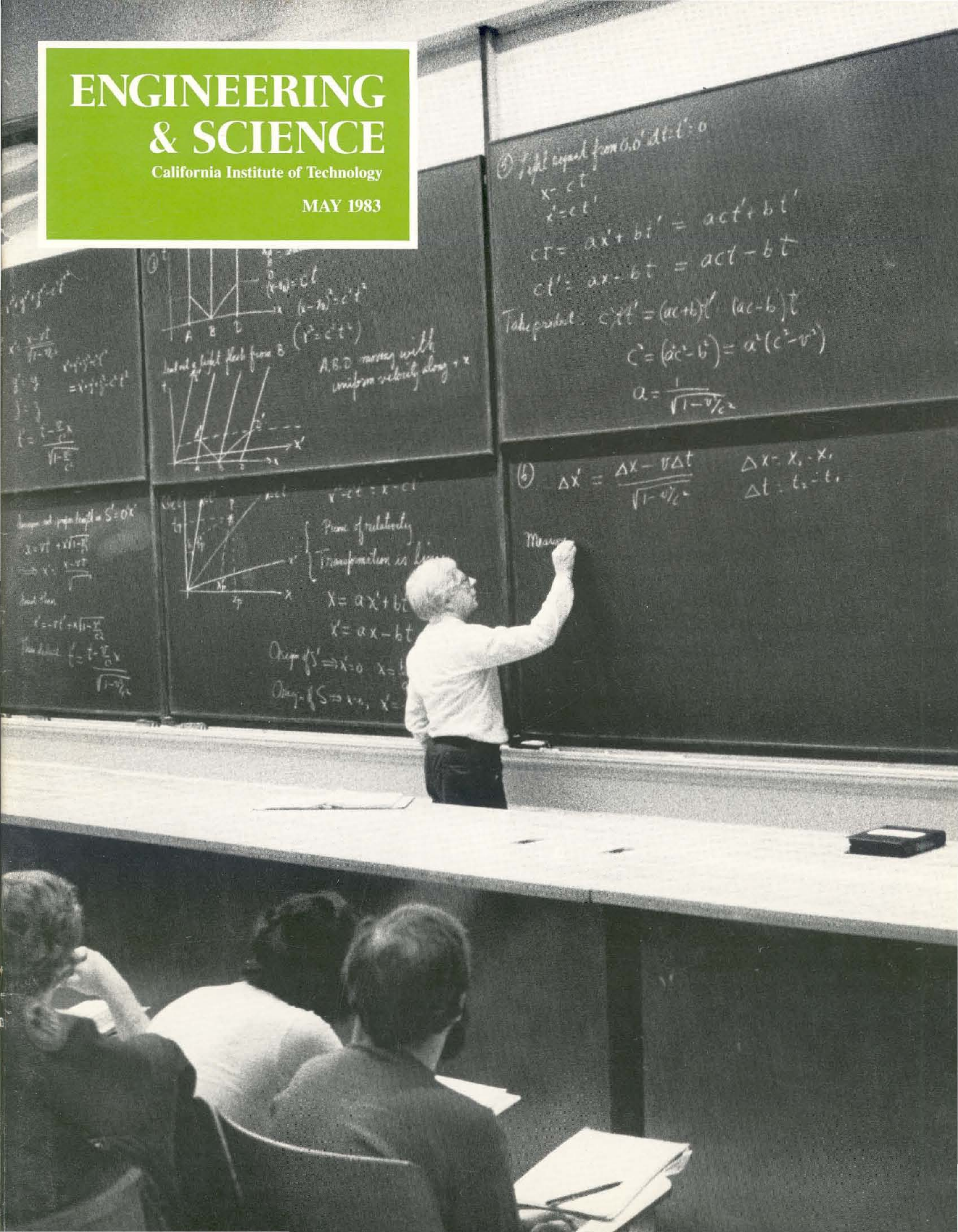
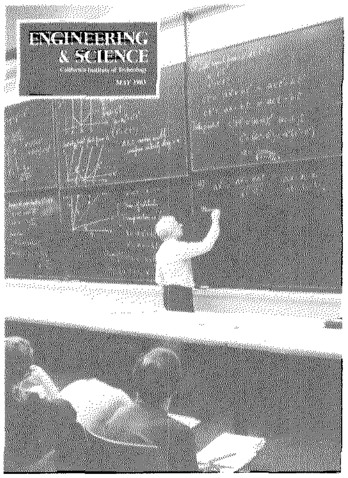
ENGINEERING & SCIENCE

California Institute of Technology

MAY 1983



In This Issue



Pedagogical President

On the cover — a sight familiar to every past or present Caltech freshman: the front of the big physics lecture hall in East Bridge Lab. The unusual aspect of the picture is that the professor covering the blackboards with the mathematical evolution of Einstein's special theory of relativity from the Lorentz transformations is Caltech President Marvin Goldberger. "A Duty to Profess" beginning on page 10 tells something of how and why he got into Physics 1.

Getting Together

Like marriage, collaborative research programs between universities and industry involve varying degrees of emotional attachment, mutual convenience, direct and indirect benefits, risk-taking, adjustments to new ideas and ways of doing things, and a host of other factors that accompany the establishment of relationships between sets of dissimilar colleagues.

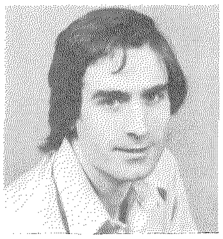
Recently the number of these associations has been increasing, and there are good reasons on both sides for wanting them to work out. The university needs industrial funding and an outlet for key research. Industry needs to keep in touch with advances in science in order to profit from emerging ideas, techniques, and technologies. With these factors in mind, *E&S* presents in this issue five short articles on this subject — two by people in the academic community, three by men from industry.

The introductory article is by Donald R. Fowler, general counsel for Caltech. Fowler recently made a two-phase study of the widely reported need for enhanced university-industry research relationships: a historical review and an empirical survey of 158 research managers from both industry and academia. "Impediments to Successful University-Industry Research Relationships," which be*gins on page 12, discusses some of* the results of the survey.

Last November the Research Directors Conference, sponsored by Caltech's Industrial Associates, looked at the same subject from a different standpoint. A panel discussion featured three speakers from industry with hands-on experience of university-industry research relationships — Martin Cooper, vice president and director of research for Motorola, Inc.; Louis Fernandez, vice chairman of the board of Monsanto Company; and John Tormey, director of corporate technical policy (since retired) for Rockwell International Corporation. And John Roberts, Institute Professor of Chemistry (and at that time, provost and vice president and dean of the faculty), gave a brief statement on the situation from the academic point of view. Excerpts from these four talks begin on page 15 in "Universities and Industry in Collaboration."

Charm and Beauty

When Hamlet pointed out nearly 400 years ago that "there are more things in heaven and earth" than his friend Horatio dreamed of, he could have been speaking for physicists today as they try to describe the particles and forces that seem to make up the universe. A few of the mysteries are, however, being slowly unraveled with the aid of some exotic but creative instruments and experiments, plus scientific logic. In "A Crystal Ball Looks at Charm and Beauty," beginning on page 4, Frank Porter and Charles Peck explain a bit about each of these factors.



Frank Porter got his BS at Caltech in 1972, *went off to* UC Berkeley for his PhD, and returned to the Institute in 1977. He became a senior research fellow in physics in 1980. His co-author, Charles Peck, is also a Caltech alumnus (PhD '64), who stayed on at the Institute, becoming a full professor of physics in 1977. Both are active in high energy physics research.

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ENGINEERING & SCIENCE

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Departments

Luis Castellanos mines copper with software.

Most copper is found deep underground. But the Bell System's 995 million miles of copper cable have tons of it above and below ground. That copper provides vital circuit paths to transmit customer voice, data and video signals for today's Information Age needs.

And Luis Castellanos, seven years out of undergraduate school, supervises one of the groups that helps Bell System companies "mine" all that copper. He works with one of the largest computer hardware and software systems in the world—the Trunks Integrated Record Keeping System (TIRKS). Every day it "mines" the vast Bell network for available circuits and equipment. As a result of efficient use of network facilities, the Bell System saves millions by eliminating the need for certain capital expenditures.

Plus, there's more to TIRKS than "mining copper." It also configures circuits and assigns components needed for each circuit path. That allows Bell companies to respond faster to customer requests for complex services like video and data transmission. Employees are more productive too, because TIRKS helps them set up circuits and forecast facility needs.

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According to computer scientists like Luis, the benefits from TIRKS are just beginning. He believes that, as more computer hardware and software systems like TIRKS interact, new benefits for customers may be possible, as well as additional productivity increases for employees.

Luis joined Bell Labs with a B.S. in computer science from Pratt Institute. Under a company-sponsored graduate study program, he attended Stevens Institute of Technology for his M.S. in computer science. At the same time, he worked part-time assuming responsibility for a large piece of TIRKS software. Working with design teams, he gained valuable insight from experienced members. Now, his technical performance has earned him a promotion to supervisor.

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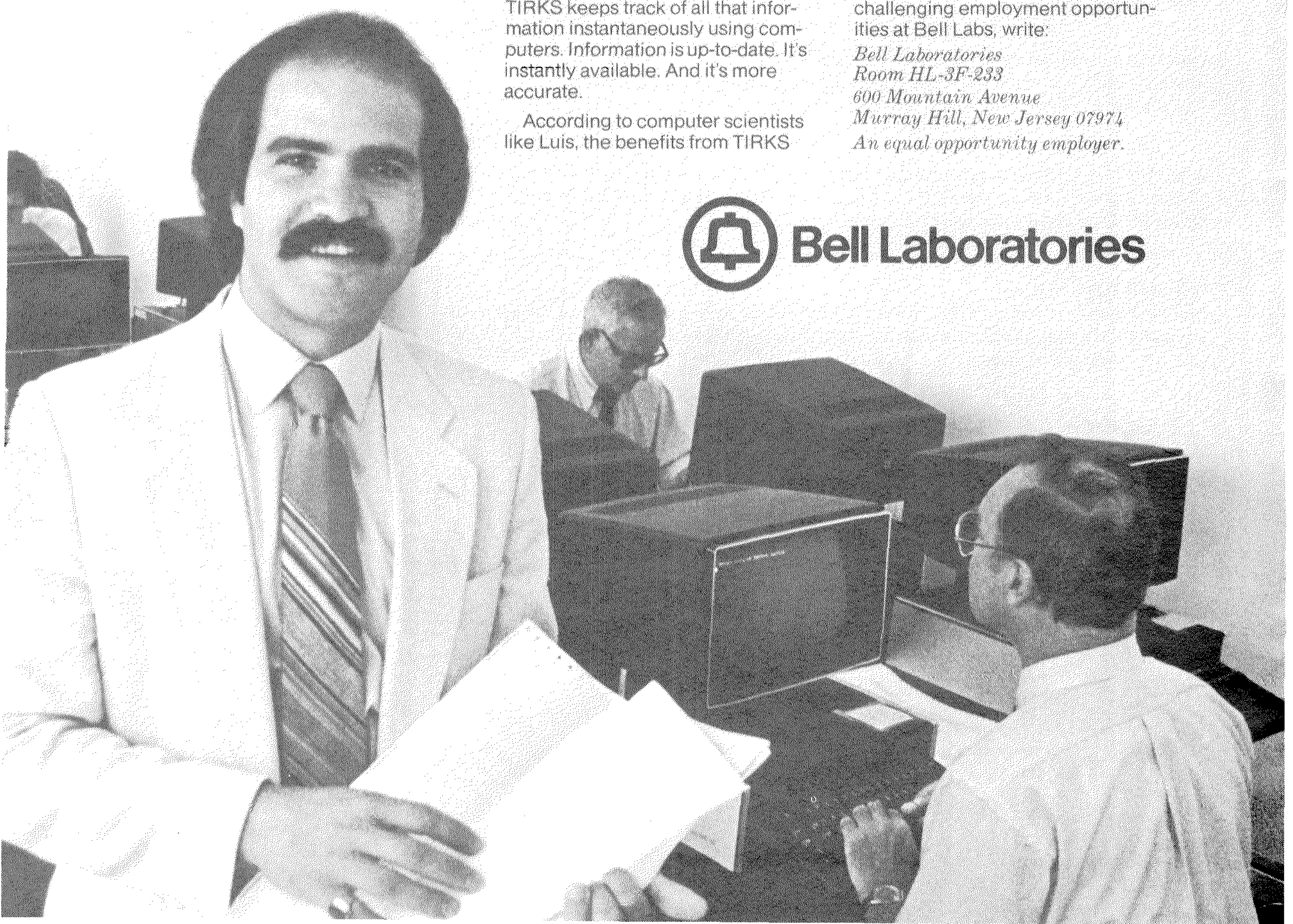

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A Crystal Ball Looks at Charm and Beauty

by *Frank C. Porter and Charles W. Peck*

SINCE THE beginnings of modern science, one of its most important and exciting goals in the quest to understand nature has been to identify and describe the fundamental forces. Over the years, four such forces have been established. Three of these have long been "understood," at least at a working level, in terms of well-defined theoretical structures: the gravitational force (17th century), the electromagnetic force (19th century), and the weak force (1930s). In the late 1960s, a great advance in our understanding was made when the theoretical descriptions of the electromagnetic and weak forces were unified into a single theory. And even more recently — in the 1970s — a likely candidate for a theory of the fourth fundamental force, the strong interaction, has finally arisen. The long time between the realization in the 1930s that such a strong force existed and the recent development of a theory to describe it was certainly not because this force is of little consequence in nature. In fact, the strong force is responsible for holding the neutrons and protons together inside the atomic nucleus, and so, in some sense at least, it governs the basic structure of all ordinary matter. A group of people from Caltech (the authors, Research Fellow Peter Ratoff, and graduate students Richard Partridge and Charles Edwards), together with collaborators from other universities, are working to increase our understanding of the strong force by doing experiments with an apparatus called the "Crystal Ball."

Given its fundamental character, you might reasonably ask why an understanding of the strong force has been so elusive. Perhaps the chief reason has been the difficulty of probing the interaction experimentally in clear-cut ways. Efforts to investigate the short-range phenomena of the strong force by ever higher energy probes simply yielded a bewildering array of new particles. The idea invented by theoretical physicists Murray Gell-Mann and George Zweig of Caltech that strongly interacting particles (called hadrons) are made of more fundamental particles (called quarks) is now well accepted, and it has been found possible to interpret much of the experimental data by assuming that all particles observed before 1974 are composed of various combinations of just three types of quarks (and the corresponding antiquarks). An attractive way to study the strong force is thus to examine how it holds the quarks together inside the hadrons. Until 1974, however, the only hadrons we knew about were made of these three types of quarks only, and it turns out that these three quarks have relatively low masses. Because of this, they typically move about inside a hadron at relativistic speeds (that is, approaching the speed of light) and, to complicate matters even more, they are bound with energies comparable to their own masses. The resulting complexities tended to obscure the underlying fundamental physics, although it was possible to make a few very powerful observations, such as the apparent impossibility of separating two quarks very far without creating new quarks in between.

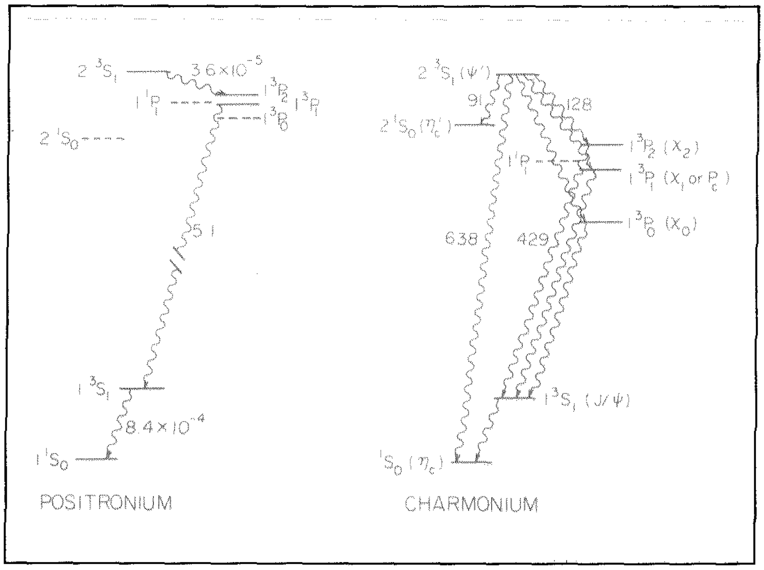
It was thus a cause for great excitement when, in November of 1974 (the "November revolution"), a new kind of quark (the fourth) was discovered. This new quark was dubbed "charmed," and deemed to carry a new attribute called "charm" in the often fanciful nomenclature of high energy particle physics. One of the things that make this new quark so special is that it is heavy — with an apparent mass of about one and a half times the mass of a hydrogen atom. In fact, what was discovered was not quite the quark itself but rather a particle (called J/ψ) made of the charmed quark bound together by the strong force with its antiparticle, the charmed antiquark. Because these quarks are so heavy, their motion inside the J/ψ is relatively slow, and the binding energy is reasonably small compared to the quark mass. Hence, it was immediately clear that we here had a chance to study the strong force, which holds the two quarks together, in a setting that avoided many of the overwhelming complexities of the earlier known particles.

This nonrelativistic bound system of a charmed quark and its antiparticle was quickly dubbed "charmonium," in analogy with "positronium," the bound system made of a positron and its antiparticle, the electron. The analogy can actually be carried much further; just as in positronium, a whole set of energy levels of charmonium bound states should exist, according to the different possible orientations of the quark spins, their relative angular momentum, and their average separation. Because the quark and the electron have the same spin, the smallest nonzero amount allowed by quantum mechanics, there is a one-to-one correspondence between the energy levels expected in the two systems.

There is, however, a fundamental difference between positronium and charmonium, and this difference is one of the reasons charmonium is so interesting. In positronium, the positron and the electron are bound together by the well-known electromagnetic force, whereas charmonium is held together by the quite different and poorly known strong force. It is of profound significance that the same rules of angular momentum seem to apply to both systems, giving them analogous energy levels. Nonetheless, positronium and charmonium are very different systems — an "atom" of positronium has a size comparable to that of ordinary atoms (also bound by the electromagnetic force), roughly one angstrom, while a charmonium "atom" is approximately a hundred thousand times smaller. Most of this difference can be understood as a consequence of the fact that the charmed quark is 3000 times more massive than the electron, but a factor of perhaps 50 remains on account of the different strengths of the forces.

This is, of course, not the whole story — the strong and electromagnetic forces differ not only in strength but, as one might guess, in form as well. Thus, the popular new theory of the strong interaction — called Quantum Chromodynamics, or just QCD — predicts a different dependence of the force on the distance between two quarks than that which the theory of the electromagnetic interaction — Quantum Electrodynamics, or QED — predicts for two electrons. This difference manifests itself very nicely in a comparison of the energy levels (masses) of the excited states of the charmonium and positronium systems, since the relative positions of the energy levels depend on the details of the binding force. For example, in positronium the lowest state with one unit of orbital angular momentum (1P state) has very nearly the same mass as the 2S state, which has no orbital angular momentum, but is excited from the ground state by virtue of having a larger average size.

On the other hand, comparison of the corresponding states in charmonium shows a much larger splitting between the 1P and 2S levels. Qualitatively, the difference can be understood in terms of the fact that the strong force becomes relatively stronger at large distance than the corresponding QED force law. For electromagnetism, the dominant part of the force was discovered by Coulomb, and it is well known to decrease as the square of the distance, r, between two charged particles. However, for the strong force under these circumstances, the main part seems to be approximately, $F_{\text{strong}} = A + B/r^2$, where A and B are constants. The two terms are equal at a distance of about 0.5×10^{-13} cm, and the position-independent part, A, has a value of about 10 tons. The strong force is strong indeed. Thus, since the 2S state is larger than the 1P state, the 2S state will have correspondingly higher mass (that is, energy) than the 1P state in charmonium. More quantitative predictions must include the fact that the quarks in charmonium are in fact moving rather quickly (about 45 percent of the speed of light), and hence there are significant relativistic corrections. The details of the level



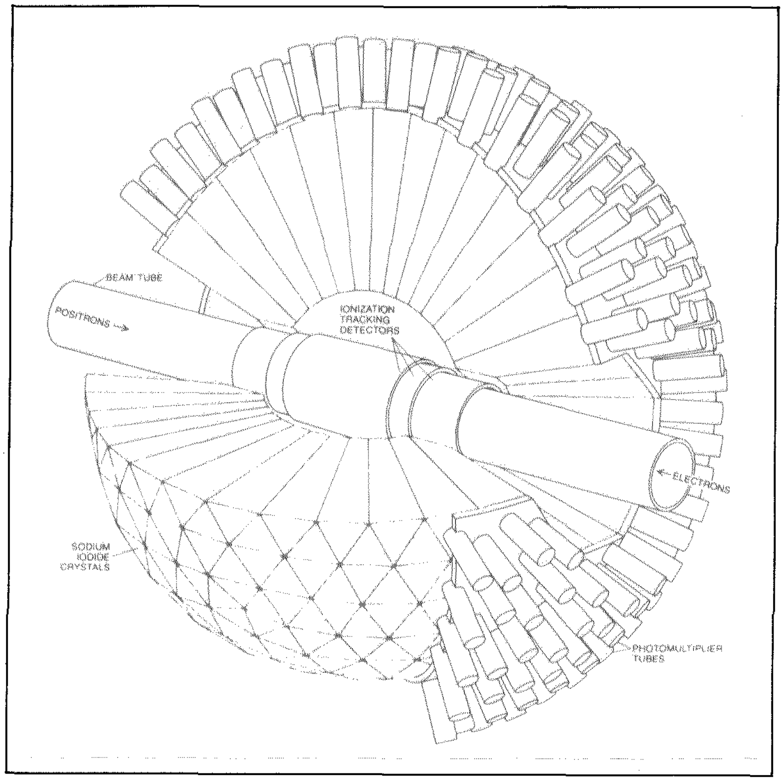
In this comparison of the energy level structure in positronium, an electron-antielectron "atom," and charmonium, a quark-antiquark "atom," each observed energy state is shown as a solid horizontal line with more massive states shown higher in the diagram. States that are thought to exist but have so far never been observed are shown as dashed lines. For charmonium, the various states have been given conventional names (J/ψ, ψ', η_c, and so on), but that practice was never adopted by people studying positronium or atomic systems; they used only the "spectroscopic" notation, such as 1^3S_1, which is also applicable to charmonium. The wiggly lines connecting states show the photon transitions that have been experimentally observed, and the number beside the transition line gives the photon's energy. For positronium, the energy units are in electron-volts and for charmonium, in millions of electron-volts. The astonishing structural similarity of these two energy level diagrams is strong qualitative evidence for the quark-antiquark interpretation of the several charmonium particles.

spacings also depend on the nature of the spin-dependent and orbital angular momentum-dependent components of the force. Thus, studying the level spacings (that is, the mass spectrum) in the charmonium system serves as a very convenient probe into the nature of the strong force.

It turns out that we can study the charmonium energy levels experimentally in a way reminiscent of atomic (and positronium) spectroscopy. First, make an excited state of the system, or "atom," under study. Then, watch it decay into a less excited state via the emission of a photon (a quantum of electromagnetic radiation, or "light"). Finally, measure the energy of the photon (that is, its "color"), and this gives the spacing between the energy levels.

In atomic spectroscopy, we might create the excited states with an electric discharre in a gas of the atoms under study. The ubiquitous neon lights, mercury vapor lamps, and sodium vapor street lights are common examples of this. Typically, the decay photons in atomic systems have energies in the visible light region, and thus, their energies can be measured with an ordinary prism. For charmonium spectroscopy, the idea is similar, but the technique is quite different. First, an "atom" of charmonium lives much too short a life (roughly 10^{-20} seconds) for anyone to be able to collect many of them as a gas. We can, however, create certain of the charmonium states (such as the 1S J/ψ and the 2S ψ') one at a time by colliding an electron and a position together at just the right energy. When the e^+ and e^- annihilate at just this right energy, there is a high probability that a charmed quark and a charmed antiquark will be created in a charmonium state. Second, the energy levels in charmonium are separated by many millions of electron volts, instead of the one or two electron volts typical of ordinary atoms. Thus, a simple prism is no longer a suitable device for measuring the energy of the decay photons from charmonium. And this brings us to the Crystal Ball apparatus.

High energy electrons and positrons collide and annihilate each other at the center of the Crystal Ball, as can be seen in this schematic cutaway diagram of its principal components. The products of the annihilation fly off in all directions. Those that are charged leave tracks in the three cylindrical ionization detectors surrounding the collision point. From the electrical signals produced by the ionization detector, the path of the charged particles can be deduced. The Ball itself consists of a close packing of truncated prisms of sodium iodide with a triangular cross section. When a high energy photon, such as from charmonium decay, hits the Ball, it deposits most of its energy in one or two prisms, but a significant amount spills out into about twelve adjacent ones. A constant fraction of this deposited energy is converted to visible light, which is detected and the amount measured by the photomultiplier tubes.



From "Quarkonium" by E. D. Bloom and G. J. Feldman. Copyright May 1982 by Scientific American, Inc. All rights reserved.

By design, the Crystal Ball detector is a device uniquely suited to the detection and measurement of photons from the decays of charmonium states. It is basically a spherical shell of crystalline sodium iodide (hence, the name) used to measure a high-energy photon's energy and direction. When a high-energy photon enters such a crystal, it interacts with an atomic nucleus in the crystal, typically producing an electron-positron pair. This pair then interacts with further atoms to produce, after a few successive generations of such processes, an elaborate "shower" of electrons, positrons, and photons. Ultimately, the particles in the shower lose their energy to the crystal atoms by ionizing or otherwise exciting them. Finally, some of the atoms de-excite by the emission of light in the visible region. Since the crystal is transparent to this visible light, it can be collected and the amount measured by a photomultiplier tube attached to the crystal. Surprisingly, this involved process is actually a very efficient means of measuring the energy of the initial high-energy photon. At the time this detector was conceived, sodium iodide was the optimal material for this purpose.

Developed by a collaboration of physicists from Caltech, Harvard, Princeton, Stanford (High Energy Physics Laboratory), and the Stanford Linear Accelerator Center (SLAC), the Crystal Ball consists of an array of 672 sodium iodide crystals. Each crystal has the shape of a truncated, triangular pyramid arranged with its small end pointing toward the center of the sphere. A photomultiplier tube views its large end, one per crystal. In general, the "shower" from a single photon spreads out into several of these pyramids. Thus the energy of a photon is determined by the sizes of the signals from the several photomultipliers involved, and its direction, by the location of the struck crystals. An electron beam and a positron beam enter the sphere from opposite directions through regions cut out for this purpose and collide at the center. Occasionally, an electron and a positron will annihilate to form, say, a

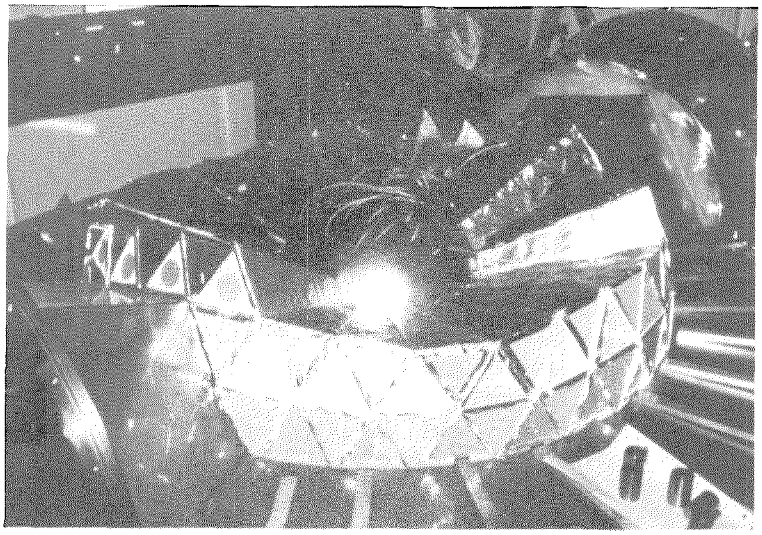
ψ' (2S charmonium state). The ψ' decays almost immediately, and the decay products are then detected in the Crystal Ball.

Although simple in concept, the construction of the Crystal Ball was actually a rather delicate and time-consuming enterprise. It was fabricated at the Harshaw Chemical Company in Cleveland, where each of the 16″-long crystals had to be precisely machined to the proper geometric shape from Harshaw's special, mechanically rugged brand of sodium iodide. An annoying complication is that sodium iodide is extremely hygroscopic, and a crystal of it is quickly ruined by even the smallest amount of water in ordinary air. Thus, the crystals must be continuously protected from the atmosphere, and after a certain point in their manufacture, all of the work on them had to be done in special, extremely dry rooms. Following machining, and further adjustments to tune optical properties, each crystal was wrapped with reflective material and carefully positioned in a hemispherical array. Once completely stacked, each of the two hemispherical arrays was hermetically sealed inside an aluminum and stainless steel container for mechanical support and protection from the atmosphere. At the large end of each crystal, a glass window was cemented over a hole in the container to allow the light to get to a photomultiplier mounted outside the shell. This part of the project, the construction of the Ball itself, cost about one million dollars.

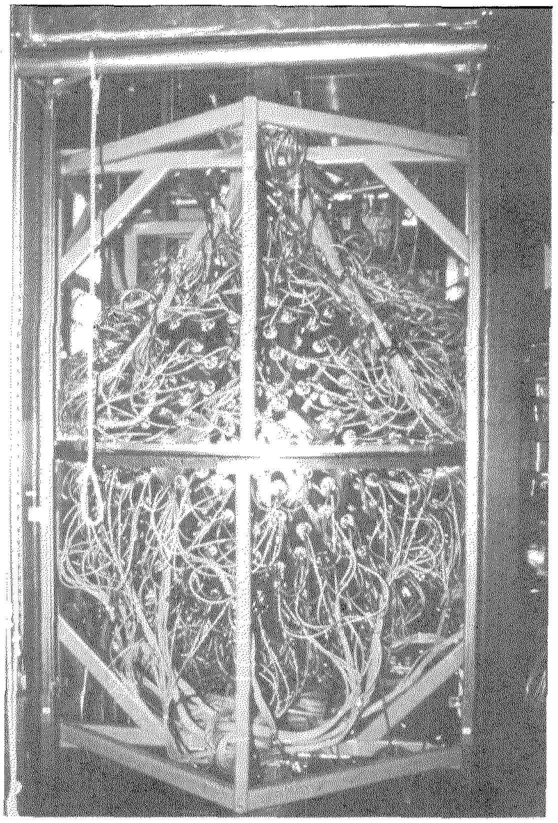
Two trips by truck brought the hemispheres to the Stanford Linear Accelerator Center, one in the fall of 1977, and the other in the spring of 1978. The trucks were specially equipped to ensure that no ordinary wet air could get near the hemisphere, so that, even if its hermetic seal happened to be broken by vibration or bumpy roads, the sodium iodide would not be damaged. Needless to say, a physicist was in nervous attendance at monitoring equipment during the whole of both trips. The summer of 1978 saw much feverish activity by an excited group of physicists, students, engineers, and technicians as the Crystal Ball experiment was installed at the SPEAR (for Stanford Positron Electron Asymmetric Ring) e^+e^- colliding beam accelerator ring at SLAC. In the fall of 1978, the accelerator was turned on, and we began to take our first data with the new detector which had been three years in the building.

Before information collected with an apparatus — the raw data — can be converted into interesting results about nature — the "physics" — there is still a lot that must be done. The raw data, which are collected onto magnetic tapes, are processed through sophisticated computer programs to interpret the electrical signals measured by the apparatus as energies and directions of photons and other particles. The results of this analysis are written on additional tapes, which are then studied in great detail to extract the physically interesting quantities. To set the scale of this effort, since 1978 we have written a few thousand tapes and have used many hundreds of hours of time on large, fast computers.

Our first goal in the study of charmonium spectroscopy was to actually find all the various states that were predicted to exist. Some of these had

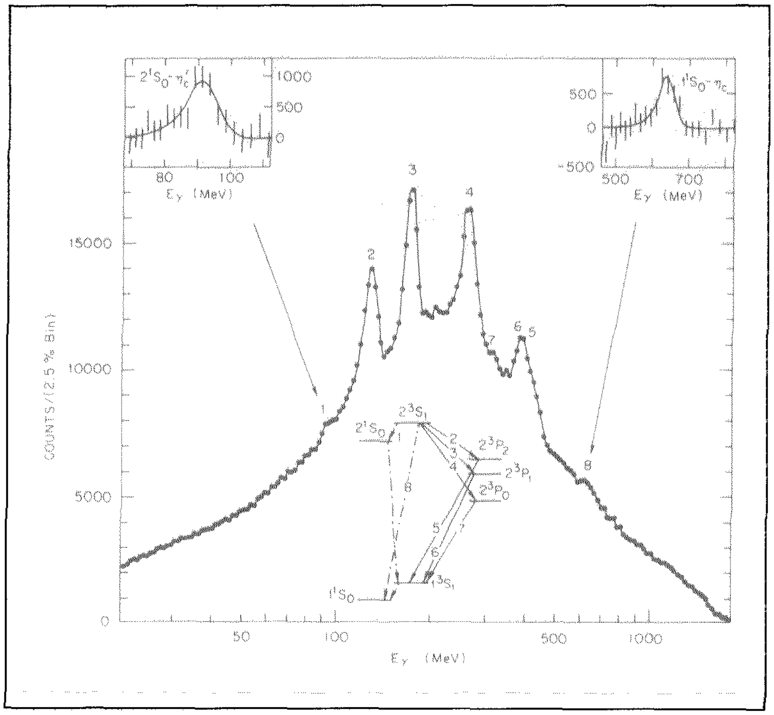


The photograph above shows the Crystal Ball at an early stage of its stacking before encapsulation. The small end of each triangular prism rests against a thin metal spherical dome of 20″ diameter to which thin cables are fixed, as can be seen. The large triangular end of most of the crystals has not yet been covered with the endpiece containing a circular hole, which is visible on a few of them. When the outer spherical shell was finally installed, the thin cables were fixed to it and radially tensioned. They function mechanically like the spokes of a bicycle wheel, giving the completed structure rigidity and stability. The outside diameter of the outer shell is about 56″.



At left the two hemispheres of the Crystal Ball are closed over the beam pipe, fully instrumented with its phototubes and a powerful lot of cables.

This diagram shows the spectrum of energy E_γ of photons resulting from the decay of the ψ' particle, the 2^3S_1 state of charmonium. Most of the photons in this distribution come from the secondary decays of hadrons produced in the primary decay of the ψ', and, in particular, from the sequence $\psi' \to \pi^0 + \dots \to \gamma\gamma + \dots$ Monochromatic photons arising from a decay like $\psi' \to \gamma + X$, where X has a definite mass, appear in this spectrum as an accumulation of events near a particular energy. Examples are numbered 1, 2, 3, 4, 8, and these refer to the correspondingly numbered transitions in the inset energy level diagram. The single peak labeled 5, 6 actually arises from two overlapping transitions; we see only inconclusive evidence for the transition labeled 7 in this spectrum. The Crystal Ball experiment was the first to see the lines numbered 1 and 8 and this observation constituted the discovery of the two states 2^1S_0 and 1^1S_0. The insets show the data near these two energies with superimposed curves showing what the instrumental response would be to monochromatic photons. The agreement of the data with these curves is important evidence that the accumulation of events near these energies is not just a statistical accident.



already been found in other experiments (with relatively crude photon-detection capabilities) before the existence of the Crystal Ball. But the situation when the Crystal Ball experiment began was actually very confused. Evidence had been reported in the literature for three states that fit very badly with the expectations of the theory. If these observations were correct, something was very wrong with our understanding of charmonium. The first triumph of the Crystal Ball was to rescue the theory from this dilemma by showing that all three of these earlier observations were incorrect.

Having eliminated the early contenders, we set about to find some of the as-yet-unobserved states, notably the 1^1S_0 and 2^1S_0 states. These differ from the corresponding $^3S_1$ states by having the quark spins aligned so as to cancel, rather than to add. The most fruitful approach for this turned out to be the one suggested earlier by analogy with atomic spectroscopy: simply looking at the energy distribution of the photons emitted in decays of an excited charmonium state (the 2^3S_1, or ψ' state). Most of these photons result from secondary decays of hadrons, which come from the primary charmonium decay, and no particular photon energy is especially favored. Direct radiative transitions to other charmonium states, however, yield photons of a unique energy (they are monochromatic), and these should appear as peaks, or "lines," in this spectrum. Indeed, we do observe several such lines. The most prominent are due to transitions involving the previously discovered 1^3P_0, 1^3P_1, and 1^3P_2 states; but careful analysis revealed two other signals in this spectrum, corresponding to transitions from the ψ' to the 2^1S_0 and 1^1S_0 states of charmonium. Note that the $^1S_0$ state is actually the ground state of charmonium — we knew a lot about several excited states before we had even proved the ground state really existed.

The predictions of the QCD theory of the strong force, with some assumptions for things that no one yet knows how to calculate in the theory, agree rather nicely with the experimental observations of charmonium. All of the expected states exist at the expected places and have the expected properties. All, that is, except for one state that has not been observed yet. It is thought, however, that this is only an experimental difficulty. The missing state is the 1^1P_1, which, because of its quantum numbers, cannot be reached from the ψ' via a single photon transition. We have searched for this state by looking for transitions involving the emission of *two* photons, which is allowed, but so far we have been unsuccessful.

So, in less than a decade since its discovery, charmonium has provided us with an important laboratory for the study of the strong force. So far, the favorite theory for the force, QCD, has come through unscathed. Where do we go from here? Certainly, the study of charmonium is far from over, but it does have its limitations. Corrections for the fact that the quark motion is not really very slow complicates comparison with theory at a detailed level. Further complications arise from the size of the charmonium "atom"; it is just too big. QCD calculations get easier for smaller systems, and, although it is useful to have systems of all sizes so that the force may be probed over different distances, the smaller the size of a system, the more reliable the QCD prediction.

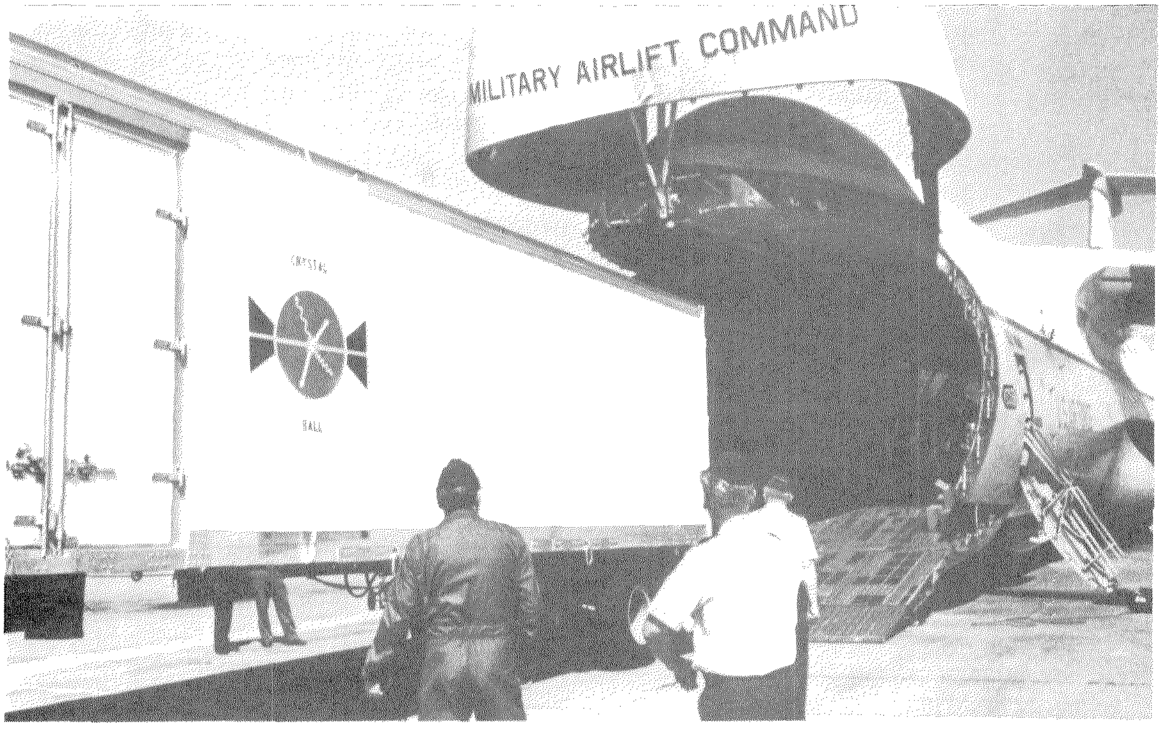
It just so happens that a new kind of quark-antiquark system was discovered in 1977. For no particular reason except whimsy, the new quark, the fifth known, is called "beauty" or, with only slightly more motivation, "bottom." (To the more prosaic, it is simply the b-quark.) The beauty quark is roughly three times heavier than the charmed quark, so the corresponding "beautiful atom" should be less relativistic and even smaller in size than charmonium. Naturally, having a device well suited to studying such systems, the Crystal Ball experimenters were eager to take data on beauty in addition to charm, and serious preparation for this option began in 1981.

Because the beauty quark is three times more massive than the charmed quark, an accelerator with three times the energy is needed to produce it. Unfortunately, the SPEAR accelerator at SLAC cannot attain the required energy, and so we had to look elsewhere. When an opportunity presented itself to do the experiment at the higher energy DORIS accelerator at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany, we enthusiastically pursued it.

Needless to say, moving a complex and delicate apparatus halfway around the world required a substantial effort. The roomful of electronics presented no serious problems — we just put it in a trailer, drove it to the dock, and put it on a boat. But moving a large array of crystals — without cracking them or getting them even very slightly wet — was another matter. Considerable research and discussion went into choosing among various options — including assorted combinations of land, sea, and air delivery (submarines were mentioned only in jest). Finally, the decision was made to fly the array aboard an Air Force C5A cargo transport. This aircraft could easily handle the size and weight of our Crystal Ball, could maintain controlled pressure and temperature in the cargo hold, and could land softly. Thus, in April of 1982, the Crystal Ball was entrusted to the flying skill of the U.S. Air Force who took it uneventfully (except for a scheduled in-flight refueling) to a base near Frankfurt, Germany. A small band of physicists, including Caltech graduate student Charles Edwards, went along for the ride as babysitters to the apparatus.

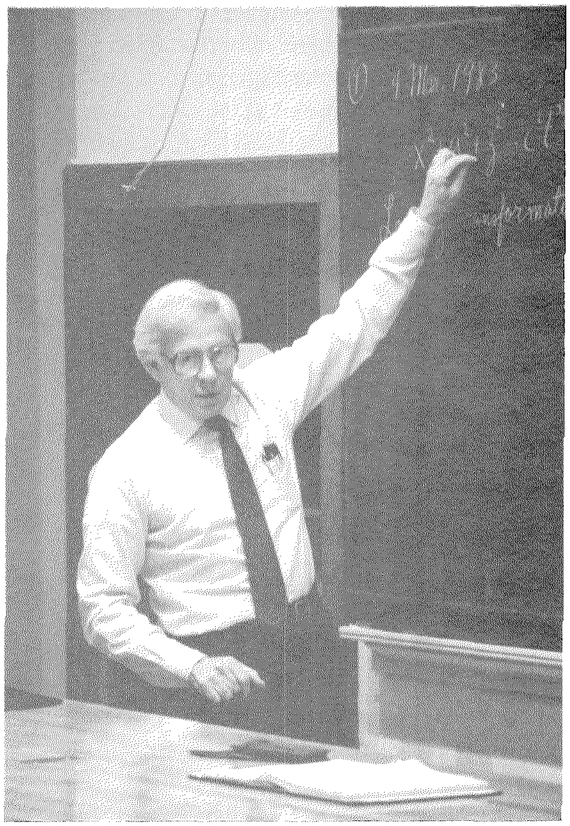
While the trip from California to Germany went like clockwork, the drive from Frankfurt to the accelerator in Hamburg did not. There are some pretty steep hills on the Autobahn between these cities, and the truck tractor turned out not to be up to the challenge; its engine blew up along the route. After some anxious and extended discussion in a mixture of broken German, English, and arm-waving, a new tractor was acquired, which finally took the experiment the rest of the way. Once again, a large group of people, now including collaborators from not only Germany but also the Netherlands, Italy, South Africa, and Poland, in addition to the United States, engaged in feverish activity to prepare the apparatus for the turn-on of the accelerator. We took our first "beautiful" data in August 1982, and are now busily working with our computers to analyze that data and produce "beautiful" physics.

Many things about the spectrum of energy levels of beautonium particles are now known, but we expect that many other things are yet to be discovered. Of course, fairly reliable predictions of many of these have been made by theorists using ideas from QCD. But physics is an *experimental* science, and experimental physicists are always on the lookout for new phenomena. We are always hopeful that the careful exploration of new ground with proven techniques will reward us with unexpected discoveries. The new ground is the energy range populated by beauty; the proven technique is the Crystal Ball. Together, we hope that they may lead to new insights into the nature of the strongest known force in the universe! ☐



As the trip to Hamburg, Germany, begins, the two hemispheres of the Crystal Ball sit carefully cushioned in a temperature-controlled, extremely low humidity compartment inside the trailer. The trailer was simply rolled into the gaping maw of the C5A and flown to Frankfurt, courtesy of the U.S. Air Force. Except for a mechanical breakdown on the Autobahn from Frankfurt to Hamburg, the trip was, happily, uneventful. After arrival in Hamburg in mid-April 1982, the fully operational Crystal Ball was again taking physics data three and a half months later.

A Duty to Profess



IN HIS inaugural address in 1978, Caltech President Marvin Goldberger noted that "the material in the undergraduate curriculum is necessarily difficult, but it is also frequently boring and the students become disillusioned and impatient. In an institution like this, where the faculty are engaged in important and absorbing research and scholarship, it is often tempting to avoid giving undergraduate teaching the attention it requires to instill a sense of excitement in the students. I want to urge the senior, most distinguished faculty to undertake this task, but I warn you, it is much more difficult than graduate teaching. I'm sure our faculty, some of whom I'm told have never taught undergraduates, can cope with the difficulties."

This year, hoping that "many of the senior faculty will follow my 'brilliant' example," Goldberger coped with the difficulties of the winter term of Physics 1 himself.

The move was not without precedent; even Robert A. Millikan taught the freshman introductory physics course. Caltech has always "trained its very biggest artillery on the problem of freshman physics," according to David Goodstein, a physics professor who also saw some action in the field. An eminent parade of faculty has tackled the course at one time or another, including Nobel laureate Richard Feynman, whose famous three red books, *The Feynman Lectures* on Physics, emerged from the experience in the early 1960s.

But by the time of Goldberger's inaugural speech, the point had been reached "where Physics 1 was the number one student complaint," says Goodstein, who is modest about which piece of faculty artillery was rolled out on that occasion. Goodstein's version of Physics 1 (Classical Mechanics and Electromagnetism) was so good that the freshmen returned to griping about the food instead. But then Goodstein himself, fortunately or unfortunately, was lured into turning his physics show into a national television course — "The Mechanical Universe," funded by a $2 million grant from the Corporation for Public Broadcasting and the Annenberg School of Communications.

This left Geoffrey Fox, whose job as executive officer for physics is to staff the course, with a tough act to follow. So he started at the top. "I knew that he was supposed to be a good teacher at Princeton, and I thought it might demonstrate the 'specialness' of Caltech for students to be taught by the president," Fox said.

The president, who is a professor of physics as well, feels that "it's the duty of all professors to profess. Also, I was very impressed with the changes that had come about in the teaching of the fundamental physics curriculum since I arrived here. Only faculty members are in charge of the recitation sections associated with the course, which is consistent with my own views about undergraduate education." Recitation sections are led by faculty from other disciplines as well as physics. And two other professors of physics have shared the year's lectures in the other two quarters — Ed Stone, who was project scientist for the Voyager missions to Jupiter and Saturn, and who has recently been appointed chairman of the Division of Physics, Mathematics and Astronomy, and Charles Peck, whose Crystal Ball research is described on page 4 of this magazine.

In his part of the course Goldberger has essentially followed Goodstein's "canonical" plan and doesn't claim to have done "anything even evolutionary, let alone revolutionary." But his lectures carried the stamp of some of his own concerns and experience. He thinks that "it's very important for an introductory course to try to convey some of the history associated with the development of a subject. It's not that I believe that one should try to drag the students through all of the agonies and false starts that really mark the actual evolution of the subject, but rather to give some flavor for what the general state of knowledge was at a given historical time. I want to dispel the idea that students sometimes have, because of the way we teach, that everything is really relatively simple and straightforward. Most of us have had the experience of doing research on hard problems where we struggle for weeks or months, and once we've finally understood the matter, we can explain it in ten minutes." Goldberger regrets that he didn't have enough time preparing for the course to "acquire a deep enough feeling about the historical evolution of many of the topics I covered to transmit enough of that flavor." This was not the only difficulty Goldberger had to cope with; there were also the demonstrations.

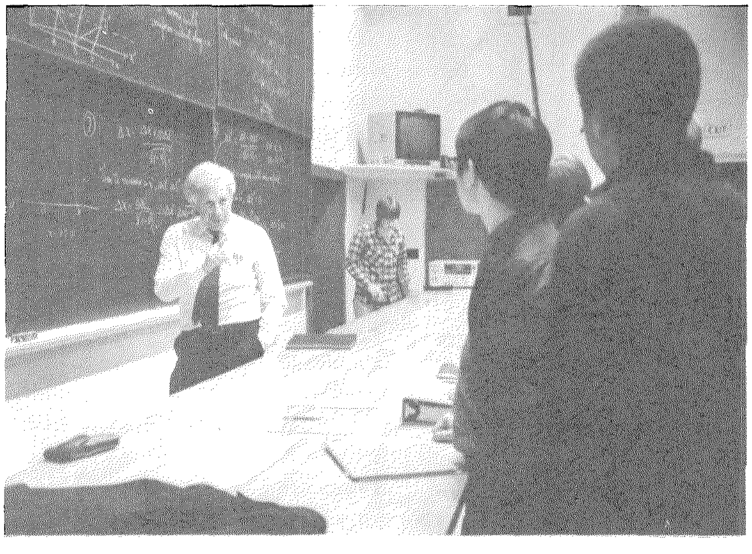
"Physics is an experimental science, but in my former life I was a theoretician, and I've consequently not been in a position to put as much emphasis on the demonstrations as an experimental physicist would have, and perhaps not as much emphasis as the students might have liked." Demonstrations bored Goldberger when he was a freshman, but he realizes that many students like them. Before his lectures he was sometimes advised by physics staff member Tom Harvey, who once worked for Millikan, to put things out on the table even if he wasn't going to use them, just so the students would think he was going to perform something exciting. Goldberger laments that in teaching relativity, which he was beginning as the quarter ended, "there are just not a lot of experiments you can do. I can't come running across the lecture room at speeds approaching the speed of light. I wish I could, but I can't."

Goldberger frequently covered all nine blackboards in the lecture hall with equations. (In the particular lecture shown on the cover, he managed to use only six, since part of the hour had been taken up with some film footage — pinch-hitting for a relativity experiment — of Einstein's 1931 visit to Caltech.) One complaint about Goldberger's presentations has been that he used too many complicated calculations and not enough intuitive arguments.

"The last is a very subtle question, this business of trying to teach intuition. It's an extraordinarily difficult thing to do. I've never been a great believer in what you might call 'physics for five fingers.' The compelling intuitive arguments almost invariably follow hard analysis, which we frequently and most commonly couch in mathematical terms because we're incapable of carrying out a lot of the steps of logical reasoning without using mathematics. As I said, physics is an experimental science, and the mathematics must always be kept subservient. Nevertheless, it's an extraordinarily effective tool, and it's impossible to be a physicist without being comfortable with mathematics."

Even with all his traveling and other presidential duties, Goldberger missed only two classes during the quarter. He enjoyed teaching but found it time consuming. "My schedule is so erratic that I've occasionally found myself under enormous pressure trying to get ready for a particular lecture. I've always found in the past when I've taught that for the most part I did nothing else, and although the actual preparation for an individual lecture might not have required more than a few hours, I was always thinking about how I was going to say things and various nuances that I would try to get across. It's the absence of that kind of time that's made this particular teaching experience more difficult."

Goldberger hasn't yet decided whether he will teach the course again next year. But in the meantime he is trying to shame others into taking on a quarter or two; he particularly has his eye on Nobel laureate Murray Gell-Mann. At least now, says Charles Peck, who took over the final quarter this year, "I think no professor can tell him, 'I'm too busy to teach.'" ☐ — JD



Impediments to Successful University-Industry Research Relationships

by Donald R. Fowler

Universities need industrial funding, and industry needs to keep in touch with advances in science and technology. Caltech's General Counsel reports here on his survey designed to identify the barriers that keep these groups apart.

A PORTION of the research for my recently completed doctoral dissertation consisted of a questionnaire directed to 80 vice presidents (or directors) of research in industry and 78 people occupying as similar a role as I could find at the campuses of the 48 United States members of the Association of American Universities. The questionnaire set forth a list of 15 assorted impediments to university-industry research relationships synthesized from an earlier historical review. I asked the respondents to rate each of the impediments as to how significant they perceived that factor to be in obstructing university-industry relationships, and to list and rate the significance of any they felt I had omitted. I also asked them to respond to a number of "yes/no/no opinion" questions designed to elicit their thoughts on, first, where we ought to go from here and what we ought to do about some of these impediments; second, what effect certain relatively recent developments may have had on the ease or difficulty of entering into research agreements; and, third, how relationships were currently faring between universities and industries. In several cases I asked them to state reasons for their yes or no answers.

Out of all this I hoped to verify a list of genuinely significant impediments and, more importantly, to find out which were most significant and, if there were any, those that were truly controlling. I also wanted to compare the responses of industry with those from the university community to see where there were areas of both agreement and disagreement.

The overall response was both amazing and gratifying — 75 percent, in almost equal proportions from industry and the universities. I want now to discuss some of these results, emphasizing, first, that none of the data given here represent the attitude of any one individual, industry or university; and, second, that since not all of the respondents answered or commented on all of the questions, any percentages explicitly stated here refer only to the percentage of those responding to the question.

I found, first, that there were no overwhelmingly important individual impediments that seem to control or dominate university-industry research relationships. In fact, given the necessary incentive (on the part of both parties) to enter into a particular relationship and given the proper attention to resolving any specific problems, the desired relationships are usually attainable. The variety of such recently announced new arrangements would tend to validate this conclusion. It also tends to be supported by the overwhelmingly yes answer to two of my questions: (1) whether "there has been a significant improvement or increase in university-industry research relationships since 1977" and (2) if so, whether they expected it "to continue during the next five years." Over three-fourths of the university people expressing an opinion said yes to both questions, as did almost two-thirds of the industry respondents.

AREAS OF DISAGREEMENT

One of the reported impediments where the universities and industry did not see eye to eye was the university's need to protect the right to publish as opposed to industry's need to protect patents and other proprietary information. This was clearly the university's greatest concern. Industry placed it sixth on its list. Ironically, however, it may also be the impediment nearest to a generally workable solution. The survey showed 82 percent of those from the universities saying yes to a question as to whether universities should agree to withhold research results from publication during the time necessary for the university or industry to obtain patent protection. On the other hand, 55 percent of the industry people joined with 87 percent of those from universities in saying no to the proposition that universities should agree to withhold publication for reasons other than patents.

This pair of responses would seem to point the way to a resolution built around whether the requested delay in publication is for a reasonable time to protect patents or is proposed for another purpose. The details of some of the more recently announced arrangements suggest that this approach is being widely adopted.

Another of the impediments where there was a wide diversity in perception was the asserted fact that industry possesses its own in-house research capabilities and will tend to use them in cases where there is no clear-cut cost advantage or unique capability on the part of the university. This was the ''most significant'' impediment according to the industry respondents. Whether the industrial capability is real or is merely perceived by industry as existing, it can serve as a very real barrier to university-industry research relationships. Hence, it becomes more important than ever to look for opportunities for research relationships where the university's capability is not perceived as being duplicated in industry. And, to nobody's surprise, this probably turns out to be far more likely in the case of basic or fundamental research.

This preference for basic research as the primary area of focus for university-industry relationships was reflected in our survey. For example, only 45 percent of those from the universities and 34 percent of those from industry thought that universities should strive to perform significantly more work oriented toward industry, while 50 percent of those in industry joined with 87 percent of those from universities in responding that significantly more basic research should be contracted out to the universities where there is no cost differential in favor of in-house performance.

The third area where the two groups did not see eye to eye had to do with what causes the most problems with regard to inventions and patents arising under proposed research agreements. Industry patent policies were relatively high (third place) on the university list of ''most significant'' impediments, and federal laws governing innovations and patents arising out of government-sponsored work was on industry's list of ''most significant'' impediments (although only in fifth place). Interestingly, industry's perception of university patent policies is that they are only a marginal problem. As the continuing string of new arrangements attest, perhaps the most important consideration is that when an attractive new opportunity presents itself, the parties seem to be able to work out the patent considerations.

ADDITIONAL IMPEDIMENTS

Among the added impediments making the ''most significant'' list were some listed by one group but not the other. In the case of industry, this was the inability of academia to effectively perform industrially sponsored directed research, a factor easily viewed as a variation on at least two others listed in the original impediments supplied by me. The fact, however, that so many industry respondents took the time and effort to rephrase and restate the problem was, I thought, quite significant.

In the case of the universities, the most often added impediment had to do with industry's reluctance to fund the university's total cost of research, indicating a reluctance or refusal on the part of industry to pay a full, allocable share of the university's indirect costs. This additional listing came as a suprise because I had not personally encountered this problem and because I would have expected industry, of all the various kinds of sponsors, to be the one most likely to recognize the concept of the ''cost of doing business.'' Subsequent discussion with knowledgeable people on this subject suggests that this type of problem will usually occur, if it does, where there is industry funding of basic or fundamental research on a gift or grant basis, as opposed to cases where industry has contracted for research with a specific objective in mind. It is important for the universities to recognize the basic difference between these two types of funding in interpreting industry's attitude toward paying indirect costs or overhead. But our study was not conclusive on this subject, and it deserves further attention.

AREAS OF AGREEMENT

Of the impediments or problems concerning which both industry and the universities were of a similar mind, the first had to do with industry's primary orientation toward short-term profits and product improvements. Quite interestingly, this factor was rated ''most significant'' of all when the responses were considered together, without regard to whether they came from industry or from the universities. Unquestionably, in the recent past this factor has had a serious, depressing effect on the funding of basic research and long-term research and development by American industry. It may well be among the most serious national problems we have, and it affects far more than just university-industry relationships.

The respondents from both groups were also overwhelmingly in favor of industry funding more basic research in relation to its total R&D budget (without regard to whether the research is to be performed in-house or at universities). This, of course, was to be expected from our particular survey, since the respondents from industry tended, because of the positions they hold, to have a vested interest in more unrestricted research funding.

Most interesting, however, was the recognition by both groups that a significant positive correlation and cause-and-effect relationship exists between the amount of money spent on basic technological research and future technological productivity. Of the university people, 98 percent said they believed that such a correlation and relationship existed, and 89 percent of those in industry agreed. Thus, it would appear that it is not a lack of recognition of this vital connection that produces industry's pronounced orientation toward short-term profits and product improvement. Rather, such short-sightedness probably must be laid at the door of the overwhelming and overriding pressure created by next quarter's or next year's ''bottom line.''

Another area of agreement was the impediment created by attitudinal factors generating a culture gap or lack of understanding that makes new or improved relationships difficult, if not impossible. The comments largely consisted of fingers of blame being pointed to a whole host of attitudes that could cause problems as, for example, ''differences in objective, philosophy, and reward system,'' lack of ''trust,'' ''antagonistic'' and ''arrogant'' attitudes on the part of university faculty, mutually ''unwarranted suspicion of motives,'' and so on. I was never able to determine, however, whether these attitudinal factors are themselves root causes or merely symptomatic reflections or magnifiers of other, more basic, impediments.

CONFLICTS OF INTEREST

Of great interest were the respondents' reactions to the conflict of interest factors, particularly the one where the university or the researcher has an equity or other financial interest in the industrial sponsor. It was third on both lists of ''most significant'' factors.

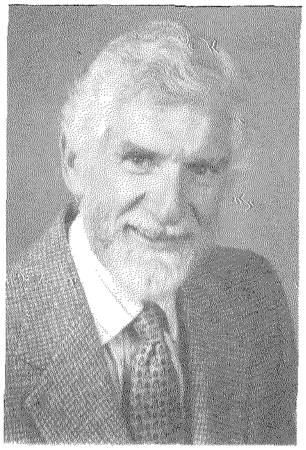
Three other conflict of interest factors were also listed: (1) inappropriate influence by industry over programs being sponsored by them; (2) inappropriate influence by industry over the choice by the university of future programs; and (3) inappropriate increased secrecy among the academic community induced by industry research relationships. These three other factors were all found to be from ''occasionally significant'' to ''significant'' by both groups, industry as often as not showing as much or more concern than the university people. None of these three situations seemed, however, to measure up to the same level of importance as the one involving equities or other financial interests. I find this interesting because it is apparent from others' observations that secrecy and inappropriate influence by industry over scholarly endeavors can indeed cause serious problems and can damage the often fragile academic infrastructure (which includes the faculty-graduate student relationship). One explanation for the apparent inconsistency between this fact and the results of my study is that the problems of secrecy and inappropriate influence by industry appear to be particularly acute in the context of a situation involving equity or other financial interest in the industrial sponsor. Thus, these factors may not even be in competition with one another. Instead, one factor may describe the environment most likely to spawn problems; the others may describe the problems most likely to occur in the environment.

In any event, these conflict of interest situations have been the subject of much debate over the past year or two at many universities, and some in the university community continue to regard financial connections between university researchers and their sponsors as an anathema to be avoided at almost any cost. Others see nothing intrinsically wrong with such arrangements, provided there is enough visibility and that properly oriented people are involved. As a result, the policies and practices that have been, or are being, developed tend to vary considerably from campus to campus. And they continue to evolve and change.

These then were some of the major conclusions I was able to draw from my study. It is by no means a complete list, but it may indicate what two roughly similar groups of people from two widely divergent home bases perceived in the spring of 1982 to be the most significant impediments to improving their joint research relationships. □

Universities and Industry in Collaboration

Three managers of industrial research and one from academia discuss their real-life experiences in university-industry research relationships.



Martin Cooper
Vice President and
Director of Research
and Development
Motorola, Inc.

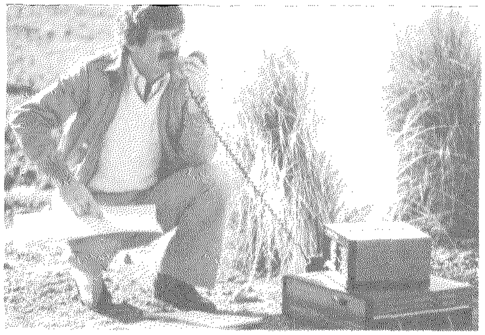
A REFRESHING initiative has recently been emanating from most of the universities that Motorola deals with, urging stronger ties between academia and industry. The sincerity of this initiative would be less questionable if the threat of severe cutbacks in government-funded university research did not also exist. Nevertheless, industry and universities do have mutual problems. The survival of our corporations is contingent on an increasing flow of graduates who are educated in the fundamentals of science and technology and who have reasonable facility in using modern problem-solving tools. The primary product of the universities is, of course, their graduates. And the market for the product is limited to the schools themselves, to government of various kinds, and to industry. I don't want to minimize the importance of government, but this nation depends on industry to produce the goods and services that are the material substance of our society. So I want to discuss Motorola's experience in bringing these reluctant bedfellows — universities and industry — together.

Universities and colleges generally agree that their first purpose is to educate. Secondly, they like to do research, partly to keep the faculty interested and because, in schools like Caltech, research is a very important part of the educational process.

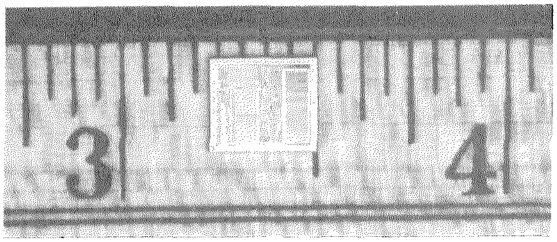
Industry also sees the schools as a source of educated engineers and scientists, and as a source of inspiration. We like to get some sense of direction in our long-range technology expenditures, and people who live in the university environment spend a lot more time thinking about what is going to happen in 10 or 15 years than those of us who have to meet this year's profit and loss requirements.

Motorola's primary funding to universities and colleges comes from the Motorola Foundation, which is purely charitable. We prefer to direct our funds to those schools that have some relationship to Motorola and that in some ways will encourage continuing dialogue between the academics and our people. The funds themselves, however, are not specifically directed; they are pure contribution. We have an industrial liaison program with MIT, and we also have a continuing grant to MIT. We are an Industrial Associate at Stanford, and we are a participant in their Center for Integrated Systems. We are doing some research at the University of Iowa. At Caltech we are an Industrial Associate and a member of the Silicon Structures Project.

Some aspects of our university relationships have not been very successful. One thing we do, for example, is to hire prospective teachers away from the schools whenever we get the chance.



Motorola, Inc.'s Falcon Mini-Ranger (left) is used for accurate electronic determination from remote locations of the position of vehicles such as dredges or offshore drilling platforms. The company's MSF5000 Base Station (below) provides superior system performance as the core of a radio system.



Motorola's MC6800 eight-bit microprocessor offers an entire computer – the equivalent of 70,000 transistors – on the surface of a single chip of silicon.

We short-sightedly offer salaries in excess of what the universities can offer. If an individual is not a dedicated educator, he'll come to work in industry. We are beginning to try to correct that situation by encouraging the financing of students who will remain in school and in teaching roles, but this alone will not solve the problem.

Our industrial liaison efforts have not been fully successful. Our people just won't be driven into productive relationships with the universities that we select; rather, they tend to concentrate on their current work. Do we have interactions with the universities by individuals? Absolutely. They almost always result from the fact that somebody in a university is working in a specific area of interest to one of our engineers or scientists. Of their own volition, they get together and establish successful relationships.

The other major failure, of course, is that we all just ignore the problems. We assume that the schools are going to manage, that they are going to produce the students that we need, and that one way or another we will all survive.

There have also been some successes. The Motorola Foundation contributes several millions of dollars every year to universities in a totally unrestricted way, and we hope this is done somewhat intelligently. We also directly fund some research. One of our scientists, for example, invented a technique that is not in our field of interest. To establish whether it was worth investing in further, we sought somebody who could carry it through at least the first stages of research. We found such a person at the University of Iowa, and we have a very successful interaction between those who created the idea and that university. We have some fine relationships between our semiconductor division at Phoenix and the materials organizations at Northwestern University and the University of Illinois. We also get involved in programs where universities perform related research and development as, for example, at the new Center for Integrated Systems at Stanford.

I have only recently learned about the power electronics program at Caltech. Its purpose is to create generalized applications directly usable by industry. It is the kind of collaborative program that industry should be reaching out for, but not everyone in industry has the foresight to invest in long-range programs.

The final successful type of program is the funding of related R&D, though I call it the "illusion" of related R&D. An example of that has been the Silicon Structures Project here at Caltech, in which Motorola was a participant for several years. The concept of that program — joint research in Very Large Scale Integration — was extraordinary, and the mechanism for creeping up on the long-range problems was structured so that there were also short-term benefits, particularly in terms of inspiration. One element of the Silicon Structures Project was having the industrial particpants live full time at Caltech, generally for a period of a year. We hoped each of these people went back to his industrial organization carrying with him the concepts, the philosophy, and the understanding of what is happening in the university.

Let me address some suggestions to industry, beginning with a proposal that our technologists be given at least some advisory capacity in the university funding programs. The chief value industry can get out of this funding is opening channels of communication — so that when one of our people has a problem, he has somebody in the university that he knows and trusts. Being able to call that person has direct value.

I also suggest that we encourage our technologists to visit universities. One of the mechanisms we have discovered for this is to hold seminars on university property. Once you get a group of technologists into the university environment, it's easy for them to meet people in their field. I just recently had a meeting of several hundred members of our science advisory board — technologists from throughout Motorola — right here at Caltech. The meeting was superb, the facilities were excellent, and a number of collaborative introductions were made that are going to persist.

That leads to one other suggestion, which is not to expect much in the way of short-term results. The money invested in university collaboration is a long-range investment; it is unproductive to fall into the trap of expecting usable product designs or software, and it is a waste of the university resource.

We also have some suggestions for the universities. I believe that the biggest challenge in American society is that of productivity. This is a long-range problem, but it has to be addressed at all levels. Every example I have given you of Motorola's university programs addresses productivity, though in very narrow areas. Yet our productivity problems are of a very general nature and have to be addressed everywhere. Collaborative programs that address the issue of productivity should be increasingly attractive to industry.

Other university problems involve the questions of publication and proprietary rights. The progressive universities are starting to figure out ways to allow those of us in industry who elect to make investments in them to maintain some kind of rights in the results of research. But many do not and also require that all research be fully published. That is a great inhibitor for industry. We are reluctant to invest in research that is likely to benefit our competitors.

I would also suggest that universities restrain their tendency to overpromise, appealing to the long-range views of whomever they approach in industry rather than promising short-term results. Both industry and the universities must attack these problems, and it is in the best interests of all of us in the United States for us to learn to work together on solutions. □

Louis Fernandez
Vice Chairman
Monsanto Company

MUCH HAS BEEN written about the internal problems with which universities must wrestle when they decide to collaborate with industry, but there has been less focus on the price many companies must pay in order to consider collaboration with an academic institution.

At Monsanto we do a great deal of soul searching before we seriously consider collaboration with a university. There are three main hurdles: the patent department, senior management, and our research and development staff.

The patent department concerns itself with the issue of secrecy, which is pivotal to whether a collaboration can work. From the university's point of view, of course, the secrecy issue appears threatening because of the need for academicians to publish, to attend meetings, and to talk about their work. From the perspective of our patent department, the issue is equally threatening. What if a breakthrough occurs and is publicized before we have time to secure adequate patent positions? What if Monsanto invests a great deal of money to finance a breakthrough to which other companies have immediate access? An invention is, after all, the least expensive part of the innovative process. For every dollar we spend to invent something, we will invest many hundreds more before that invention reaches the marketplace. The big economic risk for Monsanto comes not in supporting research, but when we decide to pour concrete and build manufacturing plants to produce new materials. Without adequate patent protection, no company can afford to invest the large amounts of money required to bring a new product to commercialization. Our patent department wants to ensure that we get that kind of protection from an academic collaboration.

For senior management, the big question is the same, no matter where the research is done: Will the potential rewards from the agreement be commensurate with the investment that is required? We have to justify to our board of directors any major research expenditures. If we cannot demonstrate the potential value in such an investment, the board simply will not approve our going ahead — not for research inside the company and certainly not for research outside.

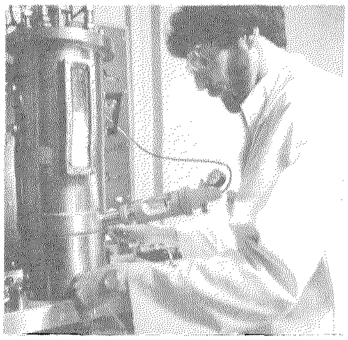
Monsanto Company's interest in biological sciences has been increasing over the last decade, and the company scientists use many vehicles for their research. Above, plant tissue is prepared for culturing. Below, hybridoma cells are studied under a stereo microscope.

Finally, we have to face the question of internal problems with our own R&D staff. Industrial scientists work for a salary, and their inventiveness is rewarded with promotion, higher salary, or occasionally with a prize. Nonetheless, making a great invention is not likely to make a company scientist rich. In many academic institutions, on the other hand, individual scientists can earn royalties on their inventions. It doesn't take too much imagination to see that a collaboration which produces significantly different rewards for the various scientists involved could lead to major morale problems within the company.

Moreover, for a corporation, the very existence of an outside research project has the potential for causing internal problems. No R&D department at Monsanto has the amount of funding or staffing that the department heads believe it deserves. Imagine trying to convince those people that their internal projects will not get more funding because we plan to go outside with some of that money.

Considering the issues of secrecy, investment value and morale, what, then, encourages us to go ahead?

In the first place, academic institutions often possess skills that are extremely valuable for industry — too valuable to wait 10 or even 20 years for a company to develop internally. Second, our experience in small collaborative programs gives us some idea of how an arrangement with an



Fermentation is a vital component in effective large-scale production of commercial biotechnology products. Here, a Monsanto scientist records conditions under which biological materials are produced in the molecular biology laboratory fermenters.

academic institution could work and where problems might arise. We know we must have partners whom we can trust; with whom we can work together in real collaboration, not just someone we can hire to do a task.

In the early 1970s, Monsanto scientists began to see the value of building up an expertise in the biological sciences beyond what we had in the agricultural chemicals area and in doing so fairly rapidly.

The result was a 1974 agreement with Harvard Medical School through which Monsanto unabashedly opened a "window on biology." The agreement runs for 12 years and is concerned generally with seeking the molecular basis for organ development. The principal Harvard investigator had previously been a Monsanto consultant, and the program involves collaborative work in Monsanto laboratories as well as in Harvard laboratories. In 1979 we accelerated our search for biological knowledge by taking three major steps: We announced the formation of a molecular biology staff within the company; we entered into a joint program with Genentech to develop animal growth hormones; and we began to investigate ways we might use biotechnology as a vehicle to enter the health care business.

The same year, Monsanto hired a new senior vice president of research and development, Howard A. Schneiderman, who came to us directly from academia. At once he began to look for ways that Monsanto science and academic science could be of mutual benefit to each other. He naturally turned to our very close neighbors at Washington University with the result that, in 1982, the two institutions entered into a five year, $23.5 million agreement with Washington University Medical School for biotechnology research. The purpose of this agreement is to fund basic research and to make discoveries that will ultimately lead to new therapeutic materials in the health care field.

Like the Harvard agreement before it, our program with Washington University has received a lot of attention in the press, in industry, in academia — even in Congress. And certainly at Monsanto.

We have done everything we possibly can to assure the success of this program. Building on our experience of the past, we have developed broad guidelines we feel are important for a truly cooperative agreement between an academic and industrial institution. The Monsanto-Washington University agreement is a good example of Monsanto's views on industry-academic collaboration.

First of all, we had to deal with an issue of great sensitivity on both sides — the tradeoff between security for patent purposes and the academician's right to publish. In this case, Monsanto has the right to a 30-day look at papers prior to their being submitted for publication and then, if patentable material is included, a chance to put off submission for a short period longer to provide time to file the proper patent applications. We feel, and Washington University agrees, that this arrangement should prove satisfactory to both institutions. Any contract must include some mechanism for dealing with a proprietary situation.

Second, we believe the arrangement should be between institutions rather than individuals. This prevents the kind of distortion that happens when one individual receives large sums of money that are not available to his colleagues. According to the Monsanto-Washington University arrangement, if major royalties should accrue to the university as a result of our work, a third of them will go to Washington University, a third will go to the individual scientist's department, and a third will go to his laboratory — but not to any individual investigator. This situation has an obvious advantage for Monsanto as well as for the university, where faculty members remain on a par whether they are working on Monsanto-funded programs or in other areas. The academic scientists will also remain on an equal level with Monsanto scientists with whom they are collaborating, thus avoiding the morale issue of one group of scientists having the possibility of becoming rich while the other does not.

In the third place, the collaboration should be a real partnership, a relationship of equals. A company cannot expect success in this kind of relationship unless it has in-house skills in the particular area of the agreement. Monsanto has in-house expertise to bring to this arrangement; we have further insured the partnership by forming an oversight committee to administer funds for the individual research projects. The committee is made up of four people from Monsanto and four from Washington University. This means that a specific research project will not go forward unless both Monsanto and the university endorse it. Washington University decides what kind of research it wishes to engage in; Monsanto selects from that menu of options the projects in which it has an interest. This way, we are not trying to tell them what to do, but rather which aspects of what they do are worthwhile for us.

Finally, to assure the scientific credibility of the program, we recognize the need for scientific peer review. The science, which is, after all, the whole point of the collaboration, must be assessed by objective, informed outsiders at regular intervals, thus assuring university officials that the efforts are of proper quality and assuring Monsanto's senior management that the work is progressing apace. Moreover, an outside panel — along with a tightly worded contract — can help insure that the research undertaken is being carried out in the arena in which it was originally intended. It will be of no use to academic scientists, and be a misuse of corporate dollars, if academic-industrial collaborations turn into development programs for new products.

Development is clearly the role of the industrial company, not the university. To ask academic researchers to do development work — other than specific tests of the type often carried out in engineering schools or clinical testing in medical schools — would be a gross mismanagement of funds, time, and an American resource.

The driving force for our collaboration is the biological revolution, accompanied by the very exciting advances in chemistry and physical measurement. As with any revolution, old technologies will be displaced, and companies like mine will find themselves needing to retool. We feel that relationships with academic institutions will speed our ability to do this retooling. We will piggyback on university skills as we build up our own skills and heighten our ability to bring important new products to the people of the world. If our collaboration works the way we believe it will, it will not just be Monsanto and Washington University that will benefit from this undertaking, but it will also be society at large.

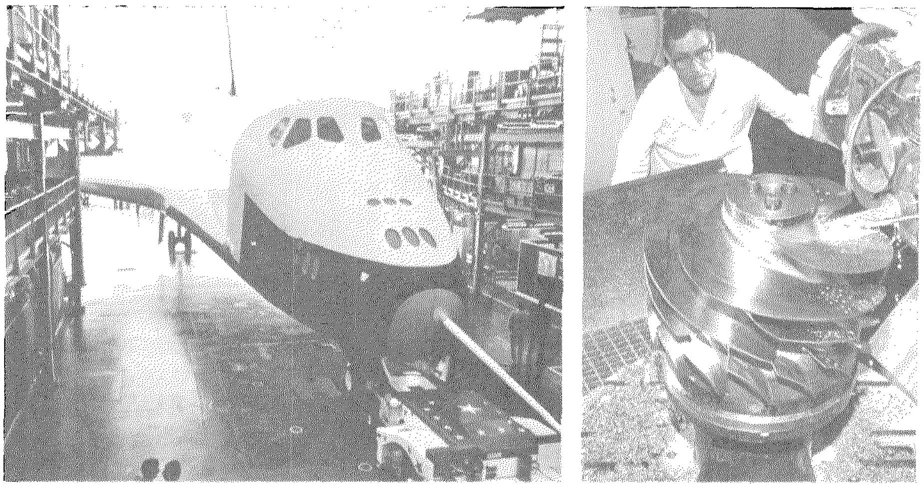
A successful academic-industrial collaboration can bring new products to consumers, but it can have another result as well. America's technological strength is being challenged as individual companies, like Monsanto, find themselves competing with whole nations in the international arena. In the United States it is difficult, because of various legal restraints, for companies to collaborate. If, however, a company were to look around and ask what other existing institutions could enhance its technological capability, the first answer would be universities. These great institutions with enormous scientific skills are an obvious key to the question of how we can be more competitive internationally. In countries like Japan and West Germany, we see a much closer interface between business and academe. That relationship shows up in new high-technology products and a keen edge against American competition. A West German or Japanese type of relationship may not be appropriate for us. But we can have one that is uniquely American. Under the right circumstances, we are natural partners. And the results of such partnerships hold great promise. ☐

John F. Tormey
Director (retired)
Corporate Technology
Policy
Rockwell International
Corporation

AT ROCKWELL INTERNATIONAL there are two major routes by which money could go to a university. One is through the Rockwell Trust, and the other is via a Rockwell normal business expense. In the latter case there are three ways that an individual division president or engineering vice president or his designee can disburse money to a university. He can use direct money out of his contract; he can use money out of his overhead; or he can fund the research through an IR&D project. He really doesn't have to consult with anybody before he acts except his own conscience, and his profit and loss statements.

Funding for direct contracts with a university — open contracts for services, say, to perform some analytical work — belongs to the business side. So do such expenses as hiring consultants, continuing education, and directed experimental research, as well as all of our Industrial Associates programs.

Out of the charitable side, or the Trust, come major and minor grants, gifts, undergraduate scholarship programs, a graduate fellowship program (through which we fund 26 PhD fellowships across the country), chairs, buildings, matching funds, and equipment. The corporation has a



The Space Shuttle (left) is one of Rockwell International's best-known products, but the company has many others. Below, for example, a machinist monitors five-axis milling of a titanium casting of a pumping element for a marine propulsion system.

reasonable but finite amount of money in the Trust, and only a portion of it goes into education; there are also the arts, the community, and health and welfare to be considered. And the education share also covers our commitments to liberal arts establishments as well as technical institutions. Among the reasons why the Trust would bestow a charitable grant to a particular university are good will, minority responsibilities, being a good neighbor in the community, acquiring employees, being a patron of science and engineering, and, finally, a direct self-interest in the particular technology of the school itself.

The case study I would like to follow here is a major grant involving both our direct technical interest and our role as patron of science and engineering — a direct grant to Caltech of a half million dollars. The period of the grant is from 1982 to 1987, and it is divided into two parts — half to a study of turbulence, and the other half to a particular field of research in semiconductors.

The establishment of this grant came about in ten steps, and there were random resistances in the smooth flow from step to step that took a little time to overcome. First, there was the prelude: those years of industrial associations with Caltech during which very little money surfaced — attending meetings like the Research Directors Conference, and lectures and annual alumni meetings, reading publications, using the library, and so on. But we didn't get past this "getting to know you" point until Robert Anderson, the chairman of the board of Rockwell, who is also a member of the Caltech board of trustees and a member of the visiting committee of the Division of Engineering and Applied Science, created a *stimulus*. A couple of years ago Mr. Anderson suggested that we in engineering do something specific about a research grant to Caltech. This stimulus got a group of executives to come to Caltech to *get acquainted* in a formal sense. This took quite a while (about four months) — not because I couldn't bring the Caltech faculty to bay, but because I couldn't corral my own associates. I had to gather together four divisional line executives and bring them to Pasadena. I think we cancelled a meeting six times. Finally, there was a superb summit meeting here at Caltech. I must say that the Caltech faculty who were at that meeting were at their best — charming, informed, and stimulating. We had a magnificent breakfast, a magnificent lunch, magnificent scientific discussions; and, as Rockwell got together afterward, there were such expressions as, "Who *were* those guys? This is a *great* school. Let's do *something*." This was one of the *key* meetings. I recall every line and nuance of it.

Then I put together a series of "*how abouts*," going around to the various vice presidents to get their suggestions for about 12 topics in technology that were of strategic concern to Rockwell across the board. Following this I met with Roy Gould, chairman of the division of engineering and applied science at Caltech. He and I went over the list, which he subsequently took to his department heads for their review. Within two weeks I received a very nice letter from Professor Gould with a package of Caltech "*how abouts*" — seven of theirs matching seven of ours. Then I sat down with the corporate vice president of engineering, and we picked two, one on turbulence and one on semiconductors.

The operation didn't proceed much beyond this point until the *money arrived*. As you might expect in corporations, it's all relatively harmless to this point. But finally the money was made available from the Trust; I had it in my hand and could begin "soft" discussions. Since Trust money is charitable (it is not expended for things that chiefly benefit the giver), I did not enter into "hard" negotiations with Caltech. On the other hand, I couldn't simply assign Caltech the money without *some* gentlemen's understanding of what they were going to do. Hence the word "soft."

As part of the "soft" discussions, I arranged with the Caltech development people to set up meetings for me with appropriate Institute staffers. I visited the public relations office, the contract office, the financial office, and so on. They understood that it was going to be a gentlemen's understanding, and so we talked through these things on how it was going to be done.

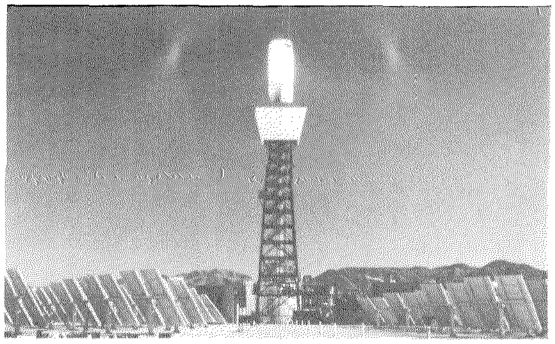
The key element was simply a personal letter between the provost and myself. (The research fields and the principal investigators were already spelled out in one-page papers submitted by each of the two faculty members.) Our letter covered such matters as starting period, contribution times, publicity (no one would rush to press without telling the others), published reports and other communications (we would get the first copy of any published report and a letter once a year just to let us know they were still alive), access, and visitation.

The letter also covered access to records, which had been a cause for uneasiness among my financial associates. They said, "Gee, you can't let them have half a million dollars without giving them a book on how to report the costs back to us." So I came and talked to the Institute accounting people and asked if we could see the Caltech accounting records on that particular project if we wanted to find out how the money was being spent. They said, "Of course." I decided that we would trust Caltech to apply the same rigor to our money that it would to its own.

We also wanted to identify four Rockwell scientists in each of the two fields as liaison scientists for the program. For me, these technical matchups were crucial to the success of the grant. We tried to pick people with good academic backgrounds — not necessarily Caltech PhDs, but those who might be comfortable in an academic atmosphere. Before I brought our people over, I came to the Caltech faculty involved and said, "Fellows, this is the most important part; everything else is paperwork. You've got to be ingratiating to my people; don't intimidate them or they won't come back." They all promised to behave.

Now we are well into the first year of these two research grants. As you might expect, and as I *knew* would happen, my people are still a tad uncomfortable coming to Caltech. This is not their turf, and although everything has been done to make them feel comfortable, it just takes a while. This is the biggest resistance for us.

This was an experiment for us because our company has never done precisely this before. We're delighted that it has worked out so well: it was relatively painless. The whole thing took about nine months altogether. What are the benefits to us? We're intermixing people; we're lifting the horizons of our people. We hope that occasionally we'll pick up a competitive edge, and we'll get experience in grants so that we can do the same thing with other universities in the future. ☐



Rockwell's Rocketdyne Division developed the central receiver boiler and the thermal storage unit for Solar One, the country's first solar electrical generating plant.

John D. Roberts
Institute Professor of Chemistry
Caltech

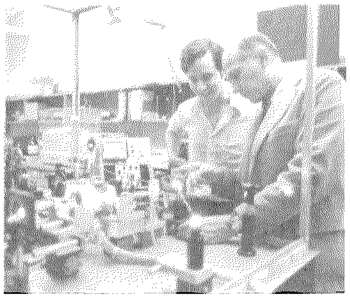
THE BENEFITS to industry and universities from mutual collaboration are obvious, but problems come along with those benefits, and I should like to discuss some of them from the academic point of view. In no particular order of importance, I list five such areas of difficulty below:

1. Should any group have preferred access to students and postdoctoral fellows with respect to consideration for employment?
2. How should we handle patent rights?
3. How should we handle proprietary information? In the purest sense, such information has no place on university campuses, but, pragmatically, it is often generated in applied research in commercially competitive areas.
4. What restrictions, if any, should there be on the publication of results?
5. How can we in the universities preserve necessary balance in our programs? Industry has rather suddenly discovered that there are rapidly developing new areas such as biotechnology, integrated optics, and computer science, in which industry is far from up to speed. Because they wish to establish positions in these areas as rapidly as possible, many corporations are very willing to pump money into university research and have their personnel participate directly in it. But it is important for each university to preserve balance in its programs (and especially set aside resources to nurture those areas where the next potential breakout may only be a gleam in a young professor's eye). One way to help achieve and maintain balance would be to have each restricted-purpose gift accompanied by an unrestricted grant to use at the university's discretion.

As a consultant for DuPont for 33 years, I do know something about how industrial research is carried out, and in the course of that relationship, my DuPont colleagues and I carried out collaborative basic research that led to several publications. My DuPont collaborations were interesting because *no* money changed hands. Each party got something it wanted, with mutual saving of time and money.

This was done under the old system where university research was financed primarily by the government, in part through corporate taxes. Cor-

In the academic community, both students and professors occupy the labs. Above, undergraduates in Caltech's new Mead Chemistry Laboratory. Below, Amnon Yariv, Myers Professor of Electrical . . .



. . . Engineering and professor of applied physics, and graduate student Tom Koch make adjustments on a dye laser and amplifier system used to study ultrafast processes and switching phenomena in semiconductors. . . .

. . . One important result of all this effort becomes visible each June as students don caps and gowns and attend commencement.

porations paid those taxes to the government, the government selected the areas for support. All industry benefited in the most general way.

No one likes to pay taxes, and taxes have been and are being reduced, but government spending for research in real dollars has also been reduced. To maintain the level of basic research the country needs to keep the economy vital in the long run, therefore, requires new sources of money. At the present time, as Martin Cooper points out, universities are knocking at industry's door. Some of the less-favored universities are in such straits, in fact, that they are willing to act as low-cost research institutes, in competition with Battelle or SRI International, for example, working on specific industrial projects. In my view, this is not a good use of universities.

I like Mr. Cooper's idea of "illusory" objectives in supporting university research, that is, for industry to benefit by inspiration and ideas as well as by fostering education of students in important fields — but to have no more than the illusion of directly benefiting by gaining exclusive patent rights to breakthrough inventions.

The publication problem is an important one. As a member of the National Academy of Sciences Panel on "Scientific Communication and National Security," I heard a lot about this problem as it relates to possible transfers of critical technology (ideas or hardware) to the Soviet Union. I recommend reading that report, which holds that simultaneous submission to journals and the sponsors should suffice for national security purposes. The industry representatives on the panel strongly supported this view. It seems that industry in general would like to have access to DOD-sponsored research promptly, but then some parts of it would argue for substantial delays in publication for industry-sponsored research where patent rights might be involved. The difference in viewpoint creates problems for universities.

What should industry-university partnerships be like? From our point of view, the best possible partnership would be a general and very open one with all of the companies interested in our work. Nonetheless, we understand that many corporations who give money for specific purposes will have rather natural proprietary feelings about open dissemination of results to those who did not support the work.

Let me point out our concern that too tight partnerships could well lead to perceptions that ideas, research programs, and students can be bought and sold on university campuses. Such perceptions could lead to serious problems for us in another direction. Many corporations contribute general support to the Institute through the Industrial Associates program. A few make additional large general contributions with no strings attached. To a degree, when we take on collaborative projects involving restricted access or patent rights from other companies in areas in which our donor companies are also interested, we may be inhibiting their right of access to ideas, results, and students. We are creating an internal conflict of interest. We must take great care in making relationships not to foster undue channeling of research and not to prejudice the collegial environment. With our very small groups, that environment plays an important role in our success.

If large enough contributions were possible, the ideal system for us would be to have corporate support largely channeled into Industrial Associates type programs. All of the corporations involved would thus be partners together. The universities could fulfill their educational mission through dissemination of their results in conferences and by individual visits, with neither side holding back. Unfortunately, as John Tormey has made so clear, it can be hard to get corporate research personnel to make the use they could and should of such visits, even when the research is in relatively specific areas of interest.

The Rockwell arrangement was fun to negotiate, and you will note that it calls for no patent rights and no restrictions on publication. It does foster our strength in areas in which Rockwell has a deep interest. This is another very useful model for collaborative research with industry, and it has many advantages. The one possible problem is that of creating some unbalance in our programs, a difficulty which might become serious if several other companies decide they want to push the same research areas here.

Clearly, a new world of industry-university relationships is with us. As yet there is great diversity, and as yet no standard well-tested model for industrial support of university research has emerged. Any search for one may be fruitless, because of the differences in objectives, concern for proprietary rights, financial resources, and research sophistication of the industries involved. Properly set up, with understanding of each participant's interests and limitations, collaboration in research can be expected to lead to great mutual benefit. Collaborations based on one side seeking specific answers to specific proprietary problems, however, and the other seeking financial support to keep academic wheels turning without proper consideration of educational objectives can only be expected to lead to mutual dissatisfaction. ☐

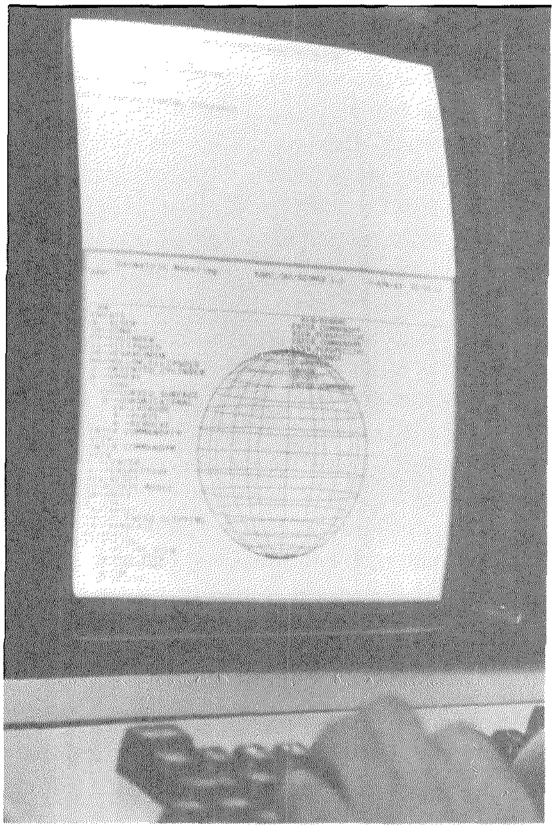
A CADRE of Engineering Computers at Caltech

by Dennis Meredith

CHARLES BABCOCK enters the small room in Caltech's Guggenheim Laboratory, touches a few keys on the computer terminal and the screen comes to life. He specifies a program for constructing models on the computer screen. The computer then lists a number of basic shapes he can choose from to begin his modeling — including blocks, cylinders, ellipsoids, hexahedrons, hollow ellipsoids, spheres, tubes, curved surfaces, and quadrilaterals.

Choosing a cylinder, he specifies its size and orientation, and directs the computer to draw it. The computer pauses, and after a moment of calculation slowly traces the lines of a cylinder onto the screen. Babcock chooses another cylinder, specifies a smaller size, rotates it, and tells the computer to insert it into the first cylinder. Once more, he tells the computer to draw the figure, and after a few moments, traced upon the screen is the small cylinder, joined to the larger one at an angle.

Babcock experiments with different shadings, directs the computer to make the cylinder hollow, and — satisfied with his work — decides to try another figure. This time, he draws a simple square and tells the computer to extrude it through space, rotating it as it is extruded. The result is a hollow, square, warped tube.



Although these two figures were simple ones, Babcock could have used combinations of simple shapes, extrusions, and specified points in space, to draw *any* shape, from the simplest arrangement of pipes, to the most complex machine part. What's more, he could then use this three-dimensional model as the basis for a complex computerized engineering study — called finite element analysis — of the model. In this procedure, he would specify the points on the structure to be used in the analysis and direct the computer to analyze how it might respond to loads. He could then tell the computer to show him visually how the model would warp in response to a given load.

The process is called computer-aided design, or CAD. In combination with the analytical power of computers, it is creating as profound a revolution in engineering as mathematical analysis did many decades ago. Such computer systems typically feature computer graphics hardware and software that visually display the progress of a design project. They also include engineering analysis programs that can perform complex calculations to determine how the real-life engineering product will behave under a range of circumstances.

Engineers in many industries now use CAD systems to design buildings, automobiles, aircraft, space probes, dams, highways, chemical plants, electrical circuits, computer chips, and any other projects requiring engineering analysis. They are also linking computer-aided design and manufacturing — creating "CAD/CAM" systems that, for example, use the design for a machine part produced on a computer to guide the production of that part by automated machine tools.

Like many of his Caltech engineering colleagues, Babcock, professor of aeronautics and applied mechanics, is now wrestling with how best to teach the powerful techniques of CAD to his students in mechanics.

It's a very active topic of conversation these days in Caltech's Division of Engineering and Applied Science, mainly because of a system, now in its early stages of development, known as CADRE — for Computer-Aided Design, Research and Education. The system development is overseen by a faculty committee chaired by Fred Culick, professor of applied physics and jet propulsion. This group of representatives from the various areas of the division is now planning CADRE as a major network of computers spread throughout the buildings of the engineering division. Although CAD is the current major focus of the effort, CADRE will ultimately encompass most of the division's computer resources for the use of computers in education and research.

Today, the system consists of two VAX minicomputers, running design software donated by the Ohio-based Structural Dynamics Research Corporation (SDRC). Eventually CADRE will consist of numerous computers, terminals, plotters, and other devices. The linked computers will provide a powerful set of tools, both for faculty research and student training in CAD.

There is no question but that engineering students at Caltech must be conversant with the new technologies, says Culick. Having the ability to visualize engineering problems and to feed in parameters and have results displayed in real time is profoundly affecting the way engineers approach engineering analysis. While engineers formerly had to figure out results from reams of paper printouts splattered with numbers, CAD brings an unprecedented freedom of conceptualization.

"If you're going to build a house, you specify the standard-size lumber — two-by-fours, for example — because that's what's available," says Culick. "It's the same with engineering analysis; you tend to bend the problem into a shape that allows you to use the analytical tools that are available." But once those tools come to include powerful number-crunching analytical programs that display their results in easy-to-grasp computer graphics form, the result will be great flexibility of engineering analysis.

To Babcock, another object of teaching CAD is to help students guard against unwise use of computers.

"In a way, we have to teach students about computers in order to vaccinate them against the machines. We can teach classical solutions to engineering problems, so the students will develop an intuitive feel for correct results that they can then use to make wise judgements." But numerical solutions to the classical equations can be as flawed when spit out of a computer as when incorrectly obtained by hand, a distinction computer-naive students may miss.

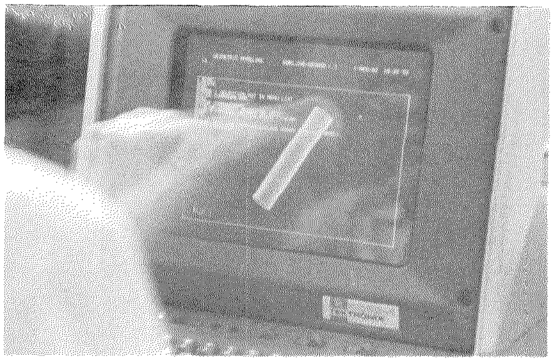
"If we don't expose them to computers here," says Babcock, "we'll find they go out into industry, start to use the computer, and often just start to do garbage. Thus, we hope to use computers partly to demonstrate how engineers can run into trouble."

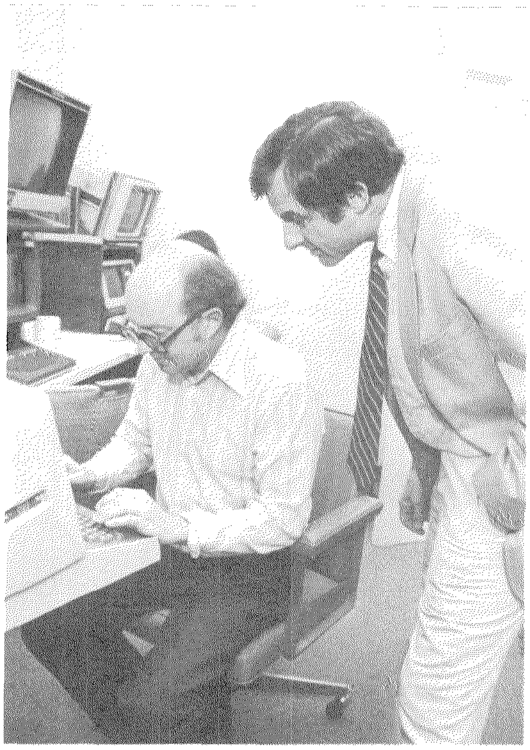
The seeds of CADRE were sown in 1979, when Culick became concerned that Caltech was behind in the teaching of CAD. His first task was to assure himself and his fellow educators that CAD possessed enough intellectual content to justify teaching it at Caltech.

"We're not in the business of training people to go out and do routine tasks," says Culick. "To put it bluntly, Caltech is not a trade school. We had to be sure that CAD would be used to further the intellectual content of our coursework."

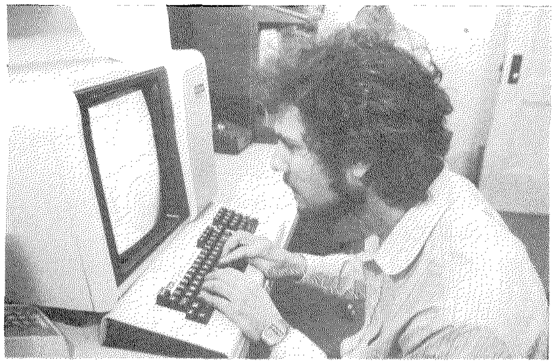
After attending meetings and workshops, Culick found that such universities as Ohio State, Rensselaer Polytechnic Institute, and the University of Michigan had established successful CAD systems for education, and that CAD was, indeed, a significant enough intellectual tool for Caltech to consider its own role in teaching the new technology.

"I quickly came to several conclusions," recalled Culick. "First, that the effort will require a great deal of money to do properly. Second, I saw that the large investment in CAD at those schools had become restricted to a small part of mechanical engineering — the area of mechanical design. The hardware and software required for CAD looked to me to offer much more novel, interesting applications than its use thus far had indicated."





Charles Babcock (left) and Fred Culick summon a cylinder to the screen with CADRE's geometric modeling program.



At a different terminal Jon Melvin (lower left) draws a sphere.

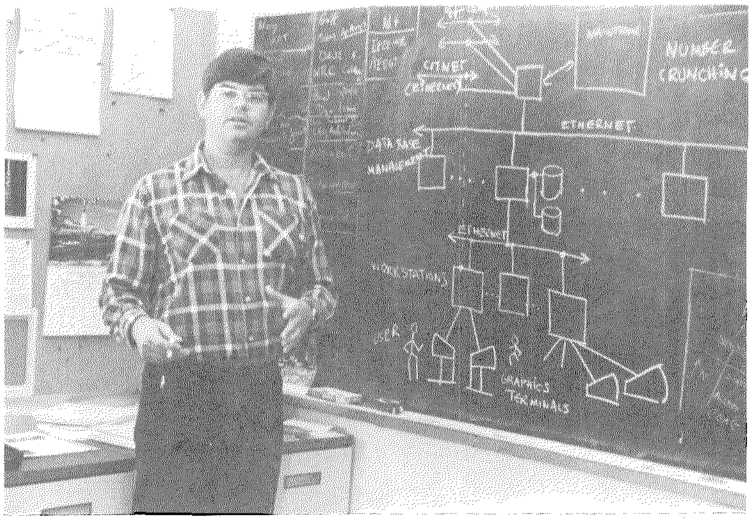
Culick also concluded that it would be far more efficient and useful for a small school like Caltech to plan a CAD system that could be used for both teaching and research. Thus, Culick and his colleagues envision CADRE as quite different from its counterparts at other universities.

"The most important difference may be that all fields in the division will be involved in the system — sharing software and use of hardware. This sharing may promote interdisciplinary exchanges not even forseen."

The next step in CADRE's formation came with the appropriation of $250,000 in Institute funds for the effort in the spring of 1981, a sum that Culick terms "only seed money." Using this money, the first hardware was purchased last summer, consisting of two Digital Equipment Corporation VAX computers, which were subsequently augmented with Tektronix graphics terminals and other necessary peripherals to form the first part of the larger CADRE system. The job of designing and implementing the initial configuration and integrating it into the future system as CADRE evolves, was taken on by Paul Dimotakis, associate professor of aeronautics and applied physics, and Jon Melvin, a part-time staff member of physics and engineering.

"We recognized at the outset," says Dimotakis, "that the problem of introducing computer-aided engineering tools has both near-term and long-term aspects. In the near term, we want to expose students and faculty to the existing technology in this area and make it available to them in both curriculum and research. So CADRE has to conform to existing software and hardware systems and standards to minimize the start-up time penalty. In the long term, we're confronted with a much more challenging problem. We have to recognize not only that CADRE may have to accommodate a technology that is advancing at a revolutionary rate, but also that these computer tools in engineering will probably affect engineering itself, and the way we think, in radical ways."

Anticipating at least one aspect of this problem, the CADRE network is designed to allow easy user access to different computers for different tasks. Instead of the traditional "star" network configuration — a central computer serving many users — that was dictated by computer characteristics in the 1970s, the CADRE system is being designed as a hierarchical distributed network of resources linked by high-speed Ethernet sub-networks. This complements the larger effort also currently under way at Caltech to provide a campus-wide computer network (supported by a grant from the Fletcher-Jones Foundation) that has already begun to provide services at selected sites on campus. The campus network should be operating on a much larger scale within 12 to 18 months. Dimotakis and Melvin are also trying from the start to design sufficient redundancy into the CADRE system to make it as resistant as possible to single-point failures.



Paul Dimotakis sketches CADRE's hierarchical architecture, in which a number of work stations, each serving one or more user terminals, are connected via Ethernet to data base management stations, which are joined in turn to the main computer. CADRE will also link up to the campus-wide network already under way, and a system of direct interconnections from the various levels will make CADRE fail-safe.

Not only will students and faculty have access to terminals in their offices and computer centers, but in the classrooms as well. Thus, a professor will be able to explore the possible solutions to a sophisticated engineering problem using real-time computer analysis, displaying the results on a large screen in the classroom. Culick expects profound effects on both engineering research and education due to the powers of CADRE.

"The way we teach and do research will change drastically in the next few years. Having easy-to-use distributed resources readily accessible to students and faculty will encourage that process," he says. "We expect much of the evolution of CADRE to come from students, and we'll be trying to provide an environment for students and faculty to work in, not just a facility with which faculty can show students how to use computers. Each year, what we do will probably be different from what we did the year before.

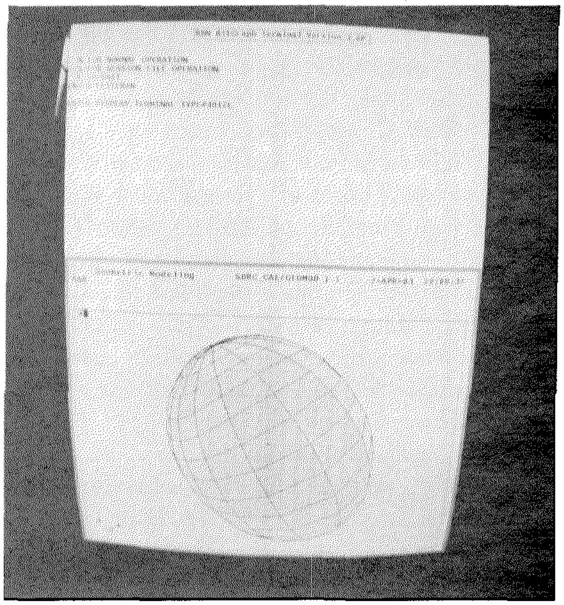
"Primarily because of the small size of Caltech, CADRE will offer truly unusual opportunities. With much less investment and support than required in other leading universities, we are able to create a unique environment for the applications of computers."

Even before the CADRE computers began functioning, however, Caltech engineering students had already begun training in CAD. For example, last year some 50 undergraduate mechanical engineering students in Associate Professor of Engineering Design David Welch's classes learned CAD on the terminals of the Pasadena-based computer-aided-design company CADRI, which is headed by Caltech graduate Louise Kirkbride (BS '75 Eng, MS '76 EE).

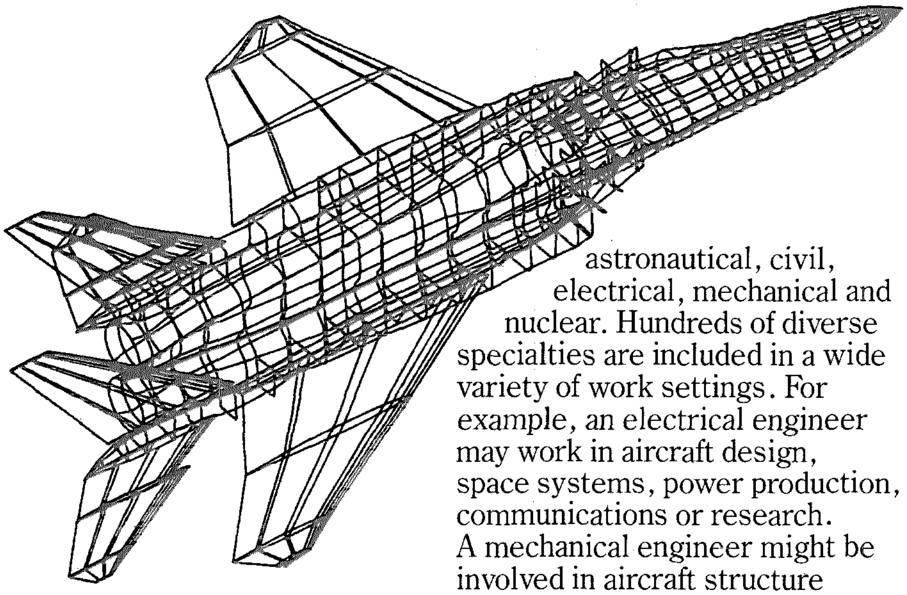
Early use of CADRE came this spring in a civil engineering course taught by James Beck, assistant professor of civil engineering and John Hall, research fellow and lecturer in civil engineering. Welch plans to use CADRE in his design courses beginning next fall.

Also this spring Dimotakis's AE 107c class, "Case Studies in Engineering," is focusing on computer-aided engineering, featuring speakers from SDRC, JPL, and Aerojet Electro Systems. During the course, students will receive hands-on experience in CAD using six graphics terminals operating in the first of CADRE's computer facilities in Thomas Laboratories. They'll use not only the enormous base of software donated by SDRC but also hardware and software donated by Tektronix, Inc. (Digital Equipment Corporation and Nippon Electric Corporation have also supplied equipment at special discount, and SDRC and Northrop Corporation have provided training.) Visitors from a number of other companies have also come to campus to discuss CADRE, and Culick and Dimotakis hope that the project will attract continuing participation by industrial personnel at the working level, in both education and research.

Despite such generous donations, future hardware and software for CADRE, Culick expects, will probably cost several million dollars. Annual operating costs, including adequate staff support, will be in excess of $200,000, he believes. He also believes, however, that "we must accept computer-aided engineering as a new responsibility of university education. If we're to continue to attract good students and faculty, and to offer a farsighted engineering education, we simply must have the very best capabilities for using computers. We've had excellent support from the Institute, as well as industry. We'll need both, as well as considerable intelligent planning, if we're to take full advantage of these remarkable tools." ☐



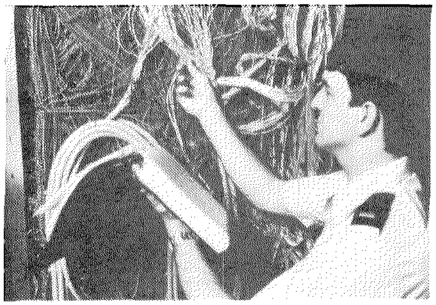
ENGINEERING TAKES ON EXCITING NEW DIMENSIONS IN THE AIR FORCE.



Computer-generated design for investigating structural strengths and weaknesses.

Developing and managing Air Force engineering projects could be the most important, exciting challenge of your life. The projects extend to virtually every engineering frontier.

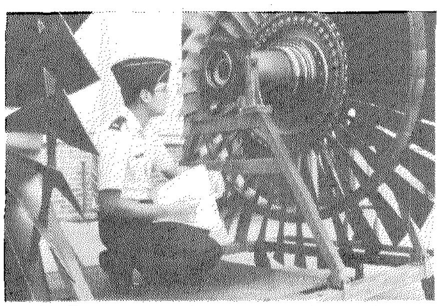
8 CAREER FIELDS FOR ENGINEERS



Air Force electrical engineer studying aircraft electrical power supply system.

Engineering opportunities in the Air Force include these eight career areas: aeronautical, aerospace, architectural, astronautical, civil, electrical, mechanical and nuclear. Hundreds of diverse specialties are included in a wide variety of work settings. For example, an electrical engineer may work in aircraft design, space systems, power production, communications or research. A mechanical engineer might be involved in aircraft structure design, space vehicle launch pad construction, or research.

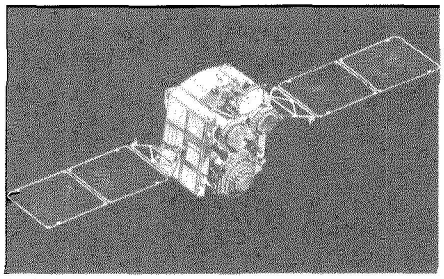
PROJECT RESPONSIBILITY COMES EARLY IN THE AIR FORCE



Air Force mechanical engineer inspecting aircraft jet engine turbine.

Most Air Force engineers have complete project responsibility early in their careers. For example, a first lieutenant directed work on a new airborne electronic system to pinpoint radiating targets. Another engineer tested the jet engines for advanced tanker and cargo aircraft.

OPPORTUNITIES IN THE NEW USAF SPACE COMMAND

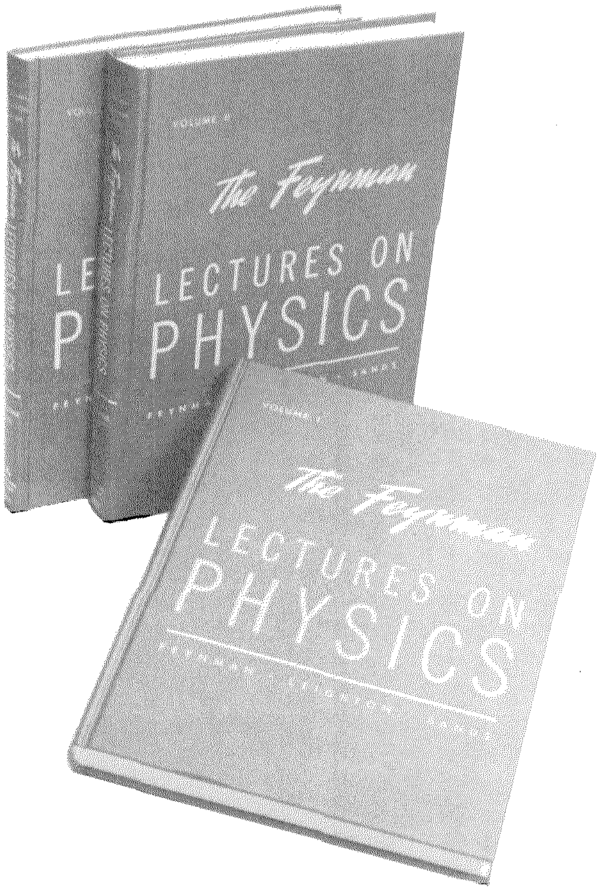


Artist's concept of the DSCS III Defense Satellite Communications System satellite. (USAF photo.)

Recently, the Air Force formed a new Space Command. Its role is to pull together space operations and research and development efforts, focusing on the unique technological needs of space systems. This can be your opportunity to join the team that develops superior space systems as the Air Force moves into the twenty-first century.

To learn more about how you can be part of the team, see your Air Force recruiter or call our Engineer Hotline toll free 1-800-531-5826 (in Texas call 1-800-292-5366). There's no obligation.

AIM HIGH
AIR FORCE



A Sonnet from Science

SCIENCE textbooks roll off the presses in relative profusion, but most are not noted for poetic expressiveness. There are, however, exceptions, as a recent letter from Jonathan V. Post (BS '73, in mathematics and literature) points out. Post says, in part, "I am reminded that 1983 will be the 20th anniversary of the publication of the world's most popular physics book: *The Feynman Lectures on Physics* by Richard P. Feynman, Robert B. Leighton, and Matthew Sands. There is a footnote in that text that comments on the relative virtues of science and poetry, and I found its language to be very poetic in itself. Consequently, I have rearranged the phrases, and added a few of my own, to compose a sonnet."

Post thought, and we agreed, that it would be most appropriate for the poem to appear in *Engineering & Science* in a 1983 issue, both to commemorate those famous bright red books and to "celebrate the bond between the humanities and sciences at Caltech." First, the footnote:

> "The stars are made of the same atoms as the earth." I usually pick one small topic like this to give a lecture on. Poets say science takes away from the beauty of the stars — mere globs of gas atoms. Nothing is "mere." I too can see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination — stuck on this carousel my little eye can catch one-million-year-old light. A vast pattern — of which I am a part — perhaps my stuff was belched from some forgotten star, as one is belching there. Or see them with the greater eye of Palomar, rushing all apart from some common starting point when they were perhaps all together. What is the pattern, or the meaning, or the *why*? It does not do harm to the mystery to know a little about it. For far more marvelous is the truth than any artists of the past imagined! Why do the poets of the present not speak of it? What men are poets who can speak of Jupiter if he were like a man, but if he is an immense spinning sphere of methane and ammonia must be silent?

The Feynman Lectures on Physics
Addison Wesley Publishing Co., Inc., Vol. I, 3-6.
©1963 by California Institute of Technology

Next, Post's sonnet:

Footnote to Feynman*

Science takes away from the beauty of the stars?
On Earth, stuck on this carousel my little eye
(atoms: my stuff was belched from some forgotten star)
my eye can catch one-million-year-old light. Do I
see less or more? Mere globs of gas? Nothing is "mere."
I see them with the greater eye of Palomar —
What is the pattern, or the meaning, or the why?

Earth, stars, a vast pattern — of which I am part —
(and the whole universe is in a glass of wine)
stars rush apart from common starting point. My heart —
red as Betelgeux, Antares, Aldebaran —
my heart beats to the mystery of the sky.

It does not harm the mystery to know our birth:
The stars are made of the same atoms as the Earth.

*Adapted with permission

And, finally, a footnote of our own: *The Feynman Lectures on Physics* arose out of a decision taken in the early 1960s that Caltech's required introductory course in physics needed revision. It would include a new course outline, a new textbook, and some new laboratory experiments. The text was produced by taping a set of lectures given in 1961-62 by Richard Feynman, then the Richard Chace Tolman Professor of Theoretical Physics and soon to be awarded the Nobel Prize. The tapes were transcribed, edited by Robert Leighton and Matthew Sands, professors of physics at Caltech, and published in 1963 by Addison-Wesley.

Whether the book then really became the "world's most popular physics book" we don't know, but the publishers have given us some impressive numbers about it. In the 20 years since the familiar three volumes were issued, nearly 350,000 copies in English have been sold. This number includes not only the separate hardbound copies but also the paperback set of three volumes that comes as a set. And this is only the beginning; the book has actually been reprinted 15 to 20 times, with more than 400,000 copies having been published in foreign languages — French, German, Hungarian, Italian, Japanese, Slovak, and Spanish.

As for Jonathan Post, he now lives in Seattle, where he does software management for a number of Boeing Aerospace Company projects. He has over 200 books, articles, stories, poems, and broadcasts to his credit, including a recent keynote address to the Washington State Legislature. He is also completing a book — *Science Poems* — on the history of the relationship between science and poetry. ☐ *-JB*

Jonathan Post

Books — by, about, or of interest to Caltech people

SCIENCE AND MORAL PRIORITY
Merging Mind, Brain, and Human Values

by Roger Sperry

Columbia University Press $16.95

Roger Sperry's scientific life has been guided by a persistent quest for understanding of the relation of mind to brain. This quest grew out of his observations of the effects of surgically dividing the brain, and led him to examine the issues of consciousness, brain, and moral values. *Science and Moral Priority* presents his resolution of the conflict between the value-devoid mechanistic descriptions of science and traditional humanistic views of man and the world.

Since the late 1960s, Sperry points out, new concepts of brain and consciousness have given science an outlook in which the mind supersedes and controls matter, and the physical world and human psyche no longer reduce to quantum mechanics. With this foundation for a new understanding of the relationships between science and values, Sperry argues that it is not only possible but vital to merge the teaching of science and value questions. He sees such a fusion of ethics, religion, and science as the strategic key to a humane reversal of worsening world conditions.

Sperry is the Hixon Professor of Psychobiology at Caltech and a winner of the Nobel Prize in 1981.

JPL AND THE AMERICAN SPACE PROGRAM
A History of the Jet Propulsion Laboratory

by Clayton R. Koppes

Yale University Press $19.95

This is the biography of an institution that has played a leading role in the American missile and space program. It began in 1936 when a group of Caltech graduate students and local enthusiasts banded together to build rockets, but space exploration eventually represented JPL's greatest achievement.

Clayton Koppes gives the reader more than technical or scientific history, however. He also recounts the political controversies and human interactions that erupted in the lab; he traces the complex relationships between JPL and Caltech, the government, and the aerospace industry; and he raises questions about the funding, control, and purposes of scientific and engineering research in relation to national security.

Koppes did his research and the bulk of the writing of the book from 1974 to 1978 while he was a senior research fellow in history at Caltech. He finished the manuscript at Oberlin College where he is currently assistant professor of history.

TOUCHED BY AFRICA

by Ned Munger

Castle Press, 516 N. Fair Oaks Ave.,
Pasadena, CA 91103.
At press ... $12.50; by mail ... $14.00

Ned Munger, professor of geography at Caltech, is the author of 7 books and more than 300 articles on Africa, and many of the 26 biographical sketches of friends and acquaintances of which this volume is composed are about Africans. Others of Munger's subjects have been touched by Africa largely through their relationship to Munger himself. They are a diverse group, including, for example, Max Delbrück, the Nobel laureate whose prize money went to a Nigerian; Martin Aliker, who may one day be president of Uganda; Henry, Doris, and Ann Dreyfuss, the industrial designer, his wife, and his daughter; Charles McGruder III, the first black American to enroll as a freshman at Caltech and graduate with a BS; and Walter Rogers, director of the Crane-Rogers Foundation, under whose aegis the American Universities Field Staff developed a corps of American specialists on foreign countries (Munger being one of them).

ENTROPY MINIMAX SOURCEBOOK

Volume 4 — Applications

edited by Ronald Christensen

Entropy Limited, So. Great Road,
Lincoln, MA 01773 .... $59.50

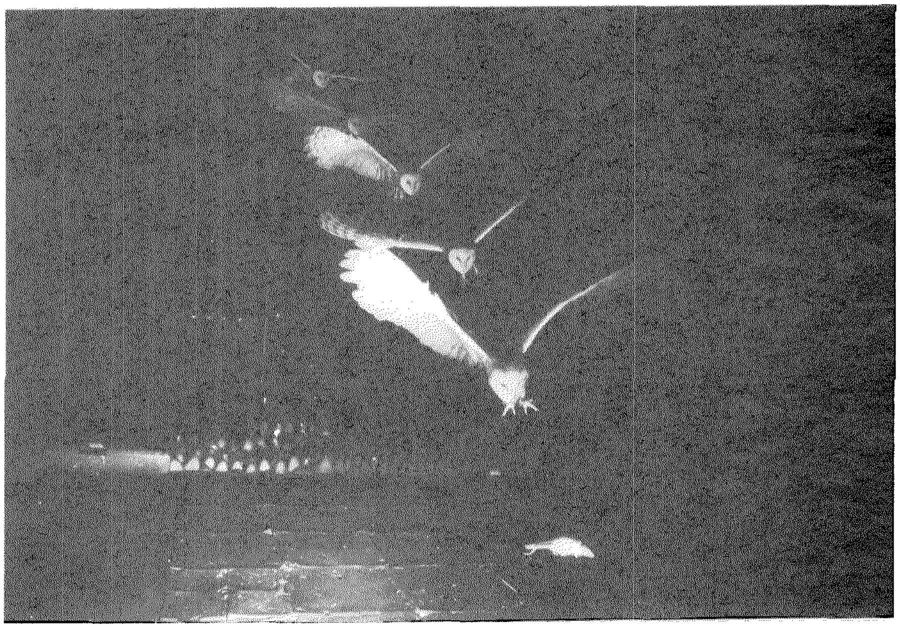
This book, part of a seven-volume series, is a compendium of entropy minimax applications covering two decades. Entropy minimax is a new approach to predicting the future behavior of complex systems from limited observational data and employs modern information theory in its formulation. Reports are from diverse fields such as engineering, materials science, medicine, meteorology, social science, and business, and include predictive patterns for California precipitation, nuclear fuel element failure, survival prognosis for coronary artery disease patients, cancer, prison population, and more. Volume I of the series is a general description; Volume II discusses philosophical origins; and Volume III is about computer implementation.

Ronald Christensen, who is the author of the first three volumes, is a Caltech alumnus (MS '59) and president of Entropy Limited, a research firm that specializes in statistical analysis, engineering, and science, using the entropy minimax method of pattern discovery.

Birdbrains

MASAKAZU (Mark) Konishi, who studies owls, is often asked whether owls can see in the daytime. Yes, they can see fine in the daytime, he answers; what they can't do is see in the dark. But they can hear, and the nocturnal owls that hunt at night can find their prey purely by sound.

Konishi, the Bing Professor of Behavioral Biology, has been doing research on barn owls for more than a decade. Initially he conducted behavioral studies but in recent years has concentrated more on neurophysiology — how the owl's brain analyzes sound. He still finds it useful, however, to do both behavioral and neurophysiological experiments, because one field can generate ideas of what to do in the other. In sound localization, Konishi says, what you see in behavior and in the brain turns out to be tightly correlated.



In total darkness the noises made by the tethered mouse provide an accurate auditory map for the barn owl, who arrives at the precise location with talons spread out in an oval shape aligned with the axis of the mouse's body. The experiment was photographed with light from an infrared strobe (the five images over one second), which the owl can't see.

Barn owls can pinpoint the source of a sound more accurately than any other terrestrial animal studied so far — as accurate as 1.5° in both the vertical and horizontal dimensions. But they exploit a different sound cue in each of those dimensions. To localize a sound in the horizontal, the owl makes use of interaural time difference, that is, the time between the arrival of a sound at one ear and at the other. For example, if a sound is coming from the right, it will reach the right ear sooner than the left ear. In man, with about 19 cm between the ears, this is a maximum difference of 570 microseconds (millionths of a second).

But a barn owl's head is five times smaller than man's, and the time span is correspondingly shorter. To determine whether the barn owl indeed responds to time in the microsecond range, Konishi and Research Fellow Andrew Moiseff outfitted their owls with tiny earphones that present sounds to the right and left ears with time differences of 10-30 microseconds. Since the owl conveniently turns its head in the direction of the perceived sound, its response can be monitored; when the owl is perched in an electromagnetic field, the slightest movement induces current in a coil placed on its head. Measurement of this current showed that the amount of head movement was proportional to the magnitude of time differences in the microsecond range.

To track sound in the vertical dimension the owl uses a different set of cues — from interaural intensity differences. (The ear nearer the sound hears it not only sooner but louder.) Humans use both time and intensity differences to localize sound on the horizontal but can't come close to the owl's sensitivity on the vertical. The barn owl is more than twice as sensitive as man to the loudness of a sound. The heart-shaped ruff of feathers that looks like an Elizabethan collar and that distinguishes the faces of all nocturnal owls is a collector, which focuses sound into the ears.

The owl's face is also conspicuously lopsided; its ears are asymmetric. Although its skull is symmetric, the skin forming the left ear opening is higher and tilted downward for increased sensitivity to sounds from below, while the right ear flap is lower and aimed upward. This amplifies the intensity differences from varying elevations.

The interaural intensity difference (vertical) and the time difference (horizontal) provide a set of unique cues for each particular point in a two-dimensional space. These correspond to a neural map in the owl's brain, which he can translate immediately into the precise site of his potential meal. Konishi and former postdoc Eric Knudsen have determined how these mechanisms work by inserting fine electrical probes in an anesthetized owl's brain to record activity of the auditory nerve cells by picking up the electrical field created by each cell. They have found that each specialized cell responds only to sound from a particular point. Perhaps the most striking finding of the Konishi group's research is that each of the systematically arranged nerve cells is tuned to a particular narrow range of *both* interaural time differences and intensity differences simultaneously.

Konishi's research group has five breeding pairs of barn owls, who produce some 50 hatchlings per year. These are raised individually so that they become extremely tame. His aviary also includes finches and sparrows. Konishi's work on finches with former grad student Mark Gurney has determined the sex-hormone link to the brain cells that control singing, and in his current work with sparrows he and grad student Dan Margoliash are studying the auditory brain cells that enable the bird to recognize the song of its own species. □ – *JD*

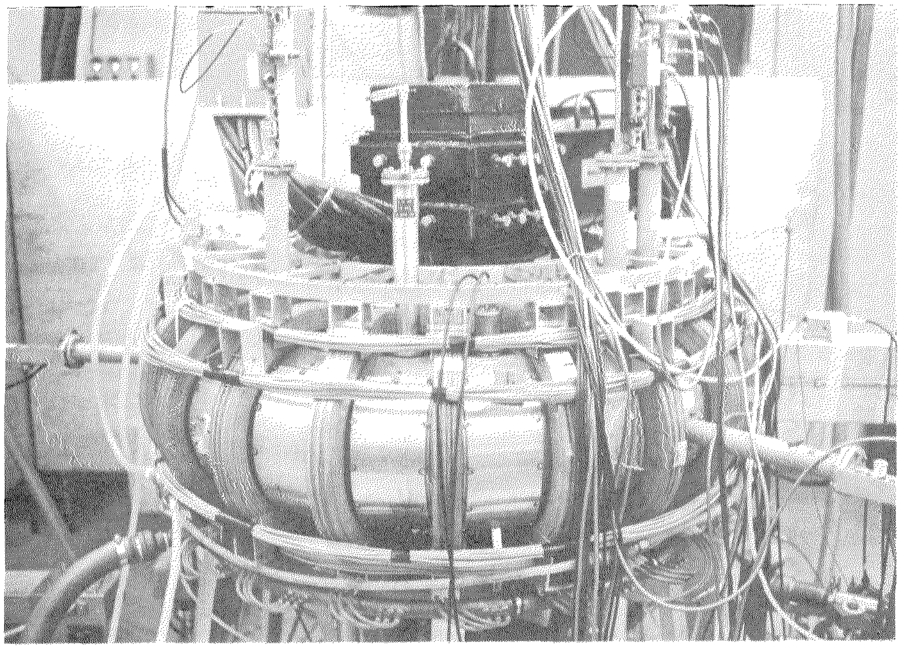
Infusion

CALTECH'S ENCORE tokamak is not so named because it's a repeat performance of the first tokamak on campus, built seven years ago by Roy Gould, chairman of the division of engineering and applied science. Nor is the name an acronym, although Paul Bellan, who designed it, is pretty sure he could think one up. Rather, Bellan, who is assistant professor of applied physics, named the device for its high repetition rate, a unique design feature that facilitates study of some of the basic physics of tokamaks.

The tokamak is the most successful device in the quest for fusion energy — the largest tokamaks under construction should be close to achieving controlled fusion. Inside a working tokamak reactor, deuterium and tritium, two isotopes of hydrogen, would be ionized to form a plasma and then would be heated to 100 million degrees C. The fusion reaction occurring on impact between the two ions would release energy greater than that used to generate the reaction and so provide net power.

A tokamak is basically an electrical transformer, in which the very hot, doughnut-shaped plasma is a one-turn secondary. (A transformer has two coils, a primary and a secondary; driving a current pulse in the primary causes an equal and opposite current pulse to flow in the secondary.) The magnetic fields associated with the current flowing in the plasma confine the plasma to keep the ions and electrons from colliding with the walls.

ENCORE is not large, as tokamaks go. About three feet across, it's not a ''parameter-pushing'' tokamak like the 25-foot-diameter machine being built at Princeton. It was designed, instead, to provide access for measuring some of the fundamental physics of a magnetically confined plasma. ENCORE's temperature of 100 thousand degrees C is much colder than what other tokamaks attain, but this relative ''coldness'' enables researchers to put in probes to see what's going on. And the high repetition rate, which allows 15 plasma pulses per second, is almost a thousand times faster than conventional tokamaks, which generate one plasma pulse per minute. Bellan compares it to the difference between a muzzle-loading rifle and a machine gun. With this capability Bellan and his colleagues can construct complicated spatial profiles of various plasma parameters by simply moving a probe to a different position for each plasma pulse.



The ENCORE tokamak fusion reactor is essentially a transformer. The black iron core in its center has a primary winding of copper wires that induces current in the one-turn, doughnut-shaped plasma secondary; magnetic fields associated with the current confine the plasma electrons and ions. Probes (the cylinders sticking out of the top of the doughnut) enable researchers to study some of the fundamental physics of a magnetically confined plasma.

Bellan achieved this high repetition rate in ENCORE with an unusual power supply (which he admits he was initially not sure would work). Where other tokamaks use capacitor banks to generate the plasma, ENCORE uses a 48-kilowatt rms amplifier with peak power output of almost one megawatt. The surplus amplifier, originally used to test rocket and satellite parts for withstanding takeoff vibrations, weighs five tons and had to be hoisted by a crane onto the roof of Steele Laboratory where it now resides.

Among the phenomena Bellan is studying are lower hybrid waves, which propagate in a microwave frequency regime where large power oscillators are readily available. These waves could be used to heat the plasma to fusion ignition. They can also be used to generate large DC currents in the plasma, which is of enormous practicality since it would allow dispensing with the tokamak's transformer and running the tokamak as a steady-state rather than a pulsed machine.

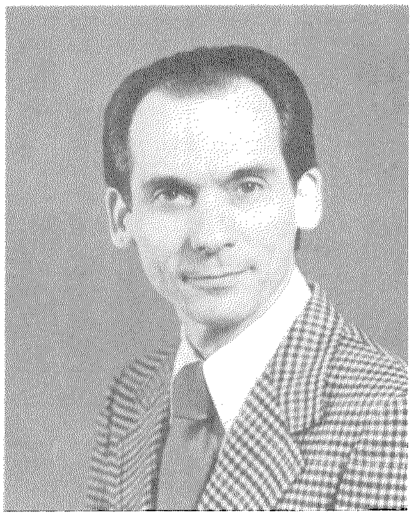
Although these complicated waves are easy to create, they are essentially impossible to observe in other tokamaks. ENCORE's high repetition rate allows Bellan and his students to measure them easily and to study how they propagate. Graduate student Larry Sverdrup is now setting up an experiment in which lower hybrid waves will generate large DC currents in ENCORE.

Another topic being actively pursued on ENCORE is the study of magnetic islands. This phenomenon has a detrimental effect on the tokamak's efficiency and is caused by fluctuation of the magnetic field confining the plasma. Grad student Eric Fredrickson is studying these islands and has developed a computerized plot of the cross section of the torus that shows up the magnetic islands very clearly — looking like extra cores in the concentric rings of an onion. He is now trying to find a coupling between islands and another mode in the plasma — a density fluctuation called a drift wave. Originally the two appeared unrelated, but experimentally a connection is showing up.

Bellan thinks that fusion is starting to look feasible, although it's not clear when it will be competitive economically. But first it's important to make it work, he believes, and the economics can come later. And ENCORE is doing its best to discover how to make fusion work — again and again and again. . . ☐ *-JD*

Random Walk

New PMA Head



EDWARD STONE, professor of physics, has been appointed chairman of the Division of Physics, Mathematics and Astronomy. He replaces Rochus Vogt, who has taken over as vice president and provost. Stone is noted for his cosmic ray studies; he has also been principal investigator on six NASA spacecraft and co-investigator on four others. Since 1972, he has been project scientist for the Voyager missions.

Commencement Speaker

JAMES A. MICHENER will address the commencement audience on June 10 this year, speaking on ''Your Revolution.'' The author was selected largely because of his recent interest in science and his perspective on the space effort, which are manifested in his most recent novel, *Space*. Michener has published 30 books since he began a writing career at the age of 40 with his Pulitzer Prize-winning *Tales of the South Pacific*. Nevertheless, he has still found time for public service, including membership since 1979 on the NASA Advisory Council.

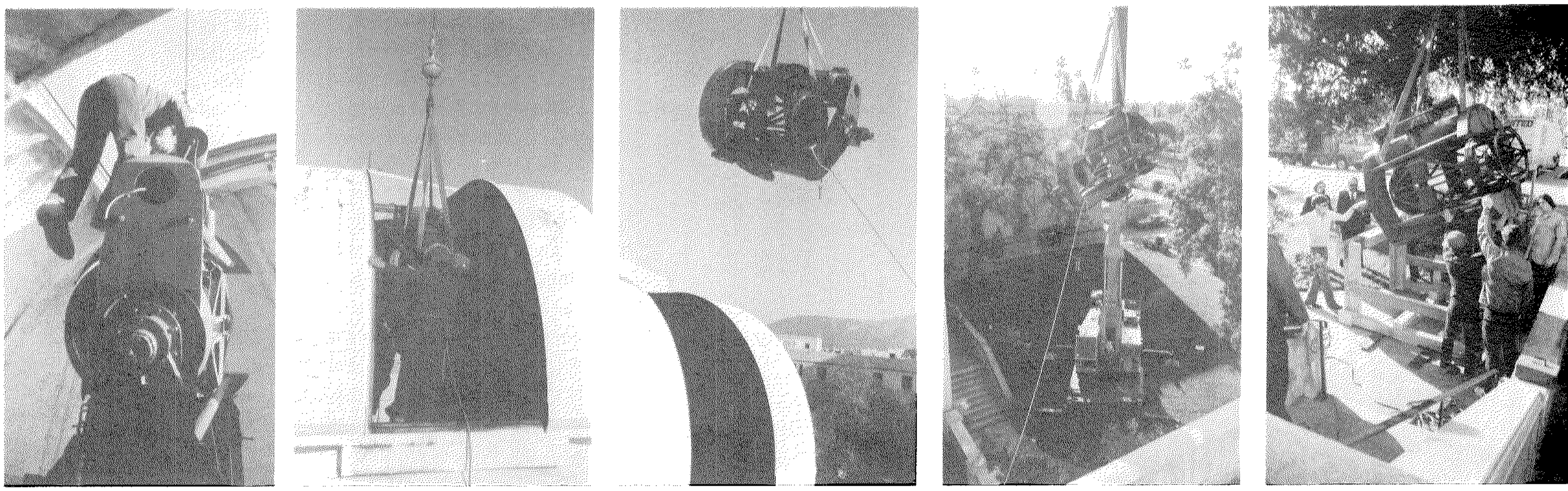
Seminar Day

THE ANNUAL Alumni Seminar Day is a little later than usual this year — May 21 — but it includes the customary star-studded cast, headed by the new director of the Jet Propulsion Laboratory, Lew Allen Jr., as speaker for the General Session. Other sessions will feature the 16 speakers listed below.

Ellen Rothenberg, ''Basic Training in the Immune System''
David Van Essen, ''Monkeying with Vision''
John Baldeschwieler, ''New Approaches to Cancer Diagnosis and Treatment''
Dennis Dougherty, ''Exotic Organic Molecules''
Robert McEliece, ''Computer Memories and Error Correcting Codes''
Amnon Yariv, ''Solid State Optical Fiber Systems''
Thomas Ahrens, ''Death of Dinosaurs''
Peter Goldreich, ''Planetary Rings''
Bruce Cain, ''Gerrymandering and Elections''
Philip Hoffman, ''The Historian as Detective''
David Goodstein, ''Creating the Mechanical Universe''
John LoSecco, ''The Search for Proton Decay''
William McLaughlin, ''Infrared Astronomical Satellite''
Sterling Huntley, a special session for high school students

Finally, Stefanos Polyzoides, first project architect for the current renovation of Gates Laboratory into Parsons-Gates Hall of Administration, and Jay Belloli, director of Baxter Art Gallery, will discuss ''The Original Caltech Campus.'' On view during Seminar Day will be the related exhibition at Baxter entitled ''Caltech 1910-1950: An Urban Architecture for Southern California.''

Getting a Move On



March 15 was moving day for Caltech's 45-year-old, 20-inch telescope – a one-tenth scale model of the 200-inch Hale Telescope at Palomar Observatory. With the aid of a 70-foot hydraulic boom, . . .

. . . a clear-headed and sure-footed guide, and lots of advice, the instrument was lifted from its resting place in the dome on top of Robinson Laboratory, swung out past the parapets, and gently lowered into a . . .

. . . specially built wooden cradle. Then it was shipped to the museum at the Corning Glass Center in New York. Corning is underwriting a 14-inch Celestron telescope as a campus replacement.

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