California Institute
of Technology

Engineering & Science

Summer 1988

*Mauna Kea;
inaugural
address;
technology
and capital;
designing
polymers*

On the Cover

The summit of an extinct Hawaiian volcano is home to a collection of telescopes. Among them are the Caltech Submillimeter Observatory (CSO, foreground) and, peeking out from behind it, the W.M. Keck Observatory, a joint project of Caltech and the University of California. The 10-meter Keck instrument will be the most powerful optical telescope in the world when it is finished in 1991. The CSO has been operating for a year and a half, collecting short radio waves that can penetrate interstellar dust clouds but can't get through much of the earth's atmosphere. The arduous life of astronomers on this remote 14,000-ft. mountaintop is described in an article beginning on page 10.

In This Issue

The second week of April was a busy one at Caltech. On Monday the 11th, ground was broken for the new Beckman Institute, which will be devoted to interdisciplinary research primarily in chemistry and biology. On April 12 Thomas E. Everhart was inaugurated as Caltech's president with all the colorful pomp and circumstance that academia brings to such occasions. About 3,000 attended the event, and greetings were extended from various segments of the Caltech community, as well as from other academic institutions and learned societies. After Robert A. Millikan's hood was placed over Everhart's shoulders as a symbol of his formal investiture, the new president delivered his inaugural address. Balloons and confetti completed the celebration, and a good time was had by all, most of whom stayed for lunch.

On Thursday, April 14, at Caltech's Industrial Relations Center, Ralph Landau delivered the 1988 Bray Lecture, whose purpose is to increase understanding of the American economic system. The Ulric B. and Evelyn L. Bray Lectureships were established by Mrs. Bray in honor of her late husband, a successful scientist and entrepreneur who was active in public affairs and maintained a strong connection to Caltech.

A New Look

In its 51-year history *E&S* has changed its face 18 times. The most durable cover design enjoyed a longevity of 14 years, from 1950 to 1964. The apparently least successful lasted for only two issues in 1969, and several designs survived only a year. So, after four years—well above the average—of the current cover (which coincidentally closely resembled the *Stanford Engineer*), we are continuing the tradition of change and coming out with *E&S*'s 19th new look—inside as well as out. Maureen Erbe was the designer. We hope our readers will find it pleasing.

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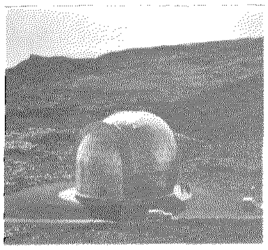

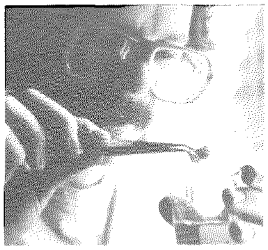

Departments

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The Inaugural Address

Caltech: People and an Institution in Pursuit of Excellence

by Thomas E. Everhart

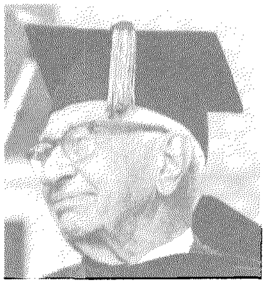
Robed in the academic garb of Cambridge University, where he earned his doctorate in engineering, Thomas Everhart pauses in the procession to his presidential inauguration ceremony on April 12.

I accept the honor and the responsibility of the presidency of the California Institute of Technology with both enthusiasm and humility. I am enthusiastic about this institution, what it has accomplished, and what it can accomplish in the future. I am humbled by my profound respect for the quality of my predecessors and what they have achieved. I am grateful to the Board of Trustees and to the Faculty Advisory Committee for this opportunity to serve Caltech, and to the Board, faculty, students, and staff for the warm welcome my wife, Doris, and I have received here.

I am also grateful to many former associates and friends who have come to share this occasion with us, and to delegates from sister institutions who honor us with their presence. I ask your help as I assume these duties, for I have learned that no one succeeds in life without a great deal of help from others. I have been fortunate to work with some superlative people throughout my career—teachers and fellow students in school, college, and graduate school; colleagues at Hughes, Ampex, and Westinghouse Research Labs; faculty colleagues, students and staff at Berkeley, Cornell, Illinois, and now Caltech; and colleagues from foreign universities, professional societies, and advisory committees. And a special word of thanks to my former graduate students, whose hard work, intelligence, and inspiration have often pushed me to the limit. Many of you have come to share this day with us, and I thank you for the help you have given me over the years. My family has been wonderfully supportive as well, and I am glad so many of them can be with us today.

Universities are among the most important of social institutions. Some have said that universities are such storehouses of knowledge because the freshmen bring so much with them when they come, and take so little away when they leave. I read not long ago that there are 62 social institutions in the western world that have been in continuous operation since 1530, and 58 of them are universities. In 1530, the purpose of universities was to preserve and interpret knowledge through the scholarship of those who professed to know—the professors—and to communicate that knowledge to the coming generations—the students. Since 1530, both the nature and the mission of universities have changed. In fact, over a century ago, Thomas Huxley commented that "The medieval university looked backwards; it professed to be a storehouse of old knowledge . . . . The modern university looks forward, and is a factory of new knowledge."

But notice that even Harvard, our oldest U.S. university, founded in 1636, misses being in this select group of 58 continuously operating universities by more than a hundred years! Indeed, the higher education system in this country, which in recent times has been the envy of much of the world, is relatively young. Some of the most distinguished institutions have been in existence for only about a century. Many of our large state institutions owe their existence to the Morrill Land Grant Act of 1862, including three institutions that I have served. These institutions have provided educations to much larger numbers of students than could be accommodated in



Lee A. DuBridge, Caltech's president from 1946 to 1968, listens to his third successor.

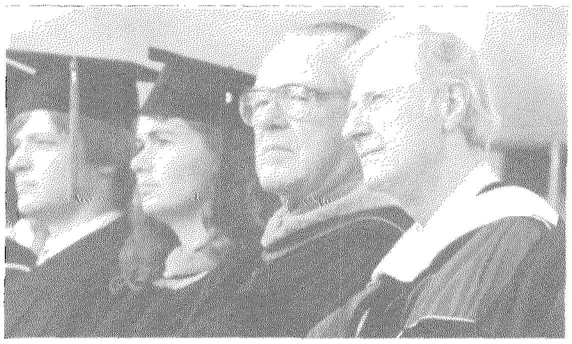
the private colleges and universities of the country, and some of them have become very distinguished in their own right. The private universities, on the other hand, have had more freedom to experiment and to innovate, be it the house system for undergraduate living at Harvard, the "great books" curriculum at St. Johns, the stimulation of and collaboration with industry that led to Stanford's Industrial Park, early computerization of the campus, as at Dartmouth, or the focus on a few important subjects, which has been the hallmark of Caltech.

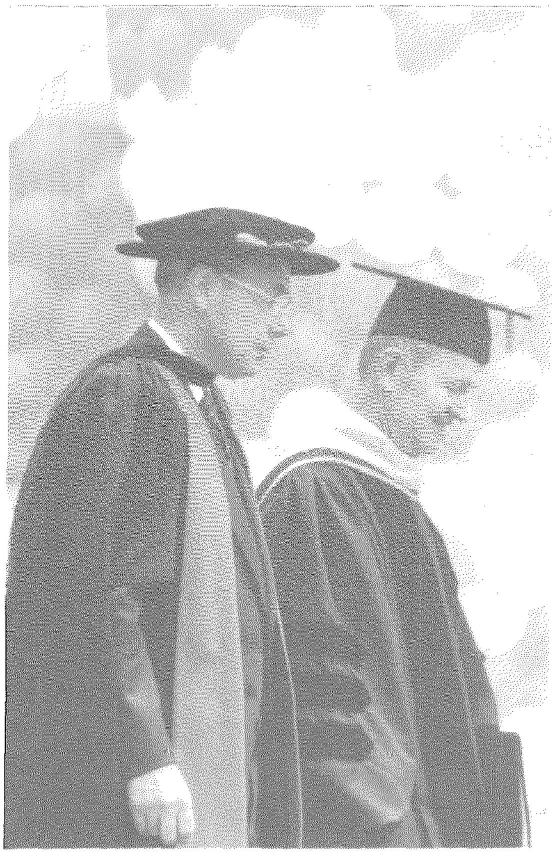
From President Rhodes of Cornell, I learned how important the traditions and heritage of an institution can be to its march toward further accomplishment. The heritage of the past is the foundation upon which we build the achievements of the present and our vision of the future. Let us consider our heritage here at this institution. Picture if you can this vast area of Los Angeles, devoid of houses, freeways, and other aspects of inhabitation by mankind. This was the scene in 1771 that greeted the Spanish founders of Mission San Gabriel, which still exists a short distance from this spot. One hundred twenty years later, as the population of settlers was increasing, Amos G. Throop founded a school of arts and crafts in Pasadena. Since its early days, under a variety of names, it has enjoyed the support of local citizens, and distinguished members of the community have served on its Board of Trustees. The vision of some of these early Board members, and especially that of George Ellery Hale, an astronomer and first director of the Mount Wilson Observatory, was the inspiration for the modern Caltech. "We must not forget," he wrote, "that the greatest engineer is not the man who is trained merely to understand machines and apply formulas, but is the man who, while knowing these things, has not failed to develop his breadth of view and the highest qualities of his imagination."

Arthur Amos Noyes, professor of chemistry and formerly acting president of M.I.T., came here part time in 1913 and full time in 1919. He, together with George Ellery Hale and others, persuaded Robert Andrews Millikan to come after World War I, first on a part-time basis and, after 1921, full time. Hale, Noyes, and Millikan were really the founding fathers of the modern California Institute of Technology, as this institution has been called since 1920. The distinguished anthropologist Margaret Mead has said: "Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it's the only thing that ever has." These three citizens, Hale, Noyes, and Millikan, backed by the Board of Trustees and other friends of the Institute, started a climb toward excellence that Caltech has pursued ever since.

Millikan served as administrative head of the Institute from 1921 until 1945. When he came, 1 PhD student had graduated from the Institute in its entire history. As few as 5 and as many as 30 bachelors students were graduating each year. And, masters students ranged from 1 to 3 annually. In his first decade, 937 students received bachelor of science degrees, 127 received master of science degrees, and 123 received PhDs. In his last decade, the number

Among those who extended an official welcome to the new president were (from left) Sam Weaver, president of the Associated Students of Caltech; Lynn Hildemann, chairman of the Graduate Student Council; the Hon. John C. Crowley, mayor of Pasadena; and Frank H. T. Rhodes, president of Cornell University, who spoke on behalf of academic institutions and learned societies. Below: Everhart and Ruben F. Mettler, chairman of the Board of Trustees, leave the podium against a festive backdrop.

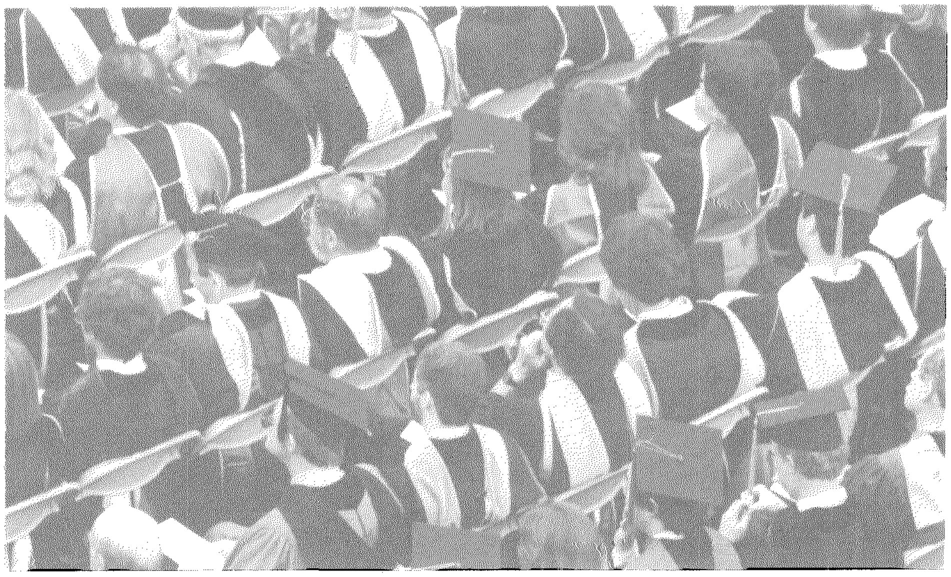




We should remember that a few thoughtful, committed citizens can still change the world.

of students who received bachelor degrees had grown slightly (to 998), the number who had received master's had grown over three and a half times (to 461) and the number who had received doctorates had more than doubled (to 263). Let me put this in better perspective, for this was a time of rapid growth in graduate higher education in the United States. In Dr. Millikan's first decade, Caltech graduated about 1.6 percent of all doctorates in the country in the fields in which it taught. In 1941, the last year before statistics were disrupted by World War II, Caltech graduated 1.7 percent of all doctorates in these same fields of science and engineering. Since that time, under three successive presidents, and in a time of continued growth in graduate education, Caltech has continued to graduate over 1 percent of all the PhDs in the United States, aggregated over those fields of science and engineering in which it participates. Like all Caltech graduates, these graduates have become known for their quality.

How was this accomplished? What were the guiding principles that led to the Caltech of today? Shortly after he came to Caltech, at the acceptance ceremony for the Norman Bridge Laboratory of Physics, which he directed, Dr. Millikan stated the ideal of the California Institute of Technology. It was: ". . . an ideal not very common in American educational institutions, an ideal not of large growth in numbers, nor of the extension of the field of study over a large range of subjects, but rather the ideal of doing work of superlative quality in the chosen and relatively limited field of the Institute's



In times like these, there need to be a few places that look ahead and still dare to do the most ambitious things that human beings can accomplish.

activities—the cultivation of the mathematical and physical sciences and their applications." He went on to insist that "there is tremendous need in the United States for some schools which are designed to furnish exceptional opportunities and to give exceptional training to exceptional men." This was to be accomplished by providing the students access to an unexcelled staff. "Four-fifths of all teaching is the teaching of example. Creative men arise spontaneously in an atmosphere in which creative men exist and in general nowhere else." (Note his emphasis on appropriate role models here, a need still present today.) Finally, he urged ". . . the cultivation of science together with the cultivation of a belief in the reality of moral and spiritual values." His hope was to create ". . . at the California Institute of Technology, not only . . . men with the highest technical skill, but . . . men of the finest character and of the broadest citizenship." Today I would amend that only by emphatically stating "men and women" where Dr. Millikan used the word "men."

The curriculum was expanded from engineering, chemistry, and physics to include geology, and economics, history, and literature (in 1925) and biology (in 1928). Although the Institute has grown somewhat over the succeeding decades, and the fields of study and research have advanced to keep up with, or indeed, have often led the popular subject matter of the times, the structure that Dr. Millikan and his colleagues established has persisted.

In 1946, Dr. Lee DuBridge became the second chief executive officer of the California Institute of Technology, and its first president. Like Millikan, he assumed office shortly after a great world war, a war that had had an impact on him. He vowed to follow the lead of his predecessor and enhance the faculty and the facilities that were needed to do the work of the Institute. He was tremendously successful. The number of faculty more than doubled, the number of buildings and the budget more than tripled, and the endowment grew by more than a factor of five. In his last decade at the Institute, while the number of bachelor degrees granted had remained constant, the number of PhDs granted was up three times from the last decade of his predecessor. Dr. DuBridge is the senior statesman of the California Institute of Technology. It is a real honor for me to have him with us today.

In the past two decades, two other presidents, Dr. Harold Brown and Dr. Marvin Goldberger, have presided over this institution; and it has continued to excel under their leadership. Modest growth has occurred, particularly among postdoctoral students. But, quality—not numbers—has been the key to our continued success.

Some reasons for that quality have become apparent to me through informal meetings with students. Undergraduates like the small size and the sense of community at Caltech, where they can know all their fellow students and many of the professors. They like the honor code, and the fact that they are treated as if they are important individuals. They appreciate knowledgeable professors who are leaders in their fields, and they are enthusiastic about the oppor-

The new president embraces his daughter, the Rev. Janet Everhart, who gave the invocation and benediction.

tunity to do research, for example, through the Summer Undergraduate Research Fellowships (SURF) program.

Graduate students appreciate the excellence of their faculty mentors, their fellow students, and the superior facilities. They also appreciate the sense of community—and the new graduate student housing which allows a majority to live within walking distance of the campus.

Both groups find Caltech to be an intense place, where they are learning a great deal, both through their education and through their experiences here. They seem intrinsically able to understand the difference between education and experience, as stated by that great natural philosopher, Pete Seeger, who said: "Education is what you get when you read the fine print. Experience is what you get when you don't."

And so today, when more scientists and engineers are discovering new knowledge and creating new technology faster than ever before, and when size is often equated with greatness, what should be our future role at the California Institute of Technology? Besides continuing to stand for quality, we should continue to focus on a few important areas, and should aspire to be second to none in these areas. If we are to stay small and vital as science and technology change, we may need to phase out certain topics as we carefully choose which new and more important ones to emphasize. As an institution, we shall need to reassess our priorities. In doing so, we should keep the following points clearly in mind.

● First, we should remember that a few thoughtful, committed citizens can still change the world. We have a good supply of such people among our faculty, students, and staff, and we can make a difference—a big difference.

● Second, we should remember Hale's reference to breadth of knowledge as well as depth, and the importance of imagination. New discoveries are liable to be made by people who know more than the details of a single field; and to augment our imaginations, we have tools of unprecedented power with which to do our calculations, make our measurements, and visualize our results.

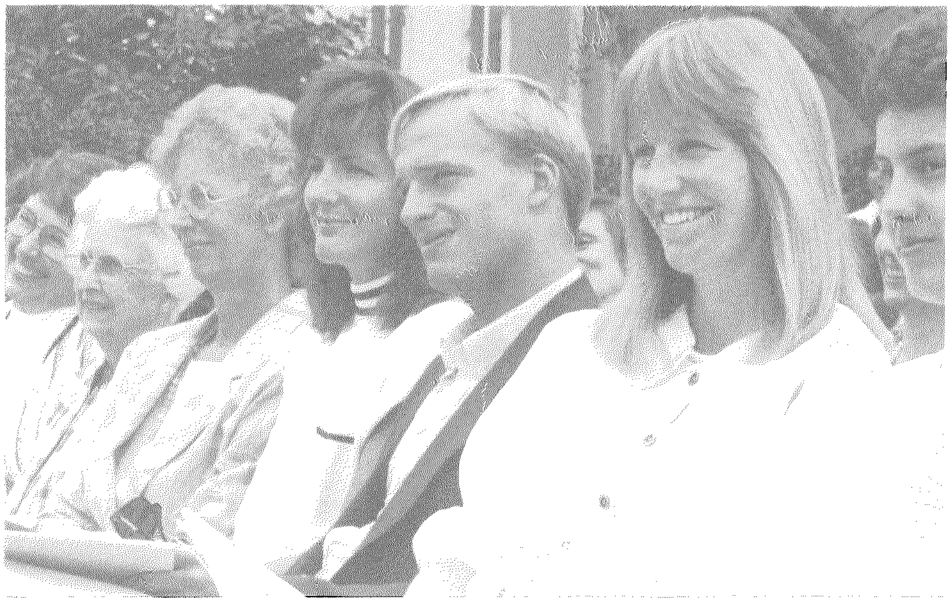
● Third, we must remember that we shall need support to accomplish our goals. We need to continually remind society that our work and our accomplishments are important to the future of our region and of our nation. Caltech has always returned good value for resources entrusted to us, and we must continue to do so.

● Fourth, we live in times of unprecedented change, and we should be ready to seek out the new and important challenges that have long-lasting implications, and meet them head-on.

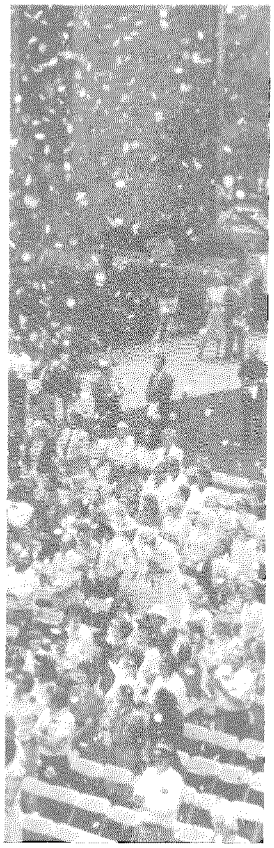
● Fifth, we shall continue to excel only if we attract to our midst the most imaginative, innovative, intelligent and industrious faculty and students, and continue to provide them with the facilities and stimulation to excel.

● Sixth, we need to remember that people think both quantitatively and subjectively. Our students need to be taught both methods. We use primarily quantitative reasoning in mathematics, science, and engineering, although intuition and imagination play an important role. But in dealing with people, with their senses and emotions, subjective reasoning is very important. It may be possible to quantify the smell of a rose, the art of Van Gogh, or a symphony by Beethoven, but most of us don't really care about that sort of quantification. We *do* care about the impact a rose, a painting, or a symphony has on our senses—and the emotional lift they give us. People, individually and collectively, are important to each of us as we go through life, and we need to understand how to interact, and how our predecessors have interacted in earlier times. Hence, lessons from the humanities and social sciences are essential to our development. That is why previous presidents have stressed the importance of the humanities, the arts, and the social sciences to our students, and that is why I reaffirm that importance today.

● Finally, we need to constantly remember that people and knowledge are our two most important products. The students who entrust their futures to us for undergraduate study or for graduate education deserve the best that we can



Members of the new president's family occupying front-row seats for the ceremony included his wife, Doris (third from left), son John, daughter Nancy (second from right), and niece Amy Harrison (right). Also seated with the family party were Shirley Gray (left), Mabel Beckman (second from left), and Tammy Schmit (center). On the opposite page Everhart and Trustee Arnold O. Beckman stand during the proceedings.



provide. They carry away new knowledge, understanding, and maturity when they leave us. Likewise, the contributions to knowledge that we learn through research and scholarship and that we communicate to others through conferences, papers, and books become part of the ever-growing foundation of human knowledge. Through these people and through this knowledge we build upon and, we hope, improve upon the heritage and culture which we have received.

Last November, I read a book about astronomy at Caltech entitled *First Light*. Although it was about science, it dealt more with people, the scientists who thought and taught astronomy, who built equipment to find out what and where the myriad stars we see on a clear night really are. I was delighted to learn recently that this book has won the 1988 American Institute of Physics award for the best book about physics for the layman. I was so taken by *First Light* that I wrote a letter of appreciation to the author, Richard Preston, whom I had never met. In the delightful letter he wrote me in reply, one paragraph seemed to catch the spirit of Caltech. Keep in mind that this was written by someone who had been educated elsewhere, and who had observed Caltech only as a subject for his book.

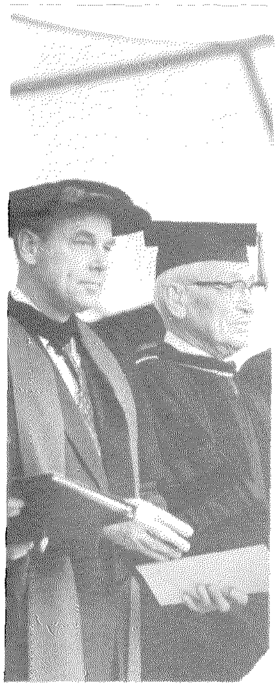
"Caltech is a unique place with a style all its own, like nothing else on earth—a small institution made up of real people, with all their complexities, and yet Caltech has had, and still has, the daring to build telescopes and instruments that leap beyond anything anybody has ever tried before, using private money, private initiative. In some sense, my book is a story of the best and most ambitious things that human beings can accomplish."

Today, we hear concerns about economic competitiveness. We are still recovering from the Challenger disaster. Our grade schools and high schools are not as competitive as we would like. We cannot find the will to balance our national budget. There are serious conflicts in several places in the world. In times like these, there need to be a few places that look ahead and still dare to do the most ambitious things that human beings can accomplish. Caltech still has that ambition and that daring.

With the generous support of the Keck Foundation, we presume to build the world's largest optical telescope. With our colleagues from the University of California, who will provide the operating funds for the first quarter century for the Keck telescope, we shall be looking farther into space and with higher resolution than ever before.

We broke ground yesterday for the Beckman Institute, which will be the largest building to be constructed on the Caltech campus. It will bring together some of our most distinguished chemists and biologists for research that increasingly depends on the expertise from both disciplines. Just as Dr. Beckman has made many key contributions to our society through his inventions, I predict that future key advances in science will be made in the Beckman Institute. Caltech is grateful for the support of all our benefactors, who, like the Beckmans, have shared our dream of a better tomorrow through vitality and excellence in science and technology today.

We have returned good measure to society, both in the results of our research and in the young people who have gone forth with an excellent education to make their mark upon the world.



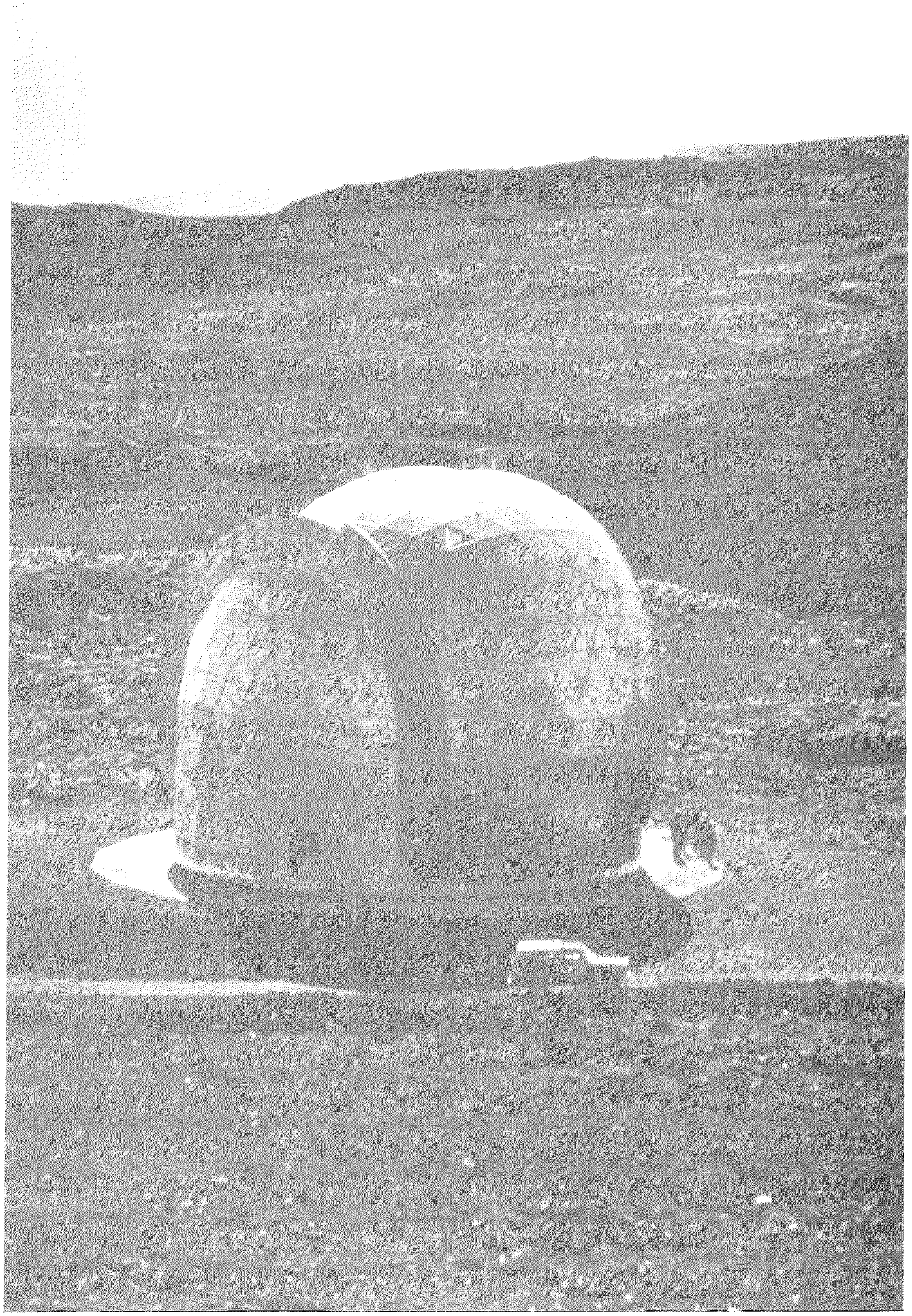
And this dream continues. In a new option, computation and neural systems, faculty from several divisions are building neural networks using integrated circuit technology to create artificial eyes and ears, for example. Others are studying more deeply how neural systems work in order to improve how future generations of computers may work. This active comparison of biological systems, created by evolution over millions of years, with artificial systems, which humans are creating in weeks and months, promises important new insight into both.

Our physicists are developing new theories that may help explain the fundamentals of matter and what happened in the first few microseconds of the "big bang" which we believe took place at the start of our universe. Our biologists are developing new instruments that make it possible to sequence genes, and to know the genetic and regulatory codes that make humans distinct from other species and one person distinct from another. Developmental biologists are also seeking to discover how complex entities like human babies develop from the information stored in a single cell. Our chemists are synthesizing new organic compounds, and measuring the dynamics of chemical reactions at unprecedented speeds. Our geologists are studying the interior of the earth, as well as chemical reactions important in outer space. Our engineers are developing new computers, new robots, new methods of simulation and visualization, as well as new understanding of the principles on which the machines of our civilization rely. We live in the most exciting age in the history of mankind, and we in research, we in academia, we at Caltech, are at the center of the action.

Caltech has striven for excellence in research and teaching since its name was changed to the California Institute of Technology in 1920. It has been blessed with an extraordinary Board of Trustees. Excellent faculty, students, and staff, have been chosen to work here, and have elected to do so. The opportunities for research and education here are outstanding, and the members of the Caltech community have worked hard to take advantage of those opportunities. In a society often worried about how to use its leisure time, the people of Caltech have remained work oriented and accomplishment driven. The society around us has been most supportive. Alumni, Associates, friends, foundations, corporations, and government have all provided resources which have been essential in helping us reach our goals. And we have returned good measure to society both in the results of our research and in the young people who have gone forth with an excellent education to make their mark upon the world.

We have made explicit contributions to the nation through the Jet Propulsion Laboratory, most recently in space exploration, one of the most exciting endeavors of our age. The aerospace industry of this region has benefited from our activities, as have many other industries. From the depths of the earth, which moves in frightening ways sometimes, to the depths of outer space as seen through our telescopes, we have tried to understand and to elucidate the forces of nature. We have also used our knowledge, understanding, and ingenuity to try to harness these forces of nature to serve all mankind.

Richard Preston ended his letter to me by telling how generous the people he had met had been, and how they trusted him "to tell the story right." His final sentence reads: "What kept me striving was my respect for Caltech itself: Caltech *deserved* the very best work that I could offer as a writer." After my seven plus months here, those words are very meaningful to me. What will keep me striving in the months and years ahead will be my respect for the example set by my predecessors, the traditions established over time by the remarkable men and women who have helped Caltech become what it is today, and the sense that there is even more that needs to be accomplished for our society in southern California, for this great nation of ours, and for the world at large. Caltech deserves the very best that I can offer as a president, and with your help, I shall try to be worthy of the task. ☐



Life on Mauna Kea:
The Fascination of What's Difficult

"Being at Mauna Kea is a kind of rite of passage for astronomers."

The Caltech Submillimeter Observatory, a 10-meter radio dish under a sheltering dome, sits on an outcropping of volcanic rock close to 14,000 feet above sea level on Mauna Kea, Hawaii. One of eight telescopes now operating at the extinct volcano's summit, the CSO is the first Caltech facility to open there.

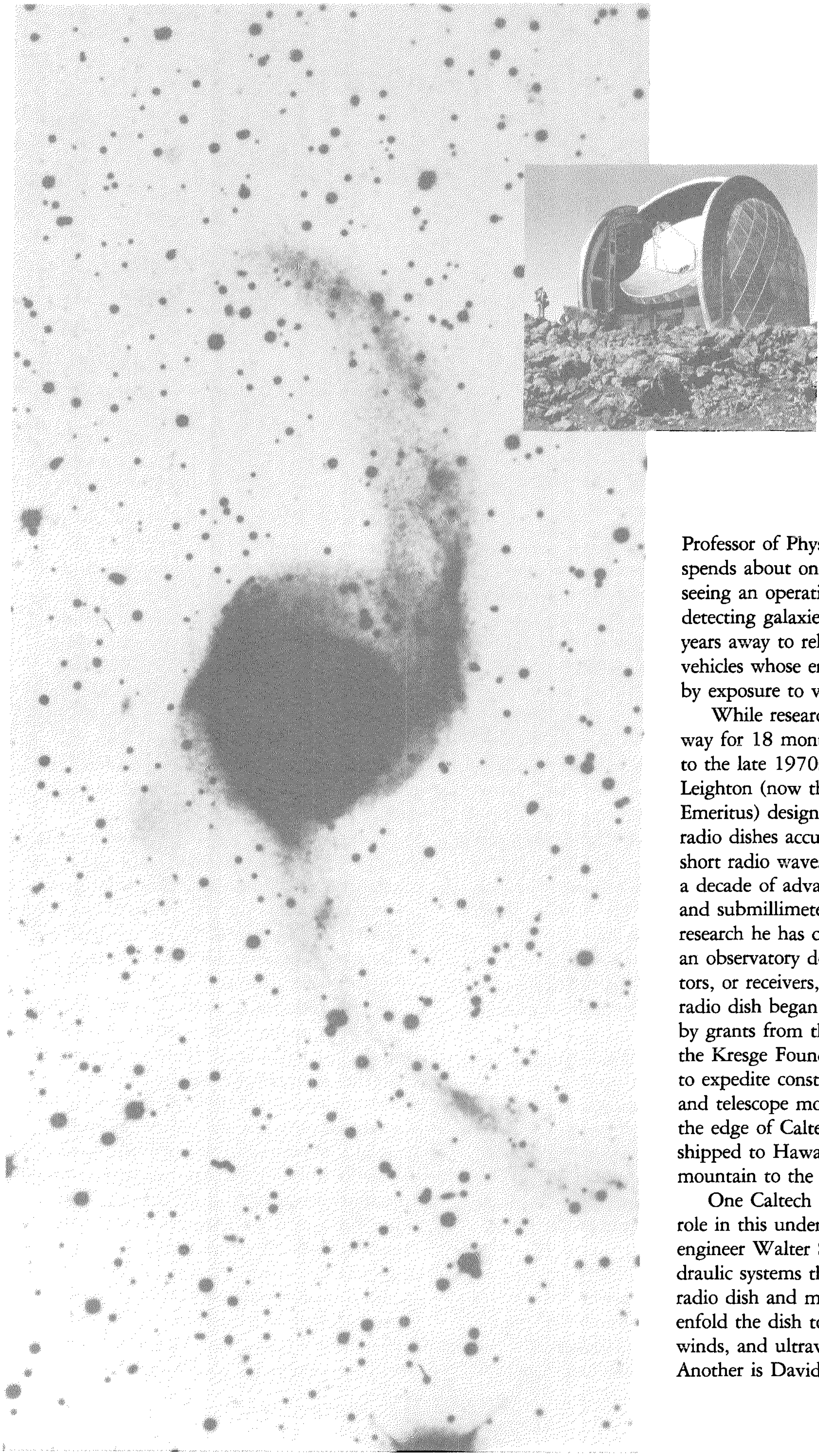
It is 4:30 in the afternoon at Hale (pronounced Hahlee) Pohaku, the picturesque astronomers' residence that the University of Hawaii maintains on the slopes of Mauna Kea—the extinct volcano on the Big Island of Hawaii whose summit is rapidly becoming the world's single largest preserve of astronomers. With eight telescopes representing six nations now operating on Mauna Kea, and a ninth—the W. M. Keck Observatory—currently under construction by Caltech and the University of California, up to 50 scientists, engineers, and technicians may be eating and sleeping at Hale Pohaku, for periods ranging from a few days to several weeks. At 9,500 feet above sea level, the complex is situated in an almost Alpine setting, ringed by fir trees, shrubs and ancient mounds of black and red volcanic ash called cinder cones. In the distance is a view of the blue slope of Mauna Loa, Mauna Kea's still-active sister volcano, as late-afternoon clouds stream toward its peak.

Inside the communal dining room, where Elvis blasts from the kitchen stereo, keeping some of the blearier astronomers alert, the view is equally pleasant: flowers on every table; large, framed pictures of white telescopes on cinder cones that resemble hills of cinnamon; and native Hawaiian plants curving over a circular staircase that leads to the facility's research offices and library.

These graceful reminders of the bright everyday are important because days on Mauna Kea have a tendency to run backward. For most of the people gathered for the evening meal, the day has just started. Their previous day ended at dawn, when a jolting, eight-mile ride down an unpaved dirt road brought them back to Hale Pohaku after a night of observing the sky from Mauna Kea's summit—a rocky wasteland perched almost 14,000 feet above the ocean. The air is thin, the plant-life nonexistent, the temperatures near-freezing, and the ability to concentrate—and sometimes even to walk and talk—for long periods under conditions of reduced oxygen is so valued that the first question a new arrival usually hears from summit veterans is "How did you do at altitude?"

"Being at Mauna Kea," says Caltech senior research fellow Anneila Sargent, who has made several visits to conduct observations at the first Institute facility to open there—the Caltech Submillimeter Observatory (CSO)—"is a kind of rite of passage for astronomers. It's the toughest astronomy work there is."

The Caltech people working at the CSO do not claim to be particularly tough. But they can claim to have established the world's first submillimeter observatory at one of the few places on earth where this demanding form of astronomy can be practiced and to have pioneered some of the most advanced technology available to practice it. At lower, less dry altitudes, most submillimeter radiation is absorbed by water vapor in the earth's atmosphere before it has a chance to reach telescopes. This is not the case at Mauna Kea, where one look at the arid, lunar landscape adds a new level of meaning to the cliche "frontiers of astronomy." "To get good access to these waves, you have to go to this highly inaccessible spot," says CSO director and

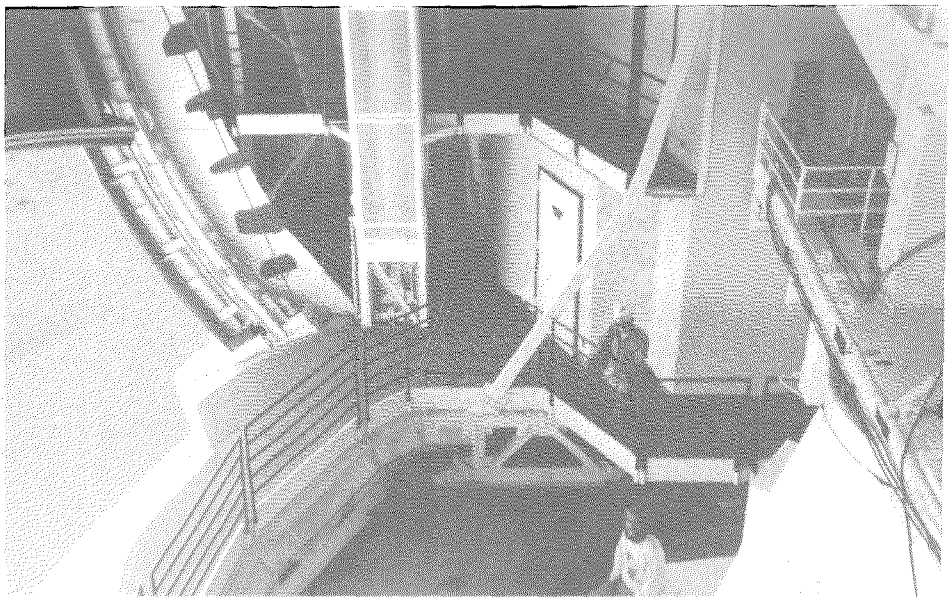


This optical photo of the starburst galaxy NGC 3256, a colliding system under study at the CSO, clearly shows the tidal tails— streamers of stars thousands of light years long—that are the signature of a galactic merger. (Opposite) On-site staffers Randy Hennings (top) and Jeff DeKok (below) wrap up an eight-hour day at the observatory. (Inset) The CSO dome and radio dish.

Professor of Physics Tom Phillips. He currently spends about one week out of four there, overseeing an operation whose dimensions range from detecting galaxies hundreds of millions of light years away to rehabilitating four-wheel-drive vehicles whose engines are repeatedly demolished by exposure to volcanic ash and grit.

While research at the CSO has been under way for 18 months, the project itself dates back to the late 1970s, when Caltech physicist Robert Leighton (now the Valentine Professor of Physics, Emeritus) designed and built one of the first radio dishes accurate enough to focus these very short radio waves. Phillips arrived in 1980, after a decade of advancing the science of millimeter- and submillimeter-wave detection at Bell Labs, research he has continued at Caltech. Work on an observatory dome to shelter Phillips's detectors, or receivers, and Leighton's 10.4-meter radio dish began in the early 1980s, supported by grants from the National Science Foundation, the Kresge Foundation, and NASA. In an effort to expedite construction at the site, the dome and telescope mount were initially assembled at the edge of Caltech's athletic field, taken apart, shipped to Hawaii, hauled piece by piece up the mountain to the summit, and reassembled there.

One Caltech employee who played a major role in this undertaking is senior mechanical engineer Walter Schaal, who designed the hydraulic systems that rotate the CSO dome and radio dish and move the automatic doors that enfold the dish to protect it from the snow, winds, and ultraviolet light at the summit. Another is David Vail, supervisor of mechanical



Refinements will ultimately enable the CSO dish and receivers to detect radiation extending from the millimeter-wave band to the far infrared, a capacity unmatched by any astronomy facility in the world.

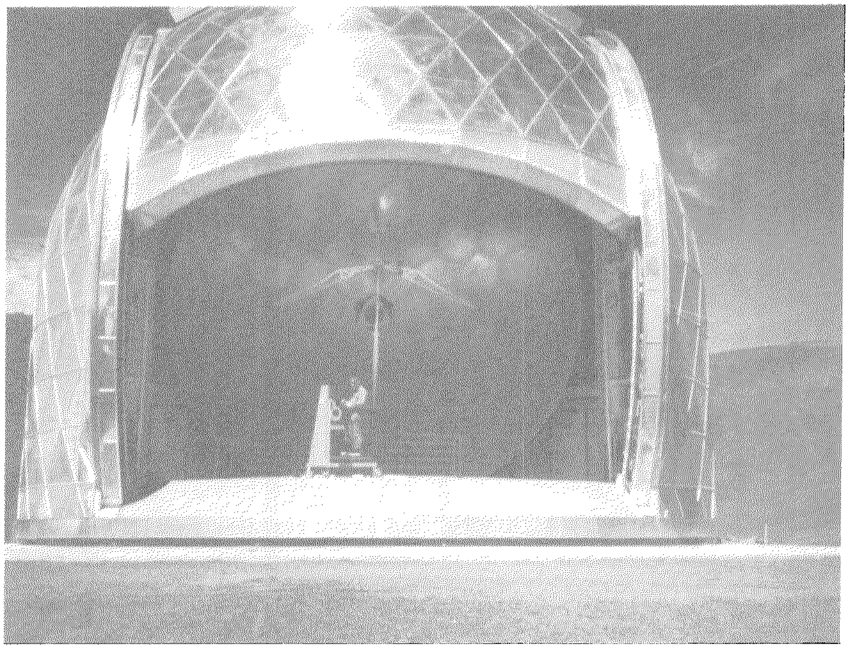
construction in space physics, who machined and modified many of the components for the dome and dish. As their handiwork went up the mountain, Vail, Schaal, Phillips, and Leighton often went with it, encountering such unforeseen problems as a blizzard that filled the exposed dome structure with snow, a subcontractor who walked out in the middle of assembly, and, in the case of Schaal, a broken ankle from slipping on ice at the site. "For about a year," recalls Vail, "Hoggan [the consulting engineer who worked with Phillips on the CSO's design] and I used to pass each other in the air going back and forth from Hawaii."

Today, on the wall of Dave Vail's machine shop in East Bridge, hangs a testament to the happy outcome of this extraordinary effort—a photo of the silver orb of the CSO, taken two days before its dedication in November 1986, with a bright rainbow arching overhead. "Yes, it's a beautiful picture," says Vail. "What makes it a bit odd is that there aren't supposed to be rainbows up there. It's supposed to be a totally dry site."

The CSO is not the world's only submillimeter observatory, a fact that is hard to overlook, since a second such facility, the James Clerk Maxwell Telescope (JCMT), a joint venture of the United Kingdom, the Netherlands, and Canada, sits only a few hundred yards away from the CSO site on Millimeter Ridge. At a time when budget cutbacks have severely curtailed federal support for U.S. astronomy, the JCMT has both a larger staff and larger budget than the CSO, another fact that is difficult to ignore. "We can't compete in terms of money or personnel, but we can try to maintain an edge in certain areas of research," says Phillips. The center of this effort is Downs Laboratory on campus, where Phillips, Leighton, staff physicist Brian Ellison, senior research associate Colin Masson, senior research fellow Jocelyn Keene, research fellow Gene Serabyn, and graduate students Thomas Buettgenbach and Ken Young are working on refinements that will ultimately enable the CSO dish and receivers to detect radiation extending from the millimeter-wave band to the far-infrared, a capacity unmatched by any astronomy facility in the world.

The majority of these refinements are developed and tested at Caltech, then retested at the observatory, a procedure that has its drawbacks. "You get up to the summit with equipment that you designed and that worked beautifully in the lab, and then breakdowns occur," says Buettgenbach, whose new receiver recently had its first on-site test-run. "A cable breaks or a component doesn't work, and you discover that some vital part you need is miles down the mountain or even back in Pasadena. You develop strategies to cope, and one of them is simply accepting the fact that some things are going to take longer."

Of all the hardships of life at the top, coping with the reduced-oxygen environment is one of the toughest. The air at the summit contains about 60 percent of the oxygen at sea level, and the effects on some people can be devastating. At one extreme is the experience of a renowned British astronomer and dynamic science popularizer who went up the mountain with a documen-



CSO technician Allen Guyer under the half-open dome. The devices and software that position dish, dome, and observatory doors were largely designed at Caltech. "There's no other building in the world like this one," says site manager Walt Steiger. "It's a marvel of engineering."

tary team and had become incoherent by the time he was scheduled to perform his part of the program. A similar fate overtook the chief aide to a Senate appropriations subcommittee who led a delegation to Mauna Kea and passed out during his fact-finding tour of the telescopes.

Most Mauna Kea astronomers do not have such dramatic reactions. Staying at Hale Pohaku, where the oxygen depletion is relatively slight, helps prepare people for the more strenuous conditions at the peak. So do repeated visits to the summit. But nobody is entirely immune to the effects of diminished oxygen.

According to Leighton, "The primary effect is that the lack of oxygen makes me feel very confident. Once I come back down to Hale Pohaku, I begin to wonder if some of my judgments at the summit haven't been too optimistic."

"More than anything else, it's exhausting," says Keene. "When I'm at work there I don't notice it so much, but a week of activity can wear you out to the point where it takes another week to recover."

"You know when you've been up there too long because you begin to feel a bit senile," says Masson. "After several hours, you find that you lose your concentration and become confused. If two people get confused in opposite directions, things can become quite argumentative."

"It doesn't bother me all that much because I'm pretty absent-minded at sea level as it is," says Serabyn. "It does provide a great excuse to go skiing the weekend before a trip to Hawaii. 'I'm going to the mountain,' you say. 'It's time to go skiing to get acclimated.' "

If research at submillimeter wavelengths is so arduous, why do astronomers go to such lengths to pursue it? A large part of the answer is that while this radiation does not easily get through the earth's atmosphere, it does easily penetrate a medium that is far more prevalent in the rest of the universe—interstellar gas and dust clouds. Hidden within these clouds, beyond the reach of optical telescopes, is an array of intriguing phenomena: the centers of galaxies; aging stars returning their outer layers of gas and dust to the interstellar medium, where the material is recycled into new stars; and cool gas clouds that are collapsing to form young stars and, possibly, planetary systems.

"By the time these stars have formed and turned on so that optical telescopes can see them, the excitement's all over," comments Phillips. He anticipates that within a year or two, the CSO will be operating at frequencies high enough to probe the most energetic portions of these gas clouds of the interstellar medium. Several such clouds lying within 1,000 light years of earth are major sites of star formation, and studies of conditions in these "stellar nurseries" may finally enable astronomers to understand how the sun and its planets were formed.

But before astronomers can begin exploring the far reaches of space, they have to make it to the top of the mountain. The road to Mauna Kea starts at Caltech, continues with a five-hour flight over the Pacific to Hilo Airport, followed by a 90-minute drive to Hale Pohaku along "Saddle Road," a windy, treacherous stretch whose twists and turns have convinced most rental-car agencies to declare it off-limits to their customers. Saddle Road was built by the U.S. Army during World War II, and legend has it that the military expressly designed the route to thwart progress across the island by a possible invader. Now that an army of astronomers is advancing on Saddle Road, the military has been called in to improve it.

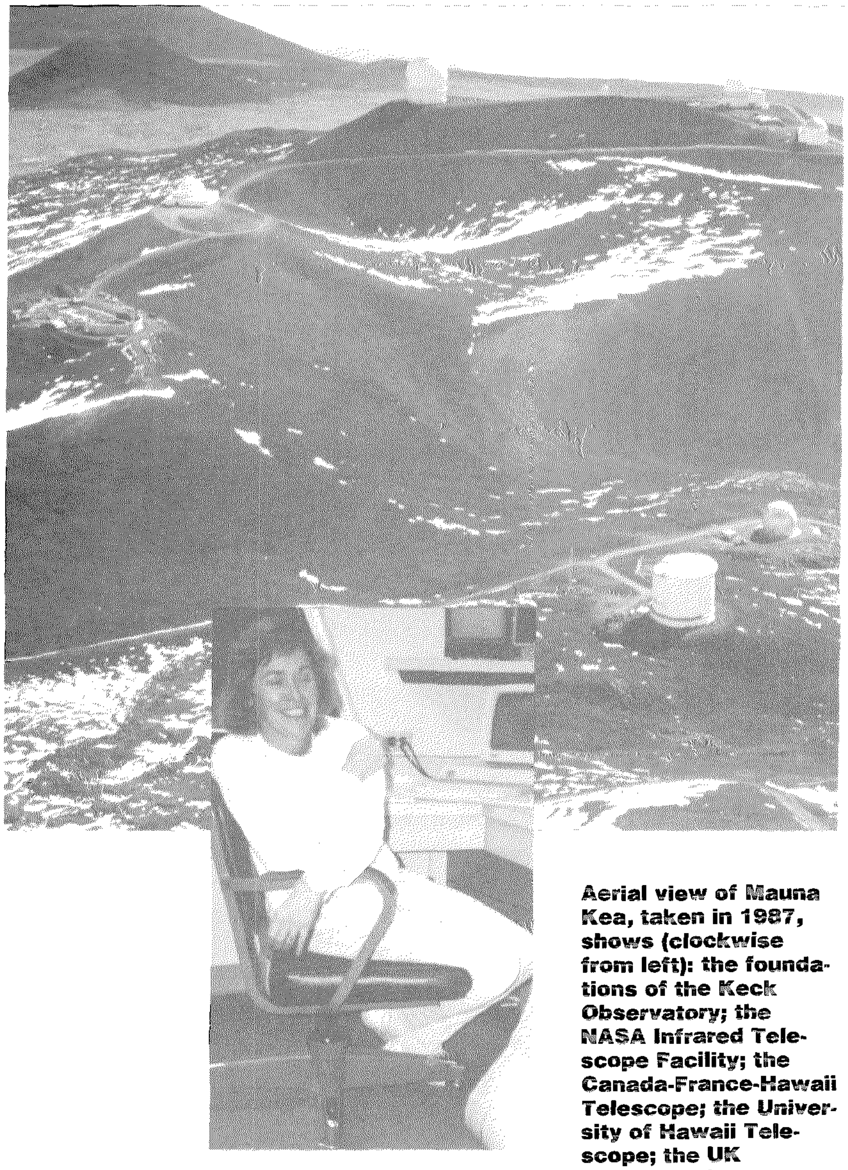
At least Saddle Road is paved. The eight-mile road from Hale Pohaku to the summit is not, and consequently is open only to four-wheel-drive vehicles. As this last lap of the trip to the top begins, Hale Pohaku is left behind in an eddy of clouds. The road twists higher, the drive becomes steeper, the trees dwindle to shrubs, the shrubs dwindle to gorse, which shrivels to grass, and finally nothing but rocks grow on either side of the road. About two miles from the peak, the jeep passes a lava quarry, where ancient Hawaiians, making the journey on foot, gathered material for stone tools. Ahead are signs of another technology: ridges of rock and dust piled so high by natural forces that they resemble man-made pueblos—and then, nine telescopes.

It's hard to imagine a better spot to view the logistics of the universe. At night, the stars overhead seem about a foot away; during the day, the clouds drift by a few thousand feet below, and the CSO, a 200-ton silver bubble at the edge of an ancient lava flow, enhances this alien landscape. The entire structure can pivot through a full turn like a small planet, greatly simplifying the art of pointing the instrument at objects in the sky. A tour of the three-story interior reveals some refinements that were not in place during the initial assembly at Caltech—a control room, electronics room, and machine shop, a lounge that doubles as a library, a small galley, and a closet holding the canisters of oxygen that are required of all facilities operating at the summit.

One frequent visitor to the site is Walt Steiger, CSO site manager and professor of solar astronomy, emeritus, at the University of Hawaii. He makes the trip from Hilo about once a week, ferrying equipment, scientists, and information, and coordinating activities between a five-man technical crew on the mountaintop and a scientific staff 2,500 miles away in southern California.

"You sit up here in this very high-altitude area—the most severe and barren region you can imagine—and you're surrounded by all this sophisticated, high-powered and computerized technology," says Steiger. "You can pick up the phone from this isolation zone and call anywhere

Mauna Kea's summit is rapidly becoming the world's single largest preserve of astronomers.



Aerial view of Mauna Kea, taken in 1987, shows (clockwise from left): the foundations of the Keck Observatory; the NASA Infrared Telescope Facility; the Canada-France-Hawaii Telescope; the University of Hawaii Telescope; the UK Infrared Telescope; the Caltech Submillimeter Observatory; the James Clerk Maxwell Observatory. (Inset) Caltech astronomer Anneila Sargent takes a break from observations.

At one in the morning, the observers are scanning ten million light years out of the Milky Way.

in the world. The contrast is amazing."

During the start-up phase of a telescope, new discoveries are as likely to be about the strengths and weaknesses of the instrumentation as they are about anything in the sky. While this can be frustrating over the short term, the long-term gains in overall performance are worth the effort, something Phillips is occasionally at pains to point out. "With enough patience and persistence, you can get very fine data," he says. "I just keep staying up on the mountain long enough to try to convince people of that fact."

On March 7, Phillips is back on the mountain, accompanied by three Caltech astronomers —senior research fellows Anneila Sargent and Dave Sanders, and Nick Scoville, professor of astronomy and director of Owens Valley Radio Observatory. Over the next several days, the researchers plan to use the CSO to study a group of extremely bright, colliding galaxies whose central regions are undergoing explosions of star formation, or "starbursts," and in the process generating 10 to 100 times the energy of the entire Milky Way. Immense clouds of hydrogen gas and dust in these galaxies are emitting millimeter and submillimeter waves, and by studying this radiation, the group hopes to obtain a clearer picture of what is actually happening in these peculiar cosmic objects.

But first a problem closer to home must be addressed. Arriving at the CSO, the Caltech group discovers that the sky over Mauna Kea, generally one of the clearest in the world, is clouding up, which could force cancellation of the night's run. Weather bulletins from the one radio station whose signals are strong enough to reach the mountain are of no help. "Every time you call and ask for a forecast, they say they have no information," says Phillips. "Ten minutes after you hang up, the broadcaster announces they've just had an exclusive report that things don't look good on Mauna Kea."

Eventually the cloud cover thins out enough for the group to aim the telescope in the direction of the nearby molecular cloud Orion A, and the appropriate directives are entered on the computer. Is the dish now pointing at Orion? Sanders is asked. "*You* are now pointing at Orion," is the reply, as the CSO dome gently swivels its freight of dish and astronomers around to point at the designated coordinates in the sky. Data on the computer screen indicate that Orion A is coming in loud and clear, a signal to Phillips that it is time to subject the receivers to a "cold load" of liquid nitrogen, an exercise that will clarify how much of what the observers are seeing is astronomical data and how much is background noise generated by the receivers.

This is the start of a long night of computer calibrations, adjustments to the receivers, phone calls to computer programmer Ken Young back in Pasadena and, as the hours wear on, of coping with exhaustion brought on by the altitude. The best antidote to creeping fatigue turns out to be the stream of data pouring in over the computer, supplemented by tea and crackers from the galley and the small pile of apples and oranges that Scoville has thoughtfully removed from Hale Pohaku's kitchen. At one in the morning, the

"What's worthwhile about all this? The prospect of getting observations that are just about impossible to obtain any other way."

The starburst galaxy NGC 1614, one of several ultraluminous galaxies being studied at the CSO, radiates 10 to 20 times the energy of the Milky Way. CSO data are shedding light on the dynamics of the hydrogen gas clouds in this system. (Opposite, from left) Phillips, Scoville, Sanders, and Sargent ponder Galaxy M82 in the CSO control room.

dome is turning, the sound system is playing classical music, and the observers are scanning ten million light years out of the Milky Way, a stone's throw by astronomical standards. Their target is Galaxy M82, sometimes known as the "firecracker" galaxy because a collision with its neighbor, M81, has ignited a spectacular starburst in the galactic center. Three hours later, with the gratifying news that the CSO dish has achieved a nearly 50 percent improvement in detection efficiency over all previous runs, it is time to to go down the mountain, get some sleep, and begin thinking about what data from this run will go into the next series of professional papers.

The next day for this group dawns at about three in the afternoon. Phillips is on his way back to Pasadena, where deadlines for funding renewal proposals are fast approaching, and Sargent, Sanders, and Scoville, buoyed by the gains of the night before, are expanding the list of galaxies they plan to study. As on the previous night, evening at the observatory opens with a series of maneuvers to assess the pointing accuracy of the dish. "We want to be sure of where we are," says Sargent, "before we go zooming all over." "Then," adds Scoville, "we can all fight about what galaxies we're going to look at." After some preliminary scans of nearby objects, they beam out 200 million light years to a starburst galaxy known as NGC 1614 and begin an hour of painstaking calibrations at the computer. A series of calculations and recalibrations, punctuated by frequent checks on the performance of the receivers, and the results are worth it. From a distance of almost a quarter billion light years, NGC 1614 announces its presence on Sargent's and Sander's monitors in a broad, clean emission spectrum that looks not unlike the peak of Mauna Kea. Further work produces a double emission peak, and Sanders is jubilant. "We have just detected," he says, "the faintest and weakest object ever seen by this telescope."

This work will go on for two more nights, culminating in the sighting of the ultraluminous galaxy Markarian 231, a colliding system whose core is believed to harbor both a starburst and a quasar.

"The work up there is incredibly rough," says astronomer Keene. "The dust rips apart your clothes and shoes, the dry air chaps your face and body, and a week on the mountain usually means three to four days' downtime just recovering from the experience. What's worthwhile about all this? The prospect of getting observations that are just about impossible to obtain any other way."

Driving down from Mauna Kea, back to sea level, it is indeed a bit hard to shake off the effects of the mountain. The only radio waves are those reaching the car's antenna, and the only messages they carry are from stations in Honolulu whose signals are strong enough to overcome the combined interference of Mauna Kea and Mauna Loa. The scenery has reverted to the tropical display expected of Hawaii, and both oxygen and greenery are abundant. Heading up the north coast, a driver who happened to look out the car window toward the west would see the pinnacle of Mauna Kea gradually sweep back into view. A little effort with the eyes and it becomes clear that the four white caps at the peak are not snow drifts but telescopes. Slightly farther down the road, one can look up again. The late afternoon clouds have ascended Mauna Kea's slope and are about to envelope the summit. For a brief instant, the telescopes shimmer at the edge of the cloud and then the mountain top and its cargo of star-gazers vanish from view. ☐ — *Heidi Aspaturian*

Heidi Aspaturian is a writer in Caltech's Office of Public Relations and associate editor of On Campus, *where this article first appeared. She visited Mauna Kea in March with a team of CSO observers.*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Polymer's Progress

"What we need now are ways of making polymers with special properties."

Graduate student Bruce Novak makes polymers that conduct ions the way cell membranes do.

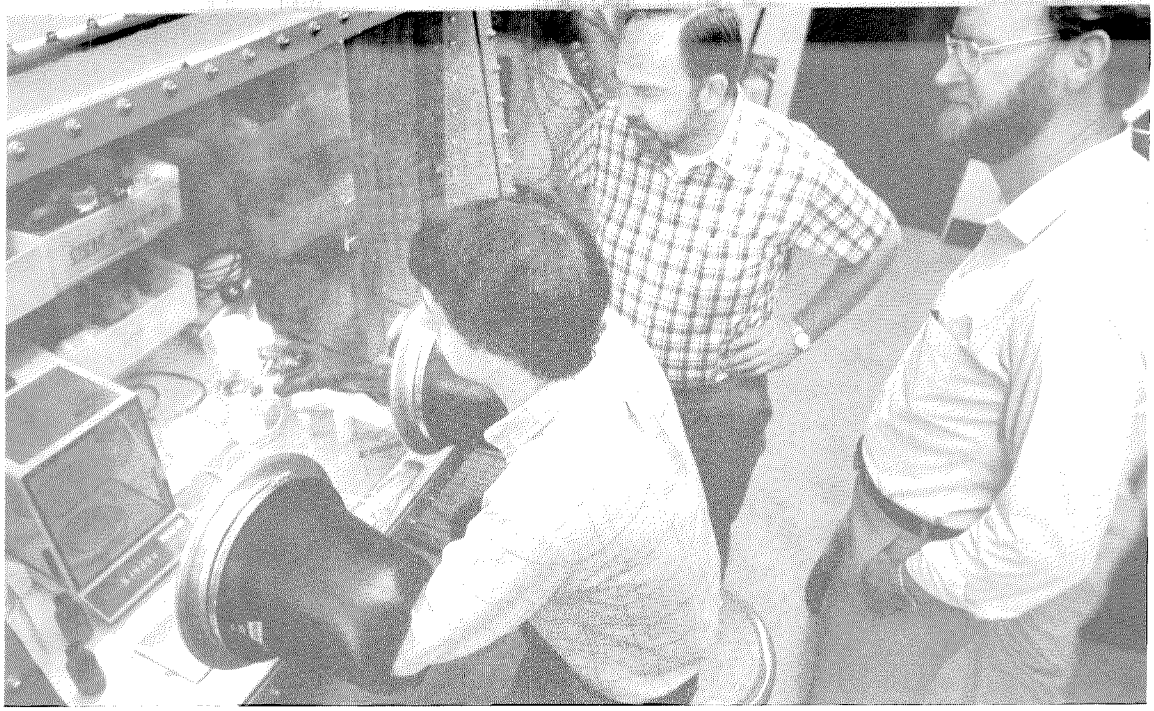
Ever since World War II, synthetic polymers have been an important part of our lives. (Natural polymers have always been part of our lives—proteins, starches, and polysaccharides are all polymers.) In general, a polymer is a large molecule created by linking many small molecules, called monomers, together. The polymer's great size gives it properties quite different from those of the monomer(s) that go into it—a single molecule of polyvinyl chloride (PVC) contains thousands of vinyl chloride monomers, yet PVC is a rigid, inert plastic used to make pipes, bottles, and other things, and vinyl chloride itself is a very reactive, poisonous gas. In the two generations since World War II, polymer chemists have gone from making substitutes for natural products (neoprene for rubber, nylon for silk) to making teflon, styrofoam, spandex, mylar, and a host of other substances Mother Nature never dreamed of.

Polymers are now so pervasive that one might think they've gone about as far as they can go. Not so, according to Professor of Chemistry Robert H. Grubbs. "Polymer synthesis has been directed at making stuff you can sell by the pound. What we need now are ways of making polymers with special properties, for applications where you only need a little bit of polymer. It's the difference between selling maleic anhydride [a basic industrial chemical] and selling a drug." Among the "drugs" under development in Grubbs's lab are polymers that conduct electricity and biological mimics that can transport ions through membranes. Molecules with even more exotic capabilities are on the drawing board.

"Our basic goal is to be able to sit down with our molecular models and a piece of paper or a computer terminal and design a polymer that has a certain molecular weight and certain kinds of functional groups, and then go into the lab and make it," Grubbs says. (A functional group is an atom or cluster of atoms that react as a unit. They dangle from the polymer's "backbone" and determine its chemical properties.) "In natural product synthesis," Grubbs continues, "you can draw a picture of a steroid, look up the right synthetic techniques, and make it. In polymer chemistry, these kinds of precise synthetic techniques are not generally available."

It's easy enough to make a polymer with the right functional groups, but well-nigh impossible to control its molecular weight precisely. Choosing the starting materials determines the polymer's functional groups. But the molecular weight (and thus the polymer's specific properties) depends on the number of monomers per polymer molecule—and on the statistical distribution of individual polymers around the average molecular weight. An ideal polymer would have exactly the same number of monomers per molecule. Real polymers tend to be distributed around the desired molecular weight, with the degree of variation as narrow as the laws of statistics, the chemist's skill, and the synthetic strategy will allow. The closer the actual distribution comes to the statistical ideal, the more "monodisperse" a polymer is said to be.

You can't change the laws of statistics, and chemists are only human, so any breakthroughs toward monodispersity must come from the syn-



Working with air- and water-sensitive chemicals takes special equipment. Graduate student Floyd Klavetter makes polyacetylene in a nitrogen-filled drybox as Professor Robert Grubbs (right) and Senior Research Associate in Chemistry William Schaefer look on.

Doing chemistry in a drybox is like planning a mission to the moon—contingencies need to be anticipated, and all conceivable supplies must be laid in before liftoff.

thetic strategy. There are two basic ways to make polymers: step synthesis and chain synthesis. Each has its own methods to control molecular weight.

Step synthesis builds up polymer molecules step by step. Two monomers make a dimer, three a trimer and so on; a dimer and a trimer make a pentamer, two pentamers a decamer. Every *n*-mer is reactive at both ends. *N*-mers continue to grow, step by step, until they become too unwieldy to mate with each other, or they precipitate out of solution, or they react with something else. During most of the reaction, small-mers will be forming middle-sized-mers. Polymers with the right molecular weight don't appear until the very end—usually when the reaction is better than 98 percent complete —when *n*-mers half the desired weight start to react with each other. The chemist stops the reaction after an elapsed time calculated to maximize yield in the desired weight range. If half-mers reacted exclusively with other half-mers, the product would be monodisperse. But half-mers react with *n*-mers of all sizes, so no matter where the reaction stops, many molecules will be over- or under-sized. The brakes are usually applied to a reaction by adding a molecule that reacts with the active ends, "capping" them. If the process dictates that the cap be added at the start of the reaction, the odds of an undersized polymer being capped prematurely also enters into the statistics. Or, if the polymer contains two monomers, the initial mixture can be adjusted to have a slight imbalance between them, with the shortfall calculated to make the reaction run out of steam at the right molecular weight. Nylon, polyester, polyurethane, and many resins are step polymers.

Chain synthesis, as the name implies, makes each polymer molecule in a single chain reaction. Chain polymers (which include polyethylene, polystyrene, PVC, and teflon) are often built by converting double bonds to single bonds, with the bonding electrons thus liberated being used to link two monomers. A chain reaction begins when an "initiator" creates an active site on a monomer. Then the active monomer adds other monomers onto itself in a chain reaction, building the polymer backbone. The reaction transfers the active site to each newly added monomer in turn, so the active site stays at the head of the growing molecule. If the active site eats something other than the monomer, the chain stops growing, but if the "something" reacts with another monomer to create a fresh active site, a new chain takes off—a process called chain transfer. The reaction finally ends when the active site swallows something that is neither a monomer nor a chain transfer agent, killing the active site. Each chain reaction is so fast that the polymer grows to maturity (and its active site dies) almost instantaneously. At any point in the reaction the vat contains dead full-grown polymers, prematurely dead undersized polymers, monomers, and a small quantity of initiator busily breeding new reactive centers. Unlike step polymerization, prolonging the reaction time does not increase the molecular weight but only improves the yield. Molecular weight control comes primarily through balancing the number

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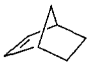

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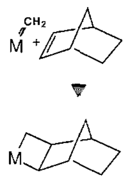

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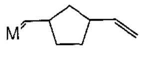

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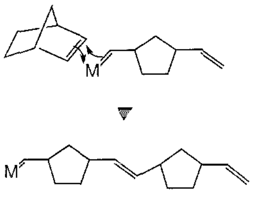

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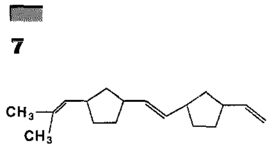

of chain transfer agents against the propagation rate, which is constant. The statistical weight distribution happens because the odds of a chain transfer agent hitting a growing chain of just the right length are fairly slim.

Most active sites are easily poisoned. They're unstable, reactive gluttons, and if a monomer doesn't come around quickly enough to suit them, they'll gobble up anything handy, including a solvent molecule, and die. A few, called "living systems," are more diet-conscious. They're comparatively stable, so they can afford to sit around and wait for their next meal. Grubbs's group has taken this idea one step further by developing temperature-dependent living systems. Unlike ordinary chain polymerizations, the active site in these systems sits on a catalyst molecule. The catalyst assembles monomers like an automatic riveter assembles steel plates. The temperature dependence makes it possible to start and stop the reaction at will, while the catalyst's specificity makes it invulnerable to chain transfer.

"We want to have a pretty rotten catalyst," Grubbs explains. "If you've got a rotten catalyst, then you can control it. If it's slow enough, you can make it very, very selective. For example, our titanium system is a miserable catalyst. It's not so miserable that it doesn't make exactly the right product, but it's miserable enough that it only works under a very special set of conditions. When we impose those conditions—we heat it to 65° C—it goes, and when we cool it to room temperature, it stops. It adds about 25 to 50 monomers per hour, so in 10 hours you can make a pretty good-sized polymer." The group has developed similar catalysts that add up to 1,000 monomers per hour. It's a trade-off—precise control versus speed. The catalyst's reactivity, or lack of it, governs another trade-off as well. The more aggressive the catalyst, the less reactive the monomer needs to be; but by the same token, the more likely the catalyst is to react with some other part of the monomer such as the functional groups that make the molecule desirable. The key, then, is to develop synthetic strategies that match monomer and catalyst.

"We've polymerized many cyclic monomers," Grubbs says. "The one we've studied most is norbornene, a reasonably strained monomer." Prospective monomers must meet a three-part standard: they must contain a carbon-carbon double bond; the double bond must be part of a ring system; and the ring must put a certain minimum strain on the double bond. A monomer falling short on any of the three criteria won't react. Norbornene (**1**), a tricyclic molecule whose three fused rings radiate from two shared carbons like the blades of an eggbeater, strains all its carbon-carbon bonds, but particularly the double bond.

The catalyst reacts through a process called ring-opening metathesis polymerization, or ROMP. The catalyst contains a metal ion, part of a metal-carbon double bond, that reacts with the monomer's strained double bond to produce a metallacycle (**2**). A metallacycle is a ring of carbon atoms incorporating a metal atom. These particular metallacycles are cyclobutanes—four atoms arranged in a square. Norbornene alleviates its strain by breaking the square and forming a new set of double bonds (**3**). When the square breaks open, so does the norbornene ring that contained the double bond. The remaining ring flattens out, relieving the strain. The product molecule (**4**) has a metal-carbon double bond that can form a new metallacycle with another norbornene (**5**). Whether the metal-carbon double bond or the metallacycle is the stable active site depends on the metal involved: titanium would rather wait as the metallacycle, while tungsten prefers the double bond. Both metals follow the same loop, but pause in different spots.

ROMP offers very precise molecular weight control. Unlike catalytic chain initiators, which turn out active centers (and thus polymer molecules) willy-nilly, each ROMP catalyst makes only one polymer molecule. Each molecule competes equally for monomer, and all grow at the same rate. All of the monomer eventually reacts, giving an almost completely monodisperse polymer. Once the monomer is gone, the catalyst can be turned off by adding a cap. The cap monomer (acetone, **6**) contains a carbonyl group—a carbon-oxygen double bond. The catalyst treats this double bond like a carbon-carbon double bond, reacting with it, but once the bond breaks, the catalyst is left holding the bag. The cap winds up on the polymer (**7**); the catalyst gets stuck with the oxygen atom and forms a very strong metal-oxygen double bond. No more metal-carbon double bond, no more reaction. To produce any given molecular weight, just multiply the number of monomers in one polymer molecule by the number of titanium atoms and add that amount of monomer.

Beside being monodisperse, the product is very clean. ROMP is very fussy about its monomer, and only produces one particular product. With a little care in solvent selection and purification to ensure that there is only the one potentially reactive double bond in the flask, product purity is easy to assure.

Some other monomers that graduate students

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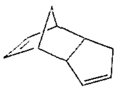

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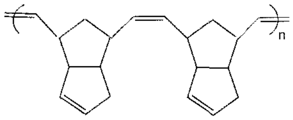

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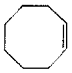

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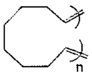

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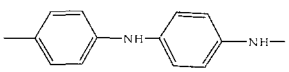

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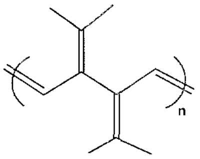

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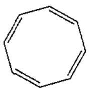

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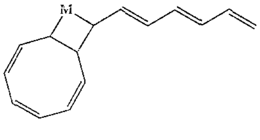

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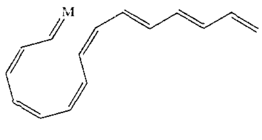

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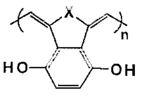

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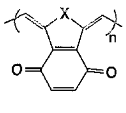


Eric Anslyn, Louis Cannizzo, and Laura Gilliom have tried successfully include dicyclopentadiene (8), which makes polydicyclopentadiene (9), and cyclooctene (10), which makes polycyclooctene (11). Polynorbornene is strong but flexible, and is widely added to the very soft rubbers used in certain flexible seals and roll covers. Polydicyclopentadiene is a strong but lightweight plastic used in snowmobile hoods and golf carts, among other things. Polycyclooctene is a thermosetting plastic which softens a few degrees above body temperature. It is used in the plastic casing for children's hearing aids: it can be remolded to fit the growing ear simply by dunking it in warm water and pressing it back into place.

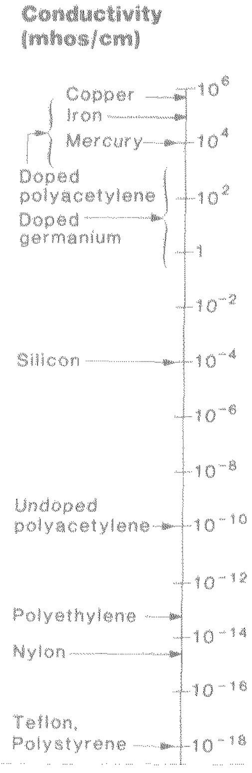
"So then the next question is what kind of monomers do you want to polymerize," Grubbs continues, "and what functional groups do you want the polymer to have? We are doing some that have interesting structural properties—elastomeric, crystalline, that sort of thing, but probably more interesting are the ones that do chemistry."

Chemists around the world are working on plastics that conduct electricity. (See box, p. 26.) A group at BASF has made a very-high-purity polyacetylene with a conductivity of about 147,000 mhos/cm, one-quarter that of copper by volume and twice that of copper by weight. The first commercial application hit the market in late 1987 when a coin-type rechargeable battery with electrodes of lithium and polyaniline (12)—a polyacetylene analog—went on sale in Japan. Even so, conducting polymers in general are very much in their infancy. One problem has to do with the starting material: polyacetylene, the granddaddy of conducting polymers, is made from acetylene gas, the explosive fuel used in welding torches. Polyacetylene also degrades slowly when exposed to air. Researchers are experimenting with protective laminations and with conjugated polymers related to polyacetylene, such as the polyaniline used in the battery. Graduate students Floyd Klavetter and Timothy Swager are looking at polyparaphenylene (13) and polydimethylenecyclobutene (14), for example, as well as polyacetylene. These polymers appear to have higher stability, but, unfortunately, lower conductivity.

Klavetter makes polyacetylene by ROMPing 1,3,5,7-cyclooctatetraene (COT, 15). COT has a ring of eight carbon atoms linked by alternating double and single bonds. The process works just like the polynorbornene reaction. The catalyst makes its square from one of the double bonds (16), and the opened rings link up to form new double bonds (17), producing a long, linear chain of alternating single and double bonds—polyacetylene. Since COT is a liquid at room temperature, it serves as its own solvent. This, along with the very specific nature of the reaction and its lack of side products, gives a very pure product. "We've got conductivities of up to 10^3 mho/cm so far," Grubbs says. "Copper's 6.4×10^5, so we're not far off. The hope is we'll be able to use some of the tricks the others used and see how well we do. Our purity, for example, should be higher, and our fabrication techniques are definitely much easier than theirs. We haven't stretched our films. That's one thing we're working on now. We're also starting to do our polymerizations under shear flow—making the liquid flow in one direction as we're polymerizing—and we hope that will align the chains."

Electrically conductive plastics have optically conductive properties as well.

Polyacetylene has proven to be a processing challenge in other ways: it is brittle, so it can't be machined, and it can't be melted and cast like thermoplastics, so it has to be synthesized in whatever shape it is to be used. The conventional method, polymerizing acetylene gas onto a catalyst-coated glass surface, gives a paper-thin film only 15 to 20 microns thick. As the polymer coats the glass, it covers the catalyst too, stopping the reaction. Furthermore, the catalyst, alkyl aluminum titanium oxide, is extremely corrosive. It devours most substrates other than glass. The catalyst has a weak stomach, though; any functional group on the substrate or impurity in the environment kills it.



The ROMP system has none of these drawbacks. The catalyst doesn't need a surface, but swims in the COT. The COT can be poured out as a sheet to make films of any desired thickness, or it can be poured into a container of any shape—the group has already made chunks of polyacetylene. The film can be deposited on different surfaces (glass, metal, plastics, and cellulose have been tried so far) because neither COT nor the catalyst seems interested in reacting outside the family. Among the various shapes produced to date are polyacetylene "wires" 1 mm in diameter, using thin teflon tubing as a mold. Such wires might eventually serve as prosthetic nerves.

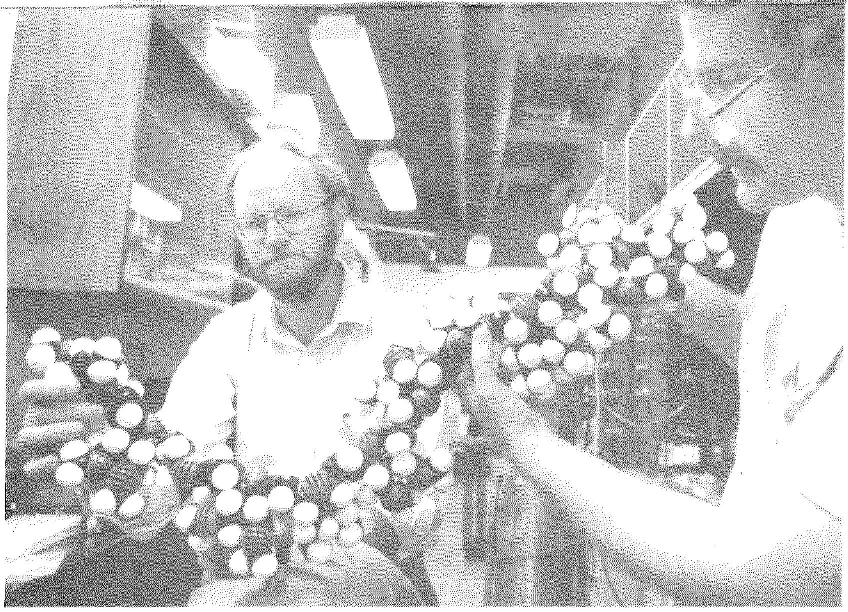
Polyacetylene films are a lustrous, highly reflective silver. Cyclooctatetraene is a yellow liquid. As the polymerization proceeds (15 to 45 seconds at room temperature, and a catalyst/COT ratio of about 1/100), the yellow darkens, turning orange, then red, magenta, and black before becoming a silver solid. Doping it with molecular iodine turns it black.

The way a polymer is doped has great influence on its electrical properties. The amount of dopant can be varied, but once added, it can't easily be removed. "One of the things we're doing now is designing built-in dopants that we can control," Grubbs says. Both molecules **18** and **19**, for example, have the alternating double bond-single bond backbone needed for conductivity. Molecule **18**'s backbone passes through a hydroquinone, a strongly delocalizing structure that should enhance electron mobility. Conversion to molecule **19** by oxidation creates a different double bond arrangement called a quinoid. "That changes the band gap significantly," says Grubbs, "so the conductivity will be controlled by how much of it we've oxidized. There's also an intermediate state called the hydroquinone anion radical, and that might be a dopant, too." A variable conductor could be used as a switch or a sensor.

Since light is an electromagnetic phenomenon, it may come as no surprise that electrically conductive plastics have optically conductive properties as well. As electrical conductivity changes, so do the optical properties. Such a plastic could be used to control the amount of light flowing through a fiber optic cable, or as a logic switch in the optical computers now being designed—chipless computers that think with light instead of electricity. In the nearer future, such a plastic could be used to protect people and equipment from damaging laser light—in the cockpit of an F-16, for example. "That might sound like an awfully expensive pair of sunglasses," Grubbs says, "but when you've got a pilot crashing a multi-million-dollar jet because someone shines a laser in his eye and blinds him, it's a pretty cheap pair of sunglasses." These optical properties are now being studied at Caltech's Jet Propulsion Laboratory by postdoc Seth Marder and JPL staff member Joe Perry.

Grubb's group is also making copolymers in which blocks of polyacetylene alternate with blocks of an insulator such as norbornene. Since partially doped polyacetylene acts as a semiconductor, such copolymers might eventually be used in electronic devices.

"It's easy to make blocks with a living system," Grubbs says. "We add A, and the system goes along until it runs out of A. Then it just sits there until we add B, and it starts up again. That's a nice straightforward way of doing things. We've also got a system that's living on both ends—you add A and get polymer growth in two directions, then if you add B you get a tri-block." Postdoc Wilhelm Risse is developing tri-block systems with "handles": the two end blocks play structural roles—orienting the mole-



Grubbs and Novak with a 3-D model of the "spinachy" ion-conducting polymer. This long molecule, when coiled up, puts all its oxygen atoms (slotted spheres) on its inner surface (opposite page, top), in position to attract and stabilize a positive ion (bottom).

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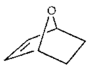

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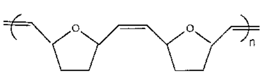

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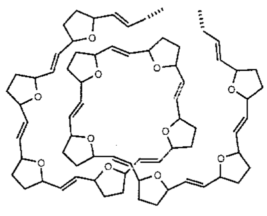


(22) "Spinach" not shown for clarity.

cule and anchoring it in position—while the middle block does chemistry. Making block polymers by other methods can be a tedious task. Reaction A must be stopped at the right time, and the A polymer separated from the reaction mixture and purified, before a new reaction with B can be started.

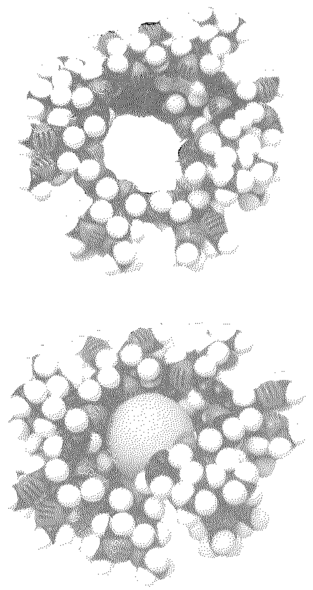
The group is working on polymers that conduct ions as well as electricity. In nature, ion-conducting polymers transport biologically important ions like calcium and sodium into and out of cells. In general, they are long proteins with a natural twist. They like to coil up into hollow tubes that penetrate the cell wall. The tube's outside is coated with fat-soluble groups that anchor the tube in the cell wall, while the inside is studded with oxygen or nitrogen atoms whose lone electron pairs attract and stabilize positive ions. The tube's inner diameter determines how big an ion it can carry, and natural ion conductors are quite selective—passing potassium but not sodium as an electrical impulse travels through a nerve, for example. These molecules may contain hundreds of amino acids in a specific sequence, however, so Grubbs's group is looking for polymers made from one simple repeating unit.

They are looking at polymers based on a norbornene analog called 7-oxanorbornene (20), in which a carbon atom in one ring has been replaced by an oxygen. After polymerization, the result is a string of five-membered, oxygen-containing rings called furans (21). "If you make a model of this polymer," Grubbs explains, "it has all these furans on the front, and all these methyl ethers hanging off the back. The methyl ethers are a sort of spinach that's left over from the synthetic technique. If all the spinach goes to the outside, putting all the oxygens in the middle, the molecule starts to make a helical channel with all the furans, which are really good ion stabilizers, on the inside—a channel just the right size to put an ion in." (22)

The group makes thin films using variations on this polymeric theme. They use the film as a barrier between two solutions in a test cell, and measure the membrane potential—the film's ability to transport ions between the solutions. The polymers now under study prefer to carry large positive ions. They do a good job of selecting cesium over sodium, but are not yet as selective as nature's design. "Once we know how to select an ion size, we'll incorporate these into tri-blocks," Grubbs says. The tri-blocks could then be used for membrane applications analogous to the ion channels in a cell wall.

"This is just the early stage," Grubbs says. "We sat down and designed this molecule two years ago. It took about a year and a half to make it, and now we're starting to look at its physical properties and ion-conducting properties. It's all been done by one graduate student, Bruce Novak." ROMP syntheses can fail if the ring includes something other than carbon. The catalyst, on the make for accessible electrons, may ignore the double bond in favor of the more tempting electron pairs on the non-carbon atom. Novak avoided this catalytic crossbreeding by developing a different, ruthenium-based ROMP catalyst.

It's not certain yet if the ruthenium ROMPer is "alive" or not. "It's not very well defined,"



"It's dynamite. It opens up a whole new area of organometallic chemistry."

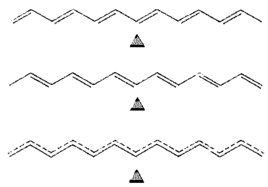
Grubbs says. "We first made it by just adding ruthenium chloride to water. We're still trying to figure out what it made, but it's dynamite. It opens up a whole new area of organometallic chemistry."

Most organometallics are hard to work with. They are air- and water-sensitive, and as a result must be handled in airtight dryboxes under an inert nitrogen atmosphere. A set of arm's-length gloves of heavy-duty rubber built into the front wall of the drybox allows the researcher to manipulate the material within, while watching the work through a thick plastic window. Just putting an empty test tube in the drybox is time-consuming. Everything entering the drybox passes through a built-in, double-doored airlock. The airlock must be pumped down to a vacuum and refilled with inert gas three times before the inner door to the drybox is opened. Doing chemistry in a drybox is like planning a mission to the moon—contingencies need to be anticipated, and all conceivable supplies must be laid in before liftoff. Otherwise the experiment could be on hold for 20 minutes for want of a spatula.

"But here's a catalyst we can just chuck in water and let sit on the lab bench overnight in the air—Pasadena air even—and then throw in the monomer and make stuff the next day," Grubbs says. "That's a pretty robust catalyst. We're doing emulsion polymerizations in water with it, and that's totally unheard-of using organometallics. That's been the fun part—it's been good fundamental research, understanding how bonds get made and broken. But after you've done all that, you've got people out there in industry who are pretty excited about all this. You can see the applications.

"We've got so many controls over the technique, we can start to tailor-make molecules now, I hope. With the new computer modeling programs you can ask questions about what structures are going to do, how things are going to coil, what effect changing cis-trans double bonds has, or hydrogenating double bonds, or putting more or less spinach on, whether you want fat spinach or skinny spinach, and so on. But once you've got a synthetic technique, you can start to dream and make molecules, and that's the whole point." This summer, the group will be launching a computer-aided design program for molecular synthesis.

"And that gets us into the next level," Grubbs continues. "When you build a polymer, you worry about putting together each individual bond in the molecule. Now you've got to worry about how the molecules stack together, and how they orient with respect to each other, which is essential for bulk properties like conductivity, magnetism, or ion transport." Since magnetism and conductivity are closely related, Grubbs and Associate Professor of Chemistry Dennis Dougherty are collaborating on the design and eventual synthesis of organic ferromagnets. Dougherty's group is experienced in designing molecules with high-spin states, a prerequisite for magnetism. The collaborators hope to make ferromagnetic plastics, permanent magnets, by tweaking the high-spin orientations. Superconducting plastics might also be possible—the conduction mechanism in doped polyacetylenes seems to resemble that of the new high-temperature superconductors.☐—*DS*



Delocalized electrons: the top two structures are equivalent, so the alternating double bonds blur into a continuous series of "1½ bonds."

Acetylene was first polymerized in 1955. Polyacetylene turned out to be a dark, brittle film that crumbled into a powder with no particularly interesting properties. Then, in the early 1970s, a graduate student at the Tokyo Institute of Technology accidentally added a thousand times too much catalyst while preparing a batch of polyacetylene. The silvery film that resulted was a cross between aluminum foil and plastic wrap. It was lustrous and reflective like a metal, but stretched and flexed like plastic. Although this new and improved polyacetylene had some metallic properties, conductivity wasn't yet one of them. It was, in fact, an insulator, with a conductivity of about 10^{-10} reciprocal ohms (or mhos) per cm. By contrast, copper has a conductivity of about 5×10^5 mho/cm.

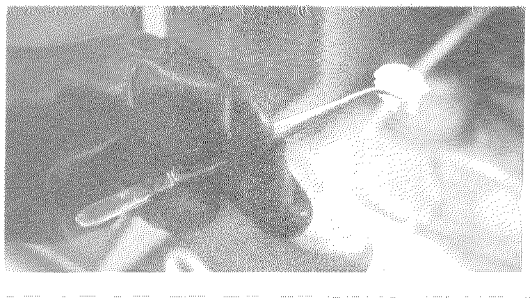
Although polyacetylene didn't conduct electricity, it seemed reasonable to think it might somehow be made to. Polyacetylene is just a long chain of carbon-hydrogen units, linked together by alternating single and double bonds between successive carbon atoms—what chemists call a conjugated system. The arrangement can be thought of as a series of single bonds with an extra bond superimposed on alternate pairs of carbon atoms. To an electron in the extra bond, every carbon atom looks the same—it has one bond to a hydrogen atom, and one each to its neighboring carbon atoms. There is no atomic cue telling the extra bond which pair of carbons it should link, so it "delocalizes"—it tries to cover all the possibilities at once. As a result, each pair of double and single bonds is more like two "bonds-and-a-half," with the delocalized electrons smeared indeterminately across the system. If these highly mobile delocalized electrons could be persuaded to move in coordinated fashion, the system would conduct electricity.

In 1976, Hideki Shirakawa, in whose lab the shiny film had been made, working with Alan Heeger and Alan MacDiarmid of the University of Pennsylvania, discovered that adding iodine to the polymer increased its conductivity a billionfold. This process was christened "doping" by analogy to semiconductor preparation, and works along somewhat similar lines.

Although the details are still debated, the general scheme works as follows. Electrons in solids occupy certain discrete energy states called bands. An electron must have a certain energy in order to occupy a given band. Every band has a finite capacity, but within that capacity, the band may be full, partially full, or empty. Bands fill in order of their increasing energy. Metals conduct because their outermost occupied band, the valence band, is partially full. Insulators (including undoped semiconductors) have full valence bands. (It's like traffic flow through a parking lot—cars move freely when there are plenty of available spaces, but come to a standstill as the lot fills up.) The next available band, the conduction band, is empty, and is separated from the valence band by a sizeable energy difference, or band gap. (The band gap is smaller in semiconductors than in insulators.) Doping either adds electrons to the conduction band (called *n*-doping, because it gives the molecule a net negative charge), or removes electrons from the valence band (*p*-doping; the molecule gets a net positive charge). Either way, the electrons are free to flow. Iodine is a *p*-dopant, sodium is an *n*-dopant.

Unlike semiconductors, where the dopant actually replaces a silicon atom in the crystal matrix, dopants in conducting polymers insinuate themselves between adjoining polymer chains. The dopant exerts its influence by donating or removing electrons in the nearby portion of the chain. Unlike metallic conductors, the electrons do not flow in any direction with equal facility, but flow preferentially along the polymer chains. In fact, conductivity can be substantially enhanced by stretching the polymer before doping it, thereby maximizing chain alignment in the direction of stretch. The preferred orientation creates an anisotropic, or nonuniform, effect: conductivity can be a thousandfold greater in the preferred direction than perpendicular to it. No single molecule extends the entire length of a polymer sample, even after stretching, so some sort of chain-hopping is going on, but the conduction mechanism between chains remains a mystery.

Polyacetylene film



Technology, Capital Formation, and the Twin Deficits

by Ralph Landau

We hear much about the lack of competitiveness of the U.S., but seldom is this term defined. It is obvious that this country could be more competitive if we reduced the wages and living standards of the American working population to the level of the Korean or Brazilian, but of course, this is not what we mean. The real goal of economic policy is to sustain an acceptable *growth* in the standard of living of the population as a whole, while providing employment for substantially all but the unemployable or temporarily unemployed, and doing so without reducing the growth in the standard of living of future generations. The latter condition thus constrains borrowing from other nations, or incurring future tax or spending obligations, to pay for the present generation's growth. And finally, economic policy seeks to assure that the fruits of growth and competitiveness are not unfairly distributed within the population.

During the 20-25 years after World War II, the U.S. enjoyed an essentially unlimited economic horizon. Since 1950 real U.S. gross domestic product (GDP) has tripled and income per capita has almost doubled, while the real GDP of the world has quadrupled and world trade has grown sevenfold.

Despite this impressive growth record, it is clear that the world of U.S. firms and farmers has irrevocably changed, and not only because other nations have caught up. International capital flows have become global and virtually instantaneous, while technology flows are not far behind. On the other hand, national policies with regard to fiscal and monetary matters, as well as trade, legal, tax, financial, and other practices, vary widely among countries. Such domestic freedom to control national destinies is, however, increasingly constrained by the discipline of the international capital markets, and by the trade in goods and services.

At the same time, the world now sees the availability of extraordinary new technologies that promise to raise global living standards more than ever. The age of the computer has only just begun. Telecommunications via satellite and fiber optics are binding the world together at an ever-increasing rate. The biotechnology revolution has hardly begun, but already its potential to affect human health and improve productivity in farm and factory is immense. Superconductivity is certain to play a major role in the 21st century; new materials are penetrating realms as diverse as medicine and aerospace; new catalysts and pharmaceuticals are improving the efficiency of industry and the human body. Many of these developments are American. To be a scientist or technologist today is to be at the frontier of human explorations and aspirations, but we must be cognizant of the economic and social limitations of these exciting prospects.

Then why are we worrying about our competitiveness?

The growth rate in real income per person in the U.S. has been almost 2 percent per year since the Civil War. With this growth rate, standards of living nearly doubled between generations, despite a simultaneous huge increase in population. Thus, from 1870 to 1984, the country's average real growth rate in gross domestic product (which differs from GNP by omitting international transactions) was about 3.39 percent per year; from 1948 until recently it exceeded this level. The U.S. surpassed the United Kingdom, at one time the leading industrial power, which grew at a per capita income increase of only 1 percent per year (a level about half that of the U.S.). Great Britain is now one of the poorer members of the Common Market. On the other hand, since 1868 Japan has surpassed even the high American growth rate. With an annual GDP growth rate of over 5 percent since 1930, it has become the second largest economy in the world.

To be a scientist or technologist today is to be at the frontier of human explorations and aspirations, but we must be cognizant of the economic and social limitations of these exciting prospects.

Such is the power of compounding over long periods of time. Differences of a few tenths of a percentage point, which may not appear very significant in the short term, are an enormous economic and social achievement when viewed in the long term. Thus it is of concern that since 1979 the U.S. real annual GDP growth rate has dropped to about 2.2 percent despite a long five-year economic recovery. Will the U.S. follow the fate of the United Kingdom, while Japan and the Far East eventually outdistance it? Or can it maintain a prominent position of economic, and hence strategic, leadership?

To achieve this goal, the promise of the new technologies must be realized, but this cannot be accomplished without taking into account the realities under which new technology is applied. Here, history is a guide.

The role of technological change

The United States could have achieved its growth in per capita income in two very different ways: 1) by using more resources, or 2) by getting more output from each unit of resource (increasing the productivity). How much of the long-term rise in per capita incomes is attributable to each? The first serious attempts at providing quantitative estimates came only during the 1950s, and the answers were a big surprise to the economics profession.

What seemed to emerge from these studies was that long-term economic growth had not come from simply using more and more resources, that is, capital and labor, but rather, overwhelmingly (85 percent) from using resources *more efficiently*. Many ascribed this increase in productivity to "technological change," although certainly many social, educational, and organizational factors, as well as economies of scale and resource allocation, also affect productivity.

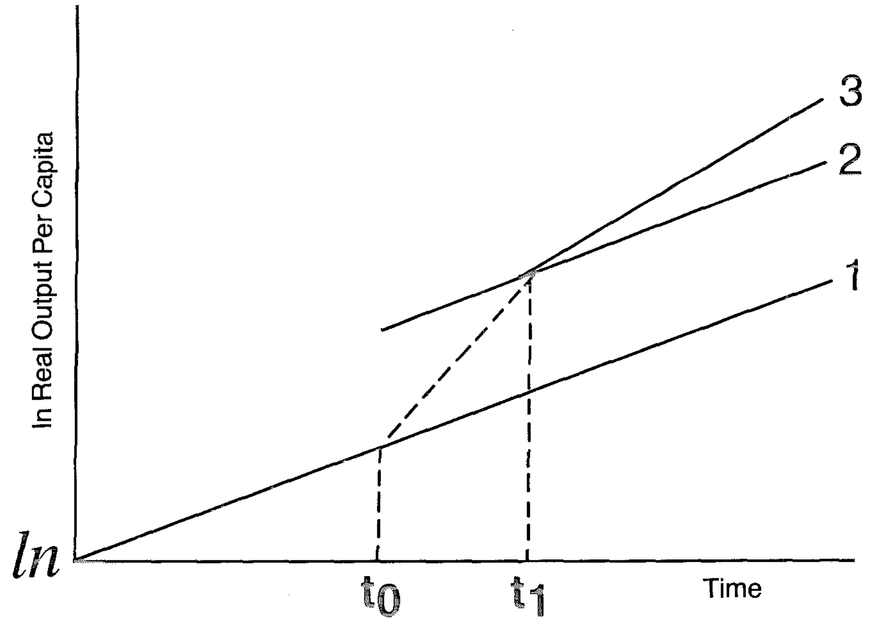
This neoclassical growth theory was developed by Robert Solow at M.I.T., and out of it came the growth accounting studies of the 1960s and 1970s. But recently other economists, including my colleagues at Stanford's Program in Technology and Economic Growth as well as at Harvard's Program in Technology and Economic Policy, have begun to examine more critically the limitations inherent in this theory.

In particular, we perceive that there are in actuality two key departures from Solow's neoclassical equilibrium theory: 1) that it does not apply for periods less than perhaps half a century, because the economy is in a dynamic transition disequilibrium stage almost continuously; and 2) technology in a mature society like the U.S. is largely endogenous (that is, new technology is generated by internal forces) and not, as assumed, exogenous (imposed from outside the economy). In a mature society it may well take 20 to 30 years to fully utilize important new technologies, but meanwhile GDP may double.

Since 1966 productivity increases in the U.S. economy have greatly diminished from previous levels. From 1964 to 1973, the labor productivity growth of the U.S. economy was 1.6 percent per year; from 1973 to 1978, it fell to −0.2, and in 1979-1986 revived to only 0.6. (The Japanese labor productivity growth rates for the same period were 8.4, 2.9, and 2.8 percent per year respectively.) In much of the later part of this period, the growth of total GDP was brought about almost entirely by increases in capital and labor, especially (in the seventies) the latter, as the baby boom peaked. While the explanations for the collapse in American productivity vary, it seems clear from extensive recent studies of the two economies by Dale Jorgenson of Harvard and his colleagues, that the comparative performance of the U.S. and Japanese labor productivity growth rates has been heavily influenced by the *much higher rate of Japanese capital investment* in a number of their industrial sectors. Coupled with very high savings rates, this helped fuel the rapid adoption by Japanese industry of the latest available technologies from abroad. The rate of Japanese investment was twice as high as the rate for many U.S. industries, which in some cases were not adopting new technology with the same urgency.

Other data also suggest a very high correlation between national investment and economic growth rates; for example, Germany and France, with investment rates roughly twice those of the U.S., also had about twice the productivity growth rate. These higher investments were due in part to higher labor costs relative to capital costs and to more rigid markets.

Jorgenson also found that capital formation



According to Michael Boskin of Stanford, the economic growth rate (1) can be temporarily kicked up to a higher level (2) by encouraging capital formation. It then continues, however, at the same pace as before. But the growth rate is accelerated (3) if technological change, capital, and labor quality are interacting so that improvements in one sphere stimulate improvements in the others.

has contributed far more significantly to long-term economic growth than earlier estimates had suggested—that it accounts for about 40 percent of economic growth in the post-war era. And technological change constitutes less than 30 percent, rather than the earlier 85 percent estimates; labor factors were the remainder.

The important point of these new studies is that there is a priority list for improving growth rates over the medium term of 20-30 years: first, capital investment, then R&D and technology, and last, although not unimportant, improvement in labor quality. There is a further complication in understanding the causes of growth, however; quantitative measures of productivity do not fully describe the performance of any economy. Quality is also of great importance but is very difficult to measure.

How growth rates can be increased

Insight into the key relationships is provided by the figure above. According to Michael Boskin of Stanford University, the fundamental variables that increase the growth rate of a country in the long term are the rate of technical change and the increase in quality of the labor force. Increasing just the capital/labor ratio will lead to only a *temporary* increase in the rate of growth (moving from growth path 1 to growth path 2). As mentioned, such an increase in capital formation occurred during the 1960-1979 period in Japan. These large growth rates have proved difficult to sustain, but permanent advantages for many industries and for the population have been created.

Measurements of productivity growth alone are not, however, a complete expression of the role of technology in economic growth. In the original formulations, the inputs of labor, capital, and productivity were deemed essentially independent of each other. However, in our experience, R&D is seldom performed all by itself—but rather only when it is expected to be employed in new or improved facilities and in superior operating modes. So technological change is not only embodied in capital investment, but it is also a powerful inducement to it, since the availability of superior technology is a major incentive to invest. Likewise, improvements in labor quality (human knowledge, skill, and training) are both a requirement of and a spur to technological change and are another form of investment—human capital. Thus technology now often takes an embodied form within each of the basic factors of production—labor and capital—to a far greater extent than ever thought before. And when workers, managers, and technologists utilize such capital investment, they are also learning from and drawing upon an expanded store of human knowledge, which yields continuing improvements in efficiency and output.

Boskin's growth path 3 in the graph above illustrates that if these interactions between technological change, capital, and labor quality are in fact occurring, then a higher rate of capital investment *can* move the economy to a higher rate of medium-term economic growth, as well as an upward shift in the level at any given time. This is especially true when it comes to exploit-

The table on the opposite page compares employment (civilian millions) in the U.S., Europe, and Japan. The first column includes the 12 EEC countries, while the second column shows figures for the original 10. In comparison, the U.S. did very well in job formation in the last three decades.

ing the results of "breakthrough" R&D, which requires large new investments. This increased growth path may be viewed as a series of transitions in a dynamic economy never really at equilibrium because of continuing, unpredictable, endogenous technical changes. If technical change is not exogenous, embodiment and learning by doing interact with capital investment to improve growth rates, and capital investment is critical in reaching a higher equilibrium at a faster rate.

Hence, in view of the substantial number of really novel technologies now becoming available and the effects of continuing R&D efforts, the need for totally new facilities, new capital investment, and the closing down of obsolete units is becoming much greater—a version of "catch-up" for the U.S. The revival of interest in growth economics has been further aided by the award of the 1987 Nobel Prize in Economics to Solow.

Solow has recently expressed his own reconsideration of the role of capital formation in long-term growth. He stated that he feared that the implications of his theory—which downplayed the importance of capital by making his long-term growth equation independent of savings—might have been carried too far, resulting in a severe underinvestment in the nation's physical infrastructure. "You can't take an old plant and teach it new tricks," he said. Such growing recognition of the critical role of capital investment leads to a study of its availability and cost relative to other countries.

My colleagues and I believe that earlier distinctions between technology, capital, and labor inputs to economic growth need to be modified in favor of a view that sees them as intertwined parts of the *same process*. It is only in this broad sense that it is correct to say that technological change has been responsible for perhaps 70 to 80 percent of U.S. economic growth in recent decades. In the past, *the successful entrepreneurial exploitation of new technologies to create new products, processes, and businesses has been a distinctive American characteristic and comparative advantage*, requiring a favorable economic climate for long-term, steady growth, and a balance between current consumption and investment for more future consumption. Do we have such a climate today?

The climates for productivity and growth

Postwar experience has indeed confirmed that long-term growth is established in the microeconomy—the world of firms and individuals who do the investing, the learning, the researching, and the conducting of the numerous businesses. Solow has termed the study of these activities the true supply-side economics. On the other hand, short-term cyclical effects are stabilized by macroeconomic policies (primarily fiscal and monetary), and these relate to the demand side of economics.

Nevertheless, the microeconomy is also adversely or benignly affected by short-term macropolicies, and may be favorably or unfavorably influenced by second-tier macropolicies such as tax, regulatory, trade, labor, and financial policies. Sometimes, these effects may be long-lasting:

- The tight monetary policy of the 1979-82 era to subdue inflation led to the hard dollar and a huge trade deficit, permanently closing down many businesses and injuring the competitiveness of many more.
- The high inflation of the seventies left a residue of high, long-term interest rates because of the negative expectations of investors, and it reduced spending by firms and individuals for capital investments by raising the cost of capital. This has had a long-term depressing effect on the competitiveness of American firms.
- The rapid succession of tax bills in the eighties has made long-term business planning more hazardous than ever, although the low marginal rate trend may eventually be beneficial if left alone for some years.
- The high government budget deficits of the eighties have reduced private savings in the U.S. and have compelled the import of capital primarily for consumption and not for investment. These deficits, plus the increasing indebtedness of firms and individuals, have led to an extraordinary expansion in money and credit growth. This growth, however, flowed into the financial markets and not into the real economy, creating excessive liquidity and speculative fever.
- The ad hoc mix of all these policies has, however, provided the large number of the jobs required to meet the demographic increase in the work force. The table above shows how well the U.S. did relative to Europe in job formation, which was a factor in mitigating social unrest here. But this extraordinary U.S. job machine, based in large measure on its unique ability to generate many new small and medium-sized companies, has had the inevitable effect of lowering its productivity increase compared with its competitors. Thus, Europe has indeed had a higher productivity growth, but at the cost of unemployment rates over 10 percent (vs. the U.S. rate of 5.5 percent), which would be totally unacceptable in the U.S. Since our criterion of

	EEC	EEC	USA	JAPAN
1955	–	101.4 Est.	62.2	41.9
1965	–	104.8 Est.	71.1	47.3
1975	121.8	105.4	85.8	52.2
1985	121.0	106.5	107.2	58.1
1986	121.5E	107.1E	109.6	58.5
Net Increase		5.7	47.4	16.6

9/14/87 Courtesy: *The Economist*

true competitiveness includes adequate job formation, the U.S., in view of its declining demographics, can have *both* if it adopts the policies advocated later in this article.

But, in addition to the domestic climate (set largely by the federal government), there is now an international climate—that of trade in goods and services, in capital, and in technology. Capital flows (say $50 trillion per year), however, dwarf trade flows ($3 trillion per year). Thus, it seems clear both from current perceptions of growth theory and from the realities of today's international climate that the driving force of international exchange is in capital flows, with trade in goods and services its derivative mirror image. So I intend to lay special emphasis on capital.

The capital formation problem

The international accounting systems provide a basic identity that illuminates the problem underlying America's uncompetitiveness in capital flows: current account balance (the net of international trade and invisible flows) is equal to domestic investment minus domestic savings. At present, the current account balance is approximately −3.5 percent of our GDP. This means that either domestic investment is too high or domestic savings too low. In view of the aging of American plants and the new technologies available, American domestic investment cannot be too high. The only rational explanation is that savings are too low and that the cost of capital is, therefore, too high.

Since it is obvious that changing the private savings rate is not easy, the U.S. has become dependent on foreign savings. This has happened to the U.S. before, and to other countries at certain stages of development, but not to fund consumption, which seems to be the current U.S. pattern. Global investors are necessarily wary of committing capital to a nation with an overconsumption problem, and interest rates must rise to tempt them to do so, which, of course, also raises the cost of capital.

As a result, control over American macroeconomic and other policies is no longer firmly in U.S. hands, and the cost of borrowing from abroad will become an increasing burden on future generations.

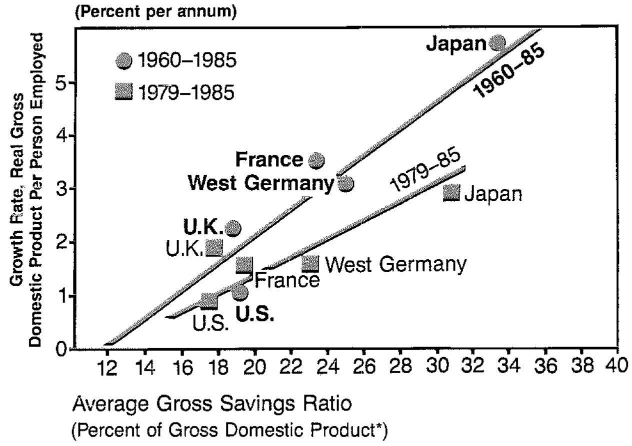
The quickest and most manageable step toward putting America's destiny back into its own hands is to reduce the government's net budget deficits. By so doing, savings available for investment would rise by 3.5 percent of GDP, and future generations would not be increasingly burdened by the growing foreign debt.

Unfortunately, there is another major obstacle to improved long-term growth: the *extreme volatility* in the seventies and eighties of government policies, resulting in wide swings in inflation rates, dollar exchange rates, interest rates, tax rates, and the like. There is a continuing threat of devaluation of the dollar staring every investor in the face and increasing prospects of excessive protectionism. These threats have also pushed up interest rates, because expectations of sudden, unhedgeable, and unpredictable changes add a real risk premium to interest rates, and this in turn limits investment rates. Such an increase in interest rates also directly raises the cost of capital to American industry. In a recent conference at Harvard University on the cost of capital, three speakers from the U.S. and Japan confirmed that hurdle rates to justify a proposed industrial investment for investors in the U.S. are 15 percent at a minimum, while in Japan they are 8 to 10 percent.

Figures 1 and 2 on the following pages present a summary of what these obstacles have done to reduce American competitiveness. Both in savings rates and investment rates, we are near the bottom. There is, however, an important element inherent in these international comparisons: the technology level of our principal competitors in 1960 was well below ours. For the investment curve in figure 2, the 1979-84 data show the declining slope due to a more nearly uniform level of technology among the nations.

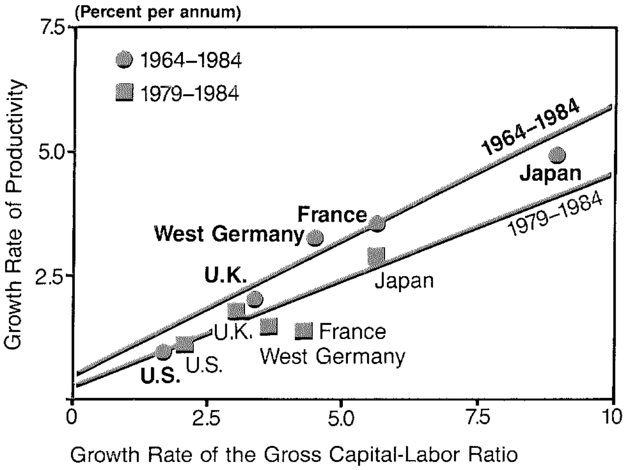
Nevertheless, the truly significant fact is that for these five mature economies, the effect of

Figure 1



*Personal, business and government savings.
Source:OECD (Courtesy U.S. Dept. of Treasury)

Figure 2



Source: OECD (Courtesy of Stephen Brooks)

The U.S. had one of the lowest rates of savings and productivity growth over both the longer and the shorter term, as seen in Figure 1 above. The flatter slope of the short-term data (1979-85) reflects the general decline of world growth rates during that period. Figure 2 shows national productivity vs. the capital-labor ratio, that is, the average annual growth rate of capital per worker. Again the slope of the more recent data is flatter; this indicates a more uniform international level of technology.

capital investment per worker on productivity is substantially higher than neoclassical theory would indicate, for some of the reasons indicated above.

The findings of figure 2 relate directly to our studies of the cost of capital. In the U.S. it has been and continues to be from two to three times as high as it is in Japan. Combined with the high availability of capital (Japan, unlike the U.S., is an exporter of capital), this permits a much longer investment horizon—a patient money approach—which is the hallmark of the Japanese company.

Thus, inevitably, we keep returning to the problems of inadequate domestic savings and investments. A budget deficit that declines to zero or close to it over perhaps a four-year period must be the primary tool to increase the savings rate of the U.S. This, in turn, would reduce the current account balance to close to zero, or at least to a modest and manageable level. Policies should be *steady*, predictable, and not subject to sudden change. Simultaneously, with this increase in savings, consideration must be given to increasing the incentives to invest, including in particular the reduction in the risk premiums. As suggested below, the possibility of accomplishing these goals is really much better than one might suppose—relatively little here and there will probably be enough to cut $150 billion a year from the deficit by 1992.

The social climate

There is another stream of economic research that deals with the social capabilities or climate for a nation to grow over the long term—including such factors as education, labor relations, the legal system, and many others. For optimum growth, a cooperative social climate is required. The preeminent example of a favorable social climate is, of course, Japan. But the Japanese have many unique advantages not open to the U.S.—high savings rates; friendly stock ownership with no takeover threats; close relations between companies, suppliers, and governments, all of whom get their returns by continuing business from growing corporations; one-party government; cooperative company-oriented trade unions; tight discipline; better secondary education; and so on. The U.S. has a different culture, and must adopt its own set of solutions, taking advantage of the unique risk-taking entrepreneurial nature of its private sector, its extraordinary research university system, its huge domestic market, its extremely broad range of manufacturing and service industries, and its many natural resources. Yet, if the problems of the high cost and inadequate amount of capital persist in the U.S., the concept of the MBA instead of the engineer as CEO will become the accepted tradition, with fatal results for our own competitiveness in an increasingly technological era.

In view of the problems cited above, priorities for policy actions must be set. The U.S. cannot solve all of its problems at once. I would divide them into the three "R's"—recession, reinvestment, and redistribution.

Recession: the short term—two to four years

● The present recovery of more than five years is widely deemed to be tired. The next president must be prepared to deal with a recession; *but it should not paralyze decisive action to plan for long-term growth, which should start as soon as he is inaugurated.*

● A sudden constriction of demand by budget deficit reduction is undesirable. It might even deepen and accelerate the recession, and could possibly drown the rest of the world. This is why I advocate a definitive four-year program for deficit reduction. On the other hand, if a favorable climate for long-term investment is created, an anti-Keynesian, investment-cum-export boom could cushion the reduction in demand that a recession or simply slow growth imply, and we may conceivably be able to avoid much of a decline altogether. Modern Keynesian economics no longer takes the simple view that a dollar of demand stimulation gives a dollar of results. The reason lies in the realization of the greater role expectations have come to play. We cannot run deficits without raising interest rates. The real purpose of future economic policy is to shrink imports, to make investment and saving a high priority, and to increase exports to a world that must not be thrown into recession either. Unfortunately, our ability to increase exports may increasingly bump up against domestic capacity constraints, as well as the ability of other nations to absorb more. This is a major reason to encourage an investment boom. This has already been occurring in basic industries such as paper, chemicals, light metals, etc. If properly managed and with proper understanding of other nations' interests, the foreign capital now coming to the U.S. will stay home instead, and add to domestic demand there, including demand for our exports. I believe the following are major ingredients of such a strategy:

a. If the budget deficit is thus gradually but definitively reduced to zero, it is still not fully predictable what the ultimate value of the dollar will be at equilibrium. There really are two equilibrium values for the dollar, one set by capital flows, and one by trade flows. In the long run, perhaps many years, these should be the same; but not in the next several years, at least, when the capital market transactions will dominate the exchange rates. Thus, if the reduced interest rates cause foreigners to lose their appetite for U.S. investments, then a side effect would be a lower dollar, and the trade deficit would disappear. At the same time, it is conceivable that, despite the reduction in interest rates, the U.S. could still be a desirable place to invest because of the perception that a stable national policy and higher potential returns are now in place in the world's largest economy. Then some dollar inflow might continue indefinitely with, of course, a continuing trade deficit and possibly even a higher value of the dollar. But because the domestic savings rate would then be 3.5 percent of GDP higher, this inflow gives a higher savings rate than is now possible. And it is mostly self-liquidating since it would only go into investment to raise productivity and increase the capital stock, and not into consumption. This was the situation of the U.S. in the 19th century.

If the budget deficit is not clearly headed toward a manageable level, the financial markets will impose a solution of their own, perhaps in the form of a more severe "crash." On the other hand, a sharply lower dollar can only temporarily accomplish the same objective as a cut in the budget deficit. Ultimately, if policies do not change, the fundamentals of exchange rates (savings and investment, inflation, productivity rates) will reassert themselves, and the dollar will resume its fall. This is a recipe for progressive impoverishment, and the American economy would be permanently damaged.

Some political solution is required to avert real irreversible damage to Japanese and European industries, before the trade deficit turns around, bringing with it rising anti-Americanism. There is a world demand shortage, and the U.S. has been the world locomotive of growth in the eighties. Greater investment possibilities offer the best way to raise world growth. In this way, it beomes possible to reap the rewards of the new technologies described above.

There are American observers who feel that any such coordinated measures, however, cannot or should not be put in place *before* the trade deficit disappears. It is my feeling that, in view of the genuine effects abroad, as described above, such a policy is unrealistic. *It is not necessary to establish a stable exchange rate too soon if we*

Earlier distinctions between technology, capital, and labor inputs to economic growth need to be modified in favor of a view that sees them as intertwined parts of the same process.

address the budget deficit problem along the lines I support; the markets will set the exchange rates.

b. Monetary policy should, therefore, continue to seek reasonable stability for the dollar so that the large stock of dollar assets held in international currency portfolios does not immediately flee and depress the dollar exchange rate too much further—and worse, increase the incentives for the "buying out" or "selling" of America. A falling dollar raises the cost of capital in the U.S. This would really happen if a "free-fall" of the dollar occurs, and probably lead to attempts at capital controls, trade wars, and world depression. But unless the budget deficit reduction plan is clearly implemented, attempts to stabilize the value of the dollar will fail as market forces push it even lower.

c. Although many economists find some features of the 1986 tax reform act to be anti-investment and anti-growth, nevertheless I insist that for the best growth policy, the government should leave the basic income tax structure alone. Business needs 5 to 10 years without new bills to adjust its activity and grow. *Volatility of economic policy is the biggest enemy of long-term strategy.*

- Even in the event of a recession or growth slowdown, we must start the process of reducing the *structural* full employment deficit in a gradual but definitive direction so as to reduce this deficit to zero by 1991-1992. But we must first address the spending side by doing some of the following:

a. Reduce all unnecessary budget expenditures that do not affect long-term growth favorably. These include removing subsidies to large farmers (much of the $20 billion spent on agriculture), which will also benefit consumers; continuing the gradual reversal of defense spending increases (the new 1989 budget shows a real decrease for the first time), but with care not to give the wrong signals; eliminating, delaying, or sharing the costs with other nations of the big-ticket "show" items of big science, such as the superconducting supercollider, the space station, and sequencing the human genome (but using a portion of the savings for more basic scientific and engineering research); applying means tests to many entitlement programs, such as bringing transfer payments within the income tax system; and considering a one-year freeze of indexations on entitlements. A two-year freeze on the spending programs would eliminate the deficit entirely, but may not be needed if all or most of the measures suggested here are adopted. The real gain in long term growth would come from spending reductions, thus freeing more resources for investment. At least half of the burden of reducing the budget deficit must and can be drawn from these measures.

b. Firmly reject a value-added-tax system, because it adds complications and uncertainties; it is an engine to fuel new spending programs that may be economically undesirable but politically attractive; it preempts state sales taxes; and it adds to inflation.

c. Add a higher gasoline tax of 25 cents/gallon at once, rising to 50 cents-$1.00 in four years. Those who must drive long distances can be aided by providing a threshold level of tax applicability. The price of oil will inevitably rise in the nineties, and everyone will be paying more for gasoline in due course. In 1988 crude oil imports are expected to be 7 million barrels per day, up from 4.9 million in 1985. Such imports account for 37 percent of the total U.S. trade deficit. As we become bigger importers, the price of oil will rise. Americans pay no more than a third to a half of the European price of gasoline. The U.S. does not require such low prices—in real terms gasoline now costs barely half as much as it did in 1980. By biting the bullet now, we can start the process of energy-saving reductions in consumption without hurting investment, encouraging more fuel-efficient cars, and reducing highway congestion and pollution. As the price of gasoline rises, the tax can be reduced.

d. Raise tobacco and alcohol taxes.

By a combination of these methods, with increased taxes also contributing about half of the money needed to resolve the budget deficit, it is quite feasible that by 1992, the structural deficit as a percentage of GDP will have been reduced to a manageable level.

- We must address the debt problem of the less-developed countries by writing much of it off at market prices. Many customers for our products cannot be restored to health without some such step. It is mostly fiction now that these debts are carried at nominal value on bank balance sheets.
- No new major spending programs that have consumption characteristics should be undertaken in this period, or the discipline of the budget will be lost, long-term interest rates will go through the roof, and inflation will come back. The time for new spending programs should come only when recovery is firmly in place, and always so as to allow a zero or slightly positive budget balance.

It is during this short period of recession that the ground must be laid for the reinvestment plan that is to come next.

A budget deficit that declines to zero or close to it over perhaps a four-year period must be the primary tool to increase the savings rate of the U.S.

Reinvestment: the middle term—a decade

- Reducing the structural budget deficit is the first and quickest step, although savings do not equal investment.
- Increasing corporate cash flow comes second. This can be changed by allowing much faster depreciation, so as to equalize more nearly the tangible and intangible investments and allow deductibility of dividends on new issues of preferred stocks so as to render neutral the choice of financing between debt and equity. This latter provision would also favor new investment and would reduce takeover risks. The ideal is to allow first-year depreciation of all kinds of assets, and to eliminate the double taxation of corporate income.
- Restoring and broadening the IRA system is the most likely method of raising personal savings.
- Interest rates will move downward with greater stability of policy and reduction of the need for borrowing abroad. While lower interest rates reduce incentives for foreign investors to send capital to the U.S., they increase the incentive for domestic investors to invest, by lowering the cost of capital. Thus, it is by international adjustments in interest rates, coupled with reduction of American "dis-saving," that a relatively longer term exchange rate stability can be sustained.
- Incentives for investment are even more important than those for R&D. The capital/labor ratio must go up as the growth of the work force diminishes, so that while job loss is minimized, productivity is raised. If productivity is raised sufficiently, we can finance our debts, hardly notice the decline in living standards, and grow our way out of the present impasse. Ultimately, the capital gains differential and the investment tax credit for certain types of investment must be restored, the former for longer-term riskier stock holdings in productive enterprises.
- The inhibition of innovation by the legal system must be attacked: problems of product liability, takeover laws, regulation, and waste disposal. There's no question that technology has a dark side, and we have to deal with it. But we must find more efficient ways of doing it than we've found so far.
- We must improve our educational system in the secondary schools, by setting national standards but allowing traditional local control.
- The adversarial atmosphere between government, industry, and labor must be changed. While we are most unlikely to adopt the Japanese policies that consistently favor the producers over the consumers, we can move away from our almost completely opposite *pro-consumption* policy, which has prevailed since the war. This does not mean industrial policy, which is *not* politically feasible because it will always become clout-based instead of merit-based.
- Management in both manufacturing and service industries must work harder and smarter at raising their productivity and quality. We need a new type of manager—more technically sophisticated, internationally minded, and conversant with other languages.
- We must deal with the drug problem, which is seriously affecting productivity.
- We must eschew protectionism. It is a negative sum game. There are those who still advocate "fair" or managed trade, but it benefits only the companies affected, injures the consumer, and slows growth. Who in the government can resist the pressure of the "losers" for favored treatment, and who will speak for the "winners" yet unborn or for the consumer?
- A serious long-term energy policy is essential.
- Some mechanism must be found to improve fiscal policymaking by the government, particularly by the Congress. While monetary policy is set by the Federal Reserve Board, no one really sets fiscal policy as a whole. Our competitors do much better at this, which is one of their great comparative advantages.

Redistribution: the long term—a generation

The underclass needs to be brought into the mainstream. This term does not mean all persons within the poverty level, but those who have essentially dropped out of the economy altogether. This is the principal area where redistribution may be feasible. In a recent article in *The New York Times*, Solow said, "Redistribution is not something that Americans are good at." Greater growth is his remedy, and my colleagues and I agree.

What remains to be done?

The influence that the federal government has on the climate for innovation and long-term growth has been discussed above. Capital formation and its costs have been pinpointed as the major problems facing American industry in its efforts to improve its competitiveness in a vastly different world economy than that of 15 years

INDUSTRY	**R&D EXPENDITURES** (Billion $)	**HOW FINANCED**
1. Aerospace	24.0	80% Government
2. Electrical Machinery & Communications	20.0	60% Industry
3. Machinery	11.9	87.5% Industry
4. Chemicals	9.4	97% Industry
5. Autos, Trucks, Transporation Equipment	9.2	77% Industry
6. Professional & Scientific Instruments	6.8	84.8% Industry
7. Petroleum Products	2.5	Nearly all Industry
8. Rubber Products	1.5	84% Industry
9. Food and Beverages	1.07	Practically all Industry
Total	86.37	

Source: Battelle Memorial Institute

This table shows the 1988 estimates of R&D investment by those industries that spend more than $1 billion a year on R&D. Since total U.S. investment is estimated at $132 billion, of which industrial R&D represents $96 billion (70 percent comes from companies and the rest from government), the industries listed here constitute the bulk of the investors in R&D.

ago. The opportunities available in new science and technology are breathtaking, but the horizons for exploring them are long, and they require cheap and abundant capital investments per worker—of both physical and intangible capital. Intangible capital encompasses R&D, engineering, experimental production, construction costs, market development, and legal precautions. These and many other expenses can frequently be deducted by the firm, but they are capital costs all the same.

But even if this fundamental capital problem is ameliorated, there is much that firms and individuals must do for themselves, particularly in the manufacturing sector, which performs 95 percent of commercial R&D (the table above shows the industries that spend more than $1 billion per year in R&D). This sector constitutes two-thirds of the nation's tradeable goods, nourishes the service sector, provides for defense needs, and boosts the overall productivity of the economy. The force of international competition will drive out the bad managements and firms.

The task of management and technologists must be to create wealth by steady cost reductions and incremental improvements in large-scale production, which will be needed for the innovative activity involved in utilization of the new technologies. This will, as is already happening in Japan, lead to a concentration on higher value-added products with advanced technology, in which the labor costs are a small part, and can justify high wages. This type of strategy fits the American entrepreneurial spirit, which is hospitable to the new. In effect, today's comparative advantages are dynamic and ever-changing. Managements must accept that firms need to become increasingly multinational and move closer to their markets. This will aid growth prospects in the world as a whole. The U.S. cannot be walled in any more. Such isolation is a recipe for progressive impoverization and technological sterility.

The national goal

What I argue for in this article is for greater growth of the economy. We should aim at the 3.5 percent real GDP growth per year, which was the rate during most of the postwar years. In the nineties the work force should only increase by 1 percent. In addition, there is a probable drag of 1 percent of GDP per year required to service the foreign capital we have borrowed (by increasing exports). Thus, even a 3.5 percent growth rate translates into a 1.5 percent per capita growth in real GDP, slightly below our historic nearly 2 percent long-term growth. If we are to achieve even this reasonable goal, great changes in national and international economic policies are inevitable. It is time the American people and their elected representatives faced the hard truths. □

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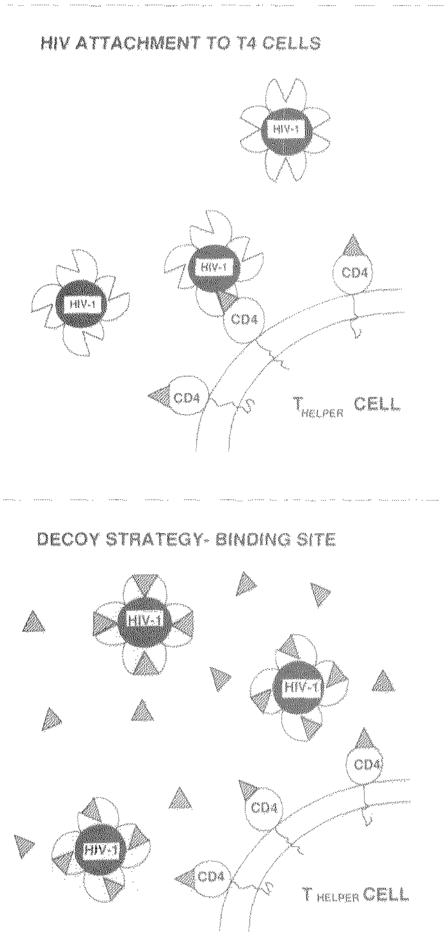
The fragment might act as a decoy—viruses and infected cells could bind to it instead of infecting other cells.



Top: HIV-1 virus infecting a T-cell. The virus recognizes and binds to a specific site (shaded triangle) on the CD4 protein found on the cell's surface. Bottom: A flood of synthetic binding sites overwhelms the virus, tying up all its recognition sites.

A Handle on AIDS

Caltech biologists have found the handle an AIDS (HIV-1) virus must grab in order to infect a cell. The handle, or binding site, is located in a protein on the cell's outside surface. The researchers also created a synthetic version of that binding site which, in a test tube, prevents the virus from infecting cells.

Bradford A. Jameson, research fellow in biology, and Stephen B.H. Kent, senior research associate in biology and group leader for the project, did the work in collaboration with researchers at ORTHO Pharmaceuticals and the University of Alabama. The scientists reported their research in the June 3, 1988, issue of *Science*.

"We do not want to give people false hope. This is not a cure for AIDS," said Kent. "Nevertheless, we believe this to be a significant advance not only in AIDS research but in virology in general. This is the first time that the binding site for *any* virus has been identified with this degree of precision. At best it is one possible step on one possible road that may possibly lead to an AIDS treatment."

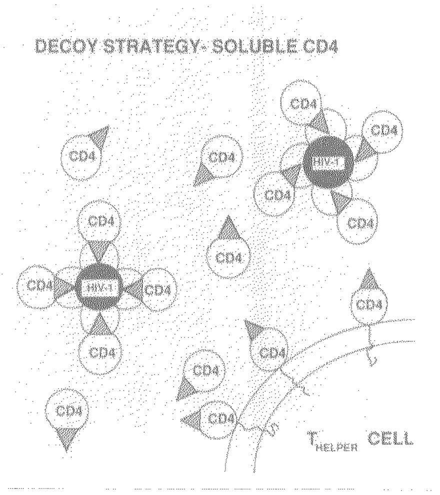
The HIV-1 virus must bind to a susceptible cell in order to infect it. Once infected, a cell may fuse with uninfected cells, killing them. Cell fusion depends on the same binding site that the virus uses to infect the cell in the first place. If researchers could introduce large quantities of a protein fragment containing the binding site into the bloodstream, the fragment might act as a decoy—viruses and infected cells could bind to it instead of infecting other cells. Such a fragment, if linked to a virus-killing drug, could also carry the drug directly to the AIDS virus.

The protein containing the binding site is called CD4, and it appears on the surface of helper T-cells—a type of white blood cell vital to the body's immune system. Scientists know the sequence in which amino acids are strung together to form CD4, so the Caltech researchers synthesized 10 overlapping segments of the molecule, each about 30 amino acids long. ORTHO Pharmaceuticals then provided an assortment of antibodies, each of which binds to a different region of the intact CD4 protein. Some of these antibodies were known to prevent HIV-1 from infecting suceptible cells, presumably by blocking the binding site, while others were ineffective.

Jameson and Kent reasoned that the antibodies which prevented HIV-1 infection were probably attaching themselves at or near the binding site, while the ineffective ones attached elsewhere. When they tested their fragments against the antibodies, they found that the effective antibodies tended to attach themselves to a particular piece of CD4. That piece, the researchers concluded, must contain the HIV-1 binding site.

But what does the binding site look like? A protein's three-dimensional shape determines its properties, and subtle differences in shape can have marked effects. Although the

CD4 protein molecules can be prepared in soluble form. A CD4 solution also overwhelms the virus, leaving the T-cells unmolested.



shape of CD4 itself is still unknown, it belongs to a class of proteins—the immunoglobulin superfamily—all of which have very similar shapes. (Another group of Caltech biologists, led by Leroy E. Hood, has pioneered the study of the immunoglobulin superfamily. Hood, the Bowles Professor of Biology and chairman of the biology division, is a coauthor of the CD4 study.) By drawing a structural analogy, the researchers were able to approximate CD4's shape. Because CD4's amino acid sequence is completely known, they knew where in the protein the active segment appeared; knowing how the protein folds up into three dimensions allowed them to deduce the binding site's general properties and its location on the protein's surface.

The next step was to see if the fragment alone could inhibit HIV-1 infectivity. The fragment, called CD4-derived synthetic peptide 25-58, was synthesized at Caltech and sent to the University of Alabama for infectivity tests. (There are no laboratories at Caltech working with the live AIDS virus.) The Alabama researchers used the most stringent test for HIV-1 infectivity, an *in vitro* (test tube) assay measuring the virus's ability to induce cell fusion. The 25-58 fragment did, in fact, inhibit infectivity in a dose-dependent fashion. Three other CD4 fragments, from regions adjacent to the presumed binding site, were used as controls. They had no inhibitory effect.

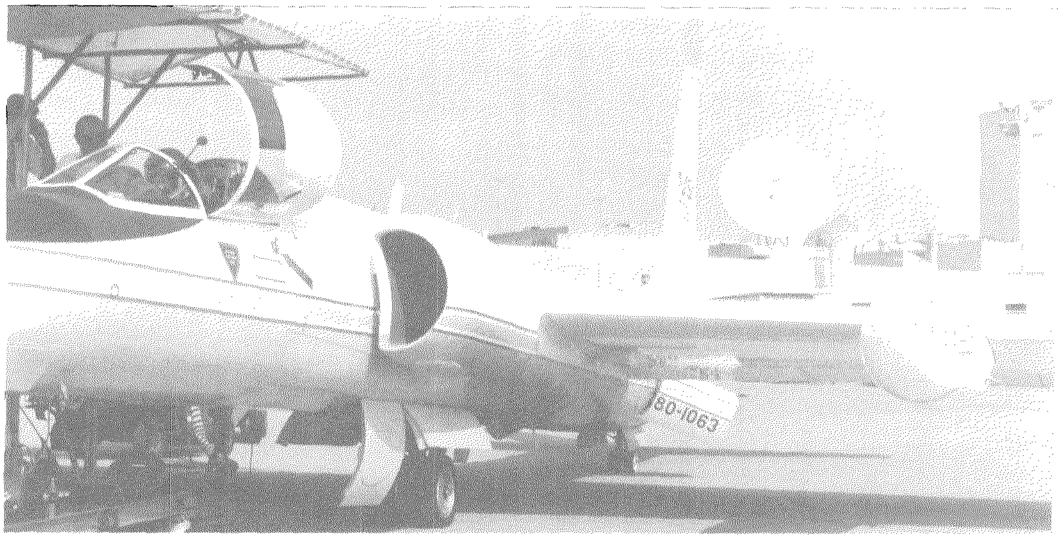
Researchers at several laboratories had first synthesized CD4 back in December, 1987, and had found that a CD4 solution prevented cells from being infected by HIV-1 *in vitro*. But for many reasons, including potential difficulties with using large proteins in therapy, many researchers had hoped to identify the specific part of the CD4 molecule to which HIV-1 binds, as this work has now done.

Kent says the next step is to define the binding site's exact shape more precisely, and to determine which specific amino acids are critical to the binding process. Then chemists can begin to synthesize analogs of the binding site, hoping to find one that binds to the virus even more strongly. Other laboratories could then begin clinical trials of the synthetic binding site. "We are going to be conducting intensive explorations into the binding site over the next two years," said Kent. "There's probably a large chance that in two years this work will no longer be thought of as a direct route to an AIDS therapy. Of course, we all hope that this turns out to be the one in a hundred that does work out."□—*DS*

Ozone: The Hole Story

Caltech's Jet Propulsion Laboratory (JPL) and the "hole" in the ozone layer go back a long way together. In 1974, JPL's Mario Molina and F. Sherwood Rowland of U.C. Irvine discovered that chlorofluorocarbons (CFCs)—chlorine-containing compounds used as refrigerants, solvents, fire extinguishing agents, and aerosol propellants—were destroying ozone in the earth's stratosphere. (The U.S. banned CFC use in aerosol cans in 1978 as a direct result of that finding.)

The hole, discovered by British scientists in 1985, isn't really a hole. It's a seasonal decline in the stratospheric ozone concentration over Antarctica—a drop of more than 50 percent compared to the late 1960s. The drop-off begins early in the austral spring (late August to early September), levels off in October, and eventually climbs back to normal in November. The hole may be getting bigger and recovery may be taking longer each year, with alarming implications for the ozone layer worldwide. (Another group, the Ozone Trends Panel, recently determined that average annual ozone concentrations over much of the Northern Hemisphere have decreased



The ER-2 research plane carried 14 automated instruments. The instruments had to be light and compact, yet rugged enough to function unattended for 7 hours at −90° C and air pressure one percent that at sea level. Gary's instrument projects from the pod at right.

by about two percent between 1969 and 1986.)

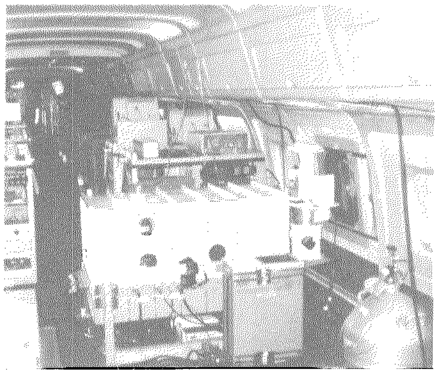
JPL's Barney Farmer and Bruce Gary joined a group of about 150 scientists from four nations who explored the hole in August through September of 1987. The Airborne Antarctic Ozone Experiment (AAOE) was designed to map the hole's chemical and physical properties in detail, shedding light on its origins and providing a database for future research.

Ozone, a form of oxygen containing three oxygen atoms per molecule instead of the usual two, absorbs ultraviolet (UV) light. Small doses of UV light cause suntans. Medium doses can damage DNA, causing skin cancer and spontaneous mutations, and large doses can kill cells outright—meat lockers have UV lamps to keep bacteria down. Five percent of the sun's energy output is in the UV region, and there's not much ozone between us and the sun: if all the stratospheric ozone were brought to the earth's surface at room temperature and pressure, it would form a layer only two to four millimeters thick.

Lab work by Molina and others has shown that chlorine atoms, knocked loose from CFCs by ultraviolet light, can convert ozone into ordinary oxygen molecules. An intermediate step in the reaction forms chlorine monoxide (ClO), which breaks down, regenerating the chlorine to destroy more ozone. But there's more to the story. Nitric oxide (NO), a naturally ocurring trace gas, reacts with ozone to form nitrogen dioxide (NO_2) and ordinary oxygen. Some gases deactivate chlorine; NO_2 and chlorine monoxide form inactive chlorine nitrate ($ClONO_2$). Unfortunately, the Antarctic stratosphere is cold enough that "good" gases can freeze out onto the tiny ice crystals that make up the polar stratospheric clouds, denitrifying the air. Reactions on the crystals' surfaces can break down reservoir gases like $ClONO_2$ and HCl, re-releasing active chlorine.

The AAOE flew 21 experiments on two aircraft based in Punta Arenas, Chile. Each plane flew about a dozen missions into the hole. Long hours were the norm—after each flight returned, enough data from it had to be analyzed to determine whether the upcoming flight plan should change. One craft, an ER-2—the civilian version of the U-2 spy plane—flew six- to eight-hour missions at altitudes of 60,000 to 65,000 feet, where ozone is most depleted. The ER-2 is a small, unpressurized aircraft with barely enough room for the pilot and 14 automated instruments. The other airplane, a converted DC-8 passenger plane, flew missions in excess of 12 hours at lower altitudes corresponding

Farmer's FTIR records infrared spectra through a specially modified window. The DC-8's pressurized passenger cabin accommodated experimenters as well as experiments.



to the bottom of the ozone-depleted layer. The final DC-8 flight traversed the continent, landing in Christchurch, New Zealand on the way home. The DC-8's pressurized passenger compartment allowed the investigators to accompany their instruments.

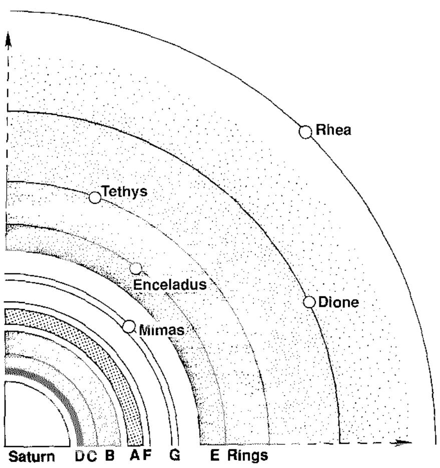
Farmer's instrument, a Fourier transform infrared spectrometer, or FTIR, flew on the DC-8. Aimed at the sun, the FTIR measured trace-gas concentrations between the sun and the aircraft by recording the gases' absorption of infrared sunlight in the 2 to 16 micron region. The scans were repeated at two-minute intervals, or approximately every 10 to 20 kilometers. One million data points per scan were stored in an onboard computer for Fourier analysis later. About 100 good spectra were obtained per flight. The method identified HCl, $ClONO_2$, N_2O, CFCs, NO, NO_2, N_2O_5, HOCl, ozone, and other species, some in concentrations as low as 0.1 part per billion. The great sensitivity was no scientific luxury: two gases of particular interest, HOCl and ClO, are present at one part per billion at best. The accumulated data show how chemical distributions change as the hole forms. (The other six experiments measured some of the same chemicals by other methods, so each verified the others; air samples were collected as well.)

Gary's instrument, a microwave temperature profiler, rode in the ER-2. (Other devices measured particle sizes, chemical constituents, air temperature and pressure, and collected air samples.) The profiler measured air temperatures by sensing thermal emission from oxygen molecules at two frequencies in the microwave range, 57.3 and 58.8 GHz. The instrument scanned through an arc from −50° to +60° relative to the plane's horizon, producing readings at 15 altitudes within an 8,000-foot slab of air centered on the aircraft. A complete set of readings was taken every three kilometers. The data were plotted as potential temperature surfaces—sheets of air that would have the same temperature if they were at 1,000 millibars pressure. The plots look like a cross section through the rumpled sheets on an unmade bed. The rumples are waves associated with vertically oscillating airmasses. Mountains on the Palmer Peninsula produce very large waves with amplitudes as large as 1,200 meters. These waves propagate into the ozone hole, where they may initiate cloud formation by elevating air parcels to colder altitudes. The larger (10 micron) ice particles fall out, taking with them any nitrogen compounds they may have collected. These mountain waves may thus be responsible for the denitrification and dehydration observed within the hole.

The hole forms within the polar vortex, a self-contained, Antarctic-sized body of air that swirls around the South Pole every winter. The vortex acts like a giant thermos bottle, keeping interfering nitrogen compounds on ice while the returning sun's UV light creates active chlorine. The vortex's boundary can be found by plotting potential vorticity, derived from wind data and Gary's potential temperature readings. The boundary plot, superimposed on chemical distribution data, correlates meteorology and chemistry.

The AAOE scientists have been digesting their data since their return from Chile. They met in Snowmass, Colorado, in mid-May to share their findings. The results agreed with those of a ground-based study at McMurdo Station in 1986, but in much more detail and over a much larger area. The compositional changes found inside the hole included strong evidence for denitrification and dehydration—allowing the chlorine chemistry to proceed unimpeded—and for reservoir gases freezing out on ice crystals. According to Farmer, "We found very strong evidence that the hole is caused by chlorine from man-made chemicals, as had been suspected; aided and abetted by natural meteorology—polar stratospheric clouds containing ice crystals where the perturbed chemistry can occur."□—*DS*

SURFboard



Saturn, its rings, and inner moons. (Not to scale.) The E ring starts near Mimas's orbit, extends out past Enceladus and Tethys, and trails off somewhere near Rhea or Dione.

> *"Enceladus is very bizarre. It's the brightest reflective body in the Solar System. It's ten times brighter than our moon per unit area."*

Moonlighting

The Summer Undergraduate Research Fellowship (SURF) program turns ten years old this summer. The program has mushroomed—from 18 students the first year to 176 students this year. SURFing has, in fact, become a prominent feature of undergraduate life. SURF is attracting notice off-campus, too; last year two SURFers won awards at the First Annual National Conference on Undergraduate Research. This issue of E&S *inaugurates SURFboard, a regular feature devoted to undergraduate research.*

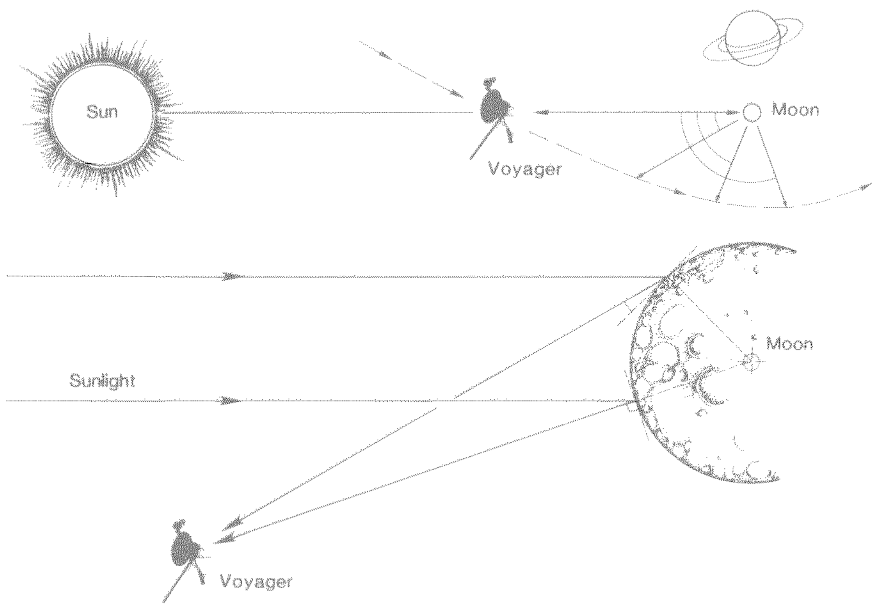
Although Voyager 2 photographed Saturn's moons in late August 1981, and nobody's been back since, there's a lot still to be learned from the images. They show features as small as 50 to 100 km across, in living (or computer-enhanced) color. They can be processed to provide additional information, too. For example, the brightness of each point in the image tells about the albedo, or degree to which light is reflected by the corresponding point on the surface.

Experience with Jupiter's moons had shown that the albedo of an icy surface relates to its age. The relation holds not only for water ice, but for ammonia, methane, and mixed ices (called clathrates) as well. New ice is very bright but gradually loses its luster under the gentle rain of interplanetary dust. Thus, adjoining topographies can have markedly different albedos, depending on their ages. A less gentle rain of meteors provides a more reliable clock: the more densely cratered a surface, the older it is. Again, newer craters tend to be brighter than their surroundings, because the impact exposes bright, fresh ice beneath the discolored surface.

But Saturn's icy moons didn't seem to work the same way. Although each moon had a different average albedo, local variations were less dramatic. Perhaps if a moon's albedo map could be superimposed on its topographic map, subtle correlations between surface features and local albedo would emerge.

Making an albedo map is not quite that simple, however. The amount of light reflected to Voyager depends not only on a region's intrinsic albedo, but on the angles between Voyager, the sun, and the reflecting surface. Reflectivity peaks when the sun, Voyager, and the planetary moon are all in a line, with the sun shining over Voyager's shoulder, as it were. As Voyager flies by, the angles keep changing, causing the apparent albedo to change as well. Furthermore, for any given arrangement of sun, Voyager, and moon, a point directly "below" Voyager, where the moon's surface is perpendicular to the camera, will appear brighter than an equally reflective point at the limb where the surface is almost parallel with Voyager's camera, and hence reflects less light back to it.

Bruce Rossiter, now a senior in Engineering and Applied Science, tackled the problem as a SURF (Summer Undergraduate Research



Top: Reflectivity peaks when the sun, Voyager, and Saturn's moon are all in line. As Voyager flies by, the angles change. Bottom: A point directly "below" Voyager, where the surface is perpendicular to the camera, seems brighter than a point on the limb, where the surface is almost parallel to the camera.

Fellowship) project last summer, working with Bonnie Buratti, a Member of the Technical Staff at the Jet Propulsion Laboratory. Armed with the laws of trigonometry and IDL—a high-level graphics programming language—he wrote a set of programs to transform observed brightness into intrinsic albedo.

Each Voyager image is a matrix of 160,000 picture elements, or pixels, laid out in an 800 × 800 square. The program adjusts each pixel's brightness to what it would be if the corresponding surface point were in the position of maximum reflectivity, using data from Voyager's navigational records to determine the three objects' relative positions, and using information about each moon's size and shape to determine surface orientations. The computer then converts brightness to albedo by calculating the amount of light reflected as a percentage of the solar flux—the amount of sunlight falling on that point. Finally, the system plots the albedos, either as contour maps or as histograms.

"People have written similar programs before," says Buratti, "but Bruce's is much easier to use, and it didn't cost millions of dollars or take years to develop, either."

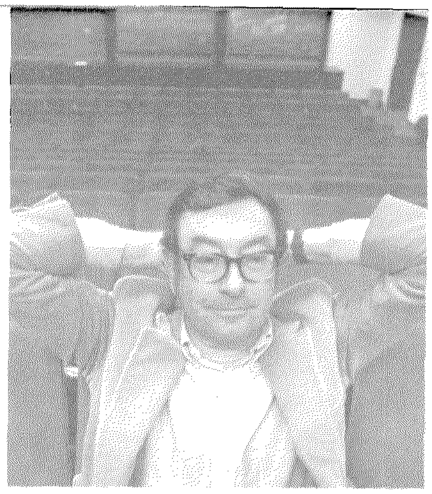
Work has continued over the past year, and Buratti and her colleagues have produced albedo maps for five of Saturn's icy moons: Mimas, Enceladus, Tethys, Dione, and Rhea.

"Enceladus is very bizarre," Buratti says. "It's the brightest reflective body in the Solar System. It's so bright that it basically reflects everything. Earth's full moon reflects about ten percent of the visible light that hits it, so Enceladus is ten times brighter than our moon per unit area." One might think that Enceladus's whole surface is very new, but it isn't: some areas are quite smooth, and probably new, but other areas are as cratered as the highlands of our moon, and presumably as old. Yet they have the same albedo. "It's like something was painted on," Buratti says.

That's a pretty good indication that the shiny stuff was deposited from an external source—an exogenic process. If it came from within (an endogenic process), it would tend to vary with the terrain: pooling in lowlands if it had oozed out like flowing lava, or leaving streaks pointing back to its source if it had been blown out by a geyser or volcano.

Saturn's E ring, a tenuous ring of unknown composition, seems to be the most likely source. The E ring starts near Mimas's orbit, extends out past Enceladus and Tethys, and trails off into nothingness somewhere near Rhea or Dione. When Rossiter and Buratti compared albedo variations with position, they found the interior satellites—Mimas, Enceladus, and Tethys—to be very bland, with little albedo variation and no correlations to surface features. Farther out, Dione and Rhea have increasingly variable albedos with better correlation to surface features. "There are different levels of things we'd like to show," according to Buratti. "And the first is that there's no correlation. So Bruce got the contour plots up and running, and quantified the albedo changes. Now we're ready to show that the albedo variation is exogenic, simply because it doesn't correlate with the geologic units. It looks like a coating."□—*DS*

Random Walk



Harry Gray's Chem 1 students commemorated his being named California Scientist of the Year by reversing the seats in 22 Gates. Unfazed, Gray delivered his 9-board lecture from the single chalkboard at the back of the hall. Gray is the Arnold O. Beckman Professor of Chemistry and director of the Beckman Institute.

Honors and Awards

Fred Anson, professor of chemistry and chairman of the Division of Chemistry and Chemical Engineering, has been elected to membership in the National Academy of Sciences in recognition of his work in electrode reactions.

Arnold O. Beckman, a life trustee of Caltech's Board of Trustees, has been named the 1989 recipient of the American Chemical Society's Charles Lathrop Parsons Award for public service.

Professor of Chemistry Peter Dervan was elected a Fellow of the American Academy of Arts and Sciences at their 208th Annual Meeting in May.

John Hopfield, the Roscoe G. Dickinson Professor of Chemistry and Biology, has been elected to the American Philosophical Society. The Society was founded by Benjamin Franklin in 1743 as the American counterpart to the Royal Society of London.

Rudy Marcus, the Arthur Amos Noyes Professor of Chemistry, has won the 1988 Willard Gibbs Medal. The gold medal, awarded annually by the Chicago Section of the American Chemical Society, recognized Marcus's work in many branches of theoretical chemical kinetics.

Philip Saffman, professor of applied mathematics and executive officer for applied mathematics, has been elected a Fellow of the Royal Society of London.

Gerald J. Wasserburg, the MacArthur Professor of Geology and Geophysics and chairman of the Division of Geological and Planetary Sciences, has been elected a member of the Norwegian Academy of Science and Letters.

Professor of Theoretical Astrophysics Roger Blandford and Barry Simon, the IBM Professor of Mathematics and Theoretical Physics, have been named Guggenheim Fellows for 1988.

Three faculty members, Assistant Professor of Biology David Anderson and Assistant Professors of Astronomy George Djorgovski and Shrinivas Kulkarni, have been named Sloan Fellows. The Alfred P. Sloan Foundation, which annually grants research stipends of $25,000 for two years to young scientists of extraordinary ability and potential, honored 90 young faculty nationwide this year.

The American Association for the Advancement of Science (AAAS) has elevated three of its Caltech members to the rank of Fellow. The election of Professor of Geophysics Don Anderson, President Thomas E. Everhart, and Millikan Professor of Theoretical Physics Murray Gell-Mann recognizes that their "efforts on behalf of the advancement of science or its applications are socially or scientifically distinguished."

The National Science Foundation has named five faculty members Presidential Young Investigators for 1988. Brent Fultz, assistant professor of materials science; Christof Koch, assistant professor of computation and neural systems; Shrinivas Kulkarni, assistant professor of astronomy; Paul Sternberg, assistant professor of biology; and Kerry Vahala, assistant professor of applied physics, will each receive a research stipend of up to $100,000 annually for five years.

Distinguished Alumni

Four Caltech alumni received Distinguished Alumni Awards this year. Benoit B. Mandelbrot (MS '48, Eng '49), a Fellow at IBM's Thomas J. Watson Research Center, developed the concept of "fractals"—geometric entities found in such complex, irregular forms as branching rivers, turbulent flows, and radio static. William R. Sears (PhD '38) oversaw the development of the P-61 Black Widow fighter and the Flying Wing at Northrop Aircraft Corporation, then went on to found the Graduate School of Aeronautical Engineering at Cornell University, where he served as its director for 28 years. Hung-Chang Yin (PhD '37), director emeritus of the Institute of Plant Physiology, Academia Sinica, People's Republic of China, is one of the chief policymakers for agricultural research in China, and one of a handful of people primarily responsible for a large increase in China's food production over the last 25 years. Robert W. Zwanzig (PhD '52), Distinguished Professor of Physical Science at the University of Maryland, was honored for his contributions to nonequilibrium statistical mechanics.

On May 25, after a traditional Hawaiian ground blessing, Howard Keck, chairman of the W. M. Keck Foundation, and Gilliard Smart of the Richard Smart Trust used o'o sticks—Hawaiian digging sticks—to break ground for the W. M. Keck Observatory's headquarters in Waimea, Hawaii. From left: Keck; William Frazer, the University of California's senior vice president for academic affairs (partly hidden); Albert Simone, president of the University of Hawaii; Smart; David Gardner, president of the University of California; and Caltech's president, Thomas Everhart, all bedecked in maile-leaf leis. The 10-meter W. M. Keck Telescope, under construction on Mauna Kea, is a joint project of Caltech and the University of California. The Keck Foundation funded the project with a gift of $70 million, and the Smart Trust contributed the seven-acre headquarters site.

Chemical Consortium Launched

Three giants in the chemical industry—Du Pont, Eastman Kodak, and the Minnesota Mining and Manufacturing Company (3M)—and a nonprofit foundation, the Shell Oil Company Foundation, have joined the Institute in establishing the Caltech Consortium of Chemistry and Chemical Engineering. Each corporate sponsor has agreed to contribute $250,000 annually for four years to fund basic research on campus. So far, faculty members have submitted 23 research proposals to the consortium's board, which includes faculty and corporate members.

Obituaries

Sterling Emerson, professor of genetics, emeritus, died May 2 at his home in Altadena. He was 87. Emerson, a specialist in plant and biochemical genetics, served Caltech for 43 years. His research began with plant genetics, and later moved to the biochemical genetics of the bread mold, *neurospora*, a favorite organism for studying the laws of heredity. He joined the Institute in 1928 as an assistant professor, was promoted to professor in 1946, and retired as professor emeritus in 1971.

James E. Olson, a trustee of Caltech since 1987 and chairman and chief executive officer of AT&T, died April 18 at his home in Short Hills, New Jersey. A former president of both the Illinois Bell Telephone Co. and the Indiana Bell Telephone Co., Olson had held a number of executive posts at AT&T. He was also chairman of the U.S.-Japan Council and a trustee of the American Enterprise Institute and the Conference Board.

On April 11, ground was broken for the Beckman Institute, a facility to be devoted to interdisciplinary research in chemistry and biology. As soon as the last shovelful of earth was turned, the ceremony became an 88th birthday party for Arnold O. Beckman, a life trustee of Caltech. The Arnold and Mabel Beckman Foundation is supporting the new facility. From left: President Thomas Everhart, Arnold Beckman, Mabel Beckman, and Ruben F. Mettler, chairman of the Board of Trustees.

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