun only recently, the magazine appears three times each year, and it is already recognized as an important publication of contemporary letters.

One of the year's most important international conferences in literature was held by Caltech in the spring of 1982, the Caltech/Weingart conference on textual criticism. Arranged under the direction of Jerome McGann, the conference was attended by a distinguished group of European and American scholars. The papers delivered are being collected for publication in a book.

Literary scholars representing various fields of textual and interpretive studies gathered to address the subject of "Textual Studies and Their Meaning for Literary Criticism."

Textual scholars analyze the transmission of literary material—including hand-copied manuscripts of the Middle Ages, as well as those of the early printing cultures and the present mass printing culture. Interpretive scholars explore meaning and content. The integration of these two disciplines developed during the 19th century began to break down in the early 1920s, and during the past 50 years the split has widened to a schism between textual and interpretive work.

To address this problem, a number of scholars—trained textual and interpretive experts—were invited to explain the relationship between the two areas and to provide new perspectives on how to unite them. The participants were carefully selected to represent a broad range of historical fields (from medieval to modern), on the one hand, and a diversity of approaches (from the most theoretical to the most practical), on the other. Increased specialization has made it all but impossible to arrange these sorts of exchanges,and the lack of them has only served to maintain and exacerbate the problem addressed by the conference.

The core group of conferees included 14 of the most distinguished English and American scholars, of varying ages, in their respective fields. In addition, a half dozen other eminent American scholars were invited to come as discussants. Several people from Caltech and the Huntington Library attended various sessions regularly, as well as a fairly large group of scholars from various area universities.

Everyone at the conference agreed that the idea of the meeting was important, and there was a surprising unanimity that it was successful as well—indeed, that the conference will probably be recognized as a watershed event in contemporary scholarly history.

Baxter Art Gallery

In its organization of special exhibitions of contemporary art during 1981-82, the Baxter Art Gallery conducted research into the work of a number of artists. These efforts resulted in the following exhibitions: "Jerry McMillan: Recent Work," "Peter Lodato: Dust," "Barry Fahr, Tom Jenkins, and Paul Re," "Doo Dah," "Berenice Abbott," "Siah Armajani," and "of no particular theme." Catalogues were published in connection with the McMillan, Lodato, Fahr/Jenkins/Re, Armajani, and "of no particular theme" exhibitions, with an essay in the McMillan catalogue by former gallery director Michael H. Smith.

Social Science

The social science program at the Institute was established more than a decade ago with the avowed goal of bringing work in economics, political science, and measurement to the problems facing society. At the level of basic theory, among the most relevant problems are those involving small group interactions and the modeling of political behavior. In economics, developments in game theory have provided an apparently fruitful approach to the small group problem. Associate Professor Kim C. Border has been working on the underlying mathematical basis of existence of equilibria in economics and game theory, and Assistant Professor Edward J. Green on special problems arising from attempts to model oligopolistic behavior, wherein each of a few producers affects but does not control the market. In political science, Professor Gerald H. Kramer has begun to explore an entire new class of political models (the so-called zero sum models) that make it possible to incorporate both the issue position and the constituent service components of a legislator's attributes. Professor Richard D. McKelvey has focused his attention on group decisionmaking. Earlier work had indicated that committee decisions could be influenced by agenda manipulation; however, McKelvey has shown that quite different results are obtained if the members of the committee are permitted to set or propose amendments to the agenda.

Basic theory, however, is seldom directly applicable to applied problems, and much of the most valuable work in social science lies in the modification and extension of results to models that can be used to examine those problems.

Professor of Economics James P. Quirk has made a substantial contribution to our understanding of research and development decisions of firms under different technological conditions and expectations. He has also shown that without government support the private sector will underinvest if an industry is faced by a cartel of low-cost producers; the American energy industry is a case in point. Finally, he is modeling the economics of "pioneer projects" in an attempt to explain the massive cost overruns that have characterized almost all large-scale pioneer innovations. An understanding of this problem is important not only for defense policy, but for the development of alternative energy sources (particularly nuclear and synthetic fuels) as well.

Professor of Economics Louis L. Wilde, too, has studied aspects of research and development, but his interest has centered on projects partly underwritten by the government. From the point of view of public policy, it is important that the contracts that govern the relationship between the government and the private sector firms be written in such a way that assures that the firms have an incentive to speed research and to reveal the total extent of their findings. Wilde's work has indicated that contracts which appear optimal in a static context may produce poor results in a dynamic situation, i.e., overtime.

Associate Professor of Economics Jennifer F. Reinganum's research is concerned with the relationship between private expenditures on R&D and industrial structure, an important problem for anyone interested in antitrust policy. Economists have generally assumed that firms in a quasi-monopolistic industry could use their insider's knowledge to speed the rate of technical progress and thus consolidate their monopolistic position. Most observers, on the other hand, have felt that new entrants to an industry have contributed a disproportionately large share of new products and processes.

Reinganum's work has indicated that under a wide variety of conditions, established firms in a monopolistic position may find it profitable to underinvest in research and development, thus leaving room for new entrants.

It is difficult to discuss policy without recognizing that the law has an important effect on all policy outcomes and, conversely, that policy may be directed at changing the legal constraints on the economic system. Alan Schwartz, professor of law and social science, and Wilde have examined the relationship between consumer decisions and the costs of acquiring information about the prices and characteristics of the products they choose to consume. The work has led to important findings about the optimal terms of contracts and warranties.

No theory, however well specified, can be successfully used in the design of policy instruments until it has been subjected to rigorous testing and examination. The faculty at the Institute is unique in that a substantial portion of their research efforts is devoted to providing an experimental basis of the theories that they employ. Professor Charles R. Plott, one of the first economists to recognize the value of experimentation, has continued his examination of the tools on which economists depend, and the results of his research call substantial parts of traditional economics into question. He has shown conclusively that even the most sacred of the economist's tools (the concepts of supply and demand, for example), do not always provide a completely adequate explanation for market behavior. Moreover, he has shown that the failures are systematically related to the market environment and the exact set of institutions employed. These findings are particularly important for policymakers charged with the design of those environments. Again, Plott has examined the "rational expectations" models recently employed by economists to explain monetary and fiscal policies. Despite the strong assumptions on which these models are based, Plott's work indicates that they appear to perform very well in a wide variety of laboratory situations.

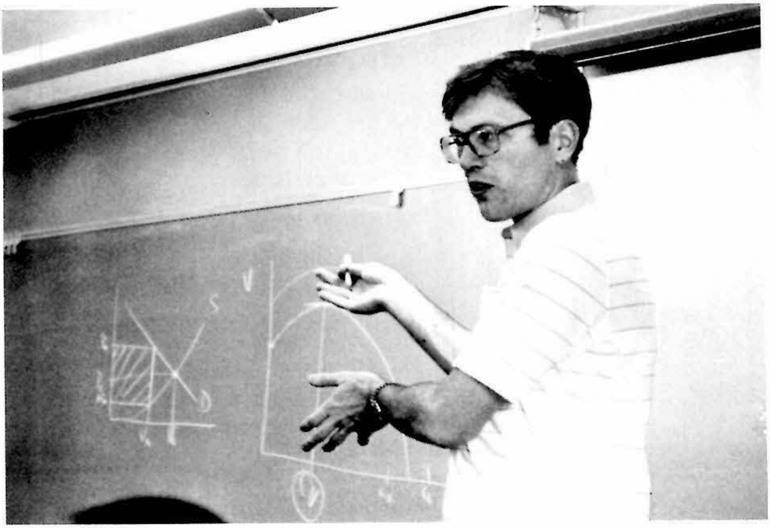
In political science, Professor McKelvey, too, has been testing the basic models of behavior. Most of the analytical models assume that voters have perfect information, but there are few observers who would argue that voters in fact have such information. McKelvey's work indicates that the models of party competition perform very well even though the "voters" have incomplete information (i.e., that all they possess is the type of information readily available in poll data or interest group endorsements).

It is, however, often either not possible or prohibitively expensive to design experiments to test certain theories. But they may be tested by looking at the past, though such evidence almost never bears directly on the questions at hand, and must be evaluated carefully.

Over the past year Associate Professor D. Roderick Kiewiet has completed a detailed study of the relationship between economic conditions and voting behavior, a subject that has also drawn the attention of Professor Kramer. Assistant Professor of Economics Jeffrey Dubin, concerned with the problem of the long-run supply of energy, has finished a study of the residential demand for electrical appliances. Questions of the behavior of firms were addressed in Assistant Professor of Economics Quang Vuong's study of backlogs, inventories, production, and price adjustments, and in Green's study of the usefulness of switching models in explaining oligopoly behavior among American railroads and the world coffee cartel.

When theories involve changes in social and economic variables over a long period of time, it is almost always necessary to turn to history to examine these propositions. Philip T. Hoffman, assistant professor of history, has just completed his large-scale study of the relationship between religious change and economic and political development; Professor of History and Social Science J. Morgan Kousser has produced some interesting insights into the relationships between politics, education, and racial discrimination in the United States; and Lance E. Davis, the Mary Stillman Harkness Professor of Social Science, has examined the relationship between business decisions and politics in the context of 19th-century Britain. All three of these studies, like Plott's experimental results, indicate that institutional structures have far more influence on policy outcomes than most social scientists had believed.

Basic theory, specification, experimentation, and empirical work by themselves do not produce policy, and the capstone of the process is policy analysis. The work within the division that has had the most impact in that area is Institute Professor of Social Sciences Roger G. Noll's studies of the feasibility of developing markets for licenses to pollute. The problem is policy relevant: In a region where pollution should be reduced but where the optimal levels are not zero, who should have the "right" to pollute? Noll's work (based on careful reformulation of economic theory and supported by experimentation) indicates that markets can be used to allocate those rights in an efficient manner. Moreover, it appears that the government is willing to move in the direction of such a market solution in the Los Angeles air basin. Of at least equal importance, Noll has begun an investigation of the causes of success or failure in government-supported projects, which range from agricultural extension centers to the space shuttle.



Institute Professor of Social Sciences Roger Noll teaches policy analysis—studying the success or failure of government or market policies in solving society's problems.

Professor Plott and David Grether, division chairman and professor of economics, have drawn on experimental economics to examine an antitrust case under active litigation. The results of their study of anticompetitive effects of market practices in oligopolistic industries were used by the Federal Trade Commission in its prosecution of the Ethyl case in particular, but has also changed the standards of evidence employed in such cases in general. The focus on the effects of "institutions" on market outcomes will certainly become increasingly important in antitrust enforcement.

Associate Professor of Political Science Bruce E. Cain has just completed his large-scale study of reapportionment in California, and his findings will almost certainly have an effect on future reapportionment decisions. Professor of Political Science Robert H. Bates has completed two major policy studies dealing with the connections between economics and political outcomes. One, *States and Markets in Tropical Africa,* has already begun to cause a revision in the agricultural policies of the less developed nations.

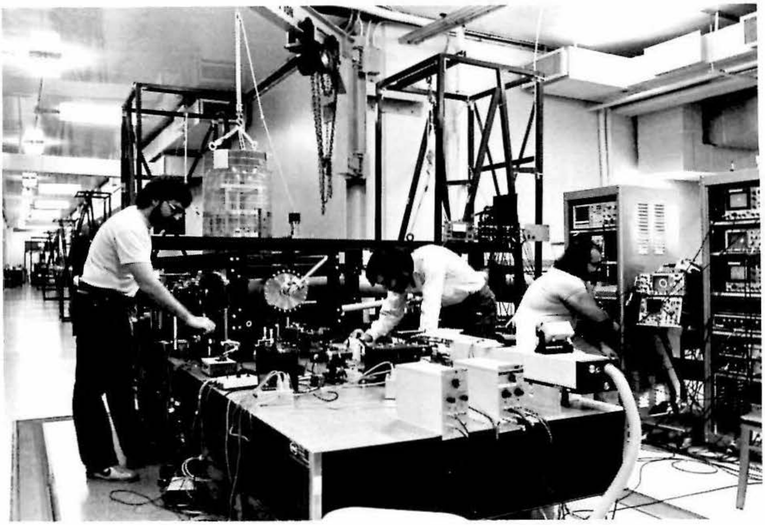
Finally, focused more broadly than either economics or political science, Professor of Anthropology Thayer Scudder has combined findings from both disciplines with the evidence yielded by his long-term study of the response of the Gwembe Tonga to the construction of the Kariba Dam to produce a work on the effects of large-scale development programs on the structure of society. The work will become a handbook for future politicians considering such large-scale projects.

Division of Physics, Mathematics and Astronomy

Rochus E. Vogt, Chairman

Thanks to the combination of a distinguished faculty, brilliant students, and an outstanding professional staff, the division has continued a vigorous program of teaching and research on the fundamental laws and constituents of the physical universe and the fundamental bases of mathematics. The programs in physics and astrophysics benefit from the existence of a powerful array of research facilities, many of them unique. For example, advances in solid state sensor technology continue to enhance the power of Caltech's astronomical observatories at Palomar, Owens Valley, and Big Bear. Among the new facilities under construction are a mm-wavelength radio interferometer at Owens Valley, a sub-mm radio telescope for a high mountain site in Hawaii, and a prototype gravity wave interferometer on campus. A number of dedicated computing facilities have come on-line, and a new electrostatic nuclear accelerator is about to begin operations. Unfortunately, the machines for research in elementary particle physics have become so complex and costly that they can only be supported on a national or international basis. Caltech faculty and students operate at the major U.S. and European particle accelerator centers, and their absence often makes it difficult for them to contribute to the campus educational program. Different opportunities and challenges face our high energy astrophysicists, whose instruments are carried on NASA spacecraft in Earth orbit and in the far reaches of the outer solar system.

The measurement of progress in basic research, although obvious to the researcher, is not always apparent to the outside observer. In this report we will present a sample of the



Research Fellow Robert Spero, Assistant Professor Stan Whitcomb, and Staff Scientist Yekta Gursel (from left to right) at the newly completed laser interferometer (40m x 40m) for the detection of the gravitational radiation from collapsing cores of supernovae, pulsars, black holes, and other exotic astrophysical sources.

division's research activities, in the hope that the reader will at least capture the flavor of the variety and vigor of these efforts, which are directed towards a better understanding of our physical world.

The Ultimate Constituents of Matter

A major focus in the division's research program is the study of the fundamental forces and constituents of matter. Elementary particle physicists now believe that quarks, leptons, and gauge bosons are the ultimate constituents of matter. They are endowed with some physical properties that have no analogues in the macroscopic world—among them the properties called "flavor" and "color." The six flavors include attributes known as "charm" and "beauty."

A Crystal Ball Looks at Charm and Beauty

Experimental study of bound states (called "charmonium") formed by "charmed" quarks and antiquarks continues to be a most fruitful line of investigation into the nature of the strong interaction (representing one of the four fundamental forces in nature). Well-suited to such study is the "Crystal Ball" apparatus, consisting principally of a spherical shell of sodium iodide crystals designed for the precise measurement of γ-rays produced in electron positron (e^+e^-) interactions. When a charmed-quark particle is made in an e^+e^- interaction, it often decays via the radiation of a γ-ray, hence the utility of γ-ray measurement. This experiment, a collaborative effort by groups from Caltech (Professor Charles Peck, Assistant Professor Frank Porter, and Research Fellow Peter Ratoff), Harvard, Princeton, and Stanford, has accumulated 3-1/2 years of data at the SPEAR e^+e^- colliding beam facility of the Stanford Linear Accelerator Center. By detecting these radiative γ-rays, the Crystal Ball physicists recently announced the discovery of a likely candidate (η_c') for one of the two remaining expected charmonium states which had eluded earlier detection. The picture that emerges for charmonium is thus remarkably complete, except for the final expected, but so far unobserved, particle ($^1P_1$), which is expected to be elusive because of its quantum numbers.

The same technique of looking for γ-rays in charmonium decays is a good way to look for particles that contain no quarks at all, but only the "gluons" that hold quarks together. Such particles (often called "glueballs") should exist if the quantum chromodynamics (QCD) theory for the strong interactions is correct. Indeed, the Crystal Ball experimenters have announced the existence of two candidates, the ι and the θ particles, which could be "glueballs." In this case, however, neither the theoretical nor the experimental pictures are complete, and, while these particles have generated a great deal of excitement and controversy, a definitive interpretation must await further results.

Even a crystal ball has a future, and the future of this one seems to be the study of quarks possessing the "beauty" attribute (also referred to as "bottom" quarks). The beautiful quark is about three times as massive as the charmed quark, and bound states with its anti-quark are predicted to exhibit a spectroscopy analogous to (but richer than) the charmonium spectroscopy. In the pursuit of beauty, the Crystal Ball detector was moved in the spring of 1982 to the DORIS e^+e^- storage ring in Hamburg, Germany. At the same time, several more institutions were added to the collaboration. The move was a story in itself: A ball made of sodium iodide crystals is very delicate (and hygroscopic!), so the experimenters had to carefully consider the pros and cons of different modes of shipment. They ultimately settled on flying the ball in a C-54 military transport as the least risky approach. The Air Force personnel were enthusiastic about the challenge, and did a superb job in flying the ball from California to Frankfurt, Germany, complete with in-flight refueling to minimize landing and take-off traumas. In fact, the only hitch came after the Air Force's job was done. On the road between Frankfurt and Hamburg, the engine in the rig hauling the ball blew up! Fortunately, the experiment survived this mishap, and is now starting to take "beautiful" data in Germany.

Protons: Are They Unstable?
Our understanding of elementary particle physics has brought us to the point of testing fundamental theories that encompass all known forces except gravity. This class of theories is referred to as grand unified theories or GUT's. An experiment conducted by Assistant Professor John LoSecco and colleagues from the University of California at Irvine, the University of Michigan, and Brookhaven National Laboratory is currently under way to measure the lifetime of the proton, a fundamental test of these models.

If the proton does decay, its lifetime will be very long. It is estimated to be in excess of 10^{30} years. To measure such large time scales by observing a single proton is, of course, impossible. Instead the experiment is studying a large number ($2x10^{33}$) of protons for a few years. The device consists of a set of radiation sensors which view a volume of highly purified water in a salt mine. The volume is very large (70′ cube) and very massive (10,000 tons). It is a detector the size of Millikan Library, with every nucleus under constant observation. The detector, observing the Cerenkov light emitted by relativistic charged particles, can recognize proton decays by the amount of light produced and by its spatial distribution. The detector has been in operation since July 1982 and the initial data are under study.

QCD Predicts: No Free Quarks
The dynamics of Quantum Chromodynamics (QCD) continues to be the subject of theoretical studies, in view of QCD's strong position as a serious contender for the fundamental theory of strong interactions. Professor Fredrik Zachariasen and colleagues James Ball (University of Utah) and Marshall Baker (University of Washington) have been able to show (subject to minimal assumptions) that the large distance behavior of this quantum field theory is entirely equivalent to a classical field theory, much like electrodynamics in an inhomogeneous anisotropic medium. (However, in QCD the attribute "color" takes over the role of the electric charge in ordinary electrodynamics.) The dielectric constant characterizing this medium produces anti-screening of chemical color charges, resulting in a force proportional to the square of the separation distance between two widely separated charges. This provides an understanding of color confinement explaining why isolated color charges, such as quarks, never occur in nature.

Superstring Theory Rears Its Head
A novel approach to unifying the description of elementary particle interactions, called "superstring theory," is being pursued by Senior Research Associate John H. Schwarz together with various collaborators. Unlike other "unified field

theories," this one promises to include gravitation in a way that is consistent with the requirements of quantum mechanics. One of its striking predictions is that space should have nine dimensions. This could be compatible with the fact that only three are observed if six of them are curled up into a sufficiently small ball or other topological structure. The theory is essentially unique with only one or two adjustable parameters and, if successful, could conceivably provide a complete description of all fundamental interactions. Much work remains, however, to understand the mathematical details and to extract specific predictions that can be compared with experiment.

A Universe Out of Balance

Elementary particle theorists often contemplate the Big Bang, the beginning of our universe, when matter was at extreme conditions of density and energy. Now, Professor Steven Frautschi has considered the apparent paradox raised by the entropy of the expanding universe. According to the Big Bang model, the early universe was in thermal and chemical equilibrium, yet the present universe is far from equilibrium. How did the second law of thermodynamics permit this to happen? Qualitatively the answer is believed to be that although matter may have been in local equilibrium in the early universe, long-range gravitational fields and the expansion of the universe were highly ordered and so were far from equilibrium. This large scale order has been partially transferred to matter, so that today relatively small scale structures such as our solar system are also far out of equilibrium. Frautschi has analyzed the development of cosmic entropy quantitatively and gone on to study the possibility that entropy might continue increasing without limit in the future. In this case, the universe avoids the heat death associated with a finite, limiting entropy, and examples of local organization (such as life) may persist indefinitely into the future.

Looking for an Arrow in Time in Nuclei and Particles

The macroscopic world around us has a definite arrow in time. There is a beginning and an end to everything, or, in scientific language, the world around us is not time reversal invariant. On the other hand, the laws of microscopic physics have not revealed experimentally such a manifest time asymmetry. (The noted exception is a small effect observed in the decay of the neutral K particle.) The smallness of the microscopic asymmetries makes them even more tantalizing—and most difficult to measure. Experiments are now being conducted by Professor Felix Boehm and his collaborators aimed at uncovering time asymmetries in the nuclear beta decay process. They are searching for a correlation between the transverse polarization of positrons, emitted from polarized nuclei, and the nuclear spin vector. In this experiment polarized nuclei are lined up with the help of a magnetic field at very low temperatures (0.02 Kelvin), using a He^3-He^4 dilution refrigerator. A scattering technique is used to uncover any asymmetry in the transverse polarization. The discovery of such an asymmetry, or even a sensitive upper limit to one, will be an important guideline for our understanding of the theory of elementary particles.

New Applications of Basic Disciplines

In some areas of physics it is believed that we possess the definitive "theory." An example is quantum electrodynamics (QED), which explains the properties of atoms. However, even in these areas much remains to be done to understand specific phenomena, which in turn can be useful tools for research in other areas.

Spectral Lines from Atoms

Laboratory measurements of the atomic parameters that astronomers use to interpret their observations have been carried out at Caltech since 1948 (continuing an even earlier program at Mt. Wilson Observatory) with particular emphasis on the transition probabilities needed for the quantitative analysis of atomic spectra. Either emission spectra or (more often) absorption spectra were used to study different elements, but not both together. Professor Ward Whaling has been investigating the advantages that can be realized by combining both kinds of spectrophotometry, absorption *and* emission.

Emission spectroscopy is well known to yield accurate transition probabilities but only for those transitions that come from a level of known radiative lifetime. Whaling finds that by combining the relative intensity of lines measured in the absorption spectrum with similar measurements of the same lines in the emission spectrum, he can determine (1) the radiative lifetime of new levels that have not been measured directly, and (2) the transition probability for the transitions by which the new levels decay. In this way he is able to measure transition probabilities for a much larger number of transitions (e.g., 314 transitions in a study of cobalt this year) than could be found by emission spectroscopy alone. Measuring each transition in two quite different ways has additional advantages: Lines that may be quite weak in emission are often much stronger in absorption and vice versa, and the most common experimental errors (blends, self-absorption, misidentification) are far less likely to slip by undetected.

Creating Better Bonds

There are many situations where it would be desirable to improve the adhesion between a thin film and an underlying material. Examples are in mirror coatings, metal contacts to semiconductor devices, and protective layers to reduce wear or corrosion. During the past year a technique has been developed by Professor Tom Tombrello and collaborators that produces a remarkable degree of adhesion in a variety of cases. For example, thin metal films have been firmly bonded to Teflon, ohmic contacts have been produced on a variety of semiconductors, and metallic coatings have been attached to other metals. The bonding is achieved by bombarding the film with high energy (MeV) heavy ion beams from the Caltech-ONR tandem accelerator. The wide applicability of the technique is still somewhat of a mystery and the mechanism seems to involve fast (10^{-15} sec) "chemistry" that may lead to new insights into the nature of adhesion.

Thermal Desorption in Vacuo

Production of high vacuum, which is essential for many purposes in science and industry, invariably involves heating the walls of the vacuum chamber in order to release gases trapped there by adsorption. The intrinsic time required for this process of thermal desorption is not only of great technological importance; it is also of fundamental scientific interest.

Professor David Goodstein and his colleagues in the Sloan Low Temperature Laboratory have for the first time devised a means of measuring the desorption time directly. The method involves metallic films evaporated onto sapphire surfaces, which can be heated or cooled in a few billionths of a second. A measurement is made of the length of time one of these films must remain hot in order for the desorption of gases from its surface to come to completion. The results that have emerged give not only a better understanding of the time needed to achieve a vacuum, but also of the fundamental processes of heat transfer at interfaces, and the kinetics of evaporation.

Astronomy

Astronomy, represented by its many subdisciplines ranging from the search for gravitons (the weakest energy quanta) to the exploration of the universe with radio and optical photons and to the capture of extra-solar system matter with cosmic ray detectors, continued to be one of the exciting intellectual endeavors in the division.

Quasars: Relics of the Early Universe

Professor Maarten Schmidt and former Research Fellow Richard F. Green have completed the Palomar Bright Quasar Survey, designed to find bright quasars in the northern sky. The survey was started by Green as a graduate student in 1972. He photographed much of the northern sky with the 18-inch Schmidt telescope through filters of different colors. Since almost all quasars are blue, he selected as quasar candidates all the blue stellar objects on the photographs, approximately 3000 in total. Schmidt and Green then observed the spectrum of each of these objects at the 200-inch and 60-inch telescopes. Many of them are galactic foreground stars, such as white dwarfs, and 0- and B-type subdwarfs. The number of quasars found is 114, of which 91 are newly discovered. Their redshifts range from 0.03 to 2.06, and their luminosities are up to 100 million million times that of our sun.

From a statistical study of the Bright Quasar Survey and other quasar surveys, Schmidt and Green have obtained new evidence on the distance scale of quasars and on their distribution throughout space. Even without using the large observed redshifts, they find that typical quasar distances are billions of light years, consistent with the cosmological interpretation of the redshifts, particularly for quasars of high luminosity. These quasars exhibit an increase in space density of a factor 100 for a distance increase of 3 billion light years. Apparently, high-luminosity quasars were much more numerous in the early universe, and have now essentially died out. The high-luminosity quasars observed by astronomers are relics of an early stage of the universe, still visible today thanks to the 10 or so billion years it takes light to reach us from very distant parts of the universe.

Galaxies Host Quasars—or Vice Versa

Professor Bev Oke and Research Fellow Tod Boroson made an exciting discovery in their study of the nebulosity around quasistellar objects. Although the existence of diffuse light around quasars has been known since the early days of quasar observations, its exact nature was unknown. Previous spectroscopic work had detected only emission lines, indicative of a corona of hot gas around some quasars. Observations made by Oke and Boroson with Palomar's new double spectrograph and CCD (charge coupled device) detectors showed conclusively that the fuzz around the luminous quasar 3C48 is a galaxy. They found spectral absorption lines that can only be produced by stars similar to those in ordinary galaxies. Rather than a giant elliptical galaxy, whose light would be dominated by old, cool stars, the galaxy in which 3C48 lives has recently (within the last billion years) undergone a global burst of star formation. This finding has important implications for the origin of quasars and the effects that they have on the material in their immediate vicinity.

In a related study, Oke and Boroson, in collaboration with Richard F. Green of Steward Observatory, studied the nebulosity around a sample of 12 low-luminosity quasars. As in the case of 3C48, it was found that most, if not all, of these quasars are embedded in galaxies.

Quasars Reveal Primordial Intergalactic Clouds

For several years Professor Wallace Sargent and his collaborators, the late Assistant Professor Peter Young and Alec Boksenberg of the Royal Greenwich Observatory, have studied the absorption lines found in the spectra of quasars. They have concluded that the absorption lines arise in three distinct ways that can be recognized from the detailed characteristics of the absorption spectra. First there are lines produced in gas which has been ejected at high speeds (up to 20 percent of the speed of light) from a small proportion of quasars. Other lines are produced by intervening galaxies—so remote that they cannot be detected in any other manner. Perhaps the most interesting are single Lyman-α lines of hydrogen—the commonest absorption features in the spectra of high redshift quasars—which are not accompanied by observable lines of any heavier element.

The single Lyman-α lines show no observable tendency to cluster in redshift, and by inference the absorbing objects have no tendency to cluster in space. Because of their clustering properties and because of the absence of heavier elements, Sargent and his associates have conjectured that the Lyman-α clouds are primordial intergalactic clouds—objects that would give a direct indication of how far element formation proceeded in the Big Bang.

During 1982 Sargent and Boksenberg made an intensive study of the spectrum of one particular quasar in order to set a quantitative limit on the proportion of elements heavier than hydrogen in the Lyman-α clouds. Their result is that the abundance of carbon in the clouds is at most 1/30 that in the sun and nearby stars. Further work is now aimed at determining the abundance of deuterium, which is thought to have been produced in the Big Bang in small proportions ($D/H \sim 10^{-5}$).

VLBI Probes Quasars

One of the most important problems in astrophysics is the nature of the central energy source in quasars and radio galaxies. Very Long Baseline Interferometry (VLBI) with radio telescopes now provides the only means of observing the structure of these nuclei on interesting physical scales. Over the last ten years there has been a steady push to higher frequency VLBI, and hence to higher resolution, as more sensitive high frequency receivers have been developed. In addition, over the last few years radio astronomers have developed new imaging techniques which enable them to make reliable maps even at high frequencies, where accurate calibration is very difficult because of variations in the transmission of the earth's atmosphere. An important breakthrough came in May 1982, when Professors Anthony Readhead and Alan Moffet and Senior Research Fellow Colin Masson detected interference fringes at 3.4 mm wavelength between telescopes at the Owens Valley Observatory (OVRO), Hat Creek (UCB), and Kitt Peak Observatory. Compact features were deduced to exist in the nuclei of the quasars 3C273 and 3C345 and the radio galaxy NGC 1275. The coherence time of the May observations was a few hundred seconds—a surprisingly good result at this high frequency. As a result of the long coherence time it is clear that problems with the earth's atmosphere are not as bad as had been feared and that millimeter VLBI will be possible on weaker sources and at wavelengths significantly shorter than 3 millimeters. These early results show that cosmic sources are considerably more compact at millimeter wavelengths than they are at centimeter wavelengths and that we are probing closer to the centers of activity than ever before. We hope to ultimately detect features such as accretion disks that are directly associated with the central engines. Such a discovery would be a major breakthrough in our understanding of these immensely powerful objects.

Molecular Lines from Orion

A program of submillimeter wave detector research, led by Professor Thomas Phillips and intended to provide Caltech's radio telescopes with the very best receivers, has recently proved most successful. An experimental and theoretical study of the properties of quasiparticle tunneling currents in superconducting photolithographic junctions has led to the development of a heterodyne detection scheme at wavelengths of 1.3 to 0.7 mm, which approaches to within about one order of magnitude of the quantum noise limit for such systems. This is the best performance ever achieved for such short wavelength radio-style receivers. Among the many astrophysical investigations now made possible by this new technique is a spectral scan of molecular line emissions from the Orion Nebula molecular cloud, using Caltech's 10.4 m telescope at OVRO. To the surprise of the investigators, Phillips and Research Fellow Edmund Sutton, almost all of the observed range of frequencies is filled with line emissions. Of the order of one hundred lines, most of which have not yet been identified, were observed in the first spectral scans, covering about 20 percent of the available range. This work will almost certainly lead to the discovery of more complex molecules in interstellar space.

Atomic Nuclei from the Galaxy
Among the astrophysical objectives of the cosmic ray observations being conducted by Professors Edward Stone and Rochus Vogt and their colleagues is a study of the isotopic and elemental composition of the cosmic rays coming from nearby regions in our galaxy. Since cosmic rays are nuclei of ordinary atoms, their composition contains information on the element-building processes occurring in those nearby regions. For example, the elements heavier than iron, such as platinum, lead, and uranium, are produced when lighter elements capture extra neutrons and then radioactively decay. In a normal star, the neutrons are captured slowly, producing elements no heavier than lead and bismuth, while in a supernova explosion, neutrons are captured so rapidly that even heavier elements such as uranium and thorium can be produced.

With a very large cosmic ray detector on the third High Energy Astronomy Observatory, Stone and his colleagues at Washington University and the University of Minnesota have been measuring how much of the relatively rare uranium there is in cosmic rays. Since supernovae were thought to be a likely source of cosmic rays, it was expected that compared with matter in the Solar System, cosmic rays would be enriched in uranium. Instead, no enrichment was found, indicating that the bulk of cosmic ray matter has not been freshly synthesized during supernovae explosions. The team of scientists also analyzed somewhat lighter elements and determined that explosively produced tellurium and xenon are less abundant than barium and tin, which are produced by slow neutron capture. Analysis of other elements such as platinum and lead should provide further indications of the stellar processes responsible for the synthesis of this sample of matter from the Galaxy.

Foundations of Mathematics: The Search for New Laws

In our continuing effort to present mathematics to the "educated" layman, a difficult task because of the maturity and abstract character of the field, this year's installment is dedicated to the discipline of mathematical logic, one of the division's areas of strength.

Mathematical Logic is the branch of mathematics concerned with the foundations of this discipline and the study of the basis of the reasoning used by mathematicians. Some of the fundamental ideas formulated and studied within its framework are the syntax and semantics of formal languages, the theory of axiomatic systems and formal proof procedures, the successful delineation of a mathematical notion of computability, and the development of the set theoretic foundations of mathematics. These purely intellectual achievements have had consequences well beyond their original theoretical motivations. There is a direct line leading from the revolutionary 1931 work of Kurt Gödel on the incompleteness of axiomatic systems, to Alan Turing's conception in 1936 of the theoretical computing machines bearing his name, and on to John von Neumann and the development of the modern computer. This close connection between mathematical logic and computer science is also manifested today in many areas of both theoretical and practical interest, such as formal languages and design of logical circuits for computers. In recent decades mathematical logic has also increasingly interacted with and found important applications in many other branches of mathematics, such as number theory, combinatorics, algebra, analysis, and topology.

Many fundamental questions facing the mathematical logicians today stem from the discovery of the incompleteness theorem by Gödel. To explain these problems, consider first the essence of the set theoretic foundations of mathematics. All currently studied mathematical objects can be viewed as sets. Moreover a small collection of basic laws of the universe of sets, known as the Zermelo-Fraenkel Axioms with the Axiom of Choice (ZFC), is sufficient as a basis for the axiomatic development of the mathematics today. Put another way, every theorem proved by a working mathematician can be understood (in principle) as a logical consequence of these classical ZFC axioms. But the celebrated Gödel Incompleteness Theorem implies that there must exist mathematical problems whose truth or falsity cannot be established within this fixed axiomatic system of ZFC, and whose solution is therefore beyond the reach of the mathematician today. This was strikingly verified in 1963 when Stanford's Paul Cohen demonstrated (in combination also with earlier work of Gödel in 1938) that one of the most famous open mathematical problems, the Cantor Continuum Hypothesis, on determining the size (cardinality) of the real number system, cannot be solved in ZFC. Since that time many other well-known problems in set theory and other areas of mathematics—including analysis, algebra, and topology—have been shown to be undecidable in this precise sense.

The inherent inability of the axioms of classical mathematics to resolve questions of fundamental interest necessitates a search for the discovery of new laws of the set theoretical universe. (This is of course an open-ended program since by the same Incompleteness Theorem, no fixed collection of laws can ever suffice to provide answers to every problem.) At present there are two main theories being explored. The first hypothesizes that sets of extremely large size (cardinality) exist, well beyond those that can be shown to exist in ZFC. The second puts forth the hypothesis of determinacy (i.e., the existence of winning strategies) for certain types of infinite two-player perfect information games. Each one of these games is specified by giving a set of real numbers in the interval (0,1). A run of the game is played in infinitely many successive rounds. In the nth round ($n = 1,2,3,\ldots$), the two players take turns in choosing a bit 0 or 1. Say the first player chooses the bit a_n and the second one the bit b_n in the nth round. These bits strung together form the real number in the interval (0,1) whose (infinite) binary expansion is $0.a_1b_1a_2b_2a_3b_3\ldots$. The first player wins this run of the game if the resulting real number belongs to the given set, and the second player wins otherwise.

Despite their totally different nature, these two theories appear to be mutually compatible. Moreover, there is quite a bit of evidence that they may be actually equivalent manifestations of the same underlying principle. Research is currently under way for developing such a unified theory.

A remarkable development in large cardinal theory has been the demonstration of the effect that the existence of large cardinals has on the properties of the "small sets" used in everyday mathematics. Specifically, large cardinal hypotheses reveal striking new facts about the real continuum and are used to solve many old problems left open in ZFC. Even more effective in that sense has been the hypothesis of determinacy. On the basis of this hypothesis a deep structure theory of the explicitly definable sets (including Borel, analytic, projective, etc.) of reals is being developed. This theory goes substantially beyond the limits of classical mathematics. In particular, significant results have been obtained concerning various formulations of the Continuum Problem for the special but important case of the definable sets of reals.

At Caltech, Professor Alexander S. Kechris and Professor W. Hugh Woodin have been particularly interested in these aspects of the foundations of mathematics, and are among the main contributors in the current development of the theories of determinacy, large cardinals, and their interrelationships. Bateman Research Instructor Moti Gitik has been a very active participant in the research program, which has been also enhanced by the visit of Professor Manachem Magidor of the Hebrew University.

Jet Propulsion Laboratory

Staffed and managed by the California Institute of Technology under operating and facilities contracts with the National Aeronautics and Space Administration.

Lew Allen Jr., Director

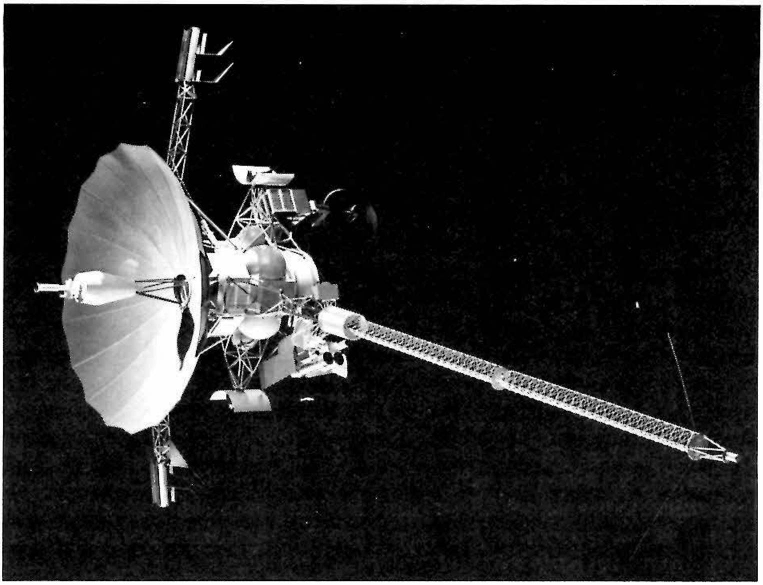
After six years of distinguished service as director of the Laboratory, Bruce Murray announced in April 1982 that he would step down as director effective June 30. My appointment as a vice president of Caltech and director of the Laboratory became effective October 1. The following report reflects the last months under Professor Murray's leadership and the interim direction of the Laboratory by the deputy director, C. H. Terhune, Jr.

Space Exploration

JPL is continuing to explore the solar system with Voyager, Galileo, and the International Solar Polar Mission. The Venus Radar Mapper mission is expected to be presented to Congress for inclusion in the FY84 budget.

Both Voyager spacecraft are probing the plasma and charged-particle environments of the outer solar system. Voyager 2 will encounter Uranus in 1986 and Neptune in 1989. The encounters should be comparable to those of Jupiter and Saturn.

Galileo is a mission to orbit Jupiter, study the four Galilean satellites in detail, and send an instrumented probe into the planet's atmosphere. JPL has overall project responsibility for Galileo, is building the orbiter, and will direct the flight operations. Excellent progress has been made in incorporating program changes brought about by adoption of the Centaur upper stage. Although the launch date slipped one year, until 1986, data return to Earth will begin a year earlier because the Centaur will cut flight time from four to two years. System



About 150 days before the spacecraft Galileo is placed in orbit about Jupiter in August 1988, a probe will separate from the main spacecraft on a flight path to enter Jupiter's atmosphere. It is expected to radio information (via the orbiter) on atmospheric gases and particles for about 60 minutes before it is destroyed by heat and pressure.

integration of the orbiter began in February, and will be completed in 1983. After delivery to JPL in December, the probe will be integrated with the orbiter, and the combined system and environmental test program will start in the first quarter of 1984 and continue through the year.

The International Solar Polar Mission will investigate the polar regions of the Sun and the heliosphere outside the ecliptic plane. The European Space Agency is providing the spacecraft and five science instruments. JPL is managing the American portion of the mission, including the development of five U.S. scientific instruments, mission design, tracking, flight operations, and data preparation and distribution. Test units of the U.S. scientific instruments have been delivered, integrated with the spacecraft, and tested. The instruments will be calibrated, refurbished, and stored until final preparations for launch begin in 1985.

Studies of a Venus Radar Mapper mission were stepped up during the year, since indications were strong that the Administration would submit the flight as a new start for next fiscal year. If the mission is approved, it will be launched by the Space Shuttle in 1988 and arrive at Venus in August. The mission has received strong endorsements from NASA' s Solar

System Exploration Committee and the Space Science Board of the National Academy of Sciences as the most important next step in exploring the terrestrial planets. After cancellation of efforts to obtain a Venus Orbiting Imaging Radar (VOIR) flight mission, JPL led efforts to organize a lower-cost Venus mission, using parts left over from Voyager, Galileo, and the International Solar Polar Mission, and a change to an elliptical orbit. VOIR would have cost about $750 million, and the Venus Radar Mapper will cost about $300 million. The Venus Radar Mapper will use a synthetic aperture radar (SAR) to produce images of the surface. In eight months it will map 70 percent of Venus's surface through the clouds. JPL's experience with Seasat and the Shuttle Imaging Radar (SIR-A) has shown that SAR images are useful for geological investigation.

The Infrared Astronomical Satellite (IRAS) was launched from the Western Space and Missile Center on January 25, 1983. The satellite, which carries a cryogenically cooled infrared telescope, was placed in a near-polar orbit at an altitude of 900 kilometers (560 miles).

The Wide Field/Planetary Camera is one of five instruments on the Space Telescope. This advanced camera, designed and built by JPL and campus, uses charge-coupled devices (CCDs) to provide photographs that are mosaics of four CCDs with 800 x 800 pixels, or picture elements, in each camera. When flown with the Space Telescope, the instrument will permit major improvements in astronomical observations. The activities at JPL are currently on schedule for delivery on July 5, 1983, to Goddard Space Flight Center for integration with the other instruments in the Space Telescope.

Environmental and Earth Observations

JPL was project manager for the Solar Mesosphere Explorer (SME), an atmospheric-research satellite that studied how ozone concentrations form and move about in the atmosphere between 20 and 90 kilometers altitude. SME was launched in October 1981 and in its second year of operation studied the ash cloud in the stratosphere from the eruption of the Mexican volcano El Chichon.

The Atmospheric Trace Molecules Observed by Spectroscopy (ATMOS) experiment, which will fly on the shuttle's Spacelab 3, is designed to obtain fundamental information on the chemistry and physics of the upper atmosphere. ATMOS will determine the detailed compositional structure of the atmosphere, its global, seasonal and long-term variability, and the absorption of sunlight at different levels in the atmosphere. Plans call for ATMOS to be flown on the space shuttle at approximately yearly intervals after its initial flight next year.

JPL will provide instruments for the Upper Atmosphere Research Satellite (UARS) experiments and mission definition program. A Microwave Limb Sounder is being developed to measure chemicals in Earth's atmosphere, including water and carbon monoxide. An Active Cavity Radiometer will fly on UARS to monitor solar radiance and its variability.

Analysis of the variations of sea-surface height measured by the Seasat altimeter provided the first detailed spatial large-scale maps of the global oceans. The measurements provide an important step in improving the ability to model the ocean circulation. Satellite altimeter readings of the ocean surface, processed to create a topographic representation of the global ocean floor, reveal previously unknown features, especially in the poorly surveyed southern oceans.

JPL has several Solid Earth observation experiments planned for the shuttle/spacelab payloads. They include the Shuttle Imaging Radar-B, a follow-up experiment to SIR-A that flew on the shuttle in 1981. SIR-B will provide data for a variety of geologic, oceanographic, and land-use studies, including cartography, geomorphology, forest monitoring, and hydrology. Unlike previous spaceborne imaging radars, SIR-B will have a movable antenna that can look at targets from different angles.

JPL's Shuttle Multispectral Infrared Radiometer, carried on the shuttle in November 1981, located a previously unprospected area, potentially rich in ore deposits, in a remote Mexican desert. A team of JPL and Mexican scientists went to the area in 1982 and verified that it is a prospective mineral deposit. That is the first time a suite of minerals typical of metal-rich areas has been discovered from space.

The JPL-developed imaging spectrometer is a remote sensing instrument aimed at the generation of Earth remote-sensing instrumentation that will follow the Landsat program. The principal feature of the imaging spectrometer concept is high spectral resolution, with images acquired simultaneously in more than 100 spectral bands, allowing direct identification of many minerals and assessment of vegetation types and their state of health. A working model, the Shuttle Imaging Spectrometer-A, will be used to evaluate the technology and experiment concepts.

Mission Support

The Deep Space Network (DSN) supports flight projects with its three main deep-space communications and tracking facilities near Goldstone, California; Canberra, Australia; and Madrid, Spain.

In preparing for the critical navigation requirements of Voyager and Galileo, the DSN used Very Long Baseline Interferometry to measure the angular position of Voyager in space to within three-millionths of a degree—equivalent to reading a Washington, D.C., freeway sign from Los Angeles.

In 1984, under the Networks Consolidation Program, one link of the Ground Spaceflight Tracking and Data Network (GSTDN) stations at Canberra, Madrid, and Goldstone will be transferred to the DSN. This consolidation of two networks' elements will provide savings in both facility and staffing costs associated with supporting the set of future missions that will use highly elliptical Earth orbits.

Preparations for the encounter of Voyager at Uranus will continue through 1984. New 34-meter, high-efficiency antennas will be completed at Australia and Goldstone to increase the amount of data returned. Plans were made in 1982 to further improve the telemetry performance by arranging for support from the Australian Commonwealth Scientific and Industrial Research Organization's 64-meter radio telescope at the Parkes Observatory. Combining the Voyager signals received at Parkes with those received at the 64-meter and 34-meter antennas at the Canberra Deep Space Communications Complex has the potential to increase picture return by 20 to 50 percent.

By 1984, the DSN will be increasingly involved with support to the international missions to Halley's Comet that are planned by Japan and the European Space Agency. The DSN will also support the International Sun-Earth Explorer 3 mission, to encounter the comet Giacobini-Zinner in September 1985.

Research and Technology

The Research and Technology Program at JPL includes efforts for development of generic technology that may be used in several application areas. One broad area of development involves autonomous systems, the design of spacecraft and subsystems capable of operating independently of man's intervention for months and, it is hoped, years. JPL is also involved in the design and application of robotic systems, teleoperator equipment, and in developing adaptive systems capable of making analytical decisions.

In the communications field the Laboratory is developing higher-frequency equipment to support planetary missions. High frequency (X-band) will enable increased bandwidth with increased data rates, and allow use of a less-crowded area of the radio-frequency spectrum. The Laboratory is also involved in the development of equipment to permit satellite communications to mobile vehicles.

For advanced spacecraft the Laboratory is developing more efficient photovoltaic power systems, improved batteries and power management equipment, and antennas with electronically steered beams. The subsystem developments are focused on requirements of new, low-cost multimission spacecraft.

JPL is performing studies and design analysis of large, controlled space structures. The structures (an antenna, for example) will be as much as 10 to 100 meters in size and require precise shape control and pointing. The design tradeoffs between communication performance, structural rigidity, and pointing require improved materials and a pointing-control system with multiple sensors and actuator.

The Laboratory also supports the scientific community in the development of instruments and sensors. They range from laser sensors for atmospheric measurements to imaging sensors for Earth and space surveys.

Utilitarian Programs

For many years, JPL has supported other federal agencies' R&D efforts. An example is the continuing decade-long commitment by NASA and JPL to national energy programs in both solar and conventional energy sources. The activities conducted for the Department of Energy and its predecessors have led to significant technological advances that should enhance U.S. industry's competitiveness in the world. At the same time, they have provided a stimulating variety of challenges to the staff.

Part of JPL's unique character is that it has a fully integrated capability to conduct space projects. JPL's capability in the full spectrum of activities, from mission conception through analysis of the returned information, enables effective management of projects with unforgiving deadlines, limited budgets, and high demands for performance.

Reduced levels of manpower will be needed for NASA's planetary projects, as the developmental phase of Galileo comes to an end and JPL, at NASA's urging, makes greater use of industry to provide spacecraft hardware. Anticipating that trend, the campus authorized JPL to seek up to 30 percent of its effort on defense-related tasks as a means of maintaining the JPL technological base in the context of a more constrained NASA-sponsored program.

NASA has encouraged JPL to seek Defense Department work that complements its continuing NASA responsibilities, maintains its unique capabilities, and enhances national security. The work will allow JPL to apply technical and project-management expertise developed for NASA to appropriate national-security tasks and will help maintain JPL's unique spectrum of technical and management skills.

As of September 1982, DOD work occupies about 10 percent of the work force and is expected to increase during the balance of FY83. The campus, through the Christy Committee, will take care that the tasks undertaken by JPL in the defense area are appropriate to its institutional character and technological skills.

The commitment to a long-term, expanded DOD program is consistent and compatible with Caltech's and NASA's desire that JPL continue as a NASA center and as a respected national technological resource whose talents are available to address national needs, including space exploration and applications, national security, and energy R&D.

Environmental Quality Laboratory

Norman H. Brooks, Director

EQL has continued a vigorous program of research centered on policy-related studies on the environment and utilization of resources. Currently the laboratory works on four closely interrelated program areas: air quality, water resources, hazardous substances, and energy. Highlights of some of the outstanding achievements are described below.

Progress in Smog Modeling

During the last decade considerable attention has been devoted to understanding the sources, causes, and environmental impacts of photochemical air pollution or smog. Professor John Seinfeld and senior research engineer Gregory McRae have developed a series of mathematical models that accurately describe the physical and chemical processes taking place in the atmosphere. These tools are now being used by state, local, and federal agencies to aid in the design of emissions control programs. With support of the California Air Resources Board and EPA, a number of different studies have been undertaken at EQL, including, for example, an examination of the likely environmental impacts of the use of methanol as an alternative automobile fuel. During the last year, also, increased research efforts have been devoted to one particular aspect of the air pollution problem—surface deposition of acidic materials.

In an urban atmosphere the major precursors of acid deposition are sulfur dioxide (SO_2) and nitrogen oxides (NO_x). These gases and their acidic oxidation products form a heterogeneous mixture of compounds that ultimately return to the earth's surface as either wet or dry deposition. While much of the initial research work has been directed at measuring ecosystem acidification by wet precipitation or acid rain, there is a growing recognition that other mechanisms, especially dry deposition, are important. A particular focus of the EQL study has been to examine the physical and chemical transformations of NO_x emissions. There are several reasons for this emphasis. One is that the dynamics of nitric acid and ammonia has a dominant influence on surface acidity. Secondly, nitrogen oxides are becoming the major components of the acid deposition, as sulfur oxides emissions are being reduced by use of low sulfur fuels and stack controls.

Control of Atmospheric Carbon Particles

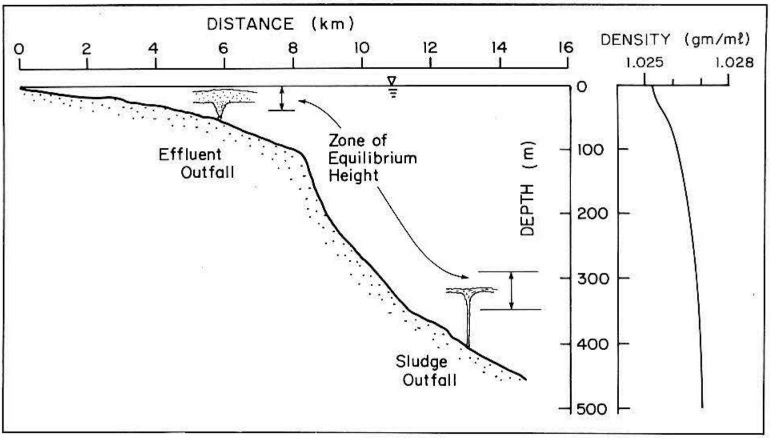
In a large urban area carbon particles are emitted from more than 50 types of pollution sources, ranging from diesel automobiles to large power plants. Soot particles decrease visibility in the atmosphere and might be carcinogenic to humans. Therefore, there is considerable interest in defining emission control strategies for abating atmospheric carbon particle concentrations.

Assistant Professor Glen Cass and graduate student H. Andrew Gray are continuing their research into control of primary aerosol carbon particles, under sponsorship of the California Air Resources Board. During 1982, they operated a network of 11 air-monitoring stations in the Los Angeles area at locations from San Nicolas Island to Riverside. Aerosol samples taken during that field experiment are being analyzed for their elemental carbon and organic carbon content. This experiment has yielded the first long-term high quality set of data for atmospheric carbon particles in the Los Angeles area.

A computer-based model of the atmospheric transport of carbon particles from pollutant emission sources has been developed and will be tested against the results of the field sampling program. When completed, the air quality model will be used to study the likely effects of emission control strategies that could be used to reduce atmospheric carbon particle concentrations.

Deep-Ocean Disposal of Sewage Sludge—An Experiment Awaiting Congressional Approval

As a result of EQL research over the past several years, the County Sanitation Districts of Orange County has proposed a research and demonstration project for deep-ocean disposal of 150 tons per day of digested sewage sludge solids (in suspension in 12,000 tons of water). The submarine pipeline for this discharge would terminate at a depth of about 400 meters at a distance of 7.5 miles from shore, off the mouth of



This cross-section of the ocean off Orange County shows the depth and distance from shore of the proposed 400-meter-deep outfall for discharge of digested sewage sludge. The effluent outfall location (at 60-meters depth) is shown for comparison. In both cases the density stratification (due to temperature and salinity changes with depth) causes the height of rise of the plumes to be restricted to the ranges shown. EQL researchers have developed the concept for this sludge outfall at unprecedented depths and have prepared a comprehensive research plan (see text).

the Santa Ana River. During 1982 a detailed research plan for this proposed deep-ocean disposal project was drawn up by Professor Norman H. Brooks, Senior Research Associate Robert Koh, graduate student Robert Arnold, and ex EQL'ers George Jackson (now at Scripps Institution of Oceanography) and William Faisst (now at Brown and Caldwell).

About 30 oceanographic scientists, environmental engineers, and agency personnel (Orange County, state of California, EPA, NOAA) contributed ideas during a special workshop and several small meetings held at EQL. The plan, which includes more than 40 different tasks, is designed not only to observe the effects of this proposed discharge at unprecedented depths, but also to understand the important physical, chemical, and biological processes, and develop reliable predictive computer models. The research project is expected to last about seven years and cost $2 million per year.

This project is still not allowed under present laws, but there has been a gradual shift of attitude in the federal and state government toward consideration of all media—air, land, and water—as possible candidates for receiving residuals, with case-by-case decisions. For Orange County the predicted impacts of deep-ocean disposal are small, and the proposed five-year experiment is not considered risky. Furthermore, the ocean disposal cost is at least five times less than that for land disposal.

When and if the project goes ahead, EQL will collaborate with other research groups to advance the science and engineering of deep-ocean disposal. In the meantime, EQL is conducting fall velocity tests on sludge suspensions, updating model predictions with new oceanographic data, and defining the design parameters for the outfall.

New Techniques for Risk Assessment

One of the most active areas of regulatory policy is the management of long-term health and environmental risks. Examples include safety regulation of nuclear power facilities, disposal of hazardous wastes, and control of toxic chemicals. Sensible procedures are needed for assessing risks, especially when information about the nature of the risk is not known with certainty. Senior Research Associate R. Talbot Page, an economist, collaborating with research fellow M. Gilbert Bogle, an engineer, has been developing decisionmaking procedures that make best use of the available information about a risky technology or material and that establish incentives for the people who produce this information to make efficient decisions about the choice of methods for generating it. The traditional approach has been to emphasize the development of tests that minimize or reduce to some predetermined acceptable level the chance that a risky product will be misclassified. But this approach inevitably leads to costly results. For instance, equally informative tests would be used for all risks, regardless of prior expectations about the nature of the risk or about the extensiveness of exposure to it among the population.

Research at EQL adopts a more appropriate framework, based on the application of statistical decision theory in developing decision procedures and on simulation methods using Monte Carlo techniques to test these properties empirically. Statistical decision theory is built on the concept that decisionmakers want to adopt procedures that minimize the total cost of errors of misclassification and of the assessment process. It follows from this way of formulating the problems that not all potential hazards should be subjected to the same testing procedure. Some will be subjected to less costly, less informative tests because the risks of misclassifying them as safe will be relatively low (or the costs of misclassifying them as dangerous will be especially high). Recently a report of a committee of the National Research Council recommended the use of the approach to these problems being developed at EQL.

Residential Demand for Energy—How Does It Respond to Rising Energy Prices?

An important element of energy policy for the past decade has been actions intended to affect the consumption of energy for residential uses. Assistant Professor Jeffrey Dubin is analyzing the long-term response of energy consumption to changes in the price of energy and to efficiency regulations.

One reason that energy demand is difficult to predict is that it is closely tied to numerous other decisions by consumers regarding the capital investments in residential structures and appliances. In the short run, consumers have a large stock of investments that limit their flexibility in energy consumption, but over time, as investments become obsolete and require replacement or repair, the energy efficiency of the capital stock of the consumer becomes more flexible. Hence a theoretically correct model for predicting energy consumption in the long run must be embedded in a more comprehensive model that predicts the rate at which household investments will be replaced or enhanced in ways that affect energy use. These models must also take proper account of how consumers make decisions about energy use—for example, how they adjust the temperature to which they heat and cool their houses as the cost of energy and the energy-efficiency of their homes and appliances change. Professor Dubin's work is innovative in attempting to account for these complexities.

Cost Overruns—A Generic Problem?

Professor James Quirk and Dr. Katsuaki Terasawa, an economist at JPL, began investigation into the problem of continually escalating cost estimates for the proposed Colony oil shale project. However, even before Colony was abandoned in 1982 due to projected losses from operations based on the last jump in construction cost estimates, it had become clear that escalation in cost estimates was a generic problem affecting all branches of industry, and not simply a peculiarity of oil shale.

The researchers' main effort so far has been directed toward developing a conceptual explanation for the persistent underestimation of construction costs, particularly for first-of-a-kind projects. This work is derived from the basic notion that decisionmaking with respect to construction projects is not based solely on the cost of such projects, but rather on their projected profitability. Given this framework, certain aspects of the cost underestimation problem can be identified quite easily.

First, data on costs of completed projects will tend to show cost overruns more often than cost underruns, even if a perfectly unbiased cost estimation method is employed. This will occur because in any sample of proposed projects, those projects that show the highest profit potential will tend to be approved for further work, and prospective profit potential is enhanced by underestimated costs. Thus, there is a sample bias in the data on completed construction projects that helps to explain at least a part of the cost underestimation phenomenon.

Second, because maximum profitability rather than minimization of cost is the criterion for decisionmaking, there is a tendency for most construction to take place during the upswing of the business cycle. This means that the concentration occurs at precisely the time when shortages of skilled labor are greatest, when delivery times of components are longest, and when costs in general are rising most rapidly.

This study and the one preceding it are just two examples of energy policy studies. Professor Noll and senior research economist Linda Cohen are continuing their research on the development and regulation of nuclear power, and, with Associate Professor Louis Wilde, the role of government research and development for new technologies. Spot markets for both water and power have been investigated, and the project on marketable emissions permits for air pollution control, described in last year's report, has been completed.

Staff and Support

Our economics faculty in EQL has been strengthened in two ways. First, Jeffrey Dubin, an applied economist with interests in resources, was appointed assistant professor in 1982; he earned his Ph.D. in economics at MIT and was associated with the MIT Energy Lab. Secondly, since Institute Professor Roger Noll resigned as chairman of the Division of the Humanities and Social Sciences in 1982, he is again able to devote full time to his research and teaching. His areas of interest (regulation, energy, and environmental management) are central to EQL's goals.

More graduate students than ever (19 in the fall quarter 1982) are being employed as research assistants on EQL projects involving 11 professors. However, our research staff (other than teaching faculty and graduate students) has decreased from eight to six (as of October 1982), while the support staff remains at six.

For EQL's financial stability in turbulent times we owe special thanks to the private foundations, corporations, and individuals who have continued their generous gifts to EQL. These private funds covered nearly half of EQL expenditures in 1981-82.

Caltech Libraries

Roderick J. Casper, Acting Director

In this year of "the interregnum," CLS (Caltech's library system) has been receiving a thorough review from the administration, the Faculty Library Committee, the search committee, division heads, and their appointed faculty library representatives. Library staff has been equally caught up in prospects of major changes. There is widespread interest in the possibility that our library system be made part of the innovative information systems now being developed and coordinated at the Institute. Sensing the importance of entering this new era, the search is on for a new director of information resources.*

Preparation for Change

The mandate from the administration was primarily to keep CLS on course during the interregnum. The interest, advice, and support from the provost's office and the Faculty Library Committee eased the burden for the acting director in areas of problem solving and policy decisions. Encouragement was also given to update, innovate, and adjust for an expanding embrace—that of new technology in information services for the Caltech community.

Faculty Library Committee chairman Harold Zirin's interest in automating CLS resulted in the acting director providing an update of Dr. Rod Paul's 1973 report, "The Nature, Dimensions, and Habits of Caltech's Library System." This study (summarized in *The President's Report* FY 72/73) was made

*Glenn L. Brudvig, formerly at the University of Minnesota, was appointed Director of Information Resources in July 1983.

as a prelude to the selection of a new director of libraries. Search Committee chairman Rod Paul, with input from his committee, did a campus-wide survey of the unique information needs of the Caltech community. Acting director Casper's update stresses CLS's progress towards the realization of many recommendations of the FY 72/73 Search Committee, especially in the areas of library automation and resource sharing via bibliographic utilities, consortia, and information networks.

Additional research by Millikan Library staff brought about a mutual conclusion with the Faculty Library Committee: A goodly amount of funding is required to get an automated system started, but it must begin sometime. Options ranged from recommending modest, in-house pilot experiments and the purchase of "turnkey" systems, to advocating a full-scale systems analysis.

Added Services

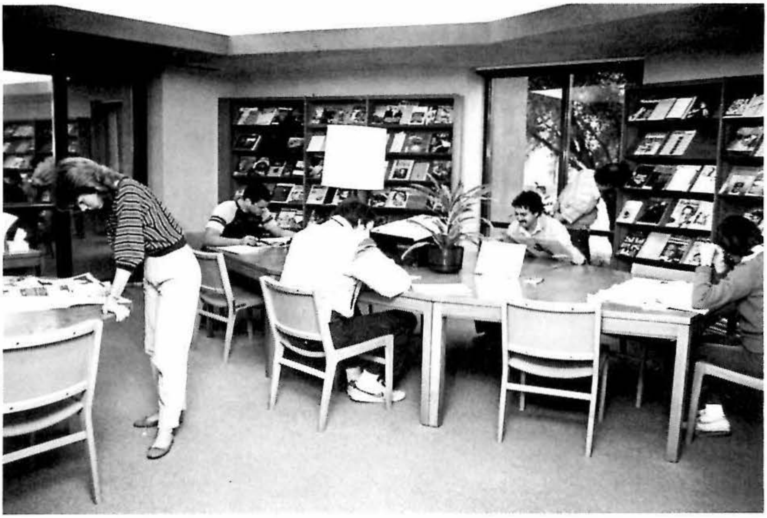
Certain changes of policy during the interregnum have resulted in new services: Members of the Caltech Alumni Association have been given full library privileges; Industrial Associate company personnel may now avail themselves of our on-line data based search capabilities.

Oral Histories

The Archives' Oral History Project continues to flourish. This year a number of Caltech professors, past and present, were interviewed, including Victor Neher, Milton Plesset, Rodman Paul, and Hallett Smith. Several non-Caltech people seemed appropriate oral history subjects because of their connections with the school at critical junctures in the past. These include Franco Rasetti and Hans Bethe.

Library Staff

The acting director has embarked on a strategy to raise staff morale and to achieve a more homogenous group. Supervisors have been asked to focus on a policy of personal interest and broader in-service training. Towards this goal a staff committee designed a new performance evaluation form to better profile the work of an employee, but more importantly to set up a closer stage for supervisor-employee interface.



The Public Affairs Room in Baxter Hall offers a wide range of current periodicals and newspapers from around the world.

TOTAL COST OF BOOKS & PERIODICALS	$746,766
HOLDINGS (in libraries for which Millikan catalogs)	
Books	240,723
Periodical volumes	155,644
Total	396,387
PERIODICAL TITLES CURRENTLY RECEIVED (through Millikan acquisitions dept.)	5,664
MICROFORM HOLDINGS	
Reels	9,887
Microfiche	397,559
Microcards	7,755
Total	415,201
CIRCULATION	
Millikan library	43,523
Six other libraries	13,645
Total	57,168

Industrial Relations Center

Victor V. Veysey, Director

Forty years ago, heated discussions were held in industrial relations and management circles about coping with militant unionism, training first-line supervisors to perform their industrial relations responsibilities, and promulgating a benign philosophy of human relations among hard-driving line managers. Today the conversation is likely to center on cooperative productivity bargaining with unions, the effects on employees of the introduction of office electronic systems and factory robots, innovative ways of involving employees in decisions at the workplace, and meeting the values of the current generation of employees.

The Industrial Relations Center is now emphasizing the improvements in productivity that must come for American industry to survive. These improvements are most likely to be available through the wise application of technology and the judicious and sensitive use of a better educated workforce. The IRC therefore is attentive to human resource problems at middle management and upward, to cooperative approaches between management and unions in achieving productivity, and to human resources problems in the environment of advanced technology.

During 1981-82, the Executive Forum, a study and discussion group of presidents, general managers, and CEOs, under the guidance of a steering committee headed by Caltech Trustee Earle M. Jorgensen, presented the following programs: "Space: The Limitless Opportunity," Robert Anderson; "Managing Automation and Robotization," Dr. Louis T. Rader; "Managing Major Industrial Change," Benjamin Biaggini;

"Technology and the Executive of the Future," John J. Connell; and "Stress and Creativity at the Top Levels," Dr. Warren L. Jones.

The Productivity Improvement Group, guided by Giles Hall, Jr., assistant director (honorary) of IRC, and Paul Doyle, vice president, Union Oil Company (retired), has grown from a small group to more than 100 as the need for productivity improvement has emerged as a national priority. Middle managers or staff specialists study possible productivity initiatives and exchange experiences on a case study basis.

The following programs were offered during the year: "Union/Management Cooperation in Setting Performance Standards," "The Creative Manager—a Key to Productivity," "Productivity Improvement Programs at Northrop," "Making Quality Circles Work," "Office Technology, Productivity, and People," "Managing for Productivity at United Parcel," and "Employee Involvement in High-Performing Organizations."

The Engineering/Management Program aids the already employed engineer who must meet management responsibilities and accomplish goals through other workers and through his organization. More than a dozen companies nominated engineers to participate in the program, and 22 engineers have completed the requirements for a certificate. Industrial users recently added to the in-company group include Northrop Aircraft Company and TRW Inc.

These participants in a seminar at the Industrial Relations Center are actively involved in "The Successful Negotiator," led by Dr. Robert D. Rutherford.

Isabella Kierkowska, a Caltech honors graduate in applied physics, has developed a remarkable tool, the "Instant Poll," which is a computerized method of surveying employee opinions quickly and easily. Described in the "Manual for Making Opinion Surveys" published by IRC in 1982, this poll measures attitudes that lead to an understanding of motivation and its effects on productivity. It also provides a feedback mechanism for management to measure receptivity of its programs and working conditions among employees.

Seminars for management development, directed by Valerie Hood, assisted by Bettye Dilworth, have been aligned to match new needs in industrial organizations, and to meet the pressures of the slack economy. New seminars offered during the year include "Middle Engineering Managers," "Stress Management," and "Time Management and Successful Negotiation Techniques." An experienced and highly motivated group of Caltech alumni, known as the Task Force, has greatly aided in improving channels of communication between the Center and industry.

The Management Library and Information Services has had moderate expansion during the year, guided by librarians Mary Mackintosh and Miki Kumomoto, consistent with budgetary restraints and the high cost of new acquisitions. The data base search terminal has been an increasingly used research tool as more sponsor companies and students of management become aware of its capabilities.

Professional groups of several types, supported by Bonnie Lobner in the director's office, meet regularly to receive information on current problems and to discuss practices of particular interest. The IRC sponsors meetings of top level industrial relations directors, the Executive Development Group, two groups of professionals in managerial compensation (one in Los Angeles and one in San Francisco), and a newly formed Equal Employment Opportunity and Affirmative Action study group.

Faculty

Changes in the Faculty 1982

ADMINISTRATIVE OFFICERS
L. E. Davis, Executive Officer for Social Sciences
D. M. Grether, Chairman of the Division of the Humanities and Social Sciences
D. C. Van Essen, Executive Officer for Biology

PROMOTIONS

To Professor Emeritus
R. P. Dilworth, Professor of Mathematics, Emeritus
W. A. Fowler, Institute Professor of Physics, Emeritus
N. H. Horowitz, Professor of Biology, Emeritus
R. D. Wayne, Associate Professor of German, Emeritus

To Named Professorship
E. H. Davidson, Norman Chandler Professor of Cell Biology
N. R. Davidson, Norman Chandler Professor of Chemical Biology
R. G. Noll, Institute Professor of Social Sciences
R. E. Vogt, R. Stanton Avery Distinguished Service Professor
G. J. Wasserburg, John D. MacArthur Professor of Geology and Geophysics

To Professor
C. E. Brennen, Professor of Mechanical Engineering
P. B. Dervan, Professor of Chemistry
A. J. Hudspeth, Professor of Biology
H. C. Martel, Professor of Electrical Engineering
D. R. Smith, Professor of Literature
A. H. Zewail, Professor of Chemical Physics

To Associate Professor
D. R. Kiewiet, Associate Professor of Political Science
J. F. Reinganum, Associate Professor of Economics
K. E. Sieh, Associate Professor of Geology
A. J. Smith, Associate Professor of French
E. M. Stolper, Associate Professor of Geology
Y. L. Yung, Associate Professor of Planetary Science

To Assistant Professor
P. T. Hoffman, Assistant Professor of History
F. C. Porter, Assistant Professor of Physics
R. K. Sparks, Assistant Professor of Chemical Physics

To Senior Research Associate
T. Kasamatsu, Senior Research Associate in Biology

To Senior Research Fellow
C. M. Caves, Senior Research Fellow in Theoretical Physics
A. Chomyn, Senior Research Fellow in Biology
K. Flytzanis, Senior Research Fellow in Biology
L. M. Kauvar, Senior Research Fellow in Biology
J. H. Lacy, Senior Research Fellow in Physics
S. L. Manley, Senior Research Fellow in Environmental Engineering Science
W. J. Nelson, Senior Research Fellow in Biology
J. M. Nerbonne, Senior Research Fellow in Biology
T. A. Prince, Senior Research Fellow in Physics
M. A. Tanouye, Senior Research Fellow in Biology

NEW APPOINTMENTS

Professors
J. N. Abelson, Professor of Biology
B. M. Barry, Professor of Philosophy
R. J. McEliece, Professor of Electrical Engineering
M. I. Simon, Professor of Biology

Associate Professors
R. L. Bush, Associate Professor of Literature
J. R. Mould, Associate Professor of Astronomy
H. B. Newman, Associate Professor of Physics

Assistant Professors
J. A. Dubin, Assistant Professor of Economics
E. Rothenberg, Assistant Professor of Biology
A. J. Rosakis, Assistant Professor of Aeronautics and Applied Mechanics
P. M. Thompson, Assistant Professor of Electrical Engineering
M. B. Wise, Assistant Professor of Theoretical Physics
T. H. Wolff, Assistant Professor of Mathematics

Instructors

H. S. Becker, Instructor in Mathematics and Part-Time Research Fellow
J. M. Bowers, Mellon Postdoctoral Instructor in Literature
M.-C. Chang, Bateman Research Instructor in Mathematics
M. Kaneda, Bateman Research Instructor in Mathematics
W. L. Kath, von Kármán Instructor in Applied Mathematics
P. J. Mann, Mellon Postdoctoral Instructor in Literature
T. K. Rockwell, Instructor in Geology

Senior Research Fellows

J. E. Avron, Senior Research Fellow and Lecturer in Theoretical Physics
R. J. Konopka, Senior Research Fellow in Biology
R. P. Mount, Senior Research Fellow in Physics
R. M. Perlmutter, Senior Research Fellow and Lecturer in Biology
R. H. Schindler, Senior Research Fellow in Physics

Faculty Associates

J. R. Goodstein, Faculty Associate in History
W. A. Ringler, Jr., Faculty Associate in Literature
D. Sundelson, Faculty Associate in Literature

Sherman Fairchild Distinguished Scholars

Philip W. Anderson, Consulting Director of Physics Research, Bell Laboratories; Joseph Henry Professor of Physics, Princeton University
Hans A. Bethe, Emeritus Professor of Physics, Cornell University
Donald J. Brown, Professor of Economics; Staff Member, Cowles dation for Research in Economics, Yale University
Michael C. Brown, Lecturer in Physiology, University of Oxford
Gerhard Closs, A. A. Michelson Distinguished Service Professor, The University of Chicago; Section Head, Radiation Chemistry, Photochemistry and Photosynthesis, Chemistry Division, Argonne National Laboratory
Giuseppe Colombo, Professor of Mechanical Vibrations and Applied Mechanics, University of Padua; Celestial Mechanician, Smithsonian Astrophysical Observatory; Associate, Harvard College Observatory; Professor of Celestial Mechanics, Scuola Normale Superiore, Pisa
James F. Crow, Professor of Genetics and Medical Genetics, The University of Wisconsin
Gabriel T. Csanady, Senior Scientist, Woods Hole Oceanographic Institution
C. Chapin Cutler, Professor of Applied Physics, Stanford University
Anthony J. DeMaria, Assistant Director of Research for Electronics and Electro-Optics Technology, United Technologies Research Center
John M. Edmond, Professor of Marine Chemistry, Massachusetts Institute of Technology
Richard B. Freeman, Professor of Economics, Harvard University
Marcus Grisaru, Professor of Physics, Brandeis University
James A. Ibers, Professor of Chemistry, Northwestern University

Officers of the Faculty—1981–82
Secretary David C. Elliot, Chairman Fred C. Anson, Vice Chairman Donald S. Cohen (from left)

Roy Jackson, Professor of Chemical Engineering, University of Houston
George G. Lorentz, Professor of Mathematics, University of Texas at Austin
Roddam Narasimha, Professor and Dean of the Engineering Faculty, Indian Institute of Science, Bangalore
Masayasu Nomura, Elvehjem Professor in Life Science, Institute for Enzyme Research, The University of Wisconsin, with joint appointments in the Departments of Genetics and Biochemistry
Bohdan Paczynski, Professor, Copernicus Institute of Astronomy, Polish Academy of Sciences
Israel Pecht, Jacques Mimran Professor of Chemical Immunology, The Weizmann Institute of Science
John C. Polanyi, University Professor of Chemistry, University of Toronto
Howard Rosenthal, Professor of Political Science and Industrial Administration, Carnegie-Mellon University
Richard T. Shield, Professor and Head, Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign
Obaid Siddiqi, Professor and Head, Molecular Biology Unit, Tata Institute of Fundamental Research, Bombay
David R. Stadler, Professor of Genetics, University of Washington
Jack H. van Lint, Professor, Mathematical Institute, Technical University, Eindhoven
David Walker, Senior Research Associate, Harvard University

Visiting Professors

J. I. Molinder (Electrical Engineering), Professor of Engineering, Harvey Mudd College; Manager (Part-time), Engineering Office, Jet Propulsion Laboratory

T. C. Spencer (Mathematics and Theoretical Physics), Professor, New York University

Visiting Associate Professors

G. C. Babcock (Finance), Associate Professor of Finance, University of Southern California

T. R. Lewis (Economics), Associate Professor of Economics, University of British Columbia

H. L. Weisberg (Physics), Physicist, Brookhaven National Laboratory

Visiting Assistant Professors

A. A. Finnerty (Geology), Member of Technical Staff, Jet Propulsion Laboratory

S. J. Morgan (Literature), Assistant Professor, Vassar College

R. D. Rivers (Political Science), Assistant Professor, Harvard University

TERMINATIONS

J. W. Bieber, Senior Research Fellow in Physics
J. P. Brockes, Associate Professor of Biology
G. J. Dick, Senior Research Fellow in Physics
R. E. Dickerson, Professor of Chemistry
M. P. Fiorina, Professor of Political Science
B. S. Freedman, Mellon Postdoctoral Instructor in Literature
J. C. Huneke, Senior Research Associate in Geochemistry
P. L. Jay, Instructor in Literature
L. M. Kauvar, Senior Research Fellow in Biology
J. H. Lacy, Senior Research Fellow in Physics
P. H. Lowy, Senior Research Associate in Biology
K. A. Marsh, Senior Research Fellow in Astronomy
R. J. Powers, Senior Research Associate in Physics
T. K. Rockwell, Instructor in Geology
R. N. Splitter, Assistant Professor of Literature
C. A. Swarts, Senior Research Fellow in Applied Physics
E. Tadmore, Bateman Research Instructor in Applied Mathematics
T. L. Thomas, Senior Research Fellow in Biology
I. Vicente-Sandoval, Senior Research Fellow in Biology
S. Wolfram, Senior Research Associate in Theoretical Physics

DEATHS

W. H. Corcoran, Institute Professor of Chemical Engineering

Honors and Awards

D. L. Anderson, Professor of Geophysics; Director of Seismological Laboratory, was elected a member of the National Academy of Sciences.

J. D. Baldeschwieler, Professor of Chemistry, was elected a fellow of the American Association for the Advancement of Science.

J. L. Beauchamp, Professor of Chemistry, was elected a fellow of the American Association for the Advancement of Science.

S. Benzer, James G. Boswell Professor of Neuroscience, gave the John M. Prather Lectures at Harvard University, and the Croonian Lecture to the Royal Society of London.

R. D. Blandford, Professor of Theoretical Astrophysics, was awarded the Warner Prize for 1982 for outstanding contributions to astronomy by a person under 35 years of age.

C. E. Brennen, Professor of Mechanical Engineering, was a recipient of the ASCIT teaching excellence award for his course in fluid mechanics.

W. B. Bridges, Professor of Electrical Engineering and Applied Physics, was a recipient of the ASCIT teaching excellence award for his courses in applied physics and electrical engineering.

J. P. Brockes, Associate Professor of Biology, was awarded a McKnight Foundation Neuroscience Development Award for advanced research on the basic mechanisms of memory and on memory-affecting disorders.

D. E. Coles, Professor of Aeronautics, was elected a fellow of the American Association for the Advancement of Science.

W. H. Corcoran, Institute Professor of Chemical Engineering, was the 1982 recipient of the Warren K. Lewis Award for Contributions to Chemical Engineering Education. He was also one of the recipients of the Distinguished Service Citation from ASEE for 1982.

E. H. Davidson, Norman Chandler Professor of Cell Biology, was elected a fellow of the American Association for the Advancement of Science.

L. Davis, Jr., Professor of Theoretical Physics, Emeritus, was elected a fellow of the American Association for the Advancement of Science.

R. P. Feynman, Richard Chace Tolman Professor of Theoretical Physics, was a recipient of the ASCIT teaching excellence award for his relativity course.

M. P. Fiorina, Professor of Political Science, was one of the recipients of the 1982 Guggenheim Fellowships.

W. A. Fowler, Institute Professor of Physics, Emeritus, was recipient of an Honorary Doctor of Science Degree from Denison University and was Francis G. Slack Lecturer at Vanderbilt University.

D. L. Goodstein, Professor of Physics and Applied Physics, was a recipient of the ASCIT teaching excellence award for his course Physics 1.

R. W. Gould, Simon Ramo Professor of Engineering and chairman of the Division of Engineering and Applied Science, was elected a fellow of the American Academy of Arts and Sciences.

H. B. Gray, Arnold O. Beckman Professor of Chemistry and chairman of the Division of Chemistry and Chemical Engineering, was elected chairman of the Chemistry Section of the National Academy of Sciences.

E. Herbolzheimer, Assistant Professor of Chemical Engineering, received an ASCIT teaching excellence award for his chemical engineering course.

L. E. Hood, Ethel Wilson Bowles and Robert Bowles Professor of Biology and chairman of the Division of Biology, was elected a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. He was also selected as the Stanhope Bayne-Jones Memorial Lecturer, Johns Hopkins Medical School; Carter-Wallace Lecturer, Princeton University; and Marrs McLean Lecturer, Baylor College of Medicine.

G. W. Housner, Carl F Braun Professor of Engineering, Emeritus, was the recipient of the Nathan M. Newmark Medal for his research on destructive earthquakes and the design of structures to resist ground shaking.

H. B. Keller, Professor of Applied Mathematics and Executive Officer for Applied Mathematics, was elected a fellow of the American Association for the Advancement of Science.

W. G. Knauss, Professor of Aeronautics and Applied Mechanics, was elected a fellow of the American Academy of Mechanics.

E. B. Lewis, Thomas Hunt Morgan Professor of Biology, was awarded an honorary Ph.D. degree by the University of Umea, Sweden.

R. A. Marcus, Arthur Amos Noyes Professor of Chemistry, was the recipient of the R. A. Robinson Silver Medal.

E. M. Meyerowitz, Assistant Professor of Biology, was awarded an Alfred P. Sloan Research Fellowship and a Sigma Xi Grant-in-Aid of Research associated with the Procter Prize.

R. D. Middlebrook, Professor of Electrical Engineering, was a recipient of the ASCIT teaching excellence award for his course in electronic circuit design.

R. D. Owen, Professor of Biology, was a recipient of the ASCIT teaching excellence award for his course in genetics.

D. A. Papanastassiou, Senior Research Associate in Geochemistry, was recipient of a Guggenheim Fellowship.

J. D. Roberts, Provost and Vice President, Dean of the Faculty, and Institute Professor of Chemistry, was the recipient of the Theodore William Richards Medal for Conspicuous Achievement in Chemistry. He was also selected as the first Carl Shipp Marvel Lecturer, University of Illinois, and the Henry Gilman Lecturer, Iowa State University.

R. F. Scott, Professor of Civil Engineering, was one of the recipients of the 1982 Thomas A. Middlebrooks Award for his joint paper "Vibration Tests of Full-Scale Earth Dam."

M. Schmidt, Institute Professor of Astronomy, has received an honorary Sc.D. degree from Wesleyan University in Connecticut.

E. M. Searle, Professor of History, was elected a fellow of the Royal Historical Society.

J. H. Seinfeld, Louis E. Nohl Professor and Professor of Chemical Engineering and Executive Officer for Chemical Engineering, was elected a member of the National Academy of Engineering.

F. H. Shair, Professor of Chemical Engineering, was named chairman-elect of the Southern California Section of the American Institute of Chemical Engineers.

K. E. Sieh, Associate Professor of Geology, received the National Academy of Sciences Award for Initiatives in Research for development and application of innovative field techniques for studying active faults to identify and date paleo-earthquakes, thereby providing quantitative assessment of earthquake hazards.

G. N. Stephanopoulos, Assistant Professor of Chemical Engineering, was a recipient of the ASCIT teaching excellence award for his chemical engineering course.

D. Sundelson, Faculty Associate in Literature, was a recipient of the ASCIT teaching excellence award for the course The Self in Literature and for his Shakespeare class.

R. R. Wark, Lecturer in Art, was a recipient of the ASCIT teaching excellence award for his course, British Art of the Georgian Period.

G. J. Wasserburg, John D. MacArthur Professor of Geology and Geophysics, was elected a member of the American Philsophical Society.

W. H. Weinberg, Chevron Professor of Chemical Engineering Related to Energy and Professor of Chemical Engineering and Chemical Physics, was the recipient of the Allan P. Colburn Award of the American Institute of Chemical Engineers. He was also a recipient of the Alexander von Humboldt Foundation Senior United States Scientist Award.

T. Y. Wu, Professor of Engineering Science, was elected a member of the National Academy of Engineering.

A. Yariv, Thomas G. Myers Professor of Electrical Engineering and Professor of Applied Physics, was elected a fellow of the American Academy of Arts and Sciences.

Student Affairs

James J. Morgan, Vice President for Student Affairs

One development during the year was the approval by the Faculty Board of a whole new series of courses to be offered under the title "Performance and Activities," or PA for short. Under this rubric students will be able to register and receive credit for the whole gamut of performing arts—glee club, orchestra, band, chamber music, theater arts, etc. This should go a long way toward providing official recognition of participation in this type of activity.

In a later action by the Faculty Board another type of PA course was approved, a course in health awareness taught at the Health Center and called Health Advocates. In this course the student learns first aid and CPR techniques, studies anatomy and physiology, develops familiarity with common college health problems in class and in a supervised clinical internship, and is prepared to provide peer health services on and off campus.

Admissions

The overall level of test scores of the students entering in 1982 remained the same as for those entering in 1981, with the exception of the biology achievement score, which increased somewhat. The overall quality of the freshman class as measured by both academic ability and academic achievement is comparable to that of the previous several years. The number of applications totaled 1,665, the largest number in Caltech's history. Initial offers of admission totaled 300, additional offers were made to 53 students on the waiting list, and 207 freshmen were enrolled—including 41 women, the highest number in any freshman class.

A special transfer program, a 3-2 dual degree program with various liberal arts colleges, and regular admissions competition based on Caltech-designed examinations provide upperclass admissions. This year two students were admitted on the special transfer program from local community colleges. Thirteen students came to Caltech under the dual degree program. In the regular upperclass admissions competition, 112 students applied, 102 took the transfer examinations, 14 were offered admission, and 11 accepted. Total upperclass admission was 26 compared to 33 in 1981 and 1980.

The Admissions Office continued a rather intensive program to recruit and enroll undergraduate women students interested in a major in science or engineering.

Secondary School Relations

The secondary school relations program continued during the school year with Saturday classes in math and science. A seven-week summer program enrolling 371 students offered four courses: molecular biology, chemistry, physics/trig, and physics/calculus. All of these classes were taught by Caltech undergraduate students, with a few lectures by graduate students and professors.

The Wednesday lecture series for secondary school students continued with Professor Alan Sweezy: "Is the Population Bomb Still Ticking?"; Professor Noel Corngold: "Radiation and Energy"; Senior Research Associate Richard Marsh: "X-Ray Diffraction and the Structure of Molecules"; Professor Harold Zirin: "Studying That Wily Old Sun"; Assistant Professor Randal Bryant: "Systems on a Chip—the Design of Microelectronic Circuits"; Professor Donald Coles: "The Fascination of Fluid Mechanics"; and Associate Professor Judith Cohen: "Novae and Their Shells."

The Undergraduate Deans

The dean and the assistant dean, who oversee the personal and academic well-being of the undergraduate students, check individual academic progress during the year and help students who are having problems. They implement programs to enrich the undergraduate life at the Institute; for example, they administer an emergency loan fund for students. Financial support is furnished for projects of interest to students. These included this year a van trip to the shuttle launch at Cape Canaveral, various special student house events, a women's annex party, and several athletic team banquets. Various attractive fellowships and scholarships are administered through their office. Again this year, two Caltech students received Watson Fellowships to spend the year in independent study and travel.

During the spring and summer, preparations were made by the deans' office staff for the incoming class of freshmen and transfers. They were welcomed at Catalina Island in an orientation program designed to introduce them to Caltech. The deans' office also organized the Parents' Day program in November, and 162 parents of freshmen attended.

Registrar

Operations continued normally. At the beginning of the 1981 school year 217 new freshmen (36 women) and 32 new transfers (three women) were registered, giving a first-of-the-year total of 860 undergraduates (131 women), plus 241 new graduate students (98 women) for a total of 888 in that category. The number of undergraduates seems to be holding more or less constant, while the number of graduates continues to grow. At commencement, June 11, 1982, we handed out 167 B.S. degrees (82 of these with honor), 130 M.S. degrees, three Engineer degrees, and 121 Ph.D.s.

Financial Aid

A year ago, members and friends of the Caltech community were alerted to the impending decline in federal assistance for needy college students. The decrease has come to pass. It is not so drastic in terms of year-to-year percentages, but quite profound in terms of real dollars and numbers of students

Undergraduate Jacquie Fernandez teaches algebra to secondary school students at the "Saturday School," which offers classes in various fields of math and science.

requiring financial aid. In 1981-82, 80 percent of all eligible undergraduates applied for federally funded (or insured) grants, loans, and jobs. As Caltech's costs continue to outpace inflation and therefore to dwarf average wage-earners' cost-of-living increases, students' financial need can shortly be expected to exceed available resources.

The FY82 undergraduate financial aid budget remained adequate because of three crucial factors: (1) increased spending from endowment income reserves; (2) unprecedented scholarship support from the Institute general fund; and (3) hefty increments in students' expected contributions from summer savings, term-time employment, and loans. These three sources of stop-gap funding are limited, however. Student contributions have been pushed to the limit the market will bear.

Caltech students have one of the nation's finest loan repayment histories. However, unreasonable debt burdens can have a significant negative impact on the extent and kind of post-baccalaureate instruction and eventual careers that upperclassmen choose. The perception of substantial cumulative loans might discourage prospective Techers from matriculation despite their conviction, and ours, that this is the best school for them.

The need is for funds sufficient to bridge the considerable and growing gap between the price of Caltech instruction and what students and their parents can realistically contribute—in cash and indebtedness—toward that price. Over the years, grants and scholarships have been donated to Caltech in order to fund the need of particularly meritorious students, and more of this money is necessary.

Master of Student Houses

The master of student houses is a faculty member appointed to minister to the needs and well-being of undergraduate students, to promote harmony in the student houses, to counsel resident associates, and to provide moral and financial support for house social programs.

The current master, Professor Sunney Chan, encourages social involvement among students by either playing host to or subsidizing various events and programs. The Don Shepard Award not only rewards three essayists with prizes of $300 each but reimburses students $20 for dinner out under the "Fun Fund." This has become extremely popular with students who flock into the master's office to sign up. The master also provides a modest budget for house parties both on and off campus, holds tea parties once each term, continues to serve students doughnuts every Friday morning, and invites them to dinners and classical music brunches on a regular basis at the master's residence.

The interhouse cooking contest was held again this year with three winners receiving microwave ovens for their respective houses. A mutual undertaking of the master and students was a Caltech party at Scripps College with the master providing a band and roast suckling pigs.

The number of students accommodated in Institute housing has grown to 810 out of an undergraduate student body of 860. The off-campus houses accommodated 140 of these students. In order to enhance the quality of living in these houses the master initiated a rehabilitation program. Twelve students were given summer jobs painting and doing other repairs on a priority basis. This will be an on-going program with peak crews operating during the summer. Finally, under the room improvement fund 140 rooms in the student houses were improved by the students themselves, who were reimbursed for painting, carpeting, and adding shelves, skybeds, and other amenities.

Health Center

Student Counseling Services

A total of 1,550 hours of direct service were spent, most of them in individual psychotherapy; some marital/couples therapy work was also done (seven couples). There was roughly a 50-50 split between graduate and undergraduate students using the clinic, involving 12 percent of the student body.

Forty women and 69 men were counseled. The proportion of women using services was 37 percent, a 4 percent increase over last year and a 12 percent increase over the 1979-80 year. This trend is hard to explain, although two counselors participated in programs sponsored by the Organization of Women at Caltech (OWC), perhaps making women a bit more aware of counseling services.

1981-82 was the fifth year of operation of the peer counseling program. This preventive medicine and community outreach program in which undergraduates are trained throughout the year follows the principles of basic counseling and crisis intervention. Though the impact of the program is difficult to measure, referrals to the Health Center counseling staff were received from both previous and present peer counselors. We hope that a lack of major crises is partly the result of this program.

Medical Services

Medical Services treated approximately the same number of patients as in previous years for a wide variety of illnesses and injuries. Also given was advice on preventive care and self-care, physical examinations, and counseling on a wide range of gynecological problems.

The campus interaction program provided an opportunity for all staff members to be involved in the promotion of health awareness and Health Center services. A series of weekly articles in the *California Tech* on health subjects, under the title "The Body Shop," continued to be well received.

The Health Advocates program was established at the Health Center, and was attended by students from different interests. Five graduated with skills of advanced first aid, cardiopulmonary resuscitation, and management of acute student-related problems.

Performing Arts

Perhaps the most significant event during the year was Olaf Frodsham's retirement after 29 years as director of the Men's Glee Club. Needless to say, he will be missed. Faced with the difficult problem of selecting a successor, a committee of faculty and students sifted through about 100 applications and finally, after a series of interviews, chose Dr. Donald Caldwell for the position of Director of Choral Music. Caldwell comes to Caltech with impeccable credentials and more than 12 years experience in college choral music directing.

In other matters, the Glee Clubs staged another sell-out Festival of Light. This will be the last because Frodsham is planning to continue this tradition at another location. The Caltech musical for this year was *South Pacific*, which was also a sell-out. The theater arts program (nicknamed TACIT by students) created another first—an outdoor production of *Two Gentlemen of Verona*—using the amphitheater adjacent to the new Braun Laboratories. An innovative children's theater touring unit was established that has presented a student-written version of *The Wind in the Willows* in several local elementary schools and shopping malls.

Athletics, Physical Education, and Recreation

The vast majority of Caltech undergraduates (76 percent) continue to participate in organized physical activity. Twenty-nine percent participated in one or more of the 11 intercollegiate sports. About 45 percent represented their student house in one or more of the eight intramural sports, while 44 percent received instruction in one of the 17 activities offered during the past year. Just under 10 percent of the undergrads designed and carried on their own fitness programs.

Grad student, faculty, and staff participation increased in both the instructional and competitive aspects of the program. Participation by women, both grad and undergrad, increased in the intercollegiate and club sports programs.

While participation in the organized sports programs increased during the past year, student participation in unorganized, indoor recreational activities continued to be severely limited by the lack of space.

Placement and Career Planning Services

Campus recruiting for graduating students was up slightly over 1981, and interviewing for continuing students seeking summer employment increased by over 300 percent. Salary offers for full-time positions increased by about 9 percent, with the average monthly salary for B.S. graduates $2,214, M.S. graduates $2,417, and Ph.D. graduates $2,815. Industrial positions were taken by 29 percent of the B.S. and 35 percent of the M.S. graduates, while 56 percent of the B.S. and 57 percent of the M.S. graduates continued their education. Of the Ph.D. recipients, 56 percent accepted industrial positions and 40 percent accepted academic positions.

In May 1982, the office held the first-ever employer career day. The event was a great success with 21 companies represented and over 150 undergraduate and graduate students participating. The office also presented seminars entitled: "Applying to Graduate School," "Job Search Strategy," "The Summer Job Search," and "Medical School Information," and arranged individual practice interviews for about 30 students.

Ten separate career-related publications were developed during the year to help students both define and obtain their career goals, and during the year the director and the career counselor advised over 500 individual students. The office also listed more than 500 part-time positions for students, both on and off campus, and listed 347 positions for alumni.

Graduate Studies

James J. Morgan, Acting Dean of Graduate Studies

Undergraduates at Caltech are selected by an admissions committee composed of approximately 15 faculty members assisted by the director of admissions and his staff. Students do not choose their options until their sophomore year.

Graduate students, on the other hand, are chosen by 19 separate graduate options after they have applied to the dean of graduate studies stating their intended major field of study and special interests. Members of the options make their decisions by considering whether the applicant is capable of original studies of an advanced character and is able to investigate scientific problems independently and efficiently.

The total enrollment at Caltech is now at an all-time high, 1,810 souls in the fall of 1982. For the past ten years there has been little or no growth in *undergraduate* enrollment, which has been at about 840 $\pm$ 20. The freshman class size has been about 215 $\pm$ 10, transfers about 30 $\pm$ 5. Apparent stability. Recent *graduate* enrollment presents a different picture: an overall increase of 36 percent in the ten years from 1973 to 1982, about 3.3 percent per year, average.

Growth is the word for our total graduate program in recent years (as it had been earlier, from before 1960 through 1967). And most of the net growth in the past ten years can be accounted for in about a half-dozen programs: chemistry, chemical engineering, electrical engineering, computer science, physics, applied physics, and social science. The current total graduate enrollment is made up of 36 percent in engineering and 64 percent in the sciences.

Theodore Y.-T. Wu, professor of engineering science, explains a fine point of fluid dynamics to one of his graduate students.

Admissions for 1982-1983

The number of graduate applications for 1982-1983 was an all-time high, 4 percent greater than for the previous year. Applications were up by 1 percent in the sciences, up by 6 percent in engineering, and by 40 percent in the small social science option.

This year 23 percent of the applicants were offered admission, compared to 24 percent last year, with 47 percent of these offers being accepted compared to 46 percent last year. A total of 269 accepted admission as new students, the largest number accepting in Caltech's history, exceeding the 267 accepting admission in 1979-1980.

Student Support

Each year there are slightly fewer fellowships and traineeships available for graduate students. One encouraging innovation this year is that a few corporations and foundations have made available fellowships specifically designed to encourage careers in teaching. Assistantships, the primary source of graduate student stipends, have increased only slightly during the past few years. Federal college work-study funds decreased significantly for 1981-1982, to half of the amount available in 1980-1981. A gradual increase in these funds is expected during the next few years.

Enrollment by Option for the Past Ten Years*

Option	1973-74	1974-75	1975-76	1976-77	1977-78	1978-79	1979-80	1980-81	1981-82	1982-83
Astronomy	23	25	26	20	22	19	20	20	18	20
Biology	66	73	86	80	82	74	76	66	67	65
Chemistry	111	134	143	158	167	164	165	172	174	181
Chemical Engineering	41	45	46	51	44	52	60	65	64	78
Geology	72	80	81	81	81	77	74	67	76	75
Mathematics	17	25	16	18	22	18	17	16	15	17
Physics	98	100	99	121	119	114	119	119	121	130
Science Totals	428	482	497	529	537	518	531	525	535	566
Aeronautics	39	37	33	42	40	47	46	42	42	49
Applied Mathematics	23	24	23	21	19	22	27	28	32	27
Applied Mechanics	9	10	11	16	15	14	15	17	22	17
Applied Physics	32	44	46	51	54	58	60	52	52	55
Civil Engineering	12	14	22	30	20	31	31	30	24	26
Computer Science†	—	—	—	—	—	—	32	23	36	42
Electrical Engineering	56	42	39	38	55	51	57	56	67	76
Engineering Science	39	32	26	28	31	36	10	9	10	9
Env. Engrng. Science	28	32	22	23	20	20	20	18	21	28
Materials Science	1	1	1	0	1	1	0	3	1	1
Mechanical Engineering	26	26	26	21	30	31	47	39	35	38
Engineering Totals	265	262	249	270	285	311	345	317	342	368
Social Sciences	4	9	15	19	20	23	22	18	20	21
Total All Fields	697	753	761	818	842	852	898	860	897	955

*Figures reflect corrected first-term registration.
†Before 1979-80, when the computer science option was established, work in that discipline came under Engineering Science.

Enrollment for 1981-1982

The graduate enrollment of 897 for 1981-1982 was 4 percent greater than the 860 enrolled in 1980-1981. These enrollments have been exceeded by the enrollment of 955 in 1982-1983, now the largest enrollment in Caltech history, 6 percent greater than the previous high of 898 in 1979-1980.

For 1981-1982 the percentage of foreign students was 31 percent, up from the five-year average of 29 percent. The distribution was 23 percent in the sciences and 44 percent in engineering.

The total number of graduate degrees awarded in June 1982 was 254, down slightly from the 266 awarded in June 1981. Ph.D. degrees awarded in 1982 totaled 121, compared to the 129 awarded in 1981. The average residence time was 5.0 years for those receiving Ph.D. degrees in 1982, compared to 4.8 years in 1981.

Summary

Interest in graduate study at Caltech continues to be high. The quality of applicants and admitted students is excellent, perhaps even increasing slightly the past few years. However, the financial support that is now available may not permit increases beyond the 1982-1983 level for the next few years.

Institute Relations

Dwain N. Fullerton, Vice President for Institute Relations

In 1981 Institute Relations set itself the tasks of making the Institute's work better understood and of increasing the flow of gifts from private sources. On both counts there was encouraging progress. Several local governments in San Diego and Riverside counties have agreed to switch to low-pressure sodium street lights, a major step in protecting Palomar Observatory from urban light pollution. This followed an intensive educational effort by astronomers and Institute public relations staff. And private donors responded with a record level of contributions. All in all, it was a good year.

Alumni Association

Alumni House has fulfilled the expectations of its founders. Not only has it provided offices for the alumni association and the alumni fund, it has provided a setting for reunions (class of '21 among others), receptions, meetings, sports banquets, division parties, and even an occasional wedding. The final fund-raising effort for the house has been successfully accomplished, and landscaping plans have been completed and approved by the board of directors.

Seminar Day in May, the 45th in Caltech history, found 1,500 alumni and their guests enjoying a return to the Caltech campus to hear 13 faculty speakers. Simon Ramo, alumnus and trustee, was the general session speaker. In June, Philip L. Reynolds, president of the alumni association for 1981-82, relinquished his post to William J. Karzas.

The high school relations program achieved much success during the year, and efforts were begun to initiate a formal admissions assistance program that will use alumni more extensively than in past years.

Development

Caltech received a total of $22.87 million in cash gifts in fiscal year 1982. This was a record and represented a 16 percent increase over last year (itself a record-breaker). Of this sum, corporations and foundations gave $15.5 million, and individuals contributed $7.3 million.

The alumni fund, chaired by David L. Hanna, also set a new record—43 percent participation by alumni donors. In the spring of 1982 The James Irvine Foundation pledged a matching grant to Caltech that alumni can earn through increased giving. That campaign, which started in July, also features the extensive involvement of alumni volunteers.

President Collis H. Holladay led The Associates in another active year of support activities on behalf of the Institute. The Associates continue to provide crucial unrestricted funds to Caltech, and serve as effective volunteers in making friends for the Institute.

Notable major gifts this past year included the R. Stanton Avery Professorship of Distinguished Service, established by R. Stanton Avery, chairman of Caltech's Board of Trustees. The first occupant of the chair is Professor Rochus Vogt. A bequest from the Josephine Halsell Trust provided more than $1 million in unrestricted funds. Pledges from the System Development Foundation totaled over $2 million for research on the physics of computation and neural networks. A grant was made by the Rockwell International Corporation Charitable Trust for research in engineering, and another from the Annenberg School of Communication and the Corporation for Public Broadcasting was given for the production of an educational TV series on physics called "The Mechanical Universe."

Public Relations

On January 26, 1982, Caltech joined with the U.S. Postal Service in staging the First Day of Issue ceremony for a 37-cent stamp—in the Great Americans series—honoring Robert A. Millikan. Community leaders, representatives of the postal service, Caltech faculty and staff, and philatelists all gathered at Beckman Auditorium to honor the administrative head of Caltech from 1921 to 1945.

Public relations is providing assistance in the battle that Palomar Observatory officials are waging against a growing

In Caltech's Seismological Laboratory, undergraduate David Sahnow discusses earthquakes with a group of tourists. Aproximately 2000 visitors tour the campus each year with student guides operating from the Institute's Public Relations office.

light-pollution problem in San Diego and Riverside counties. While the 200-inch Hale telescope (which recently rediscovered the approaching Halley's comet) can penetrate deeper and deeper into space because of new electronic detectors, viewing of faint objects is threatened by the growing brightness of the sky.

The area around Palomar Mountain is developing rapidly; hence more lighting is needed. And since the 1973 oil crisis, street lighting has been changing from mercury vapor to the less expensive high-pressure sodium vapor, which is particularly destructive to observatory viewing.

A public information program has been initiated to advise both the general public and state, county, and local governments of the problem. The aim is to gain widespread adoption of low-pressure sodium vapor lighting (which can be filtered out at the telescope). Results to date show a growing awareness of the problem, and frequently a willingness to cooperate.

Business and Finance

David W. Morrisroe, Vice President for Business and Finance and Treasurer

Fiscal year 1982 reflected improvements in the financial markets, which resulted in a marked increase in the value of Caltech's investments. Gifts and nonfederal grants were at an all-time high; however, declines were experienced in the levels of federal support for the programs conducted at the campus and the Jet Propulsion Laboratory.

During fiscal year 1982, the Braun Laboratories in Memory of Carl F and Winifred H Braun for cell biology and chemistry and the Thomas J. Watson, Sr., Laboratories for Applied Physics were occupied. These facilities provided an additional 118,000 square feet for instruction and research. Construction was started on the first phase of the Institute's cogeneration program, which will use steam produced by campus boilers to operate a turbine-generator that will provide energy for electricity, heating, and cooling. This project, scheduled for completion in January 1983, will generate power equivalent to 20% of the fiscal 1982 campus electrical power requirements. Plans were also started for the second phase of this program—a gas/oil fired combustion turbine to provide additional power. When completed as scheduled in October 1984, this facility will provide an additional 60% of the projected fiscal 1985 campus power requirements. A new graduate student apartment complex housing 156 students, and a new athletic facility, including a swimming pool and locker room and training facilities, were also in planning stages.

Gifts

Gifts and nonfederal grants increased from $17.0 million in 1980 to $22.3 million in 1981 to $25.7 million in 1982—an all-time high. These gifts and grants continue to be a major source of Caltech's financial strength. While the trend of total gifts to Caltech in the past three years has been strongly positive, endowment gifts have declined as a fraction of the total in recent years. Since these gifts represent a major source of funding for Caltech's long-term health, special efforts are under way to increase them.

Summary of Operations

The Institute's operating expenditures for the years ended September 30, 1981, and September 30, 1982, are presented on Exhibit 3 of the Financial Statements following this report. Total current fund expenditures increased from $87.7 million in 1981 to $94.6 million in 1982, or 7.9%

Direct costs at the Jet Propulsion Laboratory, funded largely by the National Aeronautics and Space Administration, decreased $11.8 million, or 3.0%, to $384.8 million, resulting primarily from a reduction in energy-related research programs. Campus federal research expenditures decreased $2.4 million, or 7.5% below the prior year, primarily in the areas of subcontracts and capital equipment. This decrease, partially offset by an increase of $1.2 million in expenditures for privately supported research, resulted in a net decrease in campus organized research of $1.2 million, or 3.5%, to $32.6 million. At this writing the fiscal 1983 outlook is for moderate growth in the federally sponsored programs at the Jet Propulsion Laboratory and the campus, thus reversing the decline in support experienced in fiscal 1982.

Instruction and departmental research expenditures, largely financed by the Institute and other private sources, increased to $32.3 million, or by 13.5%.

Scholarship and fellowship expenditures for both undergraduate and graduate programs totaled $4.5 million, an increase of 26.9%. Income from gifts and endowments and federal grants are the major sources of support for these programs.

Institutional and student support expenditures increased $1.4 million, or 12.6%, to $12.8 million. This category includes Institute Relations, Development, Public Relations, Business Affairs, Financial Affairs, Contract Administration, Student Affairs, Physical Education, and general administration of the Institute, as well as general expenses such as insurance, taxes, and so forth.

Plant operation, maintenance, and utilities expenditures totaled $8.1 million—a 23.2% increase of $1.5 million. Continued growth in the costs of energy accounted for more than half of this increase. The costs of electrical power increased from 4.8¢ to 6.1¢ per kilowatt hour, while the cost of gas increased from 38.4¢ to 49.3¢ per therm.

Auxiliary enterprises expenditures increased $349 thousand, or 9.0%, to $4.2 million, reflecting increases in purchases and services to accommodate sales increases.

Fund Groups

Caltech's financial accounts are grouped into self-balancing entities or funds. Besides the current fund, which was described above, there are four others. Their status is reported in Exhibits 1 and 2 and discussed below.

Loan Funds

Funds for interest-bearing loans to students amounted to $5.1 million at September 30, 1982. Of this amount $4.4 million represented outstanding loans to Caltech students with $2.9 million provided by the federal government under the National Direct Student Loan Program and $1.5 million from contributions by private donors. Loan principal payments in arrears for 120 days or more amounted to $201.8 thousand, or 4.5% of the total loans outstanding. This percentage continues to be well under the national average after more than two decades of student loan activity.

Endowment and Similar Funds

Primary investment objectives for endowed funds are preservation of principal, maintenance of reasonable income levels to support current operating expenses, and increase of the funds through capital growth to provide for the future needs of the Institute.

Fiscal 1982 was characterized by declining interest rates and a welcome easing in inflation. To illustrate—yields on 91-day treasury bills decreased from 15.0% at September 30, 1981, to 8.3% at September 30, 1982.

Inflation, which at the end of fiscal 1981 was running at an annual rate of 11%, had moderated to 5% at September 30, 1982. As the economy entered a transition phase and the market appeared to be starting a new cycle, the composition of the Institute's endowment was adjusted to take advantage of the evolving economic environment. Short-term commercial obligations were reduced during fiscal 1982 from 20.6% of endowment assets at September 30, 1981, to 7.1% at September 30, 1982, and invested in both the fixed income and equity markets. This move from cash equivalents to equity and fixed income sectors, together with market appreciation and gifts of $3.2 million, resulted in an increase in the market value of the Institute's endowment of $24.0 million.

Part of a massive landscaping and campus beautification program, Bechtel Mall provides an additional area for relaxation and contemplation.

Endowment fund investments at September 30, 1982 and 1981, in thousands, are summarized below:

	Market Value			
	1981	%	1982	%
Short-term commercial obligations	$ 37,934	20.6%	$ 14,824	7.1%
Fixed income securities	29,310	15.9	57,098	27.4
	67,244	36.5	71,922	34.5
Common stocks	93,427	50.7	112,134	53.8
Preferred stocks and convertible securities	4,112	2.2	2,668	1.3
Real estate, notes receivable and other	19,538	10.6	21,641	10.4
Total investments	$184,321	100.0%	$208,365	100.0%

Life Income and Annuity Funds

Life income and annuity fund balances amounted to $22.7 million at September 30, 1982, and represented some 129 trust and annuity agreements. These funds will become a major source of endowment funds upon termination of the agreements.

Plant Funds

The plant fund balances increased 6.2% from $167.1 million to $177.5 million after provision for $2.0 million of retirements. Current fund acquisitions of $6.3 million, together with gifts and transfers for capital purposes, made up the major additions to the plant funds.

California Institute of Technology
Balance Sheet

(in thousands)	September 30, 1981
	Total All Funds
Assets	
Cash (demand deposits)	$ 746
Accounts receivable:	
United States government (note B)	45,987
Other	1,813
Student accounts and notes receivable	6,257
Investments (notes A and C)	232,931
Interfund advances	
Prepaid expenses and other assets	2,226
Campus properties (note A):	
Equipment	70,679
Buildings	88,357
Land	9,937
	$458,933
Liabilities and Fund Balances	
Accounts payable and accrued expenses (note B)	$ 51,588
Deferred student revenue	2,921
Funds held in custody for others	7,046
Annuities payable (note A)	1,600
Fund balances	395,778
	$458,933
Fund balances comprise (Exhibit 2):	
United States government grants refundable	$ 2,862
Institute funds—	
Unrestricted	2,288
Discretionary endowment	
Unrestricted	34,438
Restricted	25,256
Endowment principal	123,806
Other restricted funds	43,610
Invested in plant	163,518
	$395,778

See accompanying notes to financial statements.

September 30, 1982

Total All Funds	Current Funds	Loan Funds	Endowment and Similar Funds	Life Income and Annuity Funds	Plant Funds
$ 1,151	$ 858	$ —	$ 2	$ 291	$ —
41,935	41,935	—	—	—	—
2,067	2,067	—	—	—	—
6,797	2,351	4,446	—	—	—
237,324	23,050	704	185,313	24,057	4,200
	4,867	—	—	—	(4,867)
2,668	2,668	—	—	—	
				—	
76,376	—	—	—	—	76,376
92,587	—	—	—	—	92,587
10,536	—	—	—	—	10,536
$471,441	$77,796	$5,150	$185,315	$24,348	$178,832
$ 47,628	$46,036	$—	$—	$ 286	$ 1,306
3,607	3,607	—	—	—	—
7,563	6,570	—	993	—	—
1,382	—	—	—	1,382	—
411,261	21,583	5,150	184,322	22,680	177,526
$471,441	$77,796	$5,150	$185,315	$24,348	$178,832
$ 2,949	$—	$2,949	$—	$—	$—
2,983	741	—	—	—	2,242
34,148	—	—	34,148	—	—
25,807	—	—	25,807	—	—
124,367	—	—	124,367	—	—
47,681	20,842	2,201	—	22,680	1,958
173,326	—	—	—	—	173,326
$411,261	$21,583	$5,150	$184,322	$22,680	$177,526

California Institute of Technology
Statement of Changes in Fund Balances

(in thousands)	Year Ended September 30, 1981
	Total All Funds
Fund balance at beginning of year (Exhibit 1)	**$366,691**
Revenues and other additions (notes A, D and F)	
Student tuition and fees	8,553
Investment income	19,750
Net gain (loss) on disposal of investments—	
Unrestricted	859
Restricted	3,330
Gifts and nongovernment grants	22,271
United States government grants and contracts—	
Reimbursement of direct costs	34,579
Recovery of indirect costs and management allowance	20,153
Auxiliary enterprises revenues	3,594
United States government advances	205
Plant acquisitions, etc. (including $6,333 included in campus operating expenditures and $5,432 included in plant acquisitions, payments on interfund advances and renewals)	22,815
Adjustment of actuarial liability for annuities payable (note A)	750
Other	1,277
Total revenues and other additions	138,136
Expenditures and other deductions:	
Campus operating expenditures (Exhibit 3)	(87,655)
Plant acquisitions, payments on interfund advances and renewals	(16,634)
Retirement and disposal of campus properties	(2,933)
Interest on advances for plant purposes	(224)
Payment to life beneficiaries	(1,398)
Other	(205)
Total expenditures and other deductions	(109,049)
Transfers among funds:	
Gifts allocated	—
Discretionary endowment transfers to (from) current funds	—
Allocations for plant purposes	—
Terminated trust and annuity agreements	—
Other	—
Total transfers	—
Increase (decrease) for the year	29,087
Fund balance at end of year (Exhibit 1)	**$395,778**

See accompanying notes to financial statements.

Year Ended September 30, 1982

Total All Funds	Current Funds Unre-stricted	Current Funds Re-stricted	Loan Funds	Endowment and Similar Funds	Life Income and Annuity Funds	Plant Funds
$395,778	$ 942	$17,902	$4,849	$183,500	$21,475	$167,110
10,485	10,485	—	—	—	—	—
20,441	6,228	12,210	100	—	1,493	410
(746)	—	—	—	(746)	—	—
(3,211)	—	—	—	(3,019)	(192)	—
25,652	5,196	12,917	98	3,247	1,004	3,190
31,488	—	30,688	—	—	—	800
21,147	19,362	—	—	—	—	1,785
4,103	4,103	—	—	—	—	—
108	—	—	108	—	—	—
11,765	—	—	—	—	—	11,765
216	—	—	—	—	216	—
1,493	593	69	63	—	214	554
122,941	45,967	55,884	369	(518)	2,735	18,504
(94,603)	(42,906)	(51,697)	—	—	—	—
(9,030)	—	—	—	—	—	(9,030)
(1,958)	—	—	—	—	—	(1,958)
(199)	—	—	—	—	—	(199)
(1,493)	—	—	—	—	(1,493)	
(175)	—	(102)	(73)	—	—	—
(107,458)	(42,906)	(51,799)	(73)		(1,493)	(11,187)
—	(1,742)	(707)	—	2,449	—	—
—	(899)	(330)	—	1,229	—	—
—	(193)	(386)	—	(2,520)	—	3,099
—	—	—	—	37	(37)	—
—	(428)	278	5	145	—	—
—	(3,262)	(1,145)	5	1,340	(37)	3,099
15,483	(201)	2,940	301	822	1,205	10,416
$411,261	**$ 741**	**$20,842**	**$5,150**	**$184,322**	**$22,680**	**$177,526**

California Institute of Technology
Statement of Operating Expenditures

Exhibit 3

(in thousands)	Year Ended September 30	
	1981	1982
Educational and general:		
Instruction, including departmental research	$ 28,478	$ 32,334
Organized research	33,781	32,604
Scholarships and fellowships	3,540	4,494
Institutional and student support	11,399	12,836
Plant operation, maintenance and utilities	6,587	8,116
Total educational and general	83,785	90,384
Auxiliary enterprises	3,870	4,219
Total campus expenditures	$ 87,655	$ 94,603
Direct costs of sponsored research at Jet Propulsion Laboratory (fully reimbursed by the United States government)	$396,557	$384,780

See accompanying notes to financial statements.

California Institute of Technology
Notes to Financial Statements
September 30, 1982

Note A — *Summary of Significant Accounting Policies*

Basis of accounting and reporting — The financial statements of the Institute, a not-for-profit educational organization, have been prepared in accordance with the principles of accrual basis fund accounting for colleges and universities. Under these principles Institute resources are accounted for by the use of separate funds so that visibility and control are maintained for the benefit of the Institute and its sponsors. Funds that have similar objectives and characteristics have been combined into fund groups. Within each fund group, fund balances restricted by outside sponsors for specific purposes are so indicated and are distinguished from unrestricted funds that are available for use in achieving any Institute objectives.

The financial statements of the Institute reflect the volume of activity at the Jet Propulsion Laboratory, which is managed by the Institute, but owned and supported by the United States government through the National Aeronautics and Space Administration.

Investments — Institute investments are stated at their approximate market value at date of gift, or at cost if purchased by the Institute, less applicable amortization and depreciation of real estate, unless there has been an impairment of value not considered temporary.

All investments of endowment and similar funds are carried in an investment pool unless special considerations or donor stipulations require that they be held separately. Pool share values are computed periodically based upon the total market value of the investment pool and the total number of pool shares invested.

Income on investments of endowment and similar funds is recorded as current fund revenues for the purposes specified by the donor. Such income is supplemented, where necessary, by transfers of additional amounts so as to result in a total return from the investment pool equivalent to 5% of the average market of the pool over a three-year period. This total return concept is authorized by the California Uniform Management of Institutional Funds Act, which allows the prudent use of realized appreciation on investments, thus permitting greater flexibility in investment strategy.

Campus properties and plant funds — Campus properties are recorded at cost of construction or acquisition, or at appraisal value at date of gift, and no depreciation or amortization is recorded. The Institute provides for the renewal and replacement of its campus properties from funds designated for this purpose. Expenditures for maintenance and repairs are generally charged to current funds as plant operation and maintenance expenditures.

Annuities — Annuities payable to certain donors of the Institute are recorded at the present value of the liability calculated under an actuarial method which takes into account the life expectancies of the recipients.

Tax-exempt status — The Institute is a tax-exempt educational organization under federal and state income, gift, estate, and inheritance tax laws.

Note B — *United States Government Contracts*

The Institute has many contracts with the United States government that provide for reimbursement of costs incurred for sponsored research at the Jet Propulsion Laboratory and at the campus. These contracts gave rise to a substantial portion of the accounts payable and accrued expenses in the current funds at September 30, 1982 and 1981, and in turn to accounts receivable from the United States government.

Note C — *Investments*

Institute investments, at carrying values (see Note A), comprise the following:

	September 30	
	1981	1982
Marketable securities (Approximate market value of $148,367,000 in 1981 and $196,058,000 in 1982)	$156,261,000	$178,027,000
Short-term commercial obligations	50,629,000	35,036,000
Settlements in process —		
Receivables for securities sold	2,751,000	1,117,000
Payables for securities purchased	(1,226,000)	(4,050,000)
Real estate, less amortization and accumulated depreciation of $3,560,000 and $3,622,000	18,242,000	19,982,000
Mortgages, notes and other securities	6,274,000	7,212,000
	$232,931,000	$237,324,000

Investments shown above include the investment pool as follows:

	September 30	
	1981	1982
Investment pool assets at year end —		
At carrying value	$157,845,000	$156,196,000
At approximate market value	$152,505,000	$166,534,000
Pool share value at market	$ 10.06	$ 10.81
Annualized income earned per pool share	$ .85	$ .83

Note D — *Funds Held in Trust*

The Institute is the income beneficiary of certain funds, recorded at a nominal value, which are held in trust by others and which had current market values, estimated by the Institute, of approximately $9,000,000 and $8,000,000 at September 30, 1982 and 1981, respectively. The income derived from these funds amounted to $704,000 and $635,000 for the years ended September 30, 1982 and 1981, respectively. This income has been included as investment income in the Statement of Changes in Fund Balances.

In addition, the Institute is the trustee for several revocable trusts in which it has a remainder interest and for which it makes income payments for life to the grantors of the trusts. These trusts totaling $3,750,000 and $3,450,000 at September 30, 1982 and 1981, respectively, have been excluded from the financial statements due to their revocable nature.

Note E — *Retirement Plans*

The campus has two retirement plans covering substantially all its employees that are funded by periodic transfers to the respective insurance companies. The provisions for these pension costs for the years ended September 30, 1982 and 1981, totaled $2,933,000 and $2,698,000, respectively. The Institute's policy is to fund pension costs accrued. At the most recent annual valuation, the funded amount and balance sheet accruals for retirement plans were sufficient to cover the actuarially computed value of vested benefits. A comparison of accumulated plan benefits and plan assets for the defined benefit plan at the most recent annual valuation dates (September 30, 1980 and 1981) is presented below (in thousands of dollars).

	September 30	
	1980	1981
Actuarial present value of accumulated plan benefits:		
Vested	$13,280	$13,580
Non-vested	800	810
	$14,080	$14,390
Plan assets	$14,950	$15,400

In determining the actuarial present value of accumulated plan benefits as of September 30, 1981, the rates of return used were 5-3/4 percent for fixed dollar annuities and 3-3/4 percent for variable annuities. This represents a weighted rate of 5 percent.

Note F — *Pledges*

The Institute does not record pledges in its financial statements. At September 30, 1982, the Institute had pledges on hand (principally for restricted purposes) totaling approximately $21,300,000, of which $6,700,000 is expected to be collected in 1983. It is not practicable to estimate the net realizable value of such pledges.

Price Waterhouse

West Los Angeles, California
December 30, 1982

To the Board of Trustees of
California Institute of Technology

In our opinion, the accompanying balance sheet and the related statements of changes in fund balances and of operating expenditures (Exhibits 1 through 3) present fairly the financial position of California Institute of Technology at September 30, 1982, and the changes in fund balances and the operating expenditures for the year then ended, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year. Our examination of these statements was made in accordance with generally accepted auditing standards and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

We have previously examined and reported upon the September 30, 1981, financial statements which are included in summary form for comparative purposes.

Price Waterhouse & Co.

Board of Trustees as of September 30, 1982

California Institute of Technology
Pasadena, California 91125