California Institute
of Technology

Engineering & Science

Spring 1990

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follow-up*

Portrait of John Todd and Olga Taussky Todd
Acrylic on Canvas, 36" x 30" © Sylvia Posner, 1986

Distinguished mathematicians Olga Taussky Todd and John Todd have been members of the Caltech faculty since 1957. Although they are now professors emeriti, they continue to devote their energies to number theory, matrix theory, and numerical mathematics and have little left over for the practical arithmetic of money management. So the Todds have established a charitable trust at Caltech from which they are receiving a life income without having to spend time on investment issues. And, just as important, their gift will enable Caltech to maintain the kind of teaching and research quality that they helped build as active faculty members.

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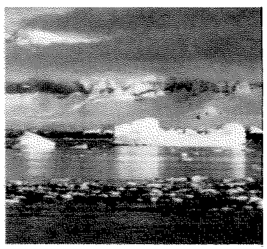

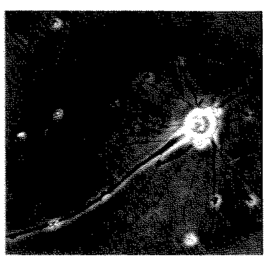

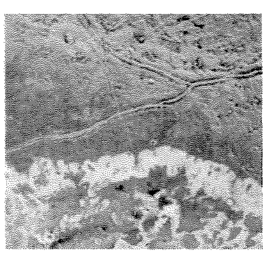

On the cover: This natural ice sculpture is typical of the chaotic jumbles of ice blocks that mark the edges of Antarctica's ice streams, which are flowing at a speed as much as a hundred times faster than the surrounding ice. A story beginning on page 4 describes the efforts of a Caltech research team to discover the mechanisms of this motion and what it might mean for the earth's future.

Departments

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Is the Antarctic Ice Sheet Disintegrating?

The consequent rise in worldwide sea levels would have substantial impact on human activity elsewhere on earth.

by Barclay Kamb

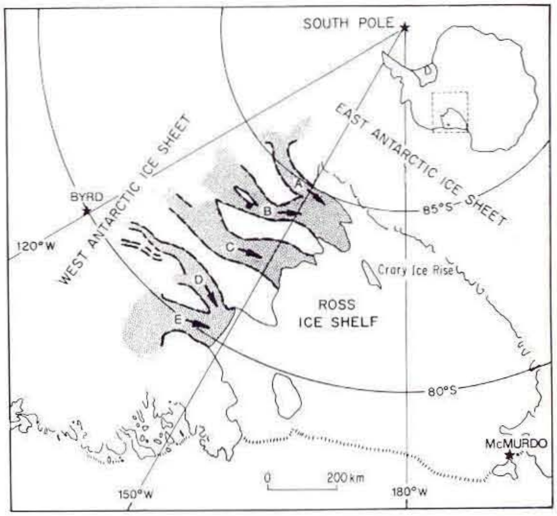
Traversing the Dragon on skis was not an ordinary cross-country outing for the Caltech/University of Alaska party that was the first to cross it. The Dragon is a 5-kilometer-wide swath of chaotically crevassed ice at the margin of Ice Stream B. The skiers here are Howard Conway (right) and Keith Echelmeyer (PhD '83) of the University of Alaska.

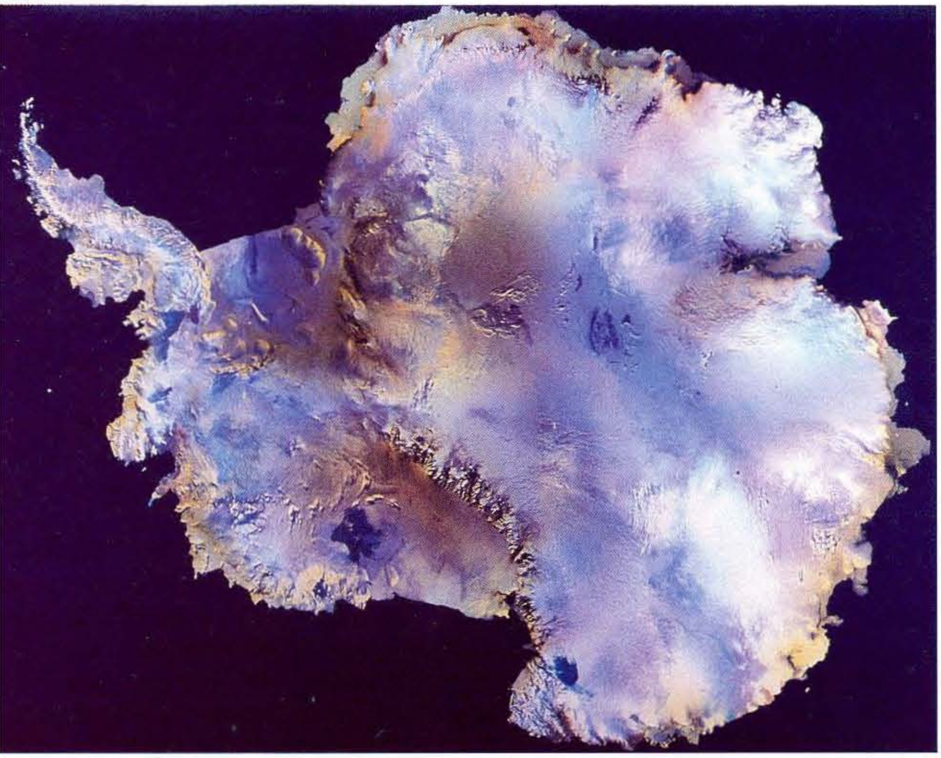
Disintegration of the Antarctic ice sheet is one of the more sensational scenarios associated with the greenhouse effect—the predicted global warming produced by an increase of carbon dioxide in the atmosphere. The consequent rise in worldwide sea levels from the melting of such a vast quantity of ice would have substantial impact on human activity elsewhere on earth. Is this happening or is it likely to happen?

The Antarctic ice sheet, which covers 98 percent of the Antarctic continent, is divided by the Transantarctic mountain range into two unequal and contrasting parts—the East Antarctic ice sheet covering 10 million square kilometers (a million larger than the United States), and the smaller West Antarctic ice sheet, a fifth the size and containing a tenth the volume of ice. If the West Antarctic ice sheet were to melt, worldwide sea level would rise 5 meters, which would already have serious consequences in coastal locations throughout the world. But if the East Antarctic ice sheet went, the sea-level rise would be a whopping 66 meters.

Fortunately, glaciologists consider the East Antarctic ice sheet to be stable and not in danger of any rapid change. But the West Antarctic ice sheet is a different story. Unlike the East Antarctic ice sheet, which to a large extent rests on bedrock near or above sea level, the West Antarctic is a "marine ice sheet," meaning that its bed lies mainly well below sea level, so that the thinner, peripheral part of the ice sheet is afloat. The floating parts are called ice shelves. The famous Ross Ice Shelf—a floating plate of ice the size of Texas, ending against the open sea in a sheer ice cliff 750 kilometers long and 300 meters high (of which 90 percent is under water)—is formed mainly from ice that flows down from the West Antarctic ice sheet to the Ross Sea and goes afloat. If the ice were to melt away, all that would remain visible of West Antarctica would be a few islands, representing isolated high points in the bedrock surface. Glaciologists recognize that marine ice sheets are subject to a condition of potential instability. According to this concept, when climatic conditions cause a marine ice sheet to shrink, the thinning of the ice mass causes an increasing amount of the peripheral ice to lose contact with the bedrock and go afloat. This reduces the constraints holding the ice sheet together and results in an accelerating process of ice outflow and dispersal, which glaciologists call ice-sheet disintegration and collapse. Such collapse is believed to have struck the North American ice sheet at the end of the last ice age about 10,000 years ago.

My interest in marine ice sheet instability was aroused when it was realized that collapse might be greatly accentuated if the ice sheet were to go into a state of surge, such as occurs occasionally in glaciers elsewhere in the world. I had been working on the mechanism of surging in Alaskan glaciers (*E&S*, May 1984), and I wondered whether the concepts developed there might be applicable in Antarctica. At first the possibility that a huge polar ice sheet could surge seemed pretty remote, but then some features were discovered in the West Antarctic ice sheet that seemed to bear some resemblance to surging. Those features are the great ice streams.





This satellite mosaic image shows the Transantarctic Mountains dividing the much larger, and fortunately stable, East Antarctic ice sheet (right) from the West Antarctic ice sheet. The Ross Ice Shelf is visible under the curve of the mountains at lower left. Ice streams A, B, C, D, and E (F isn't shown) can be seen flowing into the Ross Ice Shelf in the detail of that area (above, right). The main US scientific base is at McMurdo.

An ice stream is a current of ice within the ice sheet, moving as much as a hundred times faster than the ice sheet around it. The ice streams are made visible by long belts of chaotic crevassing at their margins, where the fast-moving ice within the ice stream shears past the slow-moving ice outside. These belts look like the ice has been churned up by a giant eggbeater cutting a swath 5 kilometers wide along the margin of the ice stream. Antarctic pilots have come to recognize them and have given some of them fanciful names—"The Snake," "The Dragon," and "Valhalla," which are the chaotic zones on the margin of Ice Stream B, one of six great ice streams flowing from the West Antarctic ice sheet down into the Ross Ice Shelf. (They are perfunctorily designated "A" through "F.") Ice Stream B is about 50 kilometers wide and extends from the inner part of the West Antarctic ice sheet for about 500 kilometers to the place where the ice goes afloat and feeds into the Ross Ice Shelf.

At a camp on Ice Stream B called Upstream Bravo, where we have been working, the ice is moving 1.2 meters per day, and farther downstream its speed increases to more than 2 meters per day. The ice outside the ice stream is moving only a few meters per *year*. The extreme contrast in motion is reminiscent of surging, in which a glacier typically speeds up for a limited time from a few tenths of a meter per day to tens or even hundreds of meters per day.

The motions of Ice Stream B and the adjacent ice sheet have to be measured by satellite navigation, because there are no bedrock refer-

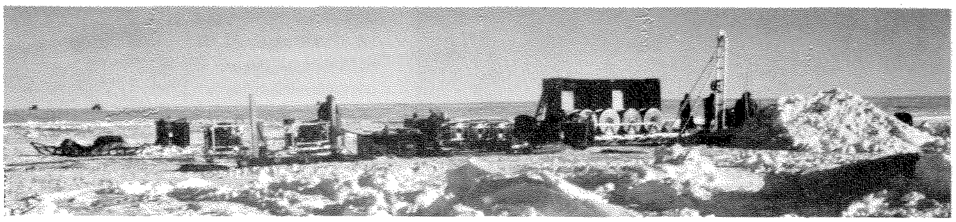
Left: from the air, ice streams are visible by the churned-up belts at their margins (bisected here by a cloud shadow). The landscape looks more daunting from a closer bird's-eye view (far left), and still more so from ground level (below), where Keith Echelmeyer poses above a deep crevasse.

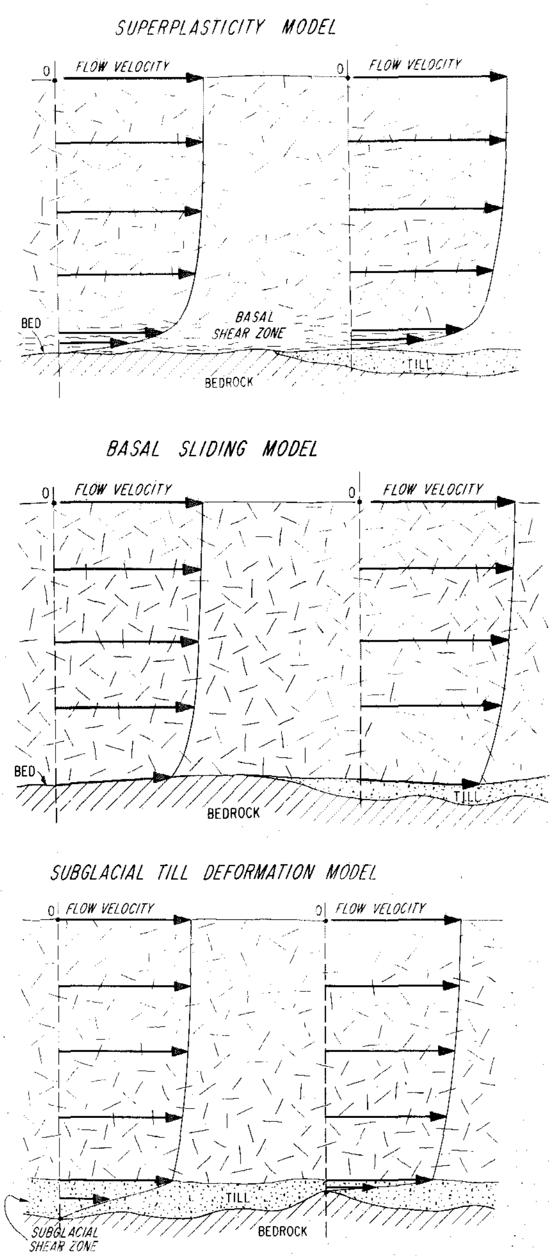
ence points sticking up through the ice. The measurements were made by Ian Whillans at Ohio State University. One surprising thing they revealed is that Ice Stream C, which is otherwise fairly similar to Ice Stream B, has recently stopped moving. This shows that the rapid ice-stream motion can start and stop, another feature in common with surging.

Why is all this happening? What are the physical conditions that make it possible for the ice streams to be moving at such high speed, and for the motion to start or stop? That is what we went to Antarctica to find out. The answers are needed in order to assess the potential role of the ice streams in the rapid collapse of the West Antarctic ice sheet. To do this we have to understand the mechanism of the ice-stream motion well enough to predict how extensively the ice streams may proliferate within the ice sheet and how fast they may ultimately move.

Not knowing the potential speed of these things is an unsettling feeling. I'm reminded of an experience on Variegated Glacier in Alaska, where we were camped as the glacier was going into surge. It was already moving 10 meters a day under our feet, but we didn't yet know how fast it could ultimately go. One night I felt a great shaking and thought, is this *it*? Is this what it feels like to go into full surge? As I bolted from my tent I heard rocks bounding down the mountainsides and realized that this was merely an earthquake, not the ultimate glacier surge!

There are three proposed explanations for the





Three explanations for the unusually rapid flow of the Antarctic ice streams have been proposed. One of them (top) attributes the motion to rapid deformation at the base due to a "superplastic" property of the ice. The basal sliding model is similar to glacier surging, which is not due to greater ice deformation but to the sliding motion of the ice over its bed when the basal ice is at the melting point. The third explanation theorizes a layer of ground-up rock (till) between the base of the ice and the bedrock, which deforms easily and lubricates the ice-stream motion.

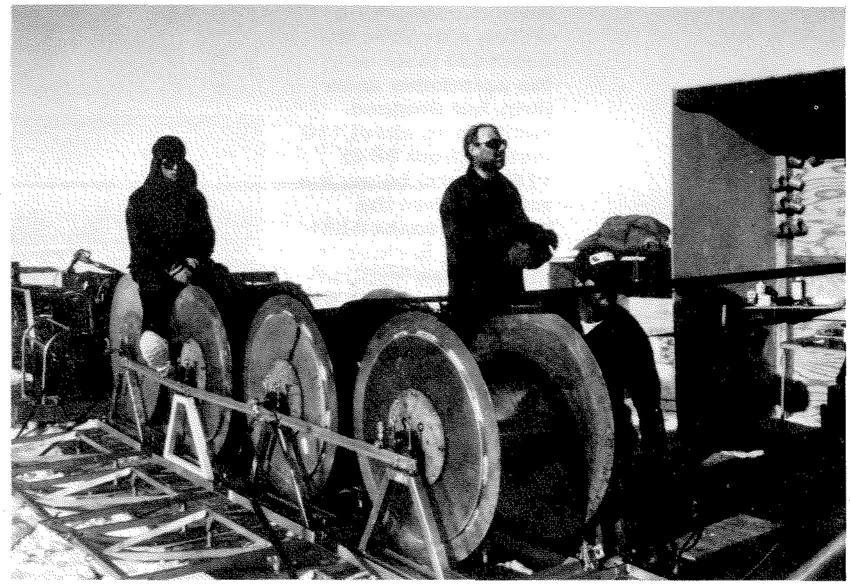
rapid motion of the Antarctic ice streams. The first ascribes a special property, "superplasticity," to the ice near the base of the streams. Ice in ordinary glaciers deforms as part of the flow process, especially near the base, but the deformation near the base of the ice streams would have to be extraordinarily rapid to allow them to move as fast as they do. The required enhancement in ice plasticity is particularly large because the shear stress near the base, which causes the ice deformation, is unusually small (0.2 bar) in comparison with typical glaciers (about 1.0 bar). The basal shear stress, which results from the downslope component of gravity acting on the ice mass, is small because the surface slope of the ice streams is very low (about 0.1°). If "superplasticity" were detected, we would be faced with the question of why the ice had changed and gone into the "superplastic" state.

A second explanation relates the rapid ice-stream motion to glacier surging. From our studies in Alaska we know that surging is due to enhancement not of ice deformation but of the sliding motion of the ice over its bed. This basal sliding can be clearly recognized in places such as New England or the Sierra Nevada where glaciation has occurred: you can see that the bedrock has been scoured and polished by the ice sliding over it. Basal sliding can occur only if the ice reaches the melting point at its base. The temperature of the ice mass near the surface at Upstream Bravo is about −25°C. A considerable source of heat at depth, greater than the normal geothermal heat, would be needed to raise the ice to the melting point at its base.

Recently a third explanation, the subglacial-till-deformation theory, has been put forward by a group of geophysicists led by Charles Bentley at the University of Wisconsin. From records of seismic-wave reflections off the base of the ice they inferred that there was a layer of ground-up rock, called glacial till, between the base of the ice and the bedrock. They theorized that the till was deforming and acting as a lubricant for the ice-stream motion; instead of a shear zone in the basal ice, there was a shear zone in the till beneath the ice, allowing the ice above to move forward rapidly.

All three of these theories concern things going on at or near the bottom of the ice stream. To test them requires observations in the basal zone. Therefore, in our study of the ice stream mechanism, my collaborators (senior research associate Hermann Engelhardt, research fellow Neil Humphrey, graduate student Mark Fahnestock, technician John Chadwick, and several capable field assistants) and I undertook the task

Opposite page: the drilling rig consists of heaters, pumps, four spools of hydraulic hose, and a derrick. Right: The spools, each of which holds 300 meters of hose, offer a rare place to sit (which, when drilling is under way, is also warm). The "coffee table" at right serves the additional function of strengthening the windbreak.



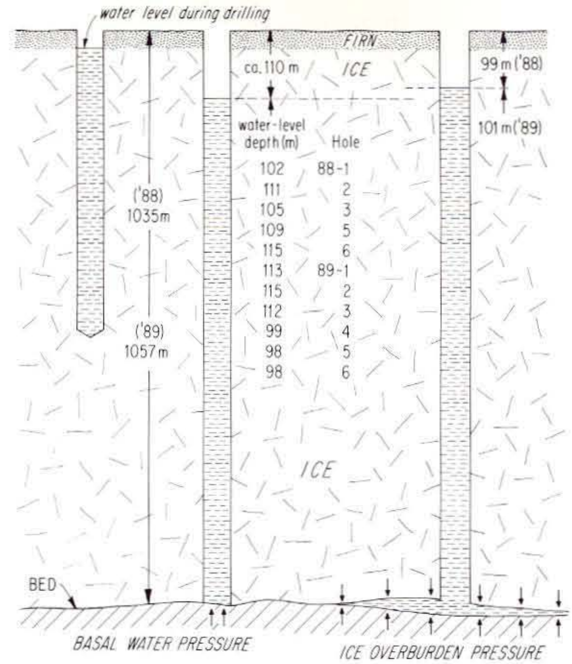
of drilling boreholes to the bottom and putting down instruments to register basal conditions. Our approach is what is known in the oil industry as "the truth of the drill." You can have seismic remote-sensing data and interpretations and theories of what is down there, deep below the surface, but until you drill there and get hold of the actual materials, you never really know.

In a project sponsored by the National Science Foundation we have carried out two field seasons of borehole work so far on Ice Stream B at camp Upstream Bravo (latitude 83.5°S, longitude 138.2°W). This site was chosen because it seems representative of the ice streams and because of logistical convenience, a camp and landing strip having been established there in 1983. We drill with a hot water jet. Water from melted snow is heated to about 90°C and pumped under a pressure of about 50 atmospheres through high-pressure hydraulic hose down to the jet tip at the lower end of a heavy drill stem. The drilling hose is handled in four spools of 300-meter length each, and on its way into the borehole it passes over a derrick where its tension is measured as a means of sensing when the drill reaches the bottom of the ice. At Upstream Bravo, where the ice is about 1,050 meters thick, we can drill a borehole to the bottom in about 24 hours, starting at a drilling speed of about 70 meters per hour, and decreasing to about 30 meters per hour near the bottom because of heat loss from the hose. The heat loss is beneficial because it counteracts refreezing of the borehole by heat conduction into the surrounding cold ice (–25°C near the surface). When the drill and hose are pulled out we have only a few hours, because of the refreezing, to work with instruments in the hole, but the useful life of the hole can be extended by hot-water reaming or by adding antifreeze. (It takes about 50 barrels of antifreeze to treat one borehole!) In the 1988-89 field season (November–January) we drilled five boreholes to the bottom, and in the 1989-90 season, six.

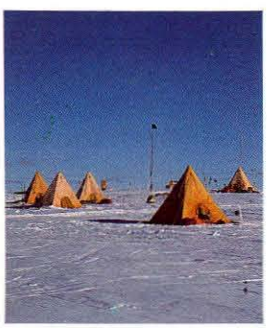
Our approach is what is known in the oil industry as "the truth of the drill."

During drilling, each borehole holds water up to a level about 30 meters below the surface, which is the depth where permeable snow (firn) converts to impermeable glacier ice. Water fills up the hole to that level where it seeps out into the firn and freezes. But when the borehole reaches the bottom something dramatic happens: the water level drops suddenly, within a few minutes, down to about 110 meters below the surface. This happened in all eleven holes, except that in one case the drop started nine hours after the drill reached bottom. In two holes the downrush of water was so forceful that it jammed the drill stem into the bottom and we were barely able to pull it back up.

The drop in water level has three important implications. First, the escape of water into the bed indicates that the temperature there must be at the melting point; if everything were frozen solid, the water could not penetrate and the water level would not drop. Second, the basal zone must contain water-filled passageways or conduits of substantial size, to allow the water to escape from the hole so rapidly. Third, the water pressure in these conduits is near the over-



Right: water during drilling stayed at the depth (30 meters) of the permeable snow (firn), but dropped suddenly to about 110 meters (from 98 to 115 meters) below the surface when the borehole reached bottom. This is close to the flotation level, at which there would be a balance between the basal water pressure and the ice overburden pressure.
Left: John Chadwick tests the reamer, necessary to keep the borehole from freezing up soon after it's drilled.
Below: Sleeping accommodations at Upstream Bravo were in Scott tents.

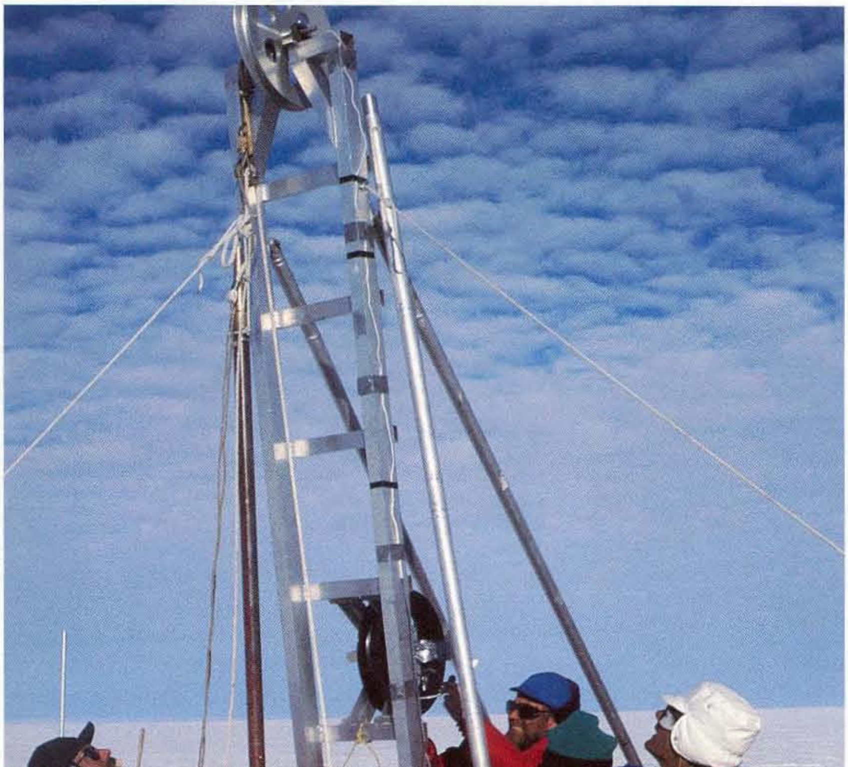


burden pressure of the ice—the pressure due to the weight of the overlying ice. This follows from the depth to which the water level drops (about 110 meters). It is near the flotation level—the water level for which the basal water pressure would be just sufficient to float the ice off its bed because basal water pressure and ice overburden pressure are balanced. Just as an iceberg floats with about one tenth of its mass above the water line, so the flotation level in a glacier borehole is about one tenth of the way from the surface to the bed. An accurate figure for the depth of the flotation level requires careful calculation, taking into account the gradual downward increase in density of the snow as it changes to ice, and of the ice as the air bubbles trapped in it are progressively compressed. Such calculation indicates a flotation-level depth of 100 meters at Upstream Bravo. The observed borehole water levels range from 98 to 115 meters' depth, which means that the pressure of water in the basal conduit system ranges from 1.5 bar (1.5 atmosphere) below the ice overburden pressure to 0.2 bar above it.

This finding is very significant mechanically because high basal water pressure, near the ice overburden pressure, promotes rapid basal sliding, as we found in the surge of Variegated Glacier. At the same time, high water pressure will reduce the mechanical strength of any subglacial till that may be present and will thus promote the lubricating action of shear in this material. So we know now that the conditions required for rapid basal motion, either by basal sliding or by sub-basal deformation, actually exist at the bottom of the ice stream.

With a string of temperature transducers, we measured the temperature at a succession of points in one of the holes after it had frozen closed and cooled down to near the ambient temperature. We could not measure the temperature all the way to the bed because our transducers failed in the bottom 100 meters of the borehole, but extrapolation from higher in the hole pointed to a temperature of about −1°C at the bed. The melting point under the ice overburden pressure at the bed is −0.7°C. The temperature measurements are thus compatible with the conclusion above that the base is at the melting point.

How is the basal temperature raised to the melting point? The geothermal heat flowing up out of the earth hasn't been measured in this region, but elsewhere it is typically about 1 heat-flow unit (hfu; 1 microcalorie per square centimeter per second). Our temperature measurements indicate that in the lower half of the ice mass the ice is conducting 1.9 hfu of heat upward from the bed. Thus the addition of an extra 0.9 hfu at or near the bed, added to a geothermal heat flow of 1.0 hfu, is necessary to supply the 1.9 hfu flowing upward and thus to maintain the basal temperature at the melting point. In fact, if the ice is sliding over its bed at 1.2 meters per day, or if this motion is accommodated by deformation of subglacial till, under a basal shear stress of 0.2 bar, frictional heating amounts to 3.7 hfu, much more than needed to supply the extra 0.9 hfu. The remainder of the frictional heat (2.8 hfu)



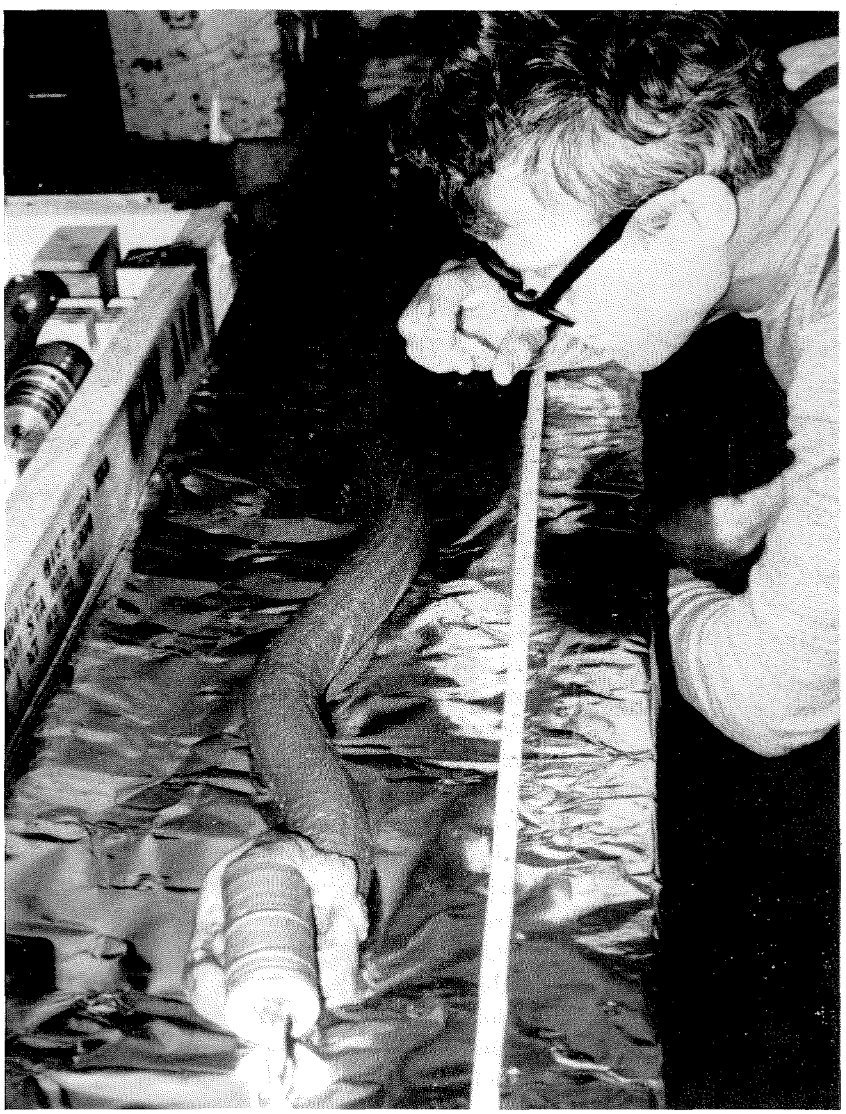
Preparing to lower a core drill to the base of the ice stream are (from left) Howard Conway, Hermann Engelhardt, Judy Zachariasen, and Neil Humphrey.

We know now that the conditions required for rapid basal motion actually exist at the bottom of the ice stream.

must go to melting ice off the base of the ice mass, thus generating water that enters the basal water conduits, through which it ultimately is conducted to the sea under the Ross Ice Shelf.

What about the supposed till under the ice? With a piston coring device we obtained four cores of the subglacial material, three cores 2 meters long and one 3 meters long, all 5 centimeters in diameter, from three different boreholes. The core material is a highly plastic but cohesive, sticky mud (not a slurry) containing abundant rock fragments of pebble size and smaller. In texture and structure, especially the wide range of grain sizes abundantly present, it strongly resembles the type of glacially deposited pebbly mud called till by geologists. The till inferred by the University of Wisconsin geophysicists is really there (truth of the drill)! They estimated it to be 6.5 meters thick under Upstream Bravo, and our cores verify a thickness of at least 3 meters. We tried to drill through it with a hot water jet; the drill penetrated about 5 meters, but we could not sense a bedrock bottom beneath the till.

Our till samples contain fossils, from shell fragments visible to the naked eye down to microscopic sponge spicules, diatoms, and other organic remains. Ages of the diatoms, determined by Richard Scherer of Ohio State University, range from 2 million to 50 million years. The till is therefore derived from a wide mixture of marine sedimentary rocks, which were deposited at times when the West Antarctic ice sheet was absent. The mixing is reasonable if the till material were picked up from an extensive area



Opposite page: A tranquil view of the Antarctic Peninsula, a part of West Antarctica where the base of the ice sheet is above sea level.

Left: Barclay Kamb inspects a core sample of till from beneath the base of the ice stream—a plastic, sticky mud that can be cut with a knife.

and transported with the movement of the ice stream. This is compatible with the till lubrication theory.

The till contains 40 percent water by volume, remarkably high for a material with so large a grain-size range. The high water content probably is an indication that the till is undergoing shear deformation as the ice stream moves. The till cores came out of the boreholes unfrozen—another proof that the bed of the ice stream is at the melting point.

We tested the shear strength of the fresh till with a small test cell put together in the field. The tests showed normal plastic behavior, with a yield stress of about 0.03 bar. This is only about a tenth the shear stress at the base of the ice stream (0.2 bar). Thus the till could very readily deform under the shear stress at the base of the ice stream, as visualized in the till lubrication theory. But there is a problem: the lubrication is *too* good; the till is too weak to support the shear stress at the base of the ice, low as it is. We hope to resolve this problem with more detailed laboratory tests of the till's mechanical properties.

While our observations have revealed that conditions suitable both for rapid basal sliding and for subglacial till deformation are present at the base of Ice Stream B, we have not succeeded in getting fully unambiguous and complete measurements of basal sliding and till deformation rates, which could show with certainty which process actually predominates in causing the ice-stream motion.

The clearest indication so far comes from a

"tethered stake" experiment carried out in January 1990 in borehole number 5. A heavy steel stake attached to a steel cable (the tether) was lowered to the bottom and driven into the bed; if basal sliding occurs, the stake will move laterally away from the bottom of the hole, and the tether cable will be pulled into the hole after it. We observed a pull-in of 20 cm in the first 3.3 hours of the experiment. (Shortly thereafter the tether became frozen in at shallow depth, and the pull-in stopped.) The observed pull-in corresponds to a basal sliding rate of 1.5 meters per day. This is somewhat faster than the surface motion of 1.2 meters per day from satellite navigation measurements in 1984-86, so either the ice stream has sped up since then, or else the observed pull-in is erroneously large. On face value we have here an indication that basal sliding is the predominating process, in spite of the other indications mentioned above that till deformation is probably involved also.

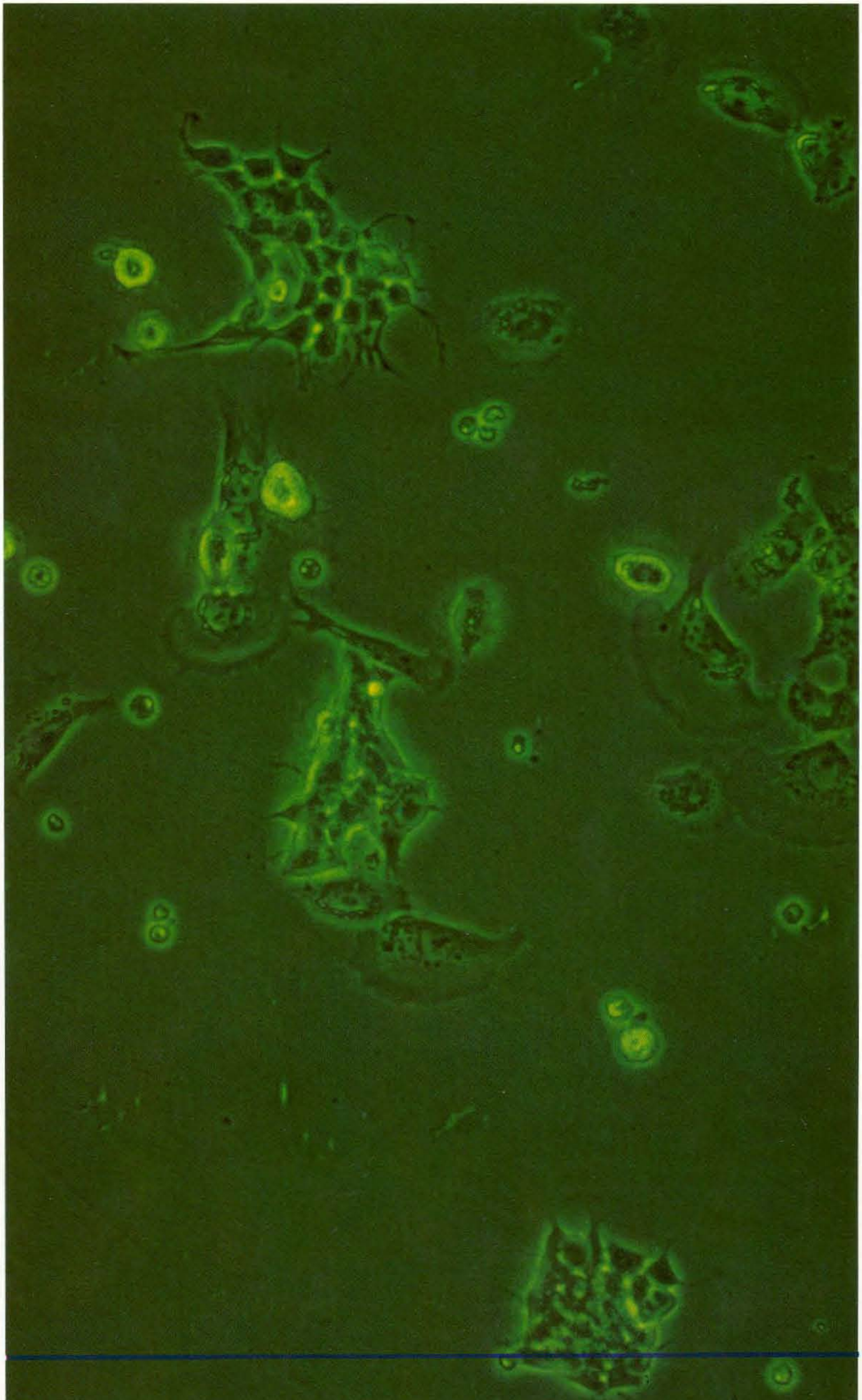
It is certainly doing some rather remarkable things in these ice streams, but that does not yet constitute disintegration.

What does all this mean as far as ice sheet disintegration is concerned? By identifying the mechanism of ice-stream motion and developing a quantitative formulation of it, we aim to provide a concrete and reliable basis for assessing how ice streaming will respond to changing environmental conditions. In this response it makes quite a difference whether the till behaves as a plastic material, as our tests show, or as a linearly viscous fluid, as has been assumed in some geophysical models of the ice stream. It also makes quite a difference whether the rate-controlling mechanism is till deformation or basal sliding. The role of water pressure in controlling the mechanical behavior of the till and basal sliding, and the role of the basal conduit system in controlling the water pressure, are probably crucial elements of the ice-stream mechanism. An instability may be lurking there: if the ice stream starts to move faster, more frictional heat will be generated, hence more water will be produced by basal melting, which will tend to increase the basal water pressure, and that will weaken the till and promote a further increase in ice-stream motion—a positive feedback loop.

The principal factors that could bring about rapid disintegration of the ice sheet are widespread proliferation of ice streams throughout the ice sheet and acceleration of the ice streams to high speeds, perhaps comparable to the approximately 100 meters per day sometimes seen in surging glaciers. At such speeds the ice sheet could disintegrate in a matter of decades. We don't yet know what the potentialities for such motions are, but the borehole data that we are gathering are beginning to build a basis for considering these problems.

Is the Antarctic ice sheet disintegrating? No, not obviously, at present. It is certainly doing some rather remarkable things in these ice streams, but that does not yet constitute disintegration. The fact that Ice Stream C has stopped shows that the whole thing is not just running away. Would the greenhouse effect provide enough of a perturbation to provoke disintegration sometime in the near future? That's what we hope the truth of the drill will eventually help us decide. □

Barclay Kamb has spent a good portion of his professional life camped on top of glaciers studying their physical properties and dynamics, a research experience that can be somewhat more exciting than ordinary lab work when the glacier surges at 65 meters per day. When he hasn't been on the ice, he's been in southern California—his career at Caltech has spanned four decades. He received his BS (physics) in 1952 and PhD (geology) in 1956, the same year he joined the faculty as assistant professor of geology. He has been professor of geology and geophysics since 1963, was chairman of the Division of Geological and Planetary Sciences from 1972 to 1983, and provost from 1987 to 1989. Last month he was named the first Barbara and Stanley R. Rawn Professor. Kamb hopes to return next year for a third summer at Upstream B to continue plumbing the depths of the West Antarctic ice streams.



Career Choices for Developing Neurons

by David J. Anderson

How does a developing cell in the embryonic brain decide which type of neuron it's going to become?

These cloned immortalized precursor cells, with their characteristic nubbin-like protrusions, could become either sympathetic neurons or adrenal chromaffin cells. They have been co-cultured with the fan-like cells, visible on the right, that harbor the defective retrovirus that injects the immortalizing gene into the precursor cells.

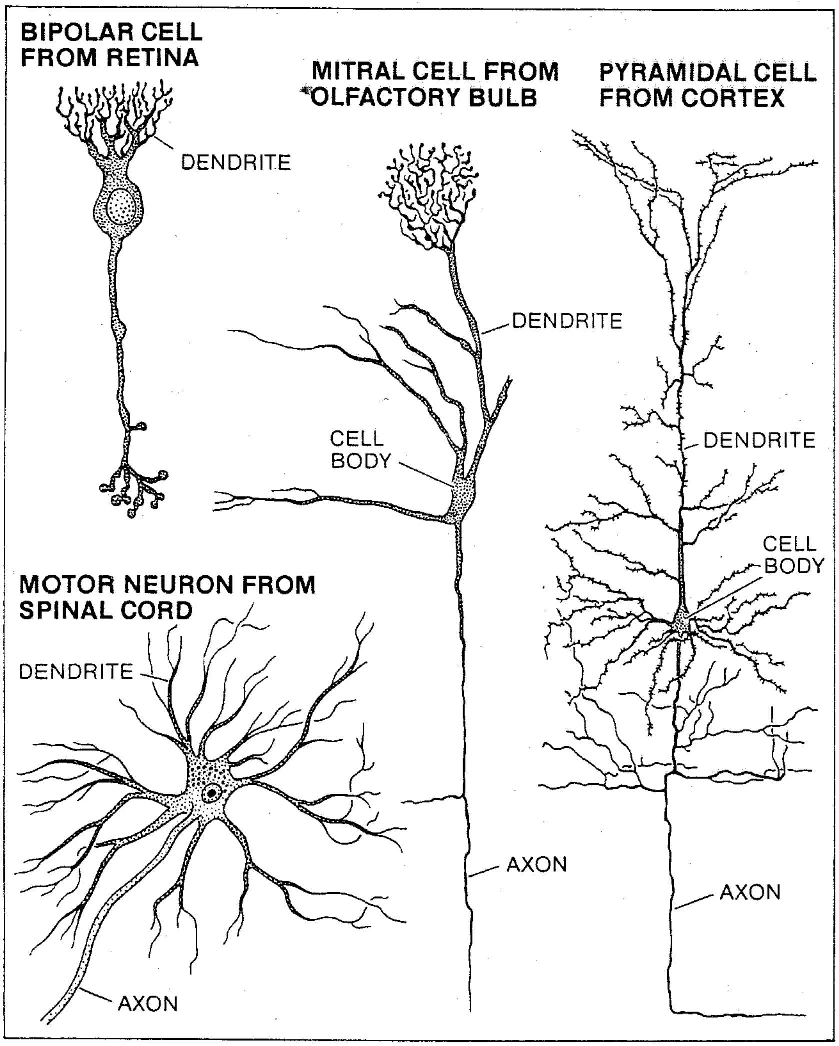
The study of the brain has become one of modern biology's last frontiers. We are fascinated by how we think, remember, and feel, and how such a complex machine capable of doing these things can assemble itself. It is the latter problem that I'm going to address—how the brain gets built. There are many aspects to this problem, but one of the central questions is the problem of neuronal diversity. The brain contains an enormous number of different types of neurons, not just one generic kind of nerve cell. The great neuroanatomist Santiago Ramón y Cajal recognized many of these different types of nerve cells almost a century ago. These neurons not only have different shapes, which were visible to Ramón y Cajal in the microscope, but are also specialized biochemically in ways that we can now observe with more modern methods. This great diversity of form subserves a diversity of function, which is extremely important for the way your brain works. Taken together, these different kinds of neurons amount to more cell types than are found in all the rest of the body combined.

How does a developing cell in the embryonic brain decide which type of neuron it's going to become? Does each precursor cell "know" intrinsically what type of neuron it is going to be, right from the start, or does it have a career choice? If precursors do have choices, what are they, and what mechanisms control the actual choice? To what extent are the choices reversible, once made? These are some of the specific questions that my laboratory has set out to address.

Our general plan of attack is quite straightforward. First we isolate the neuronal precursor cells. Then, under controlled laboratory conditions where we can vary the cells' milieu, we examine the developmental fates available to these cells. Thus we can determine the relative contributions of both the cell's local environment and its internal genetic programming, to its choice of developmental fate. In a sense, we are asking the nature versus nurture question at the cellular level.

Unfortunately, the brain is really just too complicated a structure to study in this reductionistic way. The brain contains between 100,000 and 1,000,000 different types of neurons, depending on how you define neuronal cell type. To attack this problem, therefore, we've had to break it up into bite-sized pieces that are relatively solvable. We've done that by making two simplifying decisions. First, we've decided not to work on the brain itself, but on another part of the nervous system called the peripheral nervous system. Second, we only work on two kinds of cells within that part of the nervous system.

The peripheral, or autonomic, nervous system is the part that lies outside of the brain and spinal cord, which together compose the central nervous system. The central nervous system controls conscious actions, such as deciding to call a friend, remembering the phone number, and picking up the telephone. The peripheral nervous system controls important, but unconscious, bodily functions such as heart rate, digestion, and reproductive activity. So even though you



Kuffler, Nicholls, and Martin, *From Neuron to Brain*, 2nd ed., (1984)

The central nervous system contains between 100,000 and 1,000,000 types of nerve cells. Many of these cell types were first recognized by their shapes almost a century ago by Ramón y Cajal. Dendrites collect incoming signals from other cells, while the axon carries the cell's electrical output. The cell body houses the nucleus and the cell's metabolic and secretory machinery.

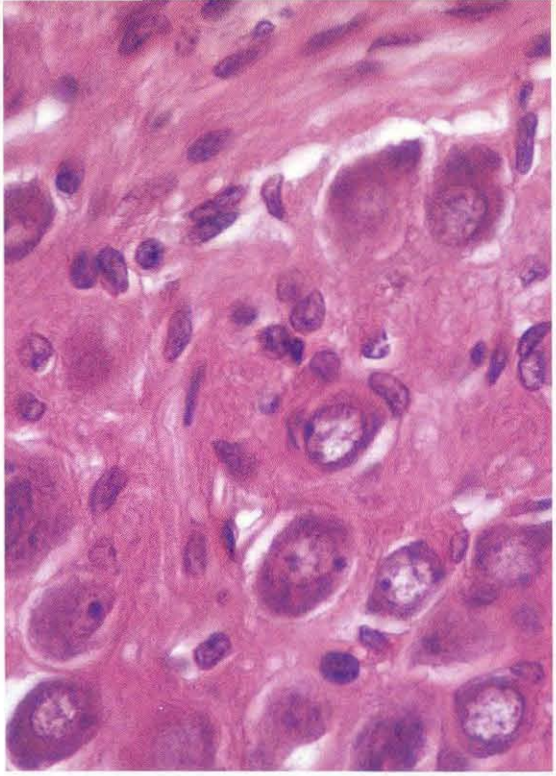
A chromaffin cell is a neuron manqué. It might have been a neuron, but during development it missed its calling.

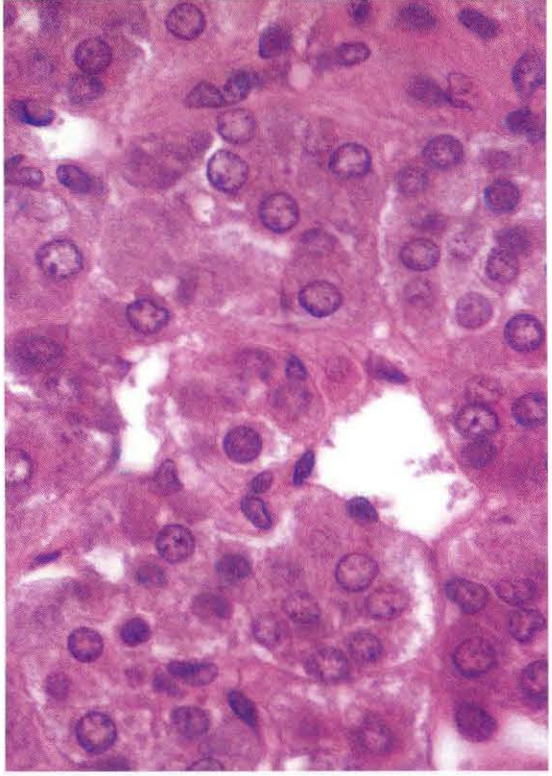
can't solve differential equations with these neurons, they're still very important to you.

Of the two particular cell types that we work on, one is the "sympathetic neuron" that exists in the little ganglia, or clusters of nerve cells, that run in two chains up and down either side of the spinal cord. Sympathetic neurons, like most other kinds of neurons, have both the long, thread-like structures ("processes") that are the wires of the nervous system, and the ability to make the connections ("synapses") that regulate the passage of nerve impulses from cell to cell. Each neuron actually has two types of processes—several comparatively short dendrites that collect incoming signals, and one very long axon that carries the cell's electrical output to its target tissue, such as the heart muscle.

The other kind of cell is an endocrine or secretory cell, called a chromaffin cell, found in the adrenal gland. The adrenal gland, a nutlike object that sits on top of the kidney, is really a gland within a gland. The outer zone is the adrenal cortex, which makes steroid hormones. The chromaffin cells exist in an inner zone called the adrenal medulla. They synthesize adrenaline, releasing it into our bloodstream when we're frightened or excited, accelerating our heart rate and preparing us to flee or fight. Chromaffin cells are little rounded cells without processes.

These two cell types appear very different superficially, but actually they are quite similar. Chromaffin cells, although they lack axons and dendrites, have much of the same molecular machinery as neurons—that involved in the synthesis, storage, and release of the catecholamines,

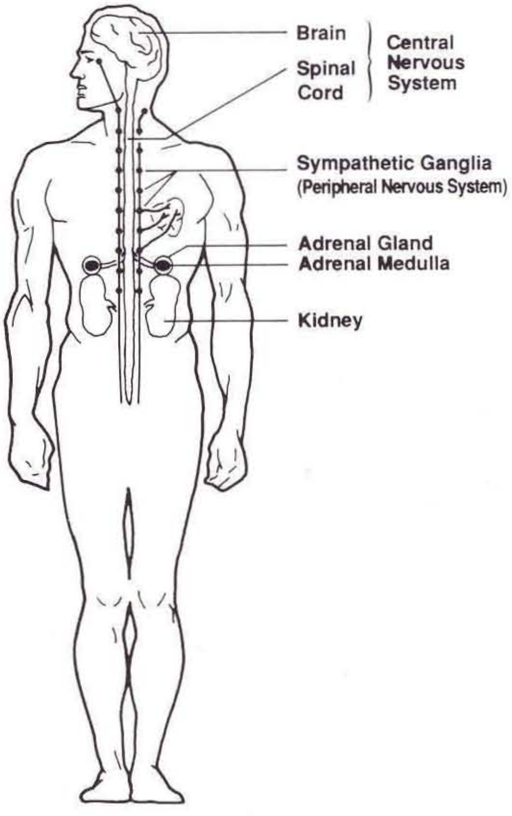




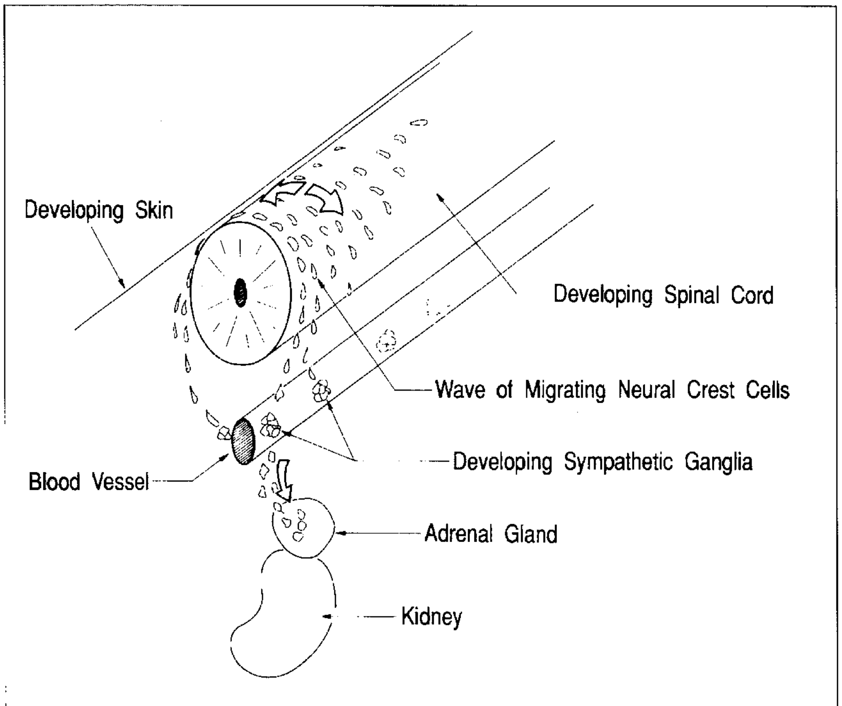
Right: A section through a sympathetic ganglion. The purple blobs are sympathetic-neuron cell bodies, and the whitish pepperoni-like structures within them are the nuclei. (The axons and dendrites aren't visible.) The stream of smaller cells crossing the top of the photo and proceeding down its left-hand side are the glial cells associated with a bundle of nerve fibers. Far right: A section through the adrenal medulla. The chromaffin cells are clustered around blood vessels (white voids) so that their adrenaline goes directly into the bloodstream. The cell bodies are indistinct, but the darker nuclei are clearly visible.

a biologically important family of chemicals. (Like a production pipeline in a chemical factory, this machinery makes dopamine, a simple catecholamine, from raw materials. Additional steps down the pipe convert dopamine into noradrenaline, and that into adrenaline. This pipeline occurs in several cell types. The cells open valves at various points along the pipeline to draw off different products—some central-nervous-system neurons make dopamine, while the sympathetic neurons produce noradrenaline, and the chromaffin cells secrete adrenaline.) Furthermore, chromaffin cells and sympathetic neurons both have electrically excitable membranes.

Thus it is accurate to say that a chromaffin cell is a neuron manqué. It might have been a neuron, but during development it missed its calling. In contrast to most other specialized cell types in the body, however, chromaffin cells retain throughout life the option to change their career in a way that many of us might envy. If these cells are taken out of the organism and exposed to a substance called nerve growth factor (NGF), they are able to drop their secretory-cell properties and acquire the properties of a nerve cell. They'll throw out processes—develop dendrites and axons—and make synapses. This involves not only a change in the shape and size of the cell, but also a change in the set of genes the cell turns on in its nucleus. This plasticity is an unusual phenomenon, and adds an extra element of interest to this developmental system. It may also be relevant, at some level, to understanding other forms of neural plasticity, such as regeneration and learning.



A road map for precursor-cell migration. The cells peel off the developing spinal cord in a wave. Some pull over and park along a nearby blood vessel to form the sympathetic ganglia, while others continue on to the adrenal gland.



The precursor cells peel off the neural tube and migrate downward through the embryo like tiny parachutists leaping from a moving airplane.

In the early 1980s, the functional similarities between sympathetic neurons and chromaffin cells, as well as the ability of adult chromaffin cells to convert into neurons, suggested to Allison Doupe, now a research fellow in biology, and Paul Patterson, now professor of biology (both then at Harvard) that these two cell types might arise from a common progenitor during embryonic development. We therefore set out to test this hypothesis in rat embryos.

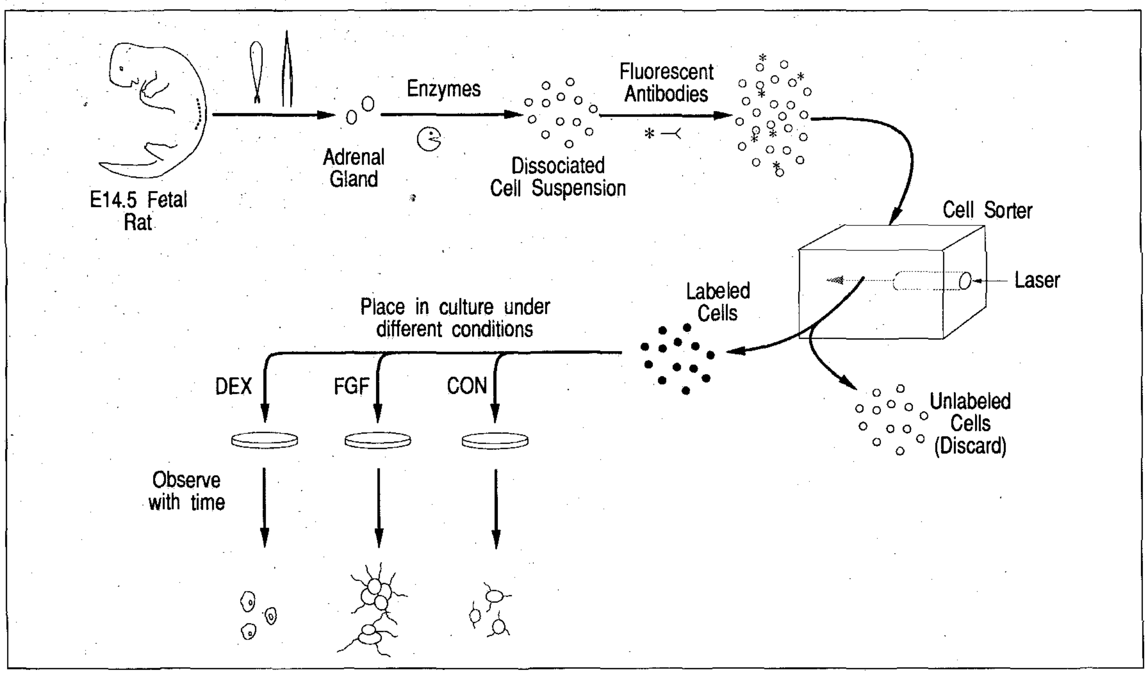
According to classical descriptive embryology, the earliest undifferentiated precursor cells in this lineage can first be identified about midway through gestation. The cells become apparent when they detach themselves from the dorsal side of the neural tube (the embryonic spinal cord) to form a transient structure called the "neural crest." The neural crest first appears just behind the brain and propagates as a wave along the neural tube to the tail. The precursor cells peel off the neural tube and migrate downward through the embryo like tiny parachutists leaping from a moving airplane. Some of the cells stop migrating very quickly and form a chain of small clumps along a nearby blood vessel, where they eventually become sympathetic neurons. Others continue their migration downward to invade the developing adrenal gland, where they proliferate and become chromaffin cells. It's like the pioneers who came west—some stopped in Colorado, while others continued on to California.

We can begin to see differences in the cells' development shortly after the migration ends. We and the Patterson laboratory have developed specific monoclonal antibody stains for these various cell types. Cells in the ganglia bind to antibodies specific for sympathetic neurons, whereas cells in the adrenal gland bind to antibodies specific for chromaffin cells. These anatomical observations support the idea of a common precursor, and suggest that the fate of a cell might be controlled by the environment into which it migrates.

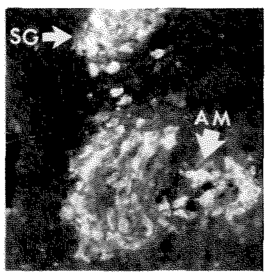
One way to test this hypothesis would be to transplant these cells to a different part of the embryo, and see how they developed there. However, this kind of experiment is very difficult to perform, especially in something as small as a rat embryo. As an alternative, therefore, we decided to isolate these cells from the embryo and put them in culture dishes. In that way we are able to watch them develop in an environment that we can control by adding different factors to the culture medium.

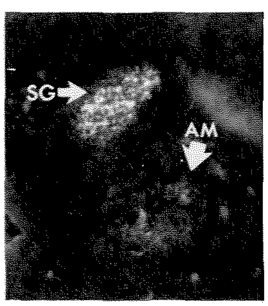
We isolate the precursor cells just after their migration into the adrenal gland. First, we dissect out the glands using very fine instruments.

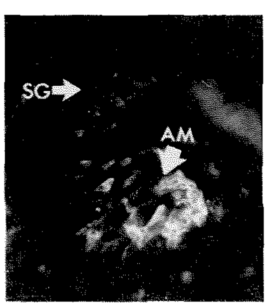
The experimental scheme. "E14.5" is the number of days into gestation—a rat comes to term in about three weeks. "DEX" is a synthetic glucocorticoid that converts the precursors to chromaffin cells; "FGF" stands for Fibroblast Growth Factor, which drives the conversion to neurons; "CON" is a control culture to which neither substance is added and whose cells start to become neurons but don't go very far.



These sections through a rat embryo, magnified 70×, were made at embryonic day 14.5, about one day after migration begins. The migration will continue for three or four days longer, but differences can already be seen among the crest cells that have reached their destinations. Top: Tyrosine hydroxylase recognizes both sympathetic ganglia (SG) and adrenal medulla (AM) cells. Middle: B2, a monoclonal antibody developed by Jane Dodd at Columbia, recognizes sympathetic neurons only. Bottom: SA-1, a monoclonal antibody developed by Josette Carnahan and Paul Patterson at Caltech, is specific for chromaffin cells. The cells still look alike, and without these antibodies, it would be very difficult to tell them apart.

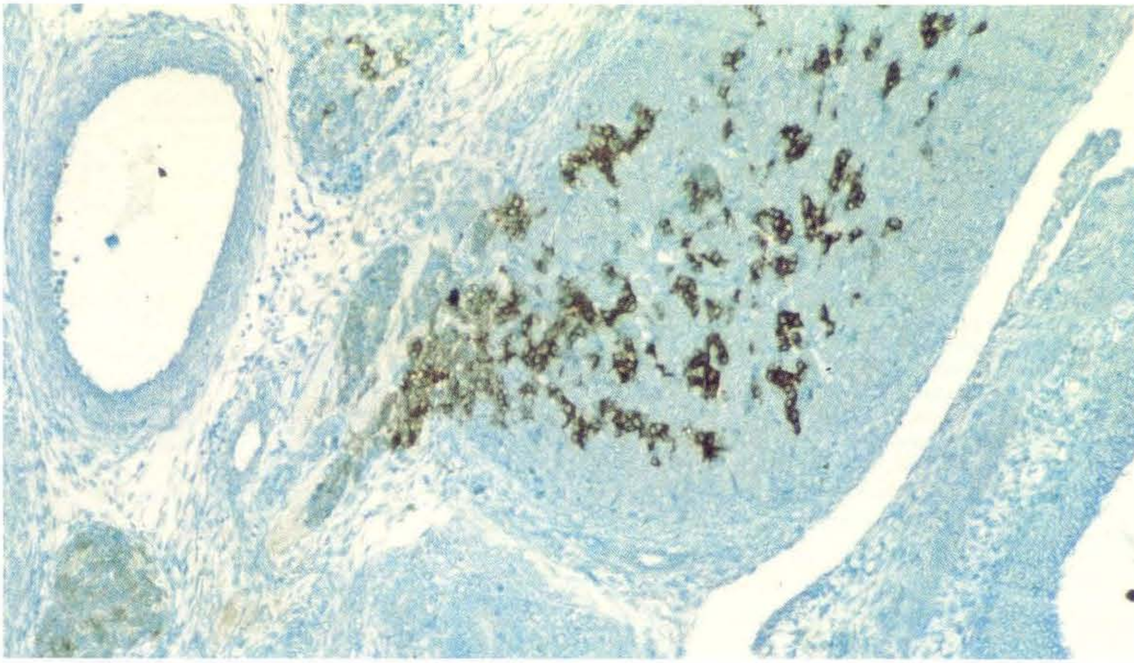




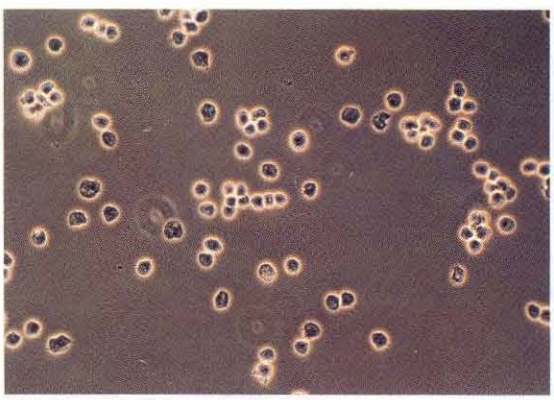


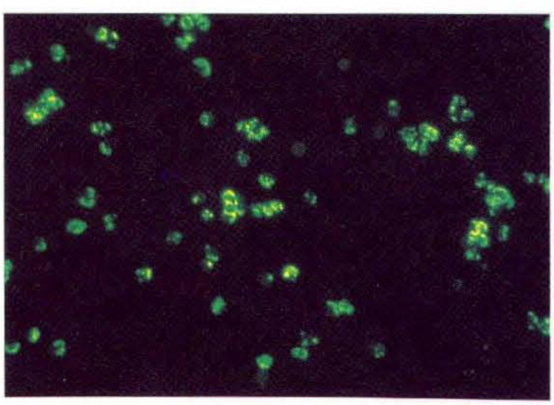
We then dissociate the glands into a suspension of individual cells, using proteolytic enzymes that cleave the bonds holding the cells together without damaging the cells themselves. This leaves us with a soup containing the cells we're interested in—the migrating precursors—mixed in with all the other adrenal cells. We use other specific antibodies to tag the precursor cells' surface with a fluorescent dye. We then run the soup through an extremely sophisticated and very expensive instrument called a Fluorescence-Activated Cell Sorter (FACS)—a part of the biology division's cell-sorter facility, which is run by Associate Professor of Biology Ellen Rothenberg. The FACS dribbles our soup through a laser beam. The soup is so dilute that each droplet contains, on average, only one cell. The laser excites the fluorescent dye, making the tagged cells glow. The other cells don't glow. If the machine senses that a tagged cell has been excited, it diverts that droplet into one tube. The other droplets fall into another tube. The precursors constitute about five percent of the starting cell population, so we obtain about a 20-fold purification.

We can now grow these isolated cells in a culture dish and watch how they develop under different environmental conditions. We divide the cells into different dishes whose culture media contain not only the nutrients and goodies necessary to keep the cells healthy, but also specific molecules whose influence on the cells' fate we would like to determine. We find that in order to get the precursors to develop into chromaffin cells, as they would have normally



Precursor cells, stained brown, caught in the act of invading the adrenal gland. These cells will set up housekeeping in the gland's center, completely surrounded by the cells of the adrenal cortex. The developing adrenal gland is the darker blue region in the center of the picture; the top of the kidney is visible below it. The white oval to the adrenal gland's left is the dorsal aorta, and a portion of the gut can be seen to the gland's right.





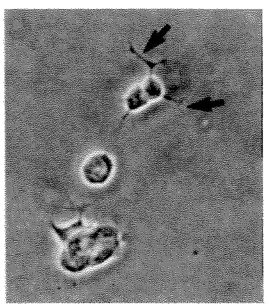
Above: A suspension of precursor cells from the FACS, as seen under phase-contrast microscopy. Below: The same cells with their fluorescent antibodies aglow. Virtually every cell in the suspension is a tagged precursor.

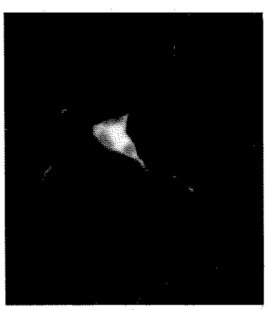
done in the embryo, we have to add substances called glucocorticoid hormones to the culture medium. If we don't do this, the cells begin to differentiate into sympathetic neurons, extending little nubbinlike processes, but they don't develop very far. We can push the cells all the way into bona fide neurons by adding two proteins called Fibroblast Growth Factor (FGF) and Nerve Growth Factor (NGF). This result strongly suggests that individual precursor cells have at least two possible alternatives—they can develop into chromaffin cells or into sympathetic neurons. Moreover, the choice does, in fact, appear to be influenced by factors in the cells' environment. In a complementary experiment, Patterson and graduate student Josette Carnahan exposed precursor cells taken from the sympathetic ganglia to FGF, NGF, and glucocorticoids and obtained similar results.

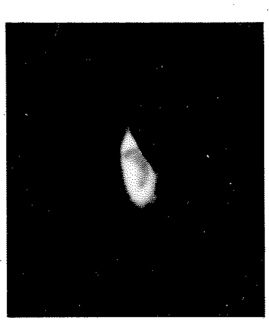
Why should glucocorticoid hormones be necessary for the precursors to develop into chromaffin cells? This result makes sense because these hormones are secreted by the cells of the adrenal cortex, through which the invading crest cells migrate en route to forming the adrenal medulla within. (I should point out that this process of migration, invasion, and proliferation is very similar to what happens when a cancer becomes metastatic and invades different parts of the body from a primary tumor. This is an example of how understanding fundamental biological mechanisms is relevant to understanding clinical specifics of disease.)

Glucocorticoids are a particular type of steroid hormone. The steroids are a family of fatty

Top: Undifferentiated precursor cells. The arrows point to the nubbinlike processes.
Middle: Adding FGF changes the cells to neurons. Here three neurons have grown up in a cluster. The three gray blobs in the white body are the three nuclei. Thread-like processes are also visible.
Bottom: Adding glucocorticoids produces a chromaffin cell. The gray banana shape is the nucleus. All three photos are magnified 250×. The top photo is of unstained living cells, but the cells in the other two photos have been fixed and stained with fluorescent antibodies.







On the one hand, the precursor cell is endowed with a limited repertoire of potential fates; on the other hand, it must choose one fate from among this repertoire.

molecules very similar to cholesterol. This family includes the sex steroids such as estrogen, and the anabolic steroids (used illegally by some athletes), as well as the glucocorticoids such as cortisol. Cortisol is the main glucocorticoid secreted by the adrenal cortex, and plays a number of roles in the adult, including controlling the inflammatory response. In the embryo, however, one of its functions is apparently to drive the neural crest cells that migrate into the adrenal gland down the chromaffin pathway of differentiation. And the precursors are migrating right into the belly of the beast—they're crawling right into the site where the steroid is synthesized, where its local concentration is extremely high. Thus the outer part of the gland-within-a-gland (the cortex) controls the development of the inner part (the medulla).

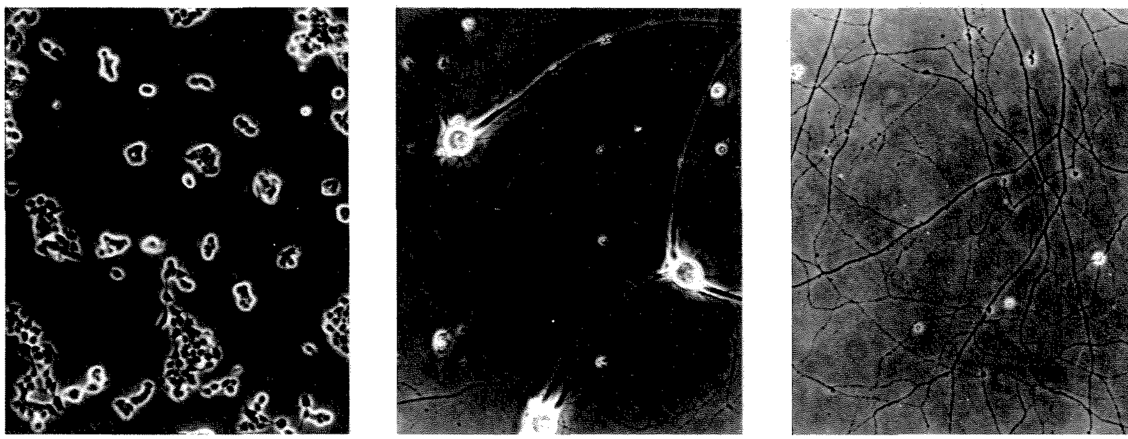
What about those cells that don't migrate into the adrenal gland, but become neurons in the sympathetic ganglia? We would like to think from our results that FGF is concentrated in the ganglia, in the same way that glucocorticoids are concentrated in the adrenal gland. The cells that stayed in the ganglia would therefore be exposed to FGF. However, we don't yet know if this is actually true. We are now using sophisticated molecular-biological techniques to see if FGF is really concentrated in the ganglia at the time that the neurons are differentiating.

This work shows how a peripheral-nervous-system cell can choose between two different fates, according to signals in the environment into which it migrates. We think that the same type of mechanism we have observed may well be true for central-nervous-system precursors that give rise to different kinds of neurons in the brain. However, this isn't the whole story.

Most other cells in the embryo—or even in the neural crest, whose cells also go on to become the bones in your face, the pigment-producers in your skin, the insulation in your nerves, and many other cell types—would not turn into sympathetic neurons or chromaffin cells in response to the hormones we've added to our culture dish. This is because the cells have to be conditioned, by their previous history, to respond to particular hormones in a particular way. Thus the cells that arrive at the sympathetic ganglia or the adrenal gland have already made, we believe, several earlier decisions that limit their choice of fate to only two final options. It's like going out for dinner—first you choose a particular kind of restaurant: Italian, Chinese, or Mexican; then, once you arrive there, you're committed to a particular *type* of food, but you can still choose from among the various dishes on the menu. The neuron-chromaffin decision is analogous to choosing among the different dishes—it's one of the final steps. To continue the analogy even further, the chromaffin cell's plasticity means that even after it has ordered dinner and started to eat, it can still send its choice back to the kitchen and order something else.

The neuron-chromaffin development decision involves an interplay between the cell's internal genetic programming and specific signals in the local environment. On the one hand, the precursor cell is endowed with a limited repertoire of potential fates; on the other hand, it must choose one fate from among this repertoire. What genes and proteins actually determine the specific repertoire of possible fates? What genes and proteins actually select a particular fate? These are the big questions we are pursuing in an effort to understand the molecular biology of this developmental system.

With the exception of the immune system, it is generally believed that every cell type in the human body, be it a neuron or a liver cell, contains in its nucleus the same set of 100,000 genes. Only a small fraction of those genes are active in any one cell type, however, and what distinguishes one type from another is the particular set of genes that the cell chooses to turn on. So at the molecular level, choosing the neuronal fate means that the precursor cell has decided to turn on some genes that are characteristic of neurons. Conversely, choosing the chromaffin fate means that the cell has decided to turn on chromaffin-specific genes. Our lab and others have cloned genes representative of each of these



Left: A culture of immortalized precursor cells.
Middle: A culture of neurons made from the immortalized precursors.
Right: Processes from these neurons grow to the farthest reaches of the dish. All three photos are magnified 100×.

Each gene is like a lamp with a dimmer switch.

two complementary classes. This enables us to study the ways in which these genes are turned on and off during development.

We have found that these genes appear to be regulated at two main levels. At one level, there is "all or nothing" control—in tissues unrelated to the nervous system, such as the liver, these genes are completely shut off. The second level of control is "more or less"—in chromaffin cells and sympathetic neurons, these genes are either turned up or turned down, according to the cell's local environment. For example, the glucocorticoid hormones that promote the differentiation of the precursor cell into a chromaffin cell act to both turn up the chromaffin-specific genes and turn down the neuron-specific genes. The converse is true for environmental signals that promote neuronal differentiation, such as FGF and NGF. A useful analogy might be that each gene is like a lamp with a dimmer switch. In the liver, the lamp is completely unplugged. In the chromaffin-neuron precursor, the lamp has been plugged in. Later, during differentiation, the lamp is turned up or turned down by the dimmer switch, depending upon which pathway the cell chooses. The environmental signals—the glucocorticoids, FGF, and NGF—control the dimmer switch.

One of the problems we've encountered in studying these precursor cells on the molecular level is that only a small number of cells can be recovered from rat fetuses. We've circumvented this problem by applying recently developed techniques to immortalize these cells. We use a defective retrovirus as a disposable molecular syringe to inject the precursor cells with a gene, called *v-myc*, that prevents them from differentiating and allows them to divide forever in the culture dish. (The precursor cells normally divide a limited number of times, and then stop for good when they differentiate.) Thus we get an endless supply of cells for experiments at any time, without having to first perform long hours of dissection on large numbers of rat fetuses. Fortunately, these immortalized precursor cell lines still appear capable of undergoing differentiation into sympathetic neurons when exposed to FGF.

These cell lines have taught us something very interesting. Developing neurons eventually come to need NGF to survive, and they acquire this chemical dependence only *after* they have first been exposed to FGF. Thus it takes at least two different factors, acting at different times, to make a neuron. I like to call this a "relay mechanism." FGF starts the cell down a pathway of differentiation and takes it through one stage, setting it up to respond to NGF. The cell can then bind to NGF, and this second factor moves it further down the pathway of differentiation into a full-blown neuron. We don't yet know if this is true in vivo, but this hypothesis makes testable predictions.

The reason that two factors may be needed is presumably that the first one is located in the ganglia, whereas the second one is located in the target tissues into which the axons grow—the heart muscle, for example. FGF starts the neurons growing their axons toward the targets, while NGF takes over after the axons arrive, helping to maintain the synapses. Neurons whose processes don't reach an NGF-secreting tissue die, which is one way that the developing nervous system ensures that the body gets wired up correctly. This two-stage process is somewhat analogous to sexual differentiation in people. The decision as to whether you will be male or female is made very early in your development, but you still have to go through puberty after you're born. FGF, we believe, controls the initial decision, and NGF controls the later maturation that is the cellular equivalent of puberty.

Although we developed these immortal cell lines for basic research, they may turn out to have an unexpected clinical relevance as well. You probably know someone who is afflicted with Parkinson's disease. It's a relatively common disease that usually begins late in life and is characterized by an uncontrolled tremor in the extremities, sometimes referred to as a pill-rolling tremor. This symptom occurs because a group of neurons in the brain—called the substantia nigra, because its cells contain a black pigment—dies. These neurons normally provide a neurotransmitter, or chemical messenger, called dopamine to another part of the brain called the striatum. Without dopamine, the striatum neurons don't function and the tremor occurs.

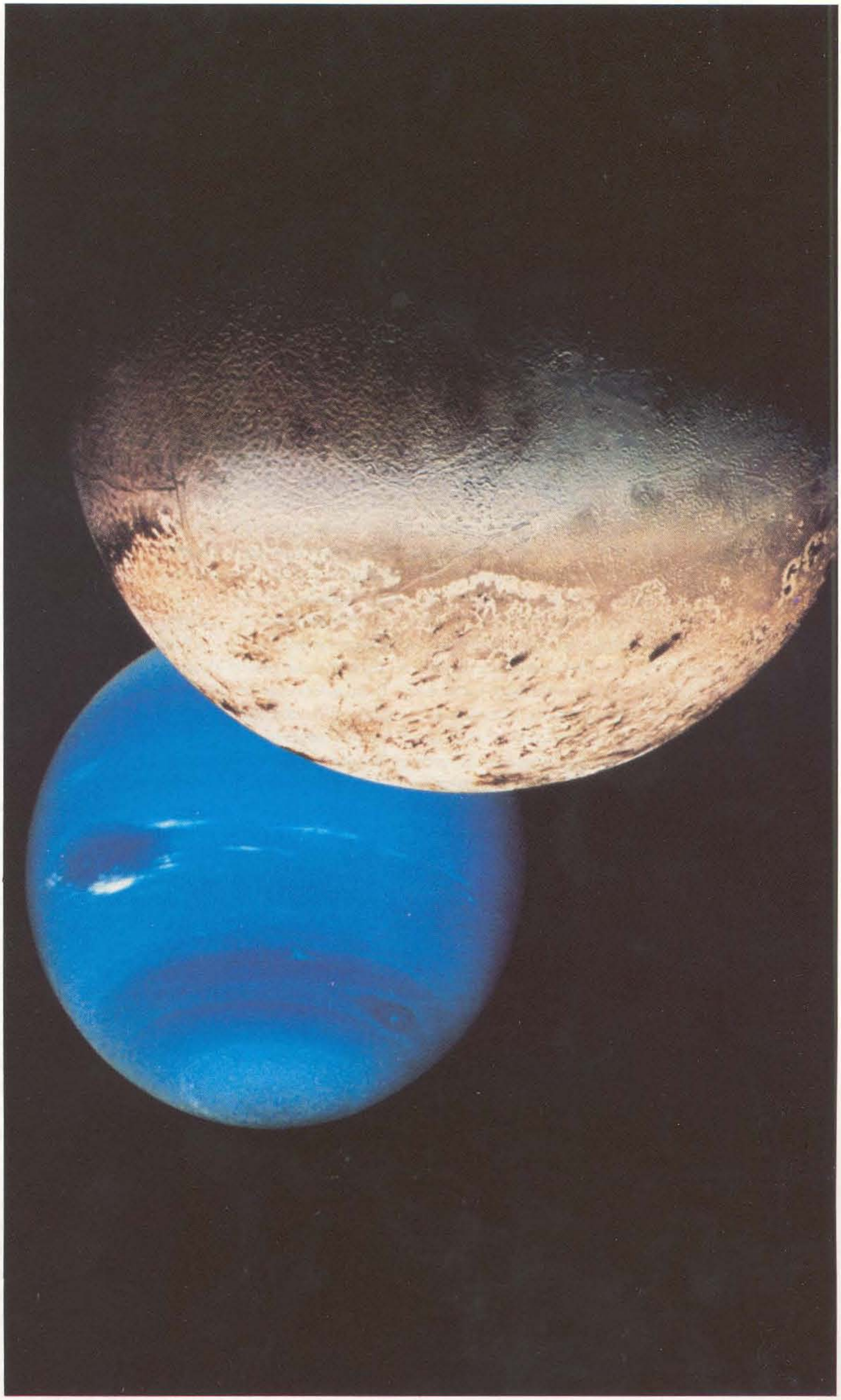
This therapy may not be limited to Parkinson's disease.

Neurosurgeons have recently begun to pioneer a technique for treating Parkinson's disease in which the patient's chromaffin cells—the very cells you've been reading about this whole time—are grafted into his or her brain to replace the dead neurons. Chromaffin cells were chosen for two reasons: one, they can manufacture dopamine by opening the proper valve on the pipeline; and two, they ought to change into neurons in the brain just as they do in the culture dish. Although this technique appeared very promising at first, it now seems that the original idea of using the patient's own chromaffin cells doesn't work very well. However, all is not lost. Animal experiments have shown that the technique works much better when fetal cells rather than adult cells are used. Presumably the immature cells can adapt to the new environment of the brain more readily. Cells apparently get old and set in their ways, just as people do.

The routine therapeutic use of human fetal tissue isn't likely to happen in the foreseeable future for a number of reasons, ethical as well as technical. One way out of this dilemma would be to use immortalized fetal-cell lines such as the ones we have developed from rats. That is, if one could gain access to some human fetal adrenal glands just once, and immortalize those cells in the way that we've immortalized the rat cells, in theory one would have a continuous supply of human cells available for transplantation therapy; on tap, as it were. To this end, we're collaborating with Dr. Fred Gage of UC San Diego to test the viability and therapeutic value of our cell lines by transplanting them into rats that have been given a chemically induced form of Parkinson's disease. Interestingly, this therapy may not be limited to Parkinson's disease. Under certain circumstances, these cells can also secrete acetylcholine, another neurotransmitter. Patterson is trying to determine if this ability can be exploited in analogous transplants to treat Alzheimer's disease.

In this article, I have tried to describe our approach to investigating an important question in neurobiology—how the different kinds of neurons in the brain form during embryonic development. We have seen that approaching this question requires making some decisions to simplify the problem, and then combining a variety of techniques at both the cellular and molecular levels to find out what's going on. In this case, the answer to the question of nature versus nurture is "a little of both." Nature, or the genetic programming of the precursor cell, endows the cell with a limited set of developmental options. Nurture, or the signals from the environment into which the cell migrates, helps it to choose from among these options. At the molecular level, this choice involves a complex network of regulatory genes that we now only dimly understand. These developing cells, therefore, make choices in their lives just as we do, as we grow up. How satisfying, then, that understanding these little cells and their microworld may help us to one day treat diseases that make it so hard for many people to live their later years fully, when they should be enjoying the benefits of their own career choices.□

David Anderson, assistant professor of biology, joined the Caltech faculty in 1986. He was named an Alfred P. Sloan Fellow in 1988, and in 1989 was given a joint appointment to the USC School of Medicine as an adjunct professor of anatomy and cell biology, as well as a joint appointment at the Howard Hughes Medical Institute as an assistant investigator. He earned his AB from Harvard in 1978 and his PhD from Rockefeller University in 1983, followed by three years of postdoctoral work at Columbia. This is his first article for E&S.



Voyager at Neptune

Voyager revealed to us a solar system with distinctive worlds of unexpected richness and diversity.

by Edward C. Stone

A mosaic of Voyager images shows blue-green Neptune behind the south polar region of its moon Triton.

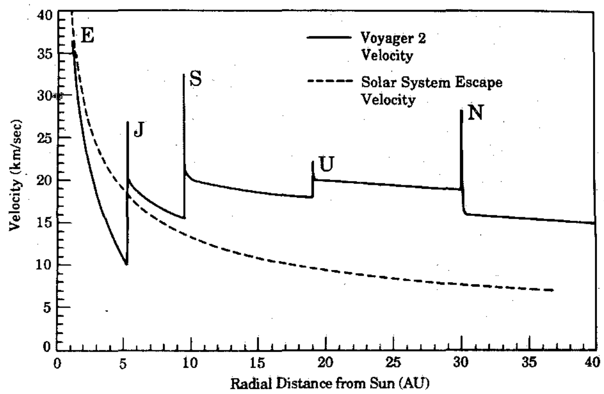
Late last August Voyager 2 flew by Neptune, the most remote object yet visited by a spacecraft and the culmination of a 12-year journey of exploration of the four giant planets. In a real sense Voyager has been writing the encyclopedia of the outer solar system over that last 12 years. For the latest volume I'd like to describe what we discovered last August, what we now understand, and what still puzzles us.

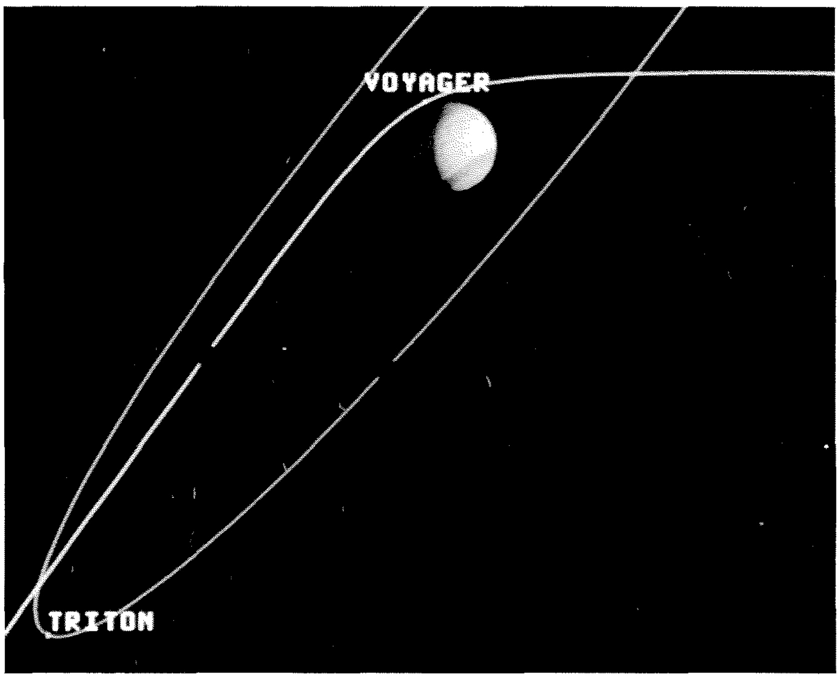
The journey to the outer planets is long because of the great distances involved. Earth, which is one of the inner four small, rocky planets, is one astronomical unit (AU) from the sun—almost 100 million miles. Of the outer giant planets, Jupiter is about 5 AU from the sun, Saturn 10, Uranus 19, and Neptune 30. When the two Voyager spacecraft were launched in 1977, Voyager 1 was on a faster trajectory. After its encounter with Jupiter, it flew by Saturn in such a way that it would, as seen from Earth, veer behind Saturn's large moon Titan as well as behind the rings, so that we could study these two important aspects of the Saturnian system. The geometry of this flyby meant that Voyager 1 would head upward out of the plane of the planets, unable to encounter any other bodies. But having accomplished those two key objectives with Voyager 1, we could leave Voyager 2's trajectory in the plane of the planets, headed toward an encounter with Uranus in January 1986 and finally Neptune in August 1989.

The planetary alignment that made this possible happens once every 176 years, but more than just the proper alignment was necessary to complete the voyage. We used the slingshot effect of flying by each of the giant planets to boost the spacecraft on to the next one. When we launched Voyager, there was enough energy from the Titan III Centaur launch rocket to almost—but not quite—reach Saturn. It was only because the Jupiter flyby gave the spacecraft as big a kick as the launch vehicle itself that Voyager had enough energy to reach Saturn. Saturn and Uranus gave Voyager 2 additional boosts, enabling it to reach Neptune in just 12 years rather than 30.

Designing a spacecraft for exploring the outer planets was also a challenge. Voyager was built and is operated by the Jet Propulsion Laboratory, which is managed by Caltech for NASA. Because the spacecraft was designed in the early and mid-seventies, much of its technology is now outdated. Although its computers have performed well, their memories are small compared with the million-byte memories in today's personal computers. For example, the computer used to control the sequences of in-flight operations has a memory of only 8,000 words. The spacecraft is powered by radioisotope thermoelectric generators using plutonium 238, which provide about 7,000 watts of heat that is converted to about 400 watts of electrical power using thermocouples—a very rugged, durable power supply. The sunlight in the outer solar system is much too feeble for solar panels to provide enough power.

Voyager was designed for a particular mission—a four-year journey to Jupiter and Saturn. To extend the journey to Uranus and



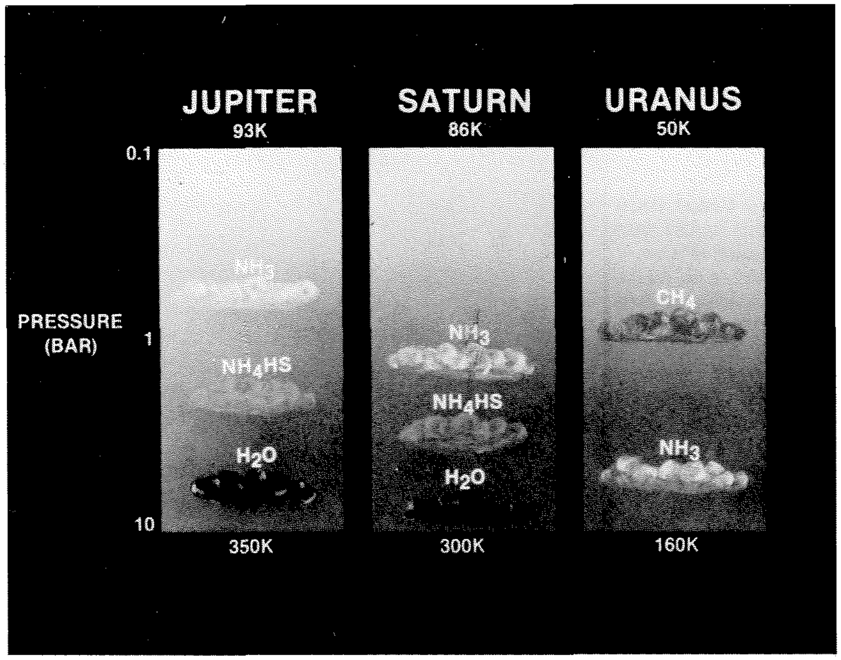


Top: Each of the planets on Voyager's Grand Tour supplied a slingshot boost to propel the spacecraft on to its next encounter. Bottom: From nearly 3 billion miles away, JPL engineers guided Voyager to within 3,000 miles of Neptune, bending its trajectory sharply to intersect Triton's orbit and fly behind Neptune's large moon.

We were able to investigate the differences in the planets progressively farther from the sun.

Neptune we had to extend the reach of Voyager three times farther than originally designed. That required a number of changes in the software of the spacecraft, changes that were actually made only *after* Saturn. For example, in order for the craft to be able to take images with exposures 10 minutes long in the decreasing light farther out (sunlight at Neptune is only about 1/900th of what it is on Earth), we had to stabilize the spacecraft much more precisely than was necessary at Saturn. This was a major engineering achievement accomplished by JPL engineers after the Saturn encounter. Also, the radio signal coming back from Neptune was only 1/9th as strong as that from Saturn, which is three times closer. So the JPL-run antennas, which are located at three sites around the world, were enlarged from 64 meters to 70 meters, and we borrowed one 64-meter antenna from the Australians and another from the Japanese. We also made use of the 27 antennas of the Very Large Array (used for radio astronomy) in the high desert of New Mexico. With a receiver on each antenna, the VLA acted as a single large antenna, which was electronically coupled to the 70-meter antenna in Goldstone to detect the very feeble signal Voyager was sending back. We had to press the capability of the spacecraft and the ground system to their very limits in order to capture the information coming back from the edge of the solar system.

Another challenge was the very close flyby that we had planned—guiding Voyager over the north polar region of Neptune a mere 3,000 miles above the cloud tops, where the spacecraft



Water clouds form in Jupiter and Saturn's atmospheres; clouds of ammonium hydrosulfide overlie that layer, with the top clouds composed of ammonia ice crystals. On Uranus (and on Neptune), where it's much colder, the ammonia clouds form deep in the atmosphere. The topmost cloud deck is made of frozen methane.

was deflected sharply downward to an encounter with Triton. We wanted to fly behind Triton so that we could look at the sun setting through Triton's atmosphere and watch the radio signal disappear. To do so required remarkably precise navigation from nearly 3 billion miles away. For one critical measurement of the atmosphere, we needed to know to within one second when the spacecraft was to arrive at a particular point. This was much more accurate timing than we had ever attempted before—and it worked. Because of these and similar improvements we were able to investigate the differences in the planets progressively farther from the Sun. And we can interpret those differences to help sort out how the solar system formed 4½ billion years ago.

Temperature

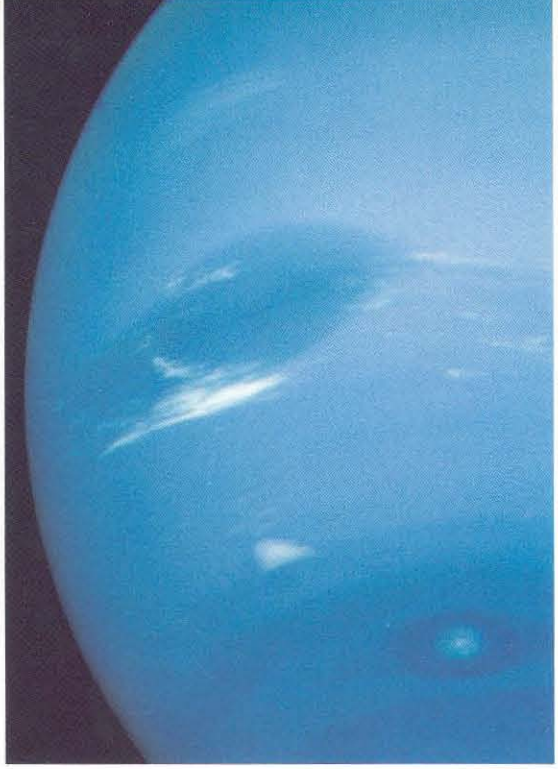
Why is the outer solar system so different from the inner? One of the reasons is that the outer planets formed at much greater distances from the Sun, where the whirling disk out of which they accumulated was much colder. Closer to the Sun where Earth formed, it was so hot that the only solids available to form planets were rocky materials. But five times farther out where Jupiter formed, the temperature was much lower, and water, which was in great abundance in the disk, was ice instead of vapor. So, the core of Jupiter accumulated out of cometlike objects containing both ice and rock. It was colder yet where Saturn formed, and the water ice could have also contained adsorbed ammonia, the form in which some of the nitrogen in the solar system was present. The water ice at Uranus, at −360° F, was cold enough to contain methane as well, which is one form in which the solar system's carbon existed at the time of planetary formation. Where Neptune formed, it was so cold (and still is) that methane itself was frozen solid and available to form giant planets.

Differences in the colors of the giant planets are a direct indication of the variation in composition of the icy materials that were accumulated to make the planetary interiors. Uranus and Neptune both look blue-green because methane is in greater abundance in those two planets; methane absorbs preferentially in the red end of the spectrum, making sunlight that is scattered back from the planet look blue-green. So even by eye we can see the importance of the temperature at which these giant planets formed.

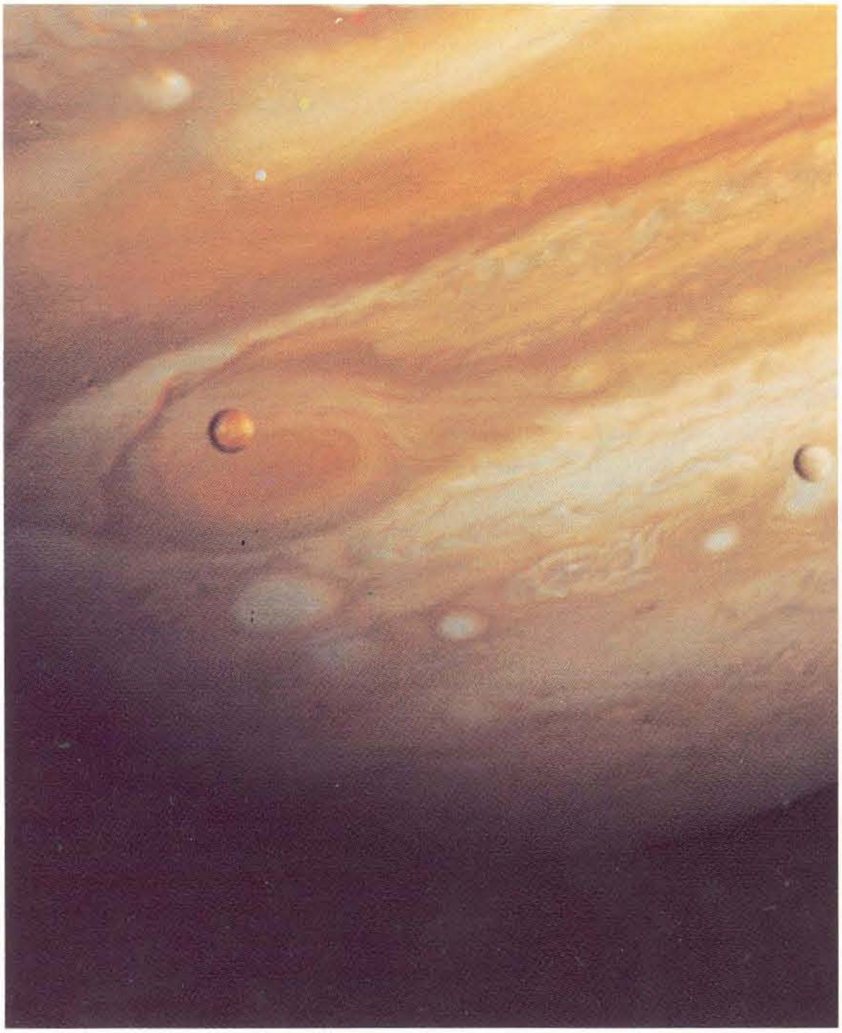
Atmosphere

What we see when we look at the giant planets is not a solid surface at all. Although the planet cores were formed out of icy and rocky objects, the heat generated by their collisional accumulation caused melting, leaving no solid surface inside these planets. Even the rocky material is melted, as it is in Earth's interior. The molten cores are buried beneath deep atmospheres of hydrogen and helium that also contain traces of water, ammonia, and methane. The interiors are very hot, but the atmosphere cools as it rises convectively, the temperature eventually dropping low enough so that water clouds form, just as water vapor rising in our own atmosphere forms water clouds. On Jupiter clouds of ammonium hydrosulfide form above the water clouds, and higher yet is the top cloud deck (the one we see in all the beautiful images of Jupiter) of ammonia ice crystals. On much colder Uranus and Neptune, the ammonia cloud deck forms deeper in the atmosphere and is difficult to see. Uranus and Neptune are both cold enough, however, that higher clouds of frozen methane can also form.

Such clouds provide an opportunity to study the weather systems in these giant rotating spheres of fluid and gas. One of the principal discoveries about Jupiter's atmosphere was that the Great Red Spot is a huge anticyclonic storm system rotating in a counterclockwise direction with a period of about six days and with winds of several hundred mph around its rim. And this was just the largest of dozens of such storm systems. Wind speed varies as a function of latitude, with a 200-mph eastward wind at the equator. With increasing latitude, westward and



Neptune's Great Dark Spot (right) is the size of Earth, and it's as large relative to Neptune as the Great Red Spot (below) is to Jupiter (shown here with its moons Io and Europa). Both are vast anticyclonic storm systems, but the higher winds on Neptune are carrying the Great Dark Spot around the planet at a speed of almost 700 mph. That storm system and the Small Dark Spot (lower right) are thought to be high pressure regions where methane is carried to a higher altitude.



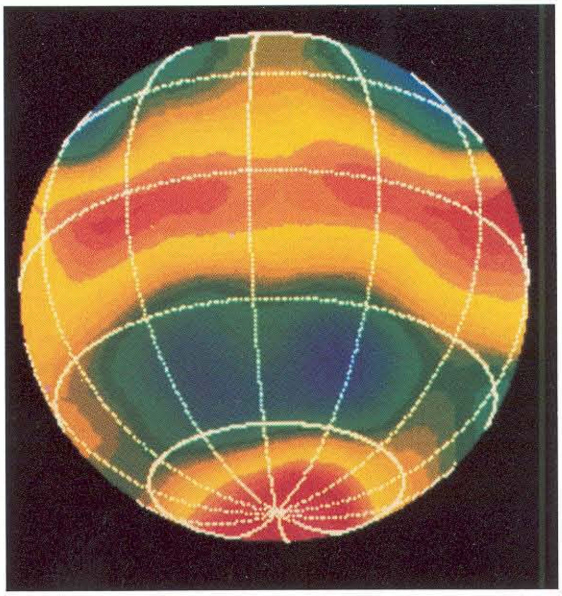
eastward jet streams alternate. Andrew Ingersoll, professor of planetary science, and former graduate student Timothy Dowling have shown that such wind shears generate small storm systems, which accumulate into larger storm systems.

Studying atmospheric dynamics on Uranus was more difficult because there aren't many visible clouds. Unlike Jupiter and Saturn, Uranus has a quiescent, stably stratified atmosphere. We think that this is partly because Uranus is radiating little more heat than it absorbs from the Sun. Jupiter, Saturn, and Neptune, on the other hand, radiate two to three times as much heat as they absorb from the Sun, indicating that their outer atmospheres are efficiently heated by an internal furnace or heat source. Uranus's atmosphere is not.

We didn't know exactly what to expect from Neptune's atmosphere. High-altitude hazes were detectable from Earth. A year ago, as Voyager 2 approached the planet, two images taken some hours apart first showed a bright cloud feature. Then, as the resolution of the images improved closer in, we discovered a Great Dark Spot, about one Earth in diameter—a hurricane-like storm as large relative to Neptune as the Great Red Spot is to Jupiter. We could also see a smaller dark spot with a white core, reminiscent of storms on Jupiter, and a small white cloud, which was named "Scooter" because it appeared to scurry so rapidly around the planet.

We believe that the high-altitude clouds next to the Great Dark Spot, which appear to have a wave-like pattern in them, are methane-ice clouds. They're perhaps similar to the clouds

Because sunlight is incident on Neptune's equator, the temperature is warmer there, as shown in this infrared map of brightness temperatures. But, surprisingly, the south pole is equally warm, while the midlatitudes are cooler, providing interesting clues to fluid flow inside Neptune.



So whether the Sun shines on the pole or on the equator, these two giant planets [Uranus and Neptune] somehow manage to have very similar temperature distributions.

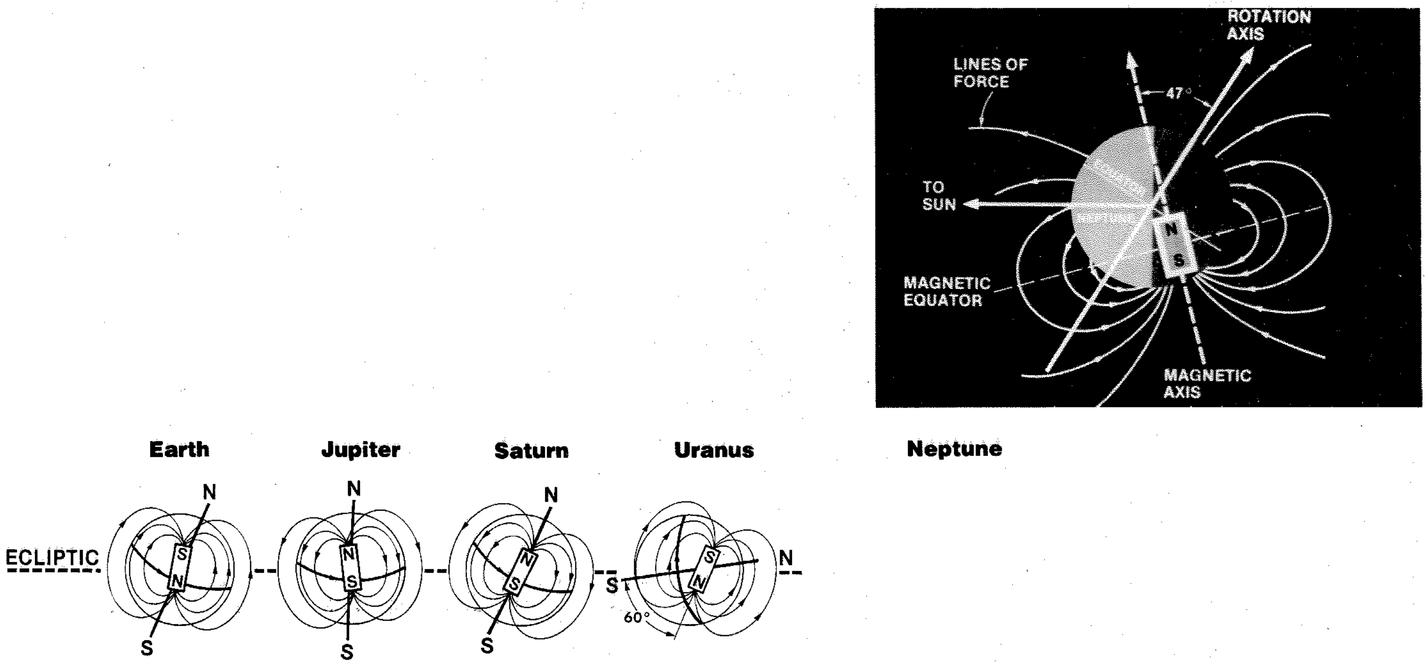
that form downwind of a mountain peak and remain attached to it. This suggests that the Great Dark Spot creates a high pressure region that forces the overlying atmosphere up to higher altitudes where it's colder. The central white cloud in the Small Dark Spot is also probably methane, suggesting that this is an upwelling region where methane is brought from deeper in the atmosphere up to an altitude where it freezes to form a cloud. We also observed some other white cirrus clouds, undoubtedly methane ice as well, which cast shadows on the deeper cloud bank 30–50 miles below. The deeper clouds are likely ammonia.

The temperatures of the two outer planets visited by Voyager are quite cold, although Neptune's temperature is about the same as that of Uranus because Neptune's internal heat source keeps it a bit warmer than it would be otherwise. Sunlight falls on Neptune's equatorial region, as on Earth, making the equatorial region warmer. But the pole is equally warm, while the mid-latitudes are colder. Although Uranus is tipped on its side with sunlight incident on its polar region, it has almost the same temperature pattern. So whether the Sun shines on the pole or on the equator, these two giant planets somehow manage to have very similar temperature distributions. This temperature pattern was a surprise, because we expected the incidence of sunlight to have some effect on the temperature. It is undoubtedly an important clue to the fluid flows inside the planets and to the means by which energy is carried from one region to the other, very important factors in understanding the weather systems on these giant planets.

We know from the magnetic field generated inside the planet that Neptune's interior is rotating with a period—that is, the length of its day—of 16.11 hours. Compared to that interior period, the Great Dark Spot is moving westward, opposite to the direction of planetary rotation, at a velocity that corresponds to a speed of almost 700 mph. Smaller clouds with twice this speed overtake the Great Dark Spot, making Neptune the windiest planet in the solar system—quite remarkable because the amount of energy available to drive the winds on Neptune is only 5 percent of the energy available on Jupiter. Yet somehow there are higher-velocity winds on this planet—an interesting puzzle for people like Andy Ingersoll and his colleagues. Although the winds have generated a great anticyclonic storm system, it's too soon to have any complete understanding of Neptune's Great Dark Spot, which looks just different enough from Jupiter's Great Red Spot to make it interesting.

Magnetic field

The interiors of Uranus and Neptune are somewhat similar—oceans of melted ice and rock, quite hot. (Jupiter and Saturn are mainly liquid hydrogen inside.) If fluid is heated from below, it will rise and convect, creating electrical currents because the water is electrically conducting. The electrical currents generate a magnetic field, which can be thought of in the simplest terms as similar to that of a bar magnet. The electrical current encircles the bar magnet, and



Earth, Jupiter, and Saturn have magnetic poles very close to their geographic poles, but the magnetic field of Uranus is tilted 60° from its axis of rotation. Although Uranus itself is tipped relative to the plane of the planets, Neptune is an upright planet like the other three. Its magnetic field, however, is also tilted 47°.

the magnetic field lines loop from one pole of the magnet to the other.

Here on Earth our magnetic pole is very near our geographic pole, which is very useful, because a compass points to the magnetic pole. That's also true of Jupiter and Saturn. Since Uranus was tipped on its side we expected its magnetic field to be similarly tipped. But one of the surprises of Uranus was that, unlike any other planet we had visited, its magnetic field was tilted 60° from the rotation axis of the planet. Also, the center of the magnetic field was not at the center of Uranus; it was offset by about three-tenths of the planet's radius. There were several explanations put forward as to why this might be the case. First, Uranus receives more solar heat in its polar regions, yet its equatorial region is equally warm. The atmospheric flow that carries the heat from the poles to the equator might also change the electrical currents deeper in the interior, so that they generate an offset, tilted magnetic field. A second suggestion is that we flew by Uranus just at the time that its magnetic field was reversing, as Earth's does every half million years or so. Although this is an unlikely occurrence, it can't be ruled out, and the debate was not resolved before we arrived at Neptune.

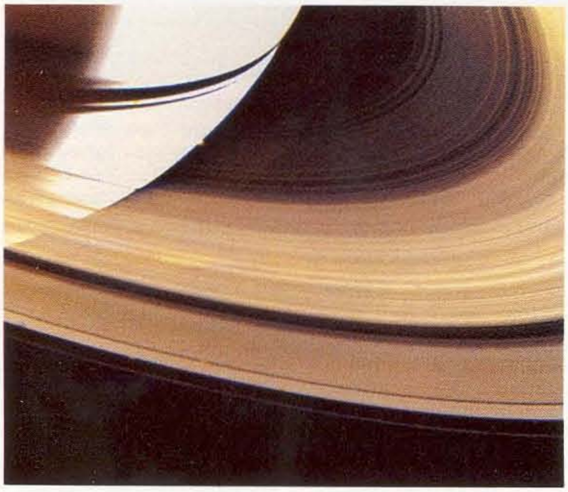
Neptune is not tipped on its side. We all expected that Neptune, being an upright planet (with sunlight on the equator, not the pole), would have an upright magnetic field. But we were surprised again: Neptune's magnetic field is tipped 47°. So it's difficult to argue that a tilted magnetic field comes from a planet's being tilted on its side, and it's even more unlikely that we flew by two planets just as their fields were reversing.

Because the tilted magnetic field rotates with Neptune, once every 16-hour day the magnetic field will be oriented so that the solar wind blows directly on the magnetic pole and compresses the field. (The solar wind is a tenuous, electrically charged gas, which blows at about a million mph outward from the Sun.) As Voyager approached Neptune we had our first observation of a pole-on magnetosphere. Of course, by the time Voyager flew over the top of the planet and down the other side, Neptune had rotated so that the magnetic equator, and not the magnetic pole, was facing into the solar wind, as is the case at the other planets.

The electrical currents that generate the magnetic field must be flowing fairly far out from the center of Neptune. The fact that both Uranus and Neptune have a similar tilt and offset to their magnetic fields is telling us something important about the nature of the flow of fluid inside these giant planets. It will likely take several years of study before we begin to understand the implications of these peculiar magnetic fields.

Rings

Saturn's rings are the quintessential ring system. Galileo discovered them in 1610, although he didn't really understand then that they were rings. Until 1977 they were the only known rings in the solar system. Voyager discovered a number of interesting features in Saturn's rings, Voyager discovered many interesting features in Saturn's quintessential ring system (top), and Neptune's quite different rings (bottom) also provided some surprises. Neptune's ring arcs, first observed by star occultations from Earth, turned out not to be isolated segments but rather three brighter portions of a very thin, transparent, outer ring. Why ring material is confined to thicker arcs is still a mystery.



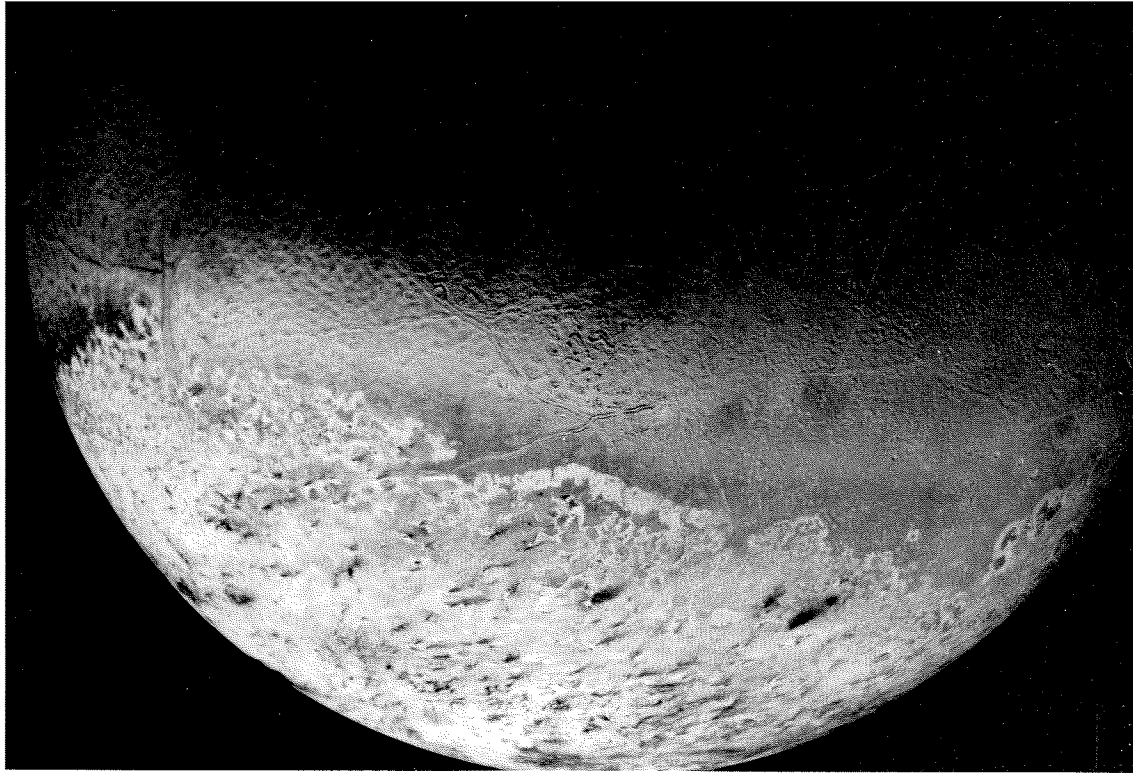
including waves that are generated by the gravitational pull of moons orbiting outside the ring. By looking carefully at these waves we have learned that the amount of water ice that makes up the particles in the rings would form a sheet about one to two feet thick if the particles could be collapsed into a solid layer.

Voyager also made an important discovery about the nature of Saturn's narrow F-ring, first observed by Pioneer 11 in 1979. Isolated narrow rings will not persist as narrow rings, because they're made up of countless numbers of particles that collide with each other, losing energy in the process. Some will spiral in to the planet and some will spiral away, causing the ring to dissipate rapidly. Peter Goldreich, the Lee A. DuBridge Professor of Astrophysics and Planetary Physics, and his colleague Scott Tremaine had earlier theorized that two shepherding satellites, one inside and one outside of a ring, would prevent it from spreading out and disappearing. As they predicted, Voyager found two moons flanking the F-ring.

From Earth we can't see rings around Neptune, but several astronomers, including Phil Nicholson (PhD '79) and his Caltech colleague Keith Matthews (BS '62), have searched for rings by observing stars as they disappear behind Neptune. About one time in ten, they found that the star would dim briefly as it passed behind material in orbit about the planet, as though there were pieces or segments of rings but not complete rings. Although we thought that there might be dozens of these ring arcs, Voyager found just three. Rather than isolated arcs, they're just somewhat brighter portions of a normal complete ring—the outermost, as it happens. The rest of the ring couldn't be seen from Earth because it's so transparent that you can see right through it. Only about 1 percent of the starlight coming through it is blocked, too small to be detected from Earth. There are a number of other rings, but they're also very thin.

The origin of the ring arcs is still a puzzle. The question is: Why do we see material concentrated in arc regions? We don't know whether the arcs are due to objects embedded in the ring at that location or to other unseen moons. We have found two moons that may shepherd the inner edges of rings, but they can't account for the ring arc regions.

We think the rings are probably the result of collisions. One of the key questions before Voyager's journey to the outer solar system was: Are rings primordial? That is, are they just material left over from when the planet and the moons formed? Or are they a more recent addi-



Triton may have hit one of Neptune's regular moons, lost enough energy so it could no longer escape, and remained in an elongated, retrograde orbit.

tion to the planet—the result, perhaps, of a catastrophe in which a moon was struck by a comet and broken up into pieces? Two larger pieces might have captured and herded some of the smaller residue of the catastrophe between them. I think that the Voyager observations are telling us that it is likely that rings are not primordial, but are the result of catastrophic processes.

There is other evidence for catastrophic collisions. Voyager discovered six dim moons at Neptune. The outermost of these new moons is only 250 miles across, is rather irregularly shaped, and is marked by a huge impact crater. If the object that made that crater had been much larger, 1989N1 would have been shattered. Several of the smaller moons closer to the rings likely resulted from such a breakup of a larger object.

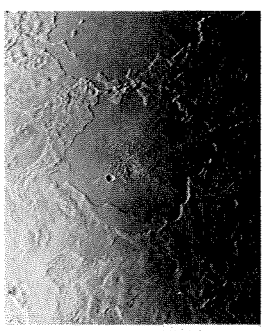
Triton

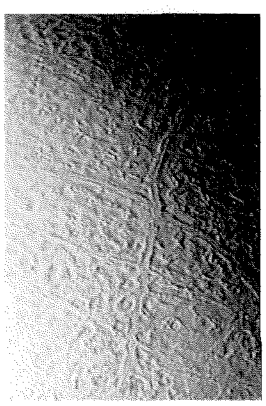
One large moon also orbits Neptune. Triton was first seen shortly after Neptune was discovered. It's remarkable how much was already known even though the moon is just a point of light when viewed from Earth. We knew that there was methane ice and possibly solid nitrogen on its surface. We knew that it orbited backwards around the planet. No other large moon orbits backwards; they all orbit in the same direction as the planet rotates because they share the rotation of the disk of gas out of which they formed. As the bodies form, they continue orbiting in that same direction. This motion, called prograde motion, is characteristic of regular satellites that form as a part of the planetary formation process itself. So how do we explain an object orbiting in the opposite way, in a retrograde orbit? It is likely that many such objects formed elsewhere in the outer solar system and were accreted by Uranus and Neptune as *they* formed. But two of them escaped that fate and survive as Pluto, which orbits the Sun, and Triton, which came close to Neptune, but not so close that it was swallowed up. Triton may have hit one of Neptune's regular moons, lost enough energy so it could no longer escape, and remained in an elongated, retrograde orbit.

But a moon in an elongated orbit has a serious problem. All the normal satellites like our own Moon have one side facing the planet. Just as the Moon raises a tide in our oceans, the Earth raises a tide in the Moon's surface, causing a permanent deformation since it always faces one way. This isn't possible in an eccentric orbit because the moon can't rotate at exactly the right rate to keep one face in. As different sides of the moon face the planet, its surface will heave up and down like the surface of our oceans. The flexing of the moon's crust generates heat that melts its interior. This energy dissipation continues until the orbit becomes circular and one side of the moon always faces the planet.

According to Peter Goldreich and his Caltech colleagues Norman Murray, Pierre Longaretti, and Donald Banfield, this is probably what happened to Triton. They calculated that Triton would have been melted by tidal pumping of its surface for about a billion years before its orbit finally became circular as it is today. We were

Triton's icy south polar cap (left) exhibits features such as the "cantaloupe terrain" toward the equator, unlike anything yet seen in the solar system. Evidence of thermal activity appears in an active geyser (lefthand arrow in stereo image at right) with a plume 5 miles high and more than 100 miles long (right arrow); in volcanic craters (below) that have undergone episodic melting and freezing; and in fault lines extruding viscous water ice (bottom).





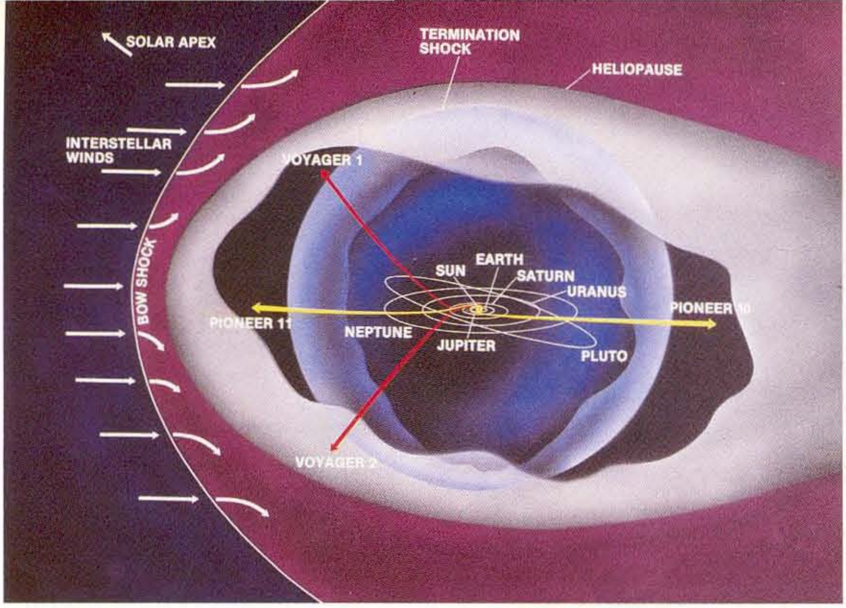
expecting that there had been an era of violent geologic activity in Triton's past resulting from its capture and orbital evolution around Neptune.

We also thought that Triton would have a seasonal polar cap of methane ice and possibly nitrogen ice. The seasons don't change quickly on Triton—its year is 165 Earth years long. When it's summer in the southern hemisphere, that polar cap will sublimate, creating a tenuous atmosphere that will flow to the dark, cold north polar region, where it will freeze out to form a new polar cap. When summer comes to the north, that polar cap will then sublimate and freeze out again on the southern pole. This idea was first proposed some years ago by Robert Leighton, the William L. Valentine Professor of Physics, Emeritus, and Professor of Planetary Science Bruce Murray to explain Mars's polar cap, which migrates in a similar fashion although it's made of carbon dioxide ice. Evaporation of the carbon dioxide from one polar cap changes the atmospheric pressure on the surface of Mars by a factor of two as the seasons wax and wane and the polar cap freezes and sublimates. Although it's much colder on Triton (−390° F) than on Mars (−200° F), Laurence Trafton (BS '60) suggested that a similar phenomenon involving methane polar caps should be occurring on Triton.

So what *did* we see on Triton? As we approached we managed to resolve the icy polar cap of the south pole and realized that our view of the surface wouldn't be obscured by a hazy atmosphere; we would indeed be able to see it in fine detail. The south polar cap probably consists of a layer of nitrogen ice and methane ice on top of a surface that is primarily water ice. At −390° F, water ice is rock hard. There is also evidence of geologic activity—long fault lines out of which viscous water ice has been extruded, forming parallel ridges. The chaotic-looking area closer to the equator has been dubbed the "cantaloupe terrain." It's unlike anything we've seen before, and we're still trying to understand what geologic processes could have created such a surface. In a nearby region there is very smooth terrain with features that look like the volcanic calderas or craters that we have on Earth. But instead of Earth's rocky crust and crater floors covered by the flow of molten rock, Triton has an icy crust and crater floors covered by water flows. The sharp detail of an impact crater about 10 miles across tells us that this material is quite hard and must therefore be water ice. If it were methane or nitrogen ice we would not see such sharp features, because even at −390° F those ices are soft and flow like glaciers flow on Earth.

If we look more closely at that caldera we see evidence of several episodes of icy flow. This icy volcanism may have occurred about a billion years ago or even more recently, perhaps the result of a combination of radioactive and tidal heating. There is no tidal heating source today, only radioactive and solar heating.

There is, however, contemporary thermal activity. In the icy polar cap there are many parallel dark streaks, which seem to emanate from points and fan out in a characteristic shape



The two Voyager spacecraft (as well as Pioneers 10 and 11) are now headed for the heliopause, which signals the actual end of the solar system. The termination shock occurs where the solar wind slows down dramatically before meeting the interstellar wind.

We're not at the end of our mission of exploration.

as though carried by a wind. In stereo views of two regions, Laurence Soderblom (PhD '70) and his colleagues found geysers with vertical streams five miles high and long plumes of material whose shadow we can see below on the surface. The shape of the plumes indicates that Triton has a stable atmospheric layer about five miles thick; above that is a strong wind shear, which carries the erupted material off in a long stream, just as smoke is wafted away from the top of a chimney.

How can there be active geysers where the surface temperature is −390° F, the coldest surface we've seen in the solar system? At that temperature nitrogen is solid and there's a little bit of vapor associated with it. But nitrogen is not much below its melting point, so a little heat will increase its vapor pressure enough to force the nitrogen out into a plume. In this sense nitrogen is behaving much like water behaves on Earth; beneath Old Faithful water is heated enough to cause it to erupt explosively from the vent.

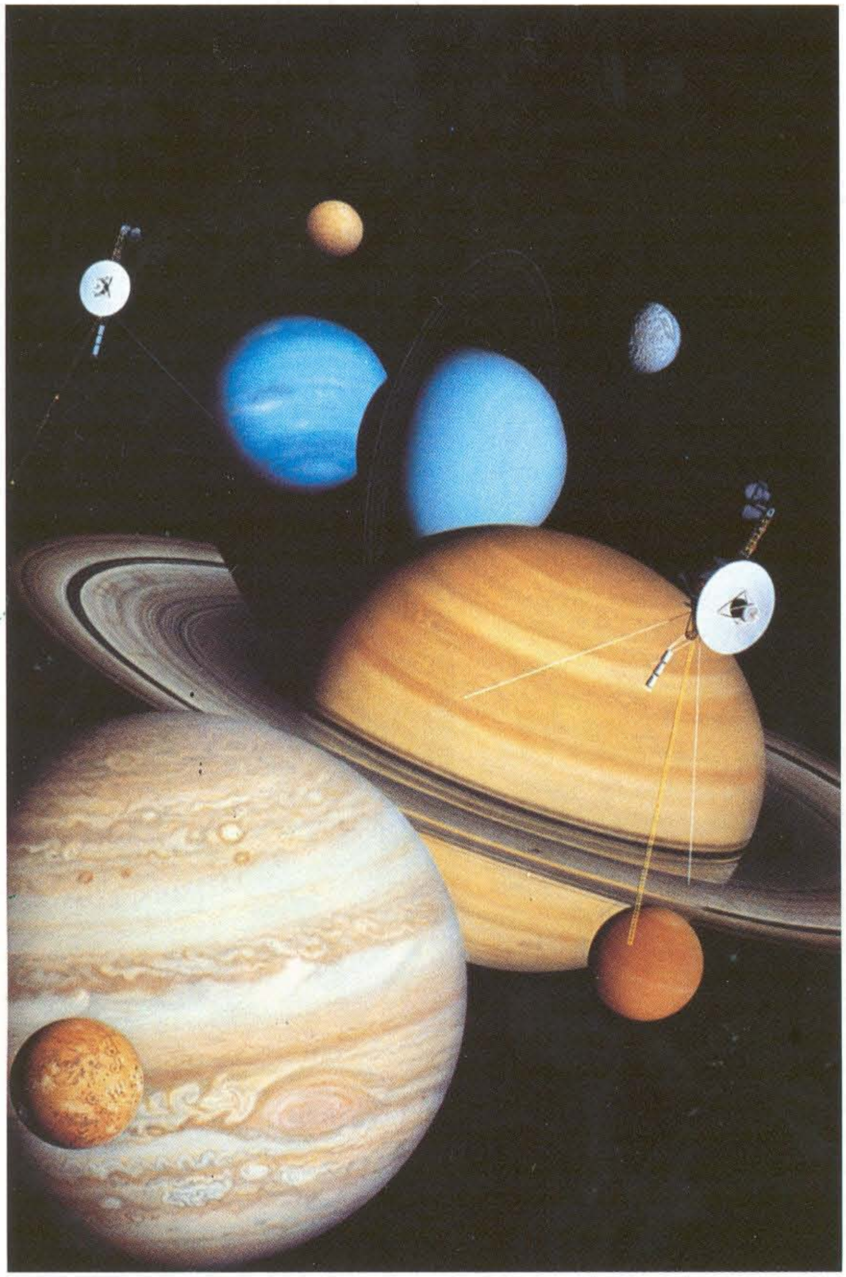
In many ways Triton is a twin of Pluto and may be providing our best look at that remote planet for many years to come. They are almost the same size; they both have methane on their surfaces; their densities are about the same—about twice that of water, which means that they are three-quarters rock and one-quarter water ice coated with methane ice. But Pluto's evolution, and thus its surface, will almost surely be quite different from Triton's, because Pluto would not have been subjected to tidal heating as Triton was in its orbit around Neptune.

Beyond Neptune

We're not at the end of our mission of exploration. The space between the stars is filled with a tenuous gas and our Sun, like all stars, is blowing a bubble in that interstellar medium. The bubble, which is called the heliosphere, is created by a million-mph wind blowing radially outward from the Sun in all directions. We don't know how far it is to the heliopause, the edge of the bubble; it may be three to four times as far as it is to Neptune, that is, 90–120 times as far from the Sun as Earth is. Before the solar wind reaches the heliopause there will probably be a supersonic shock, because the supersonic solar wind must slow down before it finally runs into the interstellar medium. We hope Voyager will tell us where these boundaries of our solar system are. This may be a unique opportunity, because in the next phase of exploration, spacecraft will go into orbit around a planet rather than escape the solar system. If nothing unfortunate happens to the two Voyager spacecraft, we can track them for another 25 years—at which point Voyager 1 will be 130 times as far from the Sun as Earth, and could be in interstellar space for the first time.

The next phase of exploration of the outer planets has already begun. Galileo was launched last October for a return to Jupiter. It will put a probe into Jupiter's atmosphere, directly measuring the winds, the temperatures, and the composition of the gas and the cloud layers. And the spacecraft will go into orbit around the planet so that we can study it over several years rather than just take snapshots as we fly by. Galileo

An all-inclusive retrospective of Voyager's journey, collapsed into one painting by artistic license, shows Jupiter and Io, Saturn and Titan, Uranus and Miranda, and Neptune and Triton.



will fly 100 times closer to Jupiter's moons than Voyager and will reveal their surfaces in much more detail. In 1996 the Cassini mission will be launched on a return to Saturn and will place a probe into Titan's atmosphere—an atmosphere that is primarily nitrogen like that here on Earth, but that has an organic chemistry that may be similar to that present in Earth's atmosphere before life evolved. Again, the spacecraft will go into orbit, allowing detailed studies of the dynamics of Saturn's ring system. In 1995 the Comet Rendezvous Asteroid Flyby (CRAF) mission will send a similar spacecraft to a comet. We believe that the cores of the giant planets are accumulations of comets that formed in the outer solar system. CRAF will measure the properties of a comet by penetrating its dark, icy crust with an instrumented probe.

Although these new missions and others to follow will add important chapters to the encyclopedia of the outer solar system, the chapters written by the two Voyager spacecraft over the last 12 years will not be forgotten, because they first revealed to us a solar system with distinctive worlds of unexpected richness and diversity. □

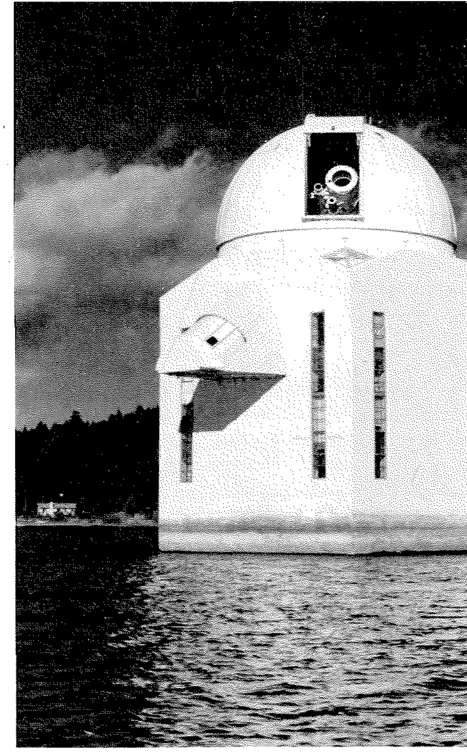
As project scientist of the Voyager mission since 1972, Ed Stone has coordinated a large team of scientists in analyzing the images and data that the two spacecraft sent back along their journeys —and he's communicated the excitement of Voyager's scientific discoveries to an audience of millions around the world. Stone joined the Caltech faculty after receiving his PhD in physics from the University of Chicago in 1964. He has been professor of physics at Caltech since 1976, chairman of the Division of Physics, Mathematics and Astronomy from 1983 to 1988, and is currently vice president for astronomical facilities. His own area of research is cosmic rays, and although the Voyager spacecraft have left the planets behind, Stone's work has just begun; an abundance of cosmic rays is waiting out there around the termination shock. Stay tuned for another 10 years or so.

The Sun Also Polarizes

The sun is generally a placid, even-tempered star, but it has a violent side. Flares—tongues of solar gas, many times larger than the earth—erupt outward from the sun's surface. These same eructations disgorge high-energy electrons, x-rays, and other particles, playing hob with the earth's ionosphere, disrupting radio communications, and draping the polar skies with the neon curtains of the aurora. These outbursts are thought to be driven by the sun's writhing magnetic field, but studying that field isn't as easy as holding a compass up at the sun. Studying it at Caltech's Big Bear Solar Observatory will be a lot easier in the future, however, thanks to a system that Glenn Eychaner, a senior in geophysics, developed there this past summer.

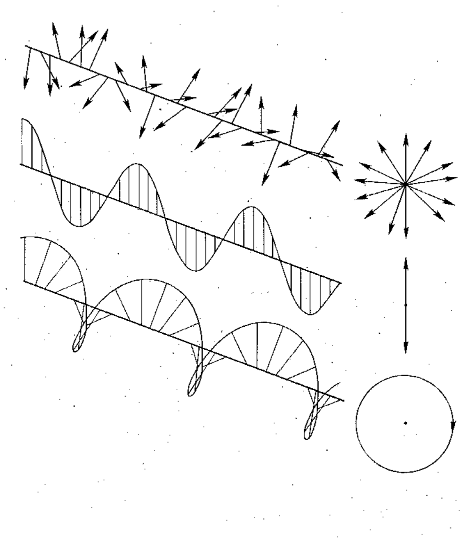
The sun's magnetic field is extremely complex. A diagram of the earth's field close to the planet looks rather like half an apple, with the north and south poles at opposite ends of the core, and the apple's skin representing a typical magnetic field line. A close-up diagram of the sun's field, however, looks more like an untidy ball of yarn the cat has been playing with—loops of magnetic field emerge from the sun's surface at many points, each of which is a magnetic pole. These points are usually visible as sunspots, and the loops connect sunspot pairs of opposite magnetic polarity. There may be dozens of sunspot pairs, as well as more complex groupings, on the sun's surface during a particularly active episode.

The sun's magnetic field is hard to measure directly, even though it's much stronger than the earth's—about 10 times stronger at the solar poles, and as much as 6,000 times stronger in the middle of a sunspot. Fortunately, light waves passing through a magnetic field become partially polarized—the waves become aligned with one another. (Unpolarized light waves are random—some go up and down, others move sideways, and the rest vibrate in any old direction.) A three-dimensional magnetic field polarizes light in two ways. The transverse field—the part perpendicular to the observer's line of sight—produces linearly polarized light whose waves lie in planes parallel to the field. The longitudinal field—the part along the observer's line of sight—produces circularly polarized light whose waves are still randomly aligned, but rotate clockwise or counterclockwise in unison. Thus, photographing the sun through a clockwise-polarized filter, say, gives a picture whose brightness at any point is proportional to the field strength. The resulting image is called a magnetogram. (The effect is actually so small as to be unobservable, except in monochromatic light—light of a single wavelength. Thus magnetographs—the instruments that make magnetograms—also contain filters to admit only the desired wavelength. These wavelengths aren't limited to the ones at which hydrogen and helium emit light. Much

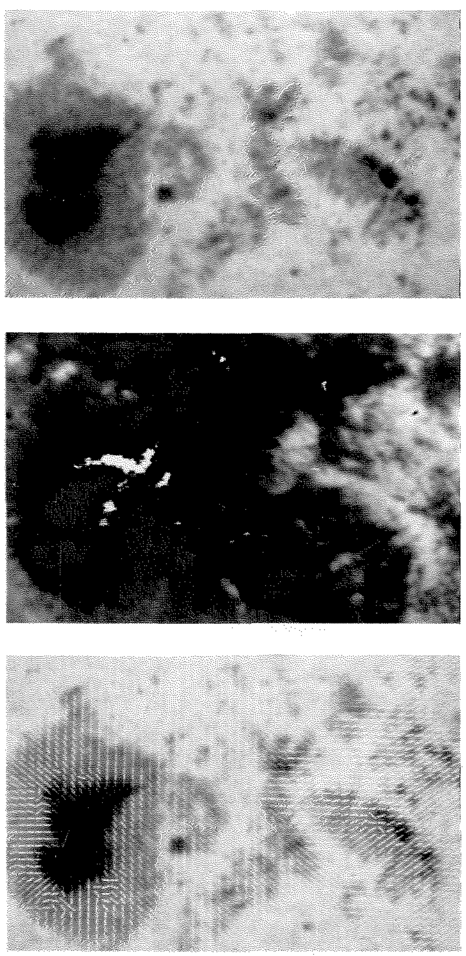


Above: The three-story Big Bear Solar Observatory sits in the middle of Big Bear Lake to minimize atmospheric turbulence. The 26-, 10-, and 8-inch telescopes are visible in the dome. The "nose" projecting from the building's side houses a spectroheliograph.

Below: Unpolarized light waves are random (top), while plane-polarized light waves lie in a plane (middle), and circularly polarized light waves rotate together (bottom).



Top: A sunspot group as seen in 6103-Angstrom light, an emission line of neutral calcium.
Middle: A longitudinal magnetogram of the same area. Clockwise areas appear bright and counterclockwise areas dark in proportion to the field strength. The white areas inside the black are artifacts.
Bottom: The transverse magnetogram superimposed on the sunspot group. Flares are expected where field lines meet at an angle, as along the diagonal toward the lower right corner.



valuable information can be gleaned from the emissions of heavier elements such as iron or calcium.)

It takes only two images—one each through a clockwise and a counterclockwise filter—to make a longitudinal magnetogram, which have been in use since the 1950s. Making a transverse magnetogram is much harder, because the polarization signal is much smaller. Creating a transverse magnetogram entails reconstructing the field from a compilation of images polarized in different directions—time-consuming even for a computer. A system at the George C. Marshall Space Flight Center in Huntsville, Alabama, can crank out a magnetogram in about three hours, but most researchers need months to produce one.

Eychaner's system generates transverse magnetograms in seconds. The system was built as a SURF (Summer Undergraduate Research Fellowship) project sponsored by Harold Zirin, professor of astrophysics and director of the Big Bear Solar Observatory, in collaboration with BBSO postdoc John Varsik. The system uses BBSO's video magnetograph. Two linearly polarized filters with axes at 45° to each other were added to the set of circularly polarized filters already on the magnetograph's computer-controlled filter wheel. Eychaner fed the video output to a computer, which he programmed to construct transverse magnetograms. The computer records the brightness of every pixel, or point in the video image, as seen though each linear filter, as well as the true brightness when neither filter is in the light path. The field's strength and direction are calculated by comparing each true brightness with the polarized brightnesses. The system displays the transverse field as a pattern of line segments oriented along the lines of force, like iron filings sprinkled around a bar magnet. Each segment's brightness corresponds to the field's local intensity. The magnetogram can be superimposed upon an unpolarized image of the same region to show the sunspots, or onto a longitudinal magnetogram.

The image processor has a limited capacity, so the system averages blocks of eight pixels on a side when making images of the entire sun. The operator can scan these images and zoom in on a particularly interesting region, telling the system to process that region on a pixel-by-pixel basis.

"We believe that solar flares get their energy from the sun's magnetic field," says Zirin. "There's really no other source that can release so much energy in so small a volume over so short a time. But as luck would have it, the longitudinal field, which is easy to measure, doesn't seem to change much during flares. So we think that the transverse field is where everything happens, and there are other arguments for this as well." Adds Eychaner, "We expect to see large variations in the transverse field and a strong longitudinal field all along where the flares are happening. The theory says that flares occur when the transverse field goes from a high-energy state to a low one. The field lines start out straight, in a low-energy state. But the regions of north and south polarity are constantly moving past each other, so the field lines connecting them get bent, and as they bend they go to higher energy states. A flare occurs when the lines break suddenly, snapping back and becoming straight again. It's sort of a magnetic earthquake. And flares happen very quickly. A small one may last only half an hour, and the real action doesn't last more than a few minutes. That's why we wanted to develop a system that could get six or eight clear pictures during the crucial first few minutes of a flare, so that we could see how they develop."

The summer's work was plagued by computer crashes and other minor problems. One problem was that the observatory's 26-inch reflector and 10-inch refractor telescopes affect polarized light differently, yet the system was supposed to be compatible with both instruments. That problem was finally licked with a custom-built filter plate for the 26-inch. The system therefore didn't get fully up and running until almost September. But as *E&S* went to press, the BBSO group had just detected their first transverse field change associated with a flare. "I think we're seeing a real effect," says Zirin. "Now we're trying to observe other flares to confirm it."□—*DS*

Previous techniques have usually been limited to a single snapshot of the crack in progress.

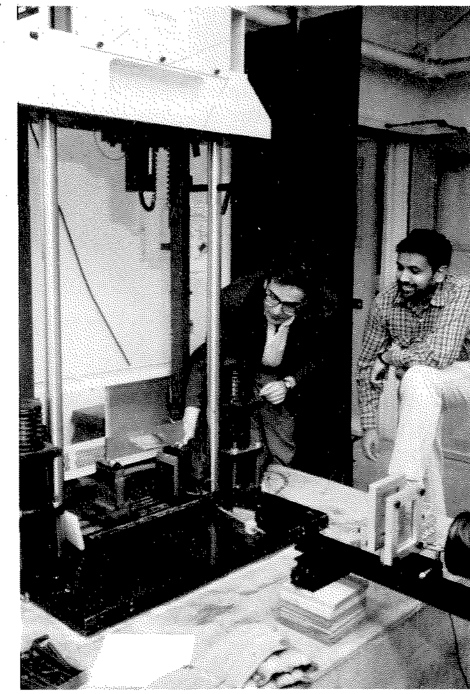
Faster than a Speeding Fracture

When the wing tears off of a jetliner, or an overloaded steel cable snaps, the crack moves through the metal faster than a mile a second. Scientists studying fracture behavior would love to watch a crack as it travels, but have been stymied by its speed. But now Ares Rosakis, associate professor of aeronautics and applied mechanics, and his colleagues have developed two techniques fast enough to catch a crack in the act.

One method measures transient temperature changes in the crack tip's vicinity. Thermocouples, the standard temperature sensors, can't respond fast enough to register these transients. Thermocouples also measure temperature over too large an area—they measure heat through physical contact and obscure any fine detail by reporting one average value for the entire contact region.

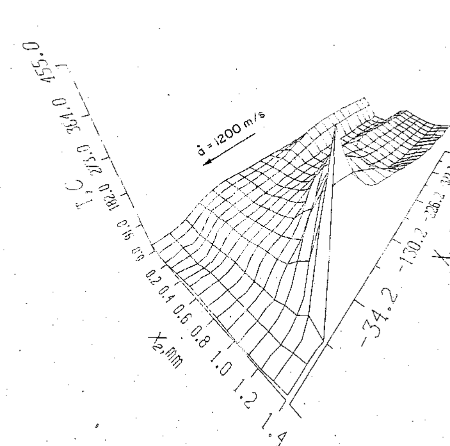
Rosakis and Alan Zehnder (now an assistant professor at Cornell) built a remote-temperature sensor based on cesium-antimonide infrared detectors, originally developed for use in heat-seeking missiles, that have a response time on the order of half a microsecond (millionth of a second). A linear array of eight detectors is focused on a narrow strip of the specimen's surface—about 0.16 mm wide by 1.5 mm long—perpendicular to, and in the projected path of, the crack. Each detector provides a continuous temperature readout for a specimen area 0.16 mm square as the crack tip approaches, passes by, and recedes. "Ideally, we'd like to have a square array of perhaps 1,000 by 1,000 of these detectors, so that we could get a series of complete pictures of the whole area," says Rosakis, "but unfortunately just the eight of them cost $40,000." So, instead, the group uses time as a proxy for distance. Electrically conductive paint is silk-screened onto the back of the specimen in a pattern of parallel lines 3 mm apart. Each line breaks in turn as the crack passes beneath it, tracking the crack's progress. Plotting the temperature readings in their correct positions relative to the crack tip gives a composite picture of the temperature all around the crack.

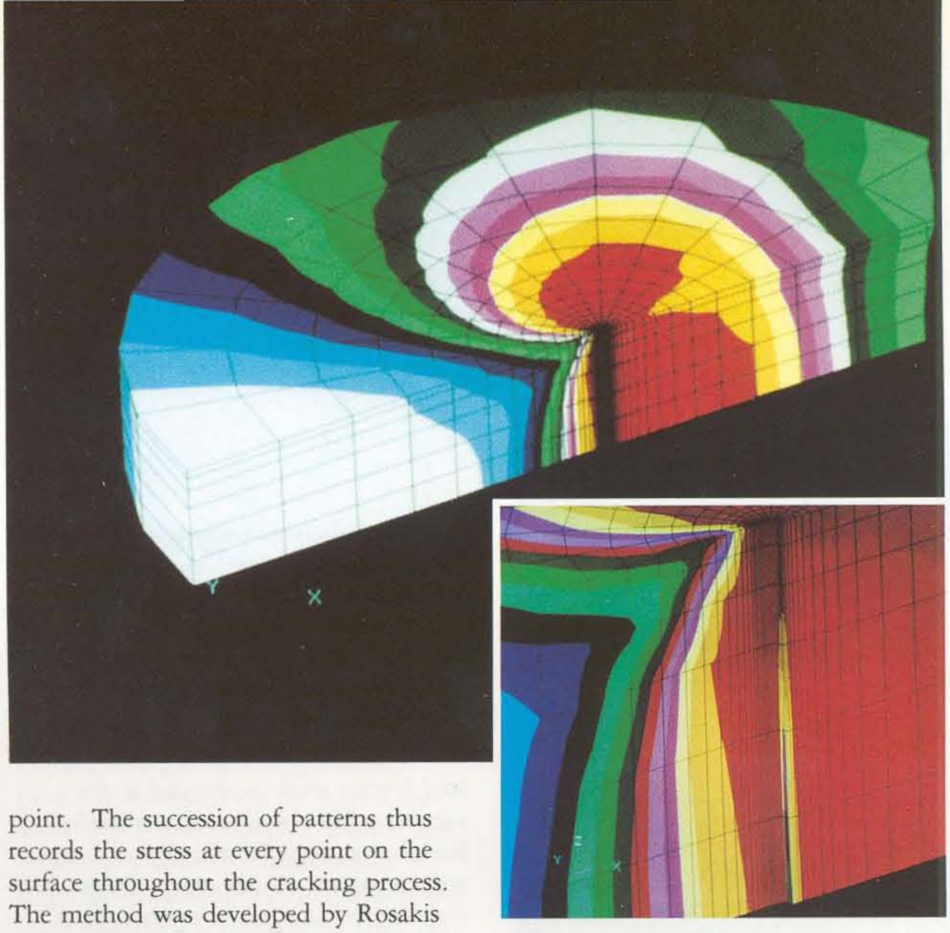
When a crack shoulders its way between atoms, rupturing the bonds



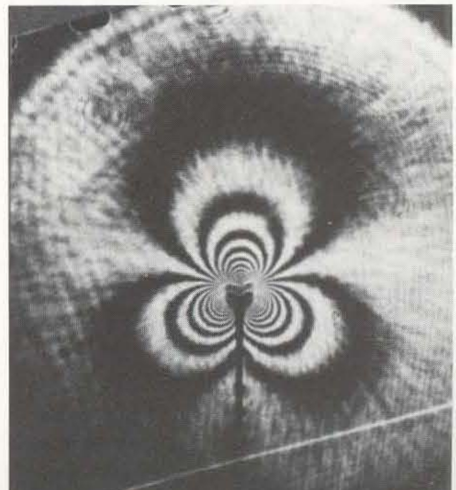
Above: Rosakis sets up a steel specimen as Tippur looks on. A 1,000-pound weight plunging from a height of two stories will crack the specimen at a precut notch. The diffraction gratings and part of the high-speed camera are visible to the lower right.

Below: A 3-D plot of temperature (vertical axis) relative to the crack tip. The crack runs down the X_1 axis, moving out of the page at 1200 m/s. The spike marks the crack tip, and the spreading wave behind it defines the zone of changed yield stress.





Above: A supercomputer model of the stresses around the crack, which is moving from left to right across the face of the model. Blue is the lowest stress, red the highest. The inset shows that bonds breaking at the crack tip relieve stress in the immediate area. Below: A typical interference pattern. The crack is moving up the middle of the photo.



between them, heat is released. Theorists knew this, but assumed that any effect on the bulk of the material would be negligible. Rosakis has found, however, that in a half-millimeter-wide zone running one millimeter ahead of the crack tip, the temperature shoots up to about 500° C in two microseconds, and it stays that hot for about 150 microseconds. "This is actually enough heat to change the local yield stress—the stress needed to break the material," he says. "So this research tells us we need to modify our theories to incorporate the heat effect, because it's important."

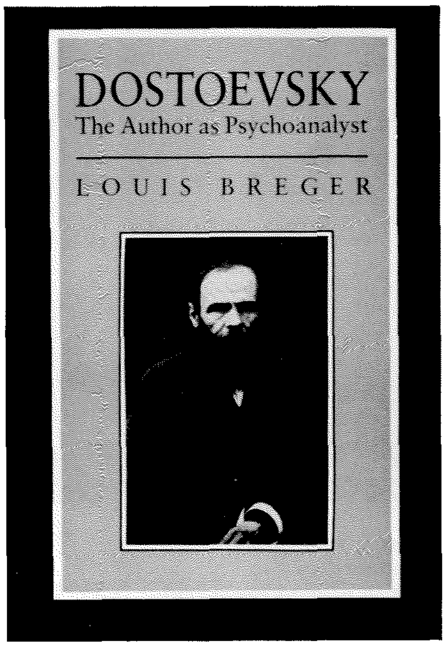
The second method, called coherent-gradient sensing, uses high-speed photography to record the stresses around the crack's path. Previous techniques have usually been limited to a single snapshot of the crack in progress, or only gave data about one point instead of the entire region surrounding the crack. Multiple images of a crack and its environment could be made, but only if the stressed material was transparent, like Plexiglas—a class of materials of limited use to structural engineers.

The new method photographs the stresses in an opaque plate such as a metal or ceramic at the rate of two million frames per second—fast enough to follow a crack as it crosses the plate. The method uses a laser, firing high-intensity pulses 20 billionths of a second long, as the flashbulb. Each pulse illuminates the area the crack will traverse. The plate has been polished until it's optically flat—any two points a centimeter apart on its surface differ in elevation by less than one wavelength of the laser light. The stresses responsible for the crack make the plate deform before it breaks, causing different regions of its surface to reflect the laser light slightly out of phase. The reflected light creates interference patterns upon passing through a set of diffraction gratings placed in front of the specimen. The diffracted light enters a drum-shaped camera, where a whirling mirror slings the patterns onto the photographic film lining the drum. The researchers analyze the interference patterns to track how much each point on the specimen's surface moves from its initial position, which in turn reveals the stresses at that point. The succession of patterns thus records the stress at every point on the surface throughout the cracking process. The method was developed by Rosakis and postdocs Hareesh Tippur and Sridhar Krishnaswamy (now a postdoc at UC San Diego).

"Previous methods for opaque materials weren't compatible with high-speed photography," Rosakis notes. "The gratings were actually glued onto the specimen, and they scattered a lot of the light. You need very intense light to expose the film at the speeds necessary to follow the crack in motion, and those methods just didn't reflect enough light back to the camera. They were essentially static techniques. This is the first method that gives full-field information on the crack environment in real time."

The research group has developed numerical models based on these experiments. These models, which run on supercomputers at Caltech's Jet Propulsion Laboratory and at the supercomputing center in San Diego, will help scientists refine theories on how cracks grow. "Fatigue cracks always exist," says Rosakis. "They cannot be prevented. And sometimes they start propagating. So the practical question is, how does one design structures so that cracks arrest themselves before there is a catastrophic failure? Our models can help engineers answer that question."□—*DS*

Books



New York University Press
295 pages

Many regard Dostoevsky as the greatest psychological novelist, and some are so gripped by his fiction that it becomes more important to them than their real lives. I recall a student in high school who, after reading *Crime and Punishment*, identified with Raskolnikov so thoroughly that he carried the book with him everywhere in a self-absorbed daze. Although this response was extreme, the emotional impact of Dostoevsky's great novels, from *Notes from Underground* to *The Brothers Karamazov*, is hard to deny. In his most recent book Louis Breger, professor of psychoanalytic studies at Caltech, offers an interpretation of Dostoevsky's life and work that explores the personal sources of the emotional intensity of the novels.

Breger declares his indebtedness to Freud's method of seeking "a common underlying explanation for symptom, childhood history, and literary theme," but he is hardly an uncritical Freudian (as readers of his *Freud's Unfinished Journey* will realize). His major departure from Freud and most psychoanalytic literary study is revealed in the subtitle—*The Author as Psychoanalyst*. Rather than treat Dostoevsky as a neurotic, a patient on the couch, Breger regards him as a fellow psychoanalyst and sees his work both as an anticipation of Freud's and as a healing process similar to Freud's own self-analysis. He suggests that writing the novels gave Dostoevsky insight into his own inner conflicts, and that this insight was an essential factor in his personal and artistic growth.

Breger contends that, when read in chronological order, Dostoevsky's novels reveal a progression from earlier to later stages of psychological development. The earlier fiction, like the opening phase of an analysis, introduces themes that will become important later, and then *Crime and Punishment* gives symbolic expression to Dostoevsky's "deepest emotional conflict," his ambivalence towards a needed but depriving mother. The novels that follow move beyond the emotional issues of the mother-infant into the world of fathers and brothers, and the characters become progressively more complicated: "the evil figures become less demonic and the saintly types less angelic; in *The Brothers*, everyone is more human, more a mixture of realistic good and bad qualities."

Breger is at his best with *Crime and Punishment*, obviously his favorite novel. The framework of his interpretation is as interesting as the interpretation itself. He suggests that we consider the novel "as a shared series of dreams." He takes the central plot concerning Raskolnikov's murder of the hateful pawnbroker and her innocent sister as the main dream and the subplots as subsidiary dreams that rework the same underlying issues and try out different imaginative solutions to a common problem. In addition, Raskolnikov's dream in which a horse is beaten to death (and which draws on a memory from Dostoevsky's childhood that he later called "my first personal insult") presents another version of the central emotional issues of the novel. I predict that even readers who are skeptical of psychoanalytic approaches to literature will come away with a keener sense of the psychological coherence of the novel and a greater appreciation of its emotional power.

After the chapters on *Crime and Punishment* and its connection with Dostoevsky's life, Breger focuses on the life, using the novels primarily as evidence for the author's emotional biography. Breger discusses Dostoevsky's family, his stay at the Academy of Military Engineering, his early success as a novelist and the nervous breakdown it helped to precipitate, the political "conspiracy" for which he spent 10 years in Siberia as a prisoner and a soldier, his first, unhappy marriage, his return to St. Petersburg and the literary scene, his epilepsy and compulsive gambling, the death of his first wife, and his second, happy marriage. The appendix on epilepsy is particularly persuasive, but all of Breger's interpretations merit consideration.

I find myself wondering about one of the book's major contentions—that

Letters

writing gave Dostoevsky insight into his own emotional issues and that this insight was essential to his growth as a novelist and a person. To my mind there is no doubt that Dostoevsky the novelist was an unusually insightful psychologist, but that does not necessarily mean that he was insightful about his own personality. I agree that Dostoevsky created characters who embody different aspects of his psychological conflicts and set them free to live out their lives; to what degree he understood and learned from this process seems to me an open question. Furthermore, I think Breger attaches too much importance to Dostoevsky's self-analysis through writing and not enough to his second marriage. For example, Dostoevsky's compulsive gambling didn't stop after writing *The Gambler*; it stopped after his wife's acceptance of his gambling or rather her acceptance of and continued love for him despite the difficulties caused by his gambling. Of course, what makes people grow, both in and out of psychotherapy, is an immensely complicated and controversial question, and it may well be that writing had a good deal to do with the change for the better that many perceived in Dostoevsky after his second marriage. But even though I would put the emphasis elsewhere, I warmly recommend *Dostoevsky: The Author as Psychoanalyst* not only to those interested in Dostoevsky but to anyone interested in the relation between a writer's life and works.

G. W. Pigman III
Associate Professor of Literature

EDITOR:

The Winter 1990 issue featuring the Loma Prieta earthquake is a masterpiece. It interested me for several reasons. My Master's Degree research and thesis was a primitive study of the response of buildings to earthquakes and other vibrations. The first six years of my engineering career was working in the California State Bridge Department, now part of Caltrans, and I knew some of the engineers who built the San Francisco Bay Bridge. Professor R. R. Martel was the one who inspired me to make structural engineering my specialty, and awakened my interest in earthquakes. Most of all, friendship through many years with George Housner and Don Hudson made this magazine fascinating reading.

James H. Jennison, BS '35, MS '36

EDITOR:

I am writing to ask whether you are planning a special article in *E&S* this fall to commemorate the founding of JPL on its 50th anniversary. If so, I might contribute a few recollections. Frankly, the whole business had slipped my mind, until I recalled it last night while reading the recently received Winter issue of *E&S*. I don't know why it prompted me to recall it, but I did. I was one of the four "regular" employees of the newly started project, which had a hush-hush name. The name was hush-hush for avoidance of questionable publicity about the Buck Rogers group at Caltech, not for military security reasons.

I guess I was employee number one at the newly acquired acreage in the wash of the canyon near Oak Grove Park. I was left there all alone one day, I think it was September 1940, and I was told to cut the grass so that a slab could be laid to start construction of a shed (unheated, unlighted), in which a gaseous fuel rocket apparatus (5-lb. thrust) could be tested; and because the terrain was rocky, I was given a scythe to cut the weeds, not a lawn mower. Being a newly minted physicist and not a mechanical engineer, I had to first learn how to swing a scythe, but I learned, and the grass (weeds) was cut properly and the slab was poured successfully.

Martin Summerfield, MS '37, PhD '41
President, PCRL, Inc.
Professor Emeritus, Princeton University

E&S *commemorated the beginning of JPL in the November 1986 issue—50 years after the first test-firing of a liquid-fueled rocket motor in the Arroyo Seco near the future site of JPL—Ed.*

E&S *welcomes letters from readers in response to material appearing in the magazine. We will publish relevant letters as space permits, but reserve the right to edit for length and clarity. Letters should be sent to* E&S, *Caltech 1-71, Pasadena, CA 91125.*

John Seinfeld

Lew Allen

E&AS Chairman

John H. Seinfeld has been designated chairman of the Division of Engineering and Applied Science, subject to approval by the board of trustees. He succeeds Paul C. Jennings, who was named provost last November.

Seinfeld, the Louis E. Nohl Professor and professor of chemical engineering, has been a member of the Caltech faculty since 1967, when he came here as an assistant professor. He has also been executive officer for chemical engineering since 1974. His research has focused on the physics and chemistry of air pollution and on formation and dynamics of atmospheric aerosols.

JPL Director to Retire

Lew Allen, who has been Caltech vice president and director of the Jet Propulsion Laboratory since 1982, plans to retire on September 30, 1990.

The board of trustees has established a search committee for a new JPL director, which will be chaired by Caltech trustee Robert Anderson, chairman emeritus of Rockwell International Corporation. Also serving on the committee are Richard M. Ferry, president of Korn/Ferry International and a Caltech trustee; Albert D. Wheelon, retired chairman and chief executive officer of Hughes Aircraft Company and a Caltech trustee; David W. Morrisroe, vice president for business and finance and Caltech treasurer; Arden L. Albee, professor of geology and dean of graduate studies; Fred E. C. Culick, professor of mechanical engineering and jet propulsion; and Duane F. Dipprey, assistant laboratory director at JPL.

Allen's tenure at JPL saw the successful completion of the Infrared Astronomical Satellite and the Voyager 2 encounters with Uranus (1986) and Neptune (1989). Under his directorship two new missions have been launched recently—the Magellan spacecraft to Venus and the Galileo mission to Jupiter. Another significant development has been the establishment of the Center for Space Microelectronics Technology. "The last eight years at JPL have been marked by a spirit of resiliency, and the last year has been hugely successful," said Caltech President Thomas E. Everhart. "We are indebted to Lew Allen for his leadership."

Watson Lectures

Still to come in the Earnest C. Watson Lecture Series for the remainder of this term are: *April 18:* Micromotors and Micromachines: A Small World—Yu-Chong Tai, assistant professor of electrical engineering; *May 9:* Travels Along the DNA Helix—Jacqueline K. Barton, professor of chemistry; *May 23:* Forecasting Large Earthquakes and Their Effects in Southern California—Kerry E. Sieh, professor of geology.

Beckman Institute recently emerged from behind a mountain of earth (excavated for the building's two-story depth) partially blocking the view from the west. Some work remains to be done—the sidewalk is being poured here at the end of March—and researchers plan to move in this summer. The institute will house several resource centers devoted to breaking new ground in fundamental research in chemistry, biology, and related sciences.

Honors and Awards

Lew Allen, Caltech vice president and JPL director, received the Robert H. Goddard Memorial Trophy, the premier award of the National Space Club for "great achievement in advancing space flight programs contributing to US leadership in astronautics."

Caltech President Thomas E. Everhart was awarded an honorary doctor of law degree by Illinois Wesleyan University and was also named the 1990 recipient of the Presidential Science Award, presented annually by the Microbeam Analysis Society in recognition of significant contributions to microanalysis and microscopy.

Three faculty members have been elected fellows of the American Association for the Advancement of Science: William A. Goddard, the Charles and Mary Ferkel Professor of Chemistry and Applied Physics; Howard Lipshitz, assistant professor of biology; and Elliot M. Meyerowitz, professor of biology.

Harry B. Gray, the Arnold O. Beckman Professor of Chemistry and director of the Beckman Institute, has been selected to receive the 1990 Gold Medal of the American Institute of Chemists.

Five assistant professors (the most of any institution this year) are among 90 outstanding young scientists named Sloan Fellows for 1990 by the Sloan Foundation for "exceptional promise to contribute to the advancement of knowledge." Each will receive $50,000 over the next two years in nonrestricted research support. They are Ursula Hamenstadt (mathematics), Andrew G. Myers (chemistry), E. Sterl Phinney (theoretical astrophysics), Nai-Chang Yeh (physics), and Kai Zinn (biology).

John J. Hopfield, the Roscoe G. Dickinson Professor of Chemistry and Biology, was the 1989 winner of Harvey Mudd College's $20,000 Wright Prize for interdisciplinary studies in science and engineering.

Professor of Physics H. Jeff Kimble was a co-winner of the 1989 Einstein Prize for Laser Science, for his "pioneering contributions to the physics of light squeezing."

Rudolph A. Marcus, the Arthur Amos Noyes Professor of Chemistry, has been awarded the Theodore William Richards Medal for Conspicuous Achievement in Chemistry by the Northeastern Section of the American Chemical Society.

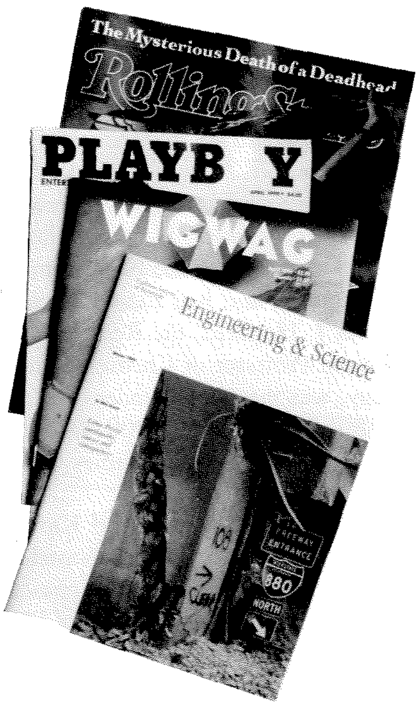
Dimitri A. Papanastassiou, senior research associate in geochemistry, has been elected a fellow of the American Geophysical Union, an honor limited to less than one percent of the total membership.

John H. Schwarz, the Harold Brown Professor of Theoretical Physics, is one of 13 distinguished scholars to be named a Phi Beta Kappa Visiting Scholar for 1990-91.

Along with the entire Voyager team, Edward C. Stone, professor of physics and vice president for astronomical facilities, is the 1989 recipient of the Aerospace Laurels Trophy, awarded by *Aviation Week and Space Technology* magazine. Stone was also co-recipient of the 1990 National Space Club Science Award.

Random Walk
continued

A party of 72 from the Caltech Alumni Association (including Barclay Kamb as guest lecturer) participated in a travel-study trip to Antarctica in February 1989. Here a group of them cruises in for a closer look at the ice off the Antarctic Peninsula.



Hey, That's Us!

E&S hanging out with the likes of *Rolling Stone, Playboy,* and *Wigwag*? An article about current issues of magazines, including the above, in the March 8 *Los Angeles Times* (under a subhead entitled "Read Them or Weep"), advised: "Before you shake off the last earthquake, pick up Caltech's *Engineering and Science* quarterly. The winter issue features an excellent scientific overview, in full color, of Northern California's Loma Prieta quake and other earthquake features, including a sobering look at liquefaction." (In case anyone is offended by the company we've been keeping, we would like to note that the article the *LA Times* highlighted in *Playboy* was an interview with theoretical physicist Stephen Hawking.

Four New Chairs Filled

Four new professorships have been established and designated. Don L. Anderson has been named the first Eleanor and John R. McMillan Professor. McMillan, BS '31, recipient of a Distinguished Alumni Award and former president of The Caltech Associates, established the professorship in memory of his wife. Anderson, professor of geophysics, is also an alumnus (MS '58, PhD '62) and has been a member of the Caltech faculty since 1962 and director of the Seismological Laboratory from 1967 to 1989. His research focuses on studies of the deep interior of the earth.

Robert H. Grubbs is the first Victor and Elizabeth Atkins Professor of Chemistry. The chair was established through a gift by Caltech trustee Victor Atkins and his wife, who are also contributing life members of The Associates and members of the President's Circle. Grubbs has been a professor at Caltech since 1978. His work is in the field of synthetic polymers—a class of materials that includes plastics and many other widely used synthetic substances.

Barclay Kamb will hold the first Barbara and Stanley R. Rawn, Jr., Professorship. Rawn is also a Caltech trustee, and he and his wife are life members of The Associates and members of the President's Circle. Rawn and Kamb were classmates at Caltech (BS '52). Kamb (PhD '56) joined the faculty in that year and became professor of geology and geophysics in 1963. He was chairman of the Division of Geological and Planetary Sciences from 1972 to 1983 and served as vice president and provost from 1987 to 1989. His current research focuses the dynamics and physical properties of glaciers and of Antarctica's ice streams; an article on the latter starts on page 4 of this issue.

The first Linus Pauling Professor of Chemical Physics is Ahmed H. Zewail. Zewail, who joined the Caltech faculty in 1976, has pioneered the development of ultra-fast laser techniques for recording the behavior of molecules during chemical reactions, a process that occurs in femtoseconds. His work has enabled scientists to witness for the first time the instant of a molecule's creation. Caltech established the chair to honor Pauling (PhD '25), two-time Nobel laureate and a member of the Caltech faculty from 1926 to 1971. He has been professor emeritus since that time.