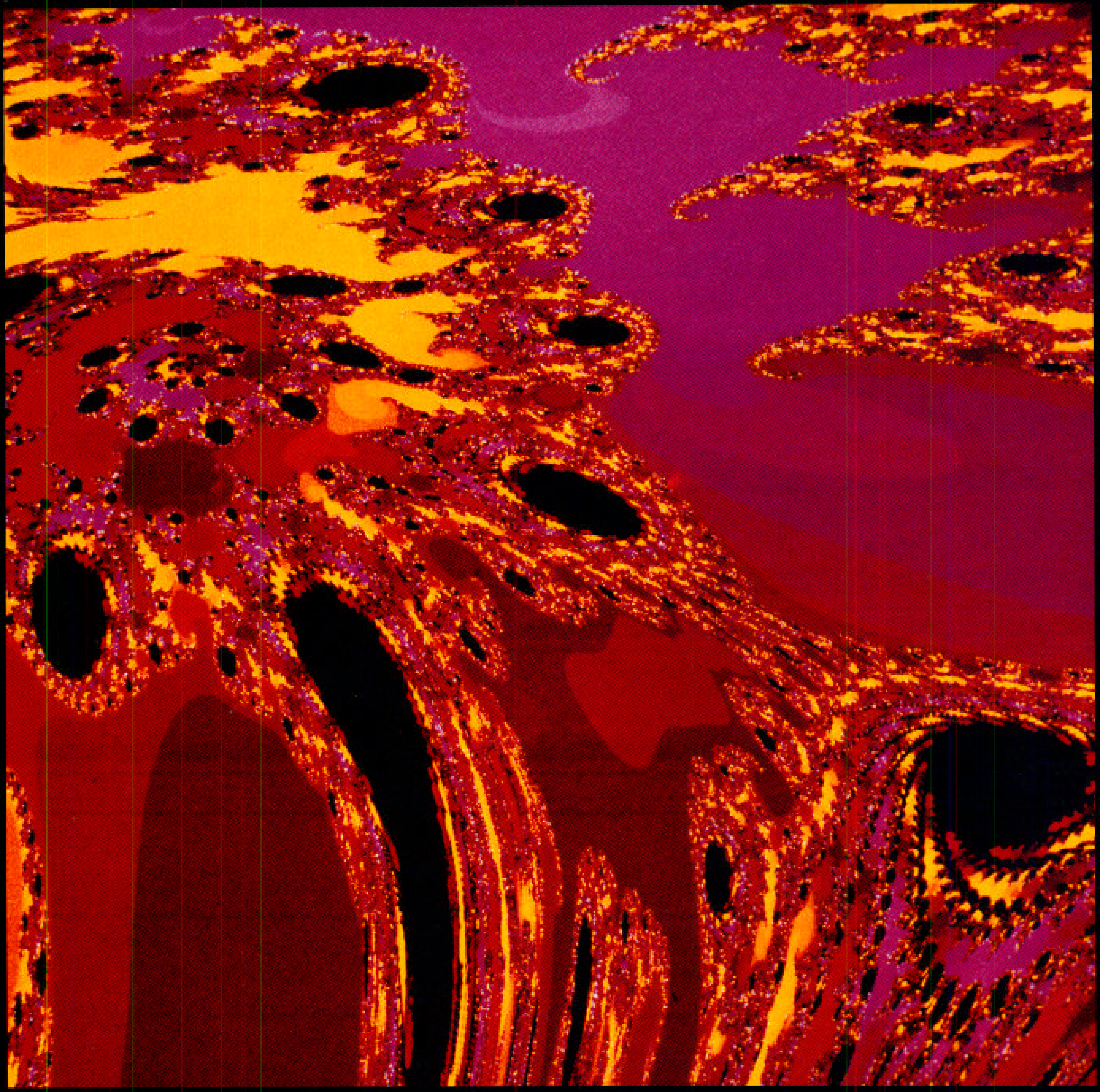
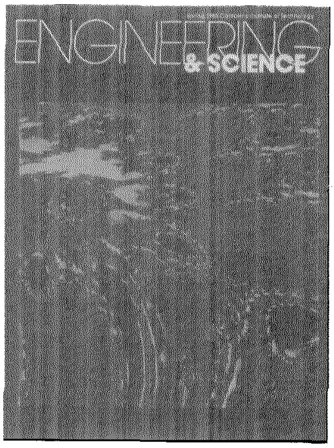
Spring 1988 California Institute of Technology

# ENGINEERING & SCIENCE



# In This Issue



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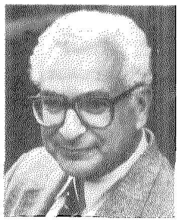
**Art or Mathematics?**
On the cover—a plane section through a four-dimensional generalized Mandelbrot set, often better known as a fractal. Benoit B. Mandelbrot, MS '48, Eng '49 in aeronautics, who recently received a Distinguished Alumni Award, generously contributed this cover illustration because, he said, "Since this award gave me surprise and pleasure, I would like to provide surprise and pleasure to my fellow alumni."

Mandelbrot, the inventor of fractals, also coined the word for this "geometry of nature" from a Latin root meaning fractured or fragmented, hence irregular. Through fractals Mandelbrot demonstrates the beauty inherent in "some of the most austerely formal chapters of mathematics"—a complex beauty that can be enjoyed purely as art.

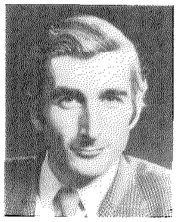
But is it complex? In "Simplicity and Complexity in the Description of Nature," Nobel laureate Murray Gell-Mann uses a more familiar version of the Mandelbrot set as a starting point for defining these terms and discussing how scientific theory seeks to organize, or reduce, the often random richness of natural detail into a hierarchy of basic laws. (Fractals, he notes, although they can be generated by a simple rule, are also connected in interesting ways to chaos.)

When Gell-Mann won the Nobel Prize in Physics in 1969, he was described as having "contributed probably more than anyone toward bringing order out of chaos" with his "eightfold way" of classifying the ever-increasing number of elementary particles. He also came up with the theory, and name, of quarks, the building blocks of elementary particles and, with others, constructed the theory of quantum chromodynamics. Gell-Mann is the Robert Andrews Millikan Professor of Theoretical Physics at Caltech, where he has been a member of the faculty since 1955. He earned his BS from Yale in 1948 and PhD from MIT in 1950. His article, which begins on page 2, was adapted from an address to The Caltech Associates at their black-tie dinner last October 1.



**Cosmic Clumps**
In "Why Do Galaxies Exist?," beginning on page 10, astrophysicist Martin Rees summarizes recent research in cosmology and discusses how, if matter was indeed originally distributed evenly throughout the cosmos, the aggregations of stars that we know as galaxies might have condensed out of the Big Bang.

Rees is the Plumian Professor of Astronomy and Experimental Philosophy (since 1973) and director of the Institute of Astronomy (since 1977) at Cambridge University, where he also received his BA, MA, and PhD degrees. He had previously come to Caltech as a research fellow in 1968 and as visiting associate professor of astrophysics in 1971.



The purpose of his most recent visit, in January, was to deliver the 11th Charles and Thomas Lauritsen Memorial Lecture, from which this article is adapted. The Lauritsen Memorial Lecture commemorates two former professors of physics, father and son, who served Caltech for a total of more than 68 years. It's particularly appropriate that many of the advances in astrophysics that Rees considered in his lecture came out of Kellogg Laboratory, founded by Charles Lauritsen in 1931.

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# ENGINEERING & SCIENCE

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**Interesting Times in Geophysics** — *by Robert Finn* *Page 23*
Varying interpretations of data from new techniques for exploring the Earth's interior yield complexity and controversy.

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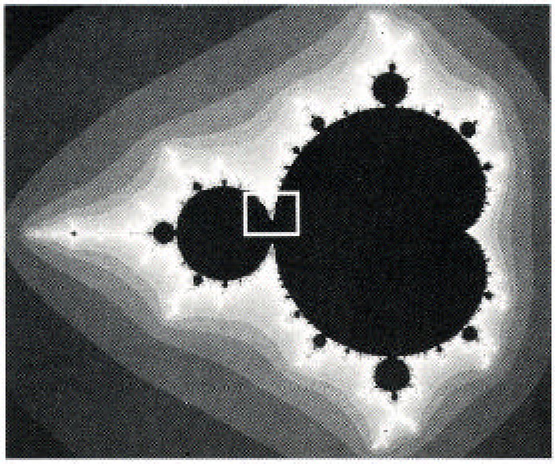
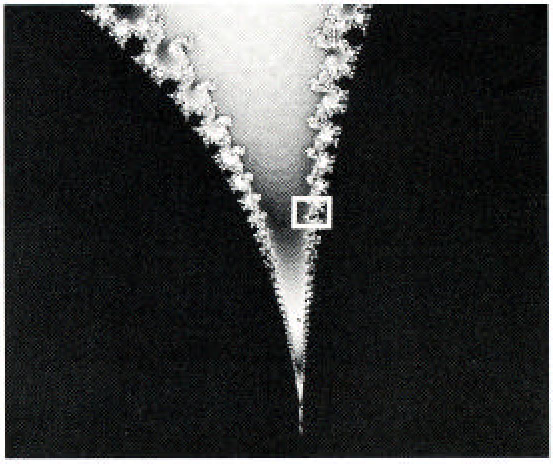
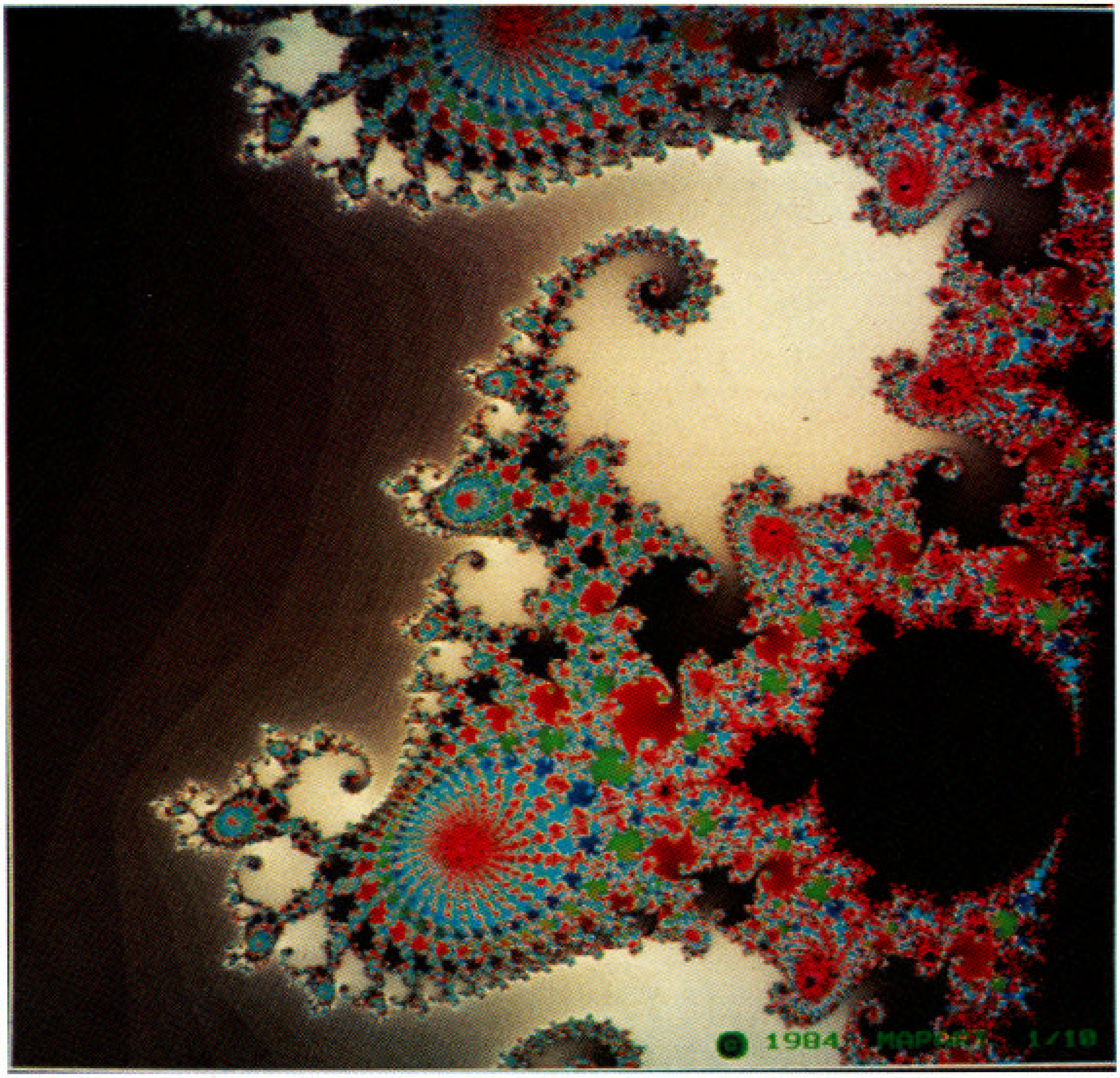






Fractal illustrations pp.2-8 © H.-O. Peitgen, P.H. Richter, *The Beauty of Fractals*, Springer-Verlag, 1986.

# Simplicity and Complexity in the Description of Nature

*On October 1, 1987, the day this talk was delivered to The Caltech Associates, a 5.9 earthquake rattled Pasadena.*

*by Murray Gell-Mann*

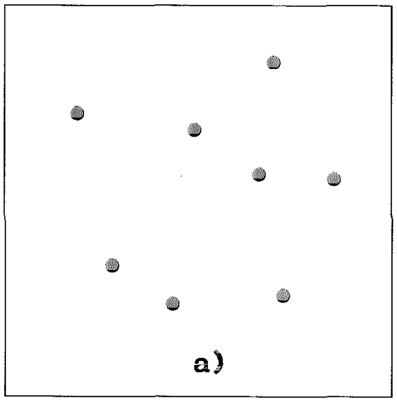
In presenting the picture of a fractal, I had hoped to show many of you something new. But in one of my rare moments of watching the idiot box, while riding my exercise bike, I noticed the same picture in an advertisement for IBM boasting of the achievements of their man, Caltech alumnus Benoit Mandelbrot.

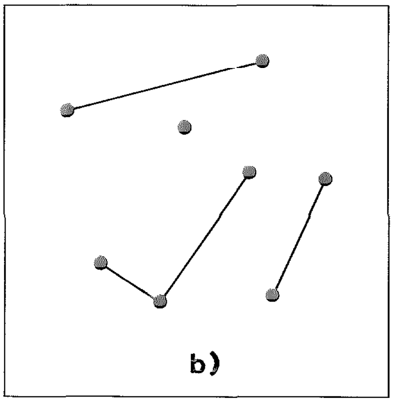
If you look carefully at the fractal on the opposite page, you can notice its remarkable self-similarity—that is, the gross structure is composed of structures of the same kind in minature. On the following pages you can see that those smaller structures are made up of still smaller similar structures and so on further down in scale.

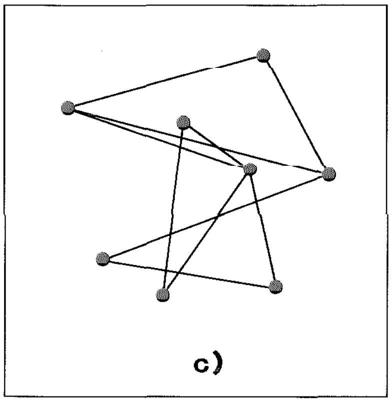
Is this fractal a simple system or a complex one? What do the concepts of simplicity and complexity mean, and, in particular, what do they mean in terms of scientific theory? In the description of nature, does deep simplicity always underlie apparent surface complexity? To what extent is the so-called reduction of each level of scientific description to a more basic level possible? When it is possible, to what extent is it a good strategy to pursue?

In the science of ecology, a debate has been going on for decades over whether complex ecosystems like tropical forests are more robust than comparatively simple ones such as the forest of oaks and conifers near the tops of the San Gabriel Mountains—robust, that is, with respect to major perturbations from climate change or fire or other environmental alterations wrought by nature or human activity. Currently those ecological scientists seem to be winning who claim that, up to a point, the simpler ecosystem is more robust. But what do they mean by simple and complex? To arrive at a definition of complexity for forests, they might count the number of species of trees (less than a dozen near the tops of the San Gabriels compared to several hundred in a tropical forest); they might count the number of species of birds, mammals, or insects. (Just imagine the number of kinds of insects in a tropical forest, and note that the estimated number has recently been revised sharply upward as a result of new experiments in which all the insects in a tree are killed and identified.) The ecologists might also count the interactions among the organisms: predator-prey, parasite-host, pollinator-pollinated, and so on. Down to what level of detail would they count? Would they look at microorganisms, even viruses? Would they look at very subtle interactions as well as the obvious ones? Clearly, to define complexity you have to specify the level of detail that you are going to talk about and ignore everything else—to do what we call in physics "coarse-graining."

For example, let us take a parallel-processing computer network such as that being developed by Geoffrey Fox, professor of theoretical physics, Charles Seitz, professor of computer science, and others. Because it is made up of individual computers linked together, they may ask what is a simple and what is a complex pattern of hooking up the constituent computers. We can "coarse-







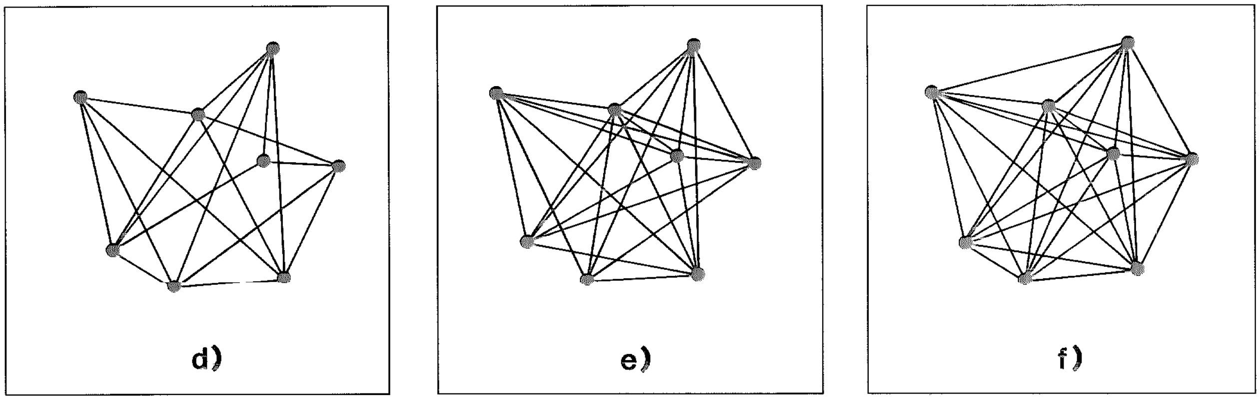
grain" by ignoring any directionality in the links and any differences among them; we can also ignore the identities of the individual computers and their geometric arrangement. Then we get a mathematical system that we can represent simply as an unlabeled bunch of dots, with the positions of the dots not significant. What are simpler ways of connecting, say, eight dots and what are more complex ways? (Actually, complexity is important only when there are lots of individual units, but let's just imagine that eight is a lot.) First we have a pattern a) with nothing connected; that's obviously very simple. We can connect a few dots with one another and still get a fairly simple pattern b). Then we can add more and more links (c, d, and e) until finally we have a pattern f) where all possible connections are made: every point is connected to every other point. An interesting question to ask is whether the pattern with all the dots connected is more complicated than the pattern with no connections. They are similar in that they are opposites of each other. Likewise, b) and e) are opposites and c) and d) are opposites in the sense of interchanging linked and unlinked pairs of dots: two dots that are linked in c) are unlinked in d) and vice versa, etc.

We have discussed examples of what might be simple or complex, but we still don't have a definition. We could try to use as a definition the length of the message that describes the system under discussion. If it's described by a very long message, then, roughly speaking, it would be complex; if it's described by a very short message, it would be simple. But we don't want the message to be what's called an ostensive definition, that is, just pointing to something; it has to be a real description, suitable for distant correspondents. Likewise, we don't want to be able to simplify the message artificially just by calling the thing we are talking about by some pet name. We can call the most complicated thing in the world "Sam"—a very short message indeed. So if we want to define in a serious way the complexity of something, we have to agree beforehand on some grammar and vocabulary for its description. Then it's a question of whether in terms of this particular grammar and vocabulary the message describing the thing is long or short. Finally, the definition shouldn't depend on how clever we are at writing a short message; thus we should use the length of the shortest message that will describe the system for distant correspondents using given vocabulary and grammar.

About 20 years ago some mathematicians, including Gregory Chaitin in the U.S. and A.N. Kolmogorov in the Soviet Union, came up with such a definition for ideal complexity. They gave it a slightly more mathematical form and used it in a mathematical context, but it amounts to what I have described above—the minimum length of a message describing a system up to a given level of detail to a distant observer using a given grammar and vocabulary. In the language of computer science, one can speak of the shortest computer program that will cause a particular type of general-purpose computer to print out the description and then stop.

Now this ideal complexity is by no means the only notion of complexity that is needed, but it is a useful one, even though it has some strange properties, as we shall see.

Suppose we consider a message reduced to a string of digits. Sometimes that message can be compressed, that is, replaced with a shorter one with the same meaning. (That's why it is the minimum length of the message that defines the complexity.) Suppose the message is 57575757575757575757575757575757575757. We can shorten this message



to "57 repeated 20 times." If the message is "3.141592 . . ." to 250 places, which we recognize as the first 250 digits of π, then we can shorten the message by calling it "π to 250 digits." Thus, when we talk about the minimum length, we mean that all possible compressions of the message have been found and used.

Actually, it can be proved that there is no finite procedure for finding all the compressions. You can never be sure that you've found all the different tricks for shortening a message. Hidden in some math book that you didn't know about, or that hasn't been written yet, or that never will be written, there might be a theorem that would let you compress the message further. Thus the definition has a peculiar flaw in it. Although you can sometimes show that a thing is simple by demonstrating that it can be described by a short message, you can never show for sure that another thing is complex and requires a long message, because an undiscovered way of shortening that message may still exist.

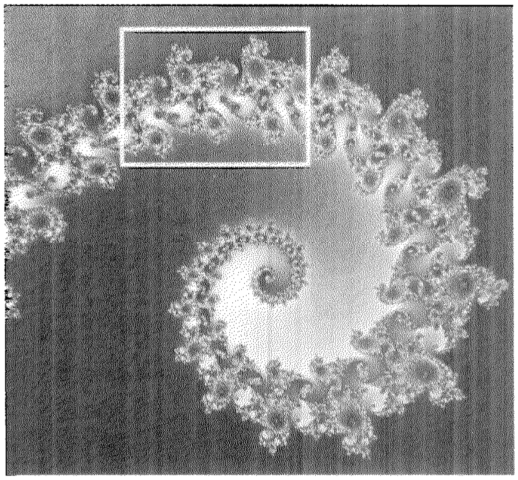
Mathematicians have shown that most long strings of digits have the property of being nearly incompressible (those are called random strings), but we will never know which ones.

We can now go back to the different ways of linking computers, or else dots in a diagram. We see that, from the point of view of ideal complexity, the opposites, such as "all links" and "no links," are about equal in complexity because the shortest messages for the opposites can just have "link" and "no link" interchanged. In the limit of a large number of dots, there will be no difference in complexity between opposites.

Now let us return to our fractal, and discuss how the picture is generated. Suppose that horizontal distance on the plane is measured by $x$ and vertical distance by $y$, so that every point on the plane is described by the pair of numbers $(x,y)$. We then consider the transformation

$$x \rightarrow x + x^2 - y^2, \qquad y \rightarrow y + 2xy$$

that takes each point into another point. We apply this transformation over and over to each point of the plane. If a given point keeps moving further and further from (0,0) under this procedure, without limit, then it is assigned a color, with the color depending on how fast it moves. If a point does not keep getting further and further from (0,0) without limit, then it appears as black. Since all the information you need to generate the fractal is this simple rule, the fractal is not complex at all from the point of view of ideal complexity. But ideal complexity does not take into account the time, the work, or the expense of generating the picture from the formula—or the difficulty of figuring out how to go back from the fractal to the simple rule that underlies it. (Clearly, other definitions of complexity need to be used from time to time.)



One way of writing a message is to express a system in terms of the sum of its parts. Suppose you try to describe a human body by looking at all the cells separately, then listing the properties of the cells and the way they are arranged in the body, and trying to identify the complexity of a human being with the sum of the complexities of all the cells plus the complexity of the arrangement. You end up with a value that is much too large because the cells are all related to one another. They have the same genes and in many cases a lot of the same chemical properties. They're *organized*, and in fact organization can be defined as the sum of the complexities of the parts and the complexity of the arrangement minus the complexity of the whole. Understanding the organization produces an enormous compression of the message describing the body.

The best way to compress an account of large numbers of facts in nature is to find a correct scientific theory, which we may regard as a way of writing down in concise form a rule that describes all the cases of a phenomenon that can be observed in nature. Stephen Wolfram (another Caltech alumnus) has emphasized this point. A scientific theory thus compresses a huge number of relationships among data into some very short statement. Of course, you need to study for a while to learn how to read that statement.

For example, my father, as a layman, struggled to understand Einstein's general theory of relativity. On one occasion he said, "You know, Einstein's equation in free space is awfully simple. All it says is that $R_{\mu\nu} = 0$, but I have to understand better what $R_{\mu\nu}$ is."

The point is that the lengths of the texts you have to study are finite, and the number of facts described by a successful scientific law is indefinitely large. Thus the complexity of what you have to learn in order to be able to read the statement of the law is not really very great compared to the *apparent* complexity of the data that are being summarized by that law. That apparent complexity is partly removed when the law is found.

Let us take Maxwell's equations for the classical electromagnetic field as an example. When they were discovered, more than a century ago, it became possible to calculate, in principle, the electric and magnetic fields in a volume of space if the conditions on the boundary of that volume were known. Thus the apparent complexity of the fields throughout the space was reduced to the lesser complexity of the boundary conditions. That is typical of what happens when a correct scientific theory makes its appearance. Great quantities of data are explained, but they are explained in terms of the particular circumstances under which the theory is applied—those circumstances must still be specified.

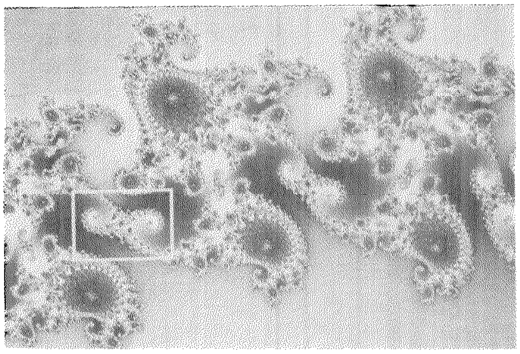
The various laws of nature can be classified according to the level at which you are studying nature. Are you studying it at the most basic level of the fundamental laws of physics? Are you studying it at the level of the rest of physics and chemistry, or the level of some branch of biology, or the level of psychology, or the level of social science, or what? We may recall that in the 19th century Auguste Comte established an order of scientific subjects: mathematics, then physics, then chemistry, then physiology, and so forth; I am told that until quite recently the faculty of sciences at a French university would discuss business in that order. (The concerns of the biologists must have been somewhat neglected as a result.)

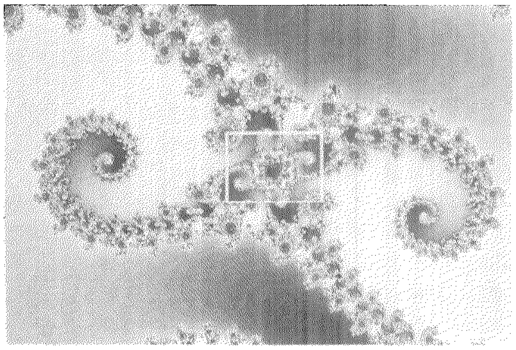
I've spent most of my career working on the most basic level, that of the fundamental laws of physics. Those have a special simplicity, as in Einstein's theory, even though, as we remarked, it takes a little while to learn what the equations mean. We seek two basic principles that underlie all of physics and chemistry. One of those is the unified theory of all the elementary particles (the constituents of all matter in the universe) and of all the forces among them. For the first time in history a likely candidate for such a theory has actually emerged—superstring theory, invented by John Schwarz, professor of theoretical physics here at Caltech, and his associates. It may even be correct.

Let us suppose that it is correct, that we have the fundamental theory of the elementary particles and their interactions; what else is there to describing nature at the most basic level? The other principle we need to know is a kind of boundary condition in time, the initial condition of the universe, the character of what is sometimes called the "big bang" that took place some 10 to 15 billion years ago. Is there a simple formula for it? If we believe that the fundamental law of the elementary particles might be described by some relatively simple equation like that of superstring theory, why not go further and conjecture that the initial condition of the universe might also be described in a simple way? A number of guesses at such a description have actually been made, starting with the one by Stephen Hawking of Cambridge University and James Hartle, a Caltech alumnus now a professor at UC Santa Barbara, in their classic paper "The Wave Function of the Universe," which gave a strong impetus to the field of quantum cosmology. Actually it is the simplicity of the early universe that is responsible for the "second law of thermodynamics" that describes the tendency of the entropy of the universe to increase with time. In layman's language, we are talking about the arrow of time that allows us to recognize whether a film of a macroscopic event, such as today's earthquake, is being shown forward or backward—if we see piles of bricks on the ground assembling into chimneys and perching on the tops of buildings, we know time is being made to run backwards.

Now suppose we know both of these fundamental principles, the theory of the elementary particles and the condition of the early universe. Then we have a complete formula that accounts for all the laws of physics and chemistry. Would that tell us in principle about the behavior of everything in the universe? No, it would not, because the theory is quantum-mechanical, and quantum mechanics gives only a formula for probabilities. Much is still up to chance. There are very many throws of the quantum dice in addition to these fundamental laws. And those unpredictable quantum fluctuations are responsible for many of the details of the particular universe that we experience. Quantum mechanics describes many possible universes, but we are interested in the details of *this one*, and a lot of those details depend on the throws of the dice and are not predictable from the formula, except probabilistically.

Even in the approximation of deterministic classical physics, there is the widespread phenomenon known as "chaos" (which is, by the way, connected in interesting ways with fractals). In a "chaotic" situation, the outcome is infinitely sensitive to the initial conditions, and thus, even in the deterministic classical approximation, prediction of details becomes practically impossible. The fundamental indeterminacy of quantum mechanics compounds the situation. Believe it or not, there was a recent editorial in the *Los Angeles Times* on this subject.

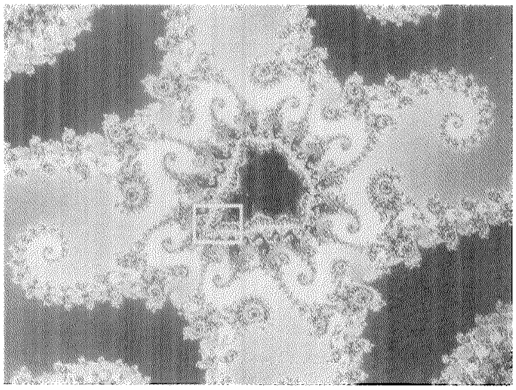


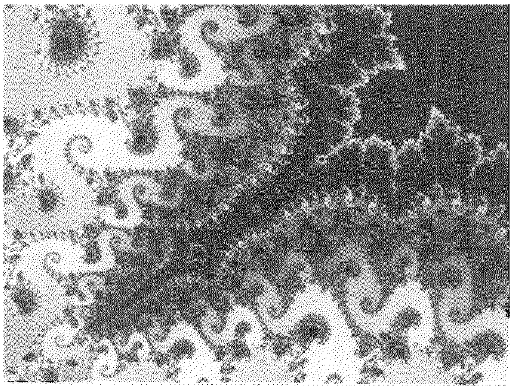


When we look beyond physics and chemistry to what we might call the environmental sciences (astronomy, geology and planetary science, biology, anthropology, human history, and so on), we are dealing with many kinds of detailed events that depend to some extent on inherently unpredictable fluctuations. Much of the information in those details cannot be determined from the fundamental underlying laws. There are patterns and correlations that can be so derived, in principle, but the rest of the information, idiosyncratic for this particular universe, is random and incompressible.

While the statistical distribution of galactic shapes and sizes may be derivable from elementary particle physics and quantum cosmology, the details of the structure of any particular galaxy, such as our own, must depend on particular chance events. Likewise, the detailed characteristics of the solar system are inherently unpredictable, and so are the details of the history of life on Earth. The specific events of human history, including the existence of particular individuals, also depend to a great extent on chance.

Typically, an object of study in the environmental sciences is a complex system, which, however, being organized, is less complex than the sum of its parts, and may be much less complex than it appears to be. Most scientists think that a certain minimum true complexity is needed in order to have life, with its characteristic features of reproduction, variation, and selection. Even more complexity is no doubt required for intelli-





gence, such as we human beings are alleged to possess.

Life may or may not be required by the fundamental principles of physical science to utilize DNA, with the same four nucleotides with which we are familiar; perhaps elsewhere in the universe there are other kinds of life. But even if all life in the universe has the same basic structure, surely the details of particular species that have evolved on the Earth, including our own, are idiosyncratic. In fact, in biological evolution there is an interesting interplay of *fundamental requirements*, *pure accidents* (probably including, for example, the choice of right-handed molecules over left-handed ones), and *survival of characteristics that are adaptive*. The same is true of many other evolutionary processes.

Today, the whole subject of complex adaptive systems, systems that exhibit random variation and selection resulting in learning or evolution, has become extremely exciting. It involves interdisciplinary research spanning a vast number of traditional fields, such as evolutionary biology; psychology and psychiatry, as well as the more fundamental level of neurobiology; linguistics; and many of the social sciences.

Computer science also comes into play, for example where it involves "genetic algorithms," as in the work of John Holland of the University of Michigan, who trains a computer to generate entirely new strategies for solving problems, strategies that no human being has ever developed. By introducing random "mutations" into his computer programs and arranging for the promotion of those parts of the programs that help to achieve a better strategy and the elimination of those parts of programs that get in the way, Holland causes strategies to be evolved in the computer much as life evolves on Earth.

Whereas Holland makes use of existing computers, there are other researchers who are trying to design new types of computers that are intrinsically adaptive in their mode of operation. Here at Caltech, for example, the program called "Computation and Neural Systems" emphasizes computers based on so-called "neural nets" and possible analogies with situations encountered in neurobiology.

The study of adaptive complex systems embraces these efforts in computer science and in neurobiology along with theoretical work, linked to experiment and observations, on such subjects as biological evolution, prebiotic chemical evolution, the operation of the immune system, learning and thinking in the higher animals including humans, and the evolution of human language. Most of these areas of research are now largely or wholly lacking at Caltech, but it is important to include them, because of the ideas and insights that each subject can contribute to the others. Remarkable parallels are starting to turn up in the search for general principles that govern adaptive complex systems.

I mentioned earlier that at every level there are characteristic scientific laws not only at the most fundamental level of elementary particle physics and cosmology, but in the rest of physics and chemistry, astronomy and planetary science, biology, psychology, and the social sciences. Is it possible in principle, and is it wise in practice to try to reduce each level of scientific description to some lower level? Most of us are of course reductionists in the sense that we don't believe that there are mysterious forces explaining chemistry that have nothing to do with physics; or mysterious "vital forces" that explain biology but don't depend on chemistry and physics; or mysterious mental processes responsible for psychology that are not biological, physical, or chemical in character. Nevertheless, we may still ask: Is a full reduction really possible, and as a strategy is it wise to rely on the reduction of one level of science to what seem to be more basic levels?

My own answer is no—for three reasons. First, one of the major activities of science is to build bridges between one level and the next—between the mind and the brain, for example, or between biology and chemistry, or between chemistry and fundamental physics, and so forth. Usually these bridges take a long time to build, and while we're building them, we still need to know about the subject that lies at the higher level of complexity. For instance, we can't wait for the bridge to be completed between geology on the one hand and chemistry and physics on the other, in order to learn about the behavior of the earth. We want seismologists to proceed as rapidly as possible in their work of explaining today's earthquake and not to have to wait until they can derive earthquakes from superstrings.

Second, when we elucidate the patterns that appear at each level of organization, we find that neat and useful laws emerge. Principles of psychology are found long before they can be explained by neurobiology; principles of anthropology are found long before they can be explained by psychology, let alone fundamental biology; and so forth. Furthermore, in building a bridge to the more basic levels of description, it's much easier to relate the laws of the higher level of organization, rather than a mass of raw data, to the laws at the lower level.

Third, there are fundamental limitations to the amount of reduction that can be carried out, even in principle, because of the indeterminacies—particularly the indeterminacy of quantum mechanics.

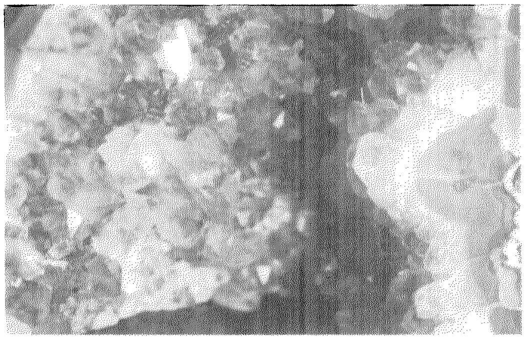
At each level of description, then, there are many important features of the world around us that are fundamentally unpredictable from the basic laws of physics but depend on the accidents of this particular universe. There are others that for practical reasons are difficult to derive from the laws at lower levels of organization. But there are patterns at each level of description that give the appropriate laws for that level, and I am suggesting that it is among those laws that one tends to find opportunities for practical reduction to more basic levels, with deep simplicity explaining away a great deal of the surface complexity.

There are, of course, many other patterns that can be reduced in principle but not in practice, at least in any reasonable time. But what of the random features that are impossible to reduce? In many cases they are of great scientific interest. For example, suppose it should turn out that life is possible without DNA chains made of the familiar four nucleotides. It is nevertheless very important for us on Earth that life does have that character here—even if it is a local law based on a local accident. Still more striking examples may occur in elementary particle physics, where it may turn out, even in parameter-free superstring theory, that there are various equally valid solutions to the equation, one of which is chosen by our universe. There would then be parameters after all with particular values in our universe. We would be dealing with "local" conditions that prevail throughout the whole universe, and elementary particle physics would, to some degree at least, join the environmental sciences.

Other random features, also of great scientific interest, may have the character of natural history rather than that of analytic science.

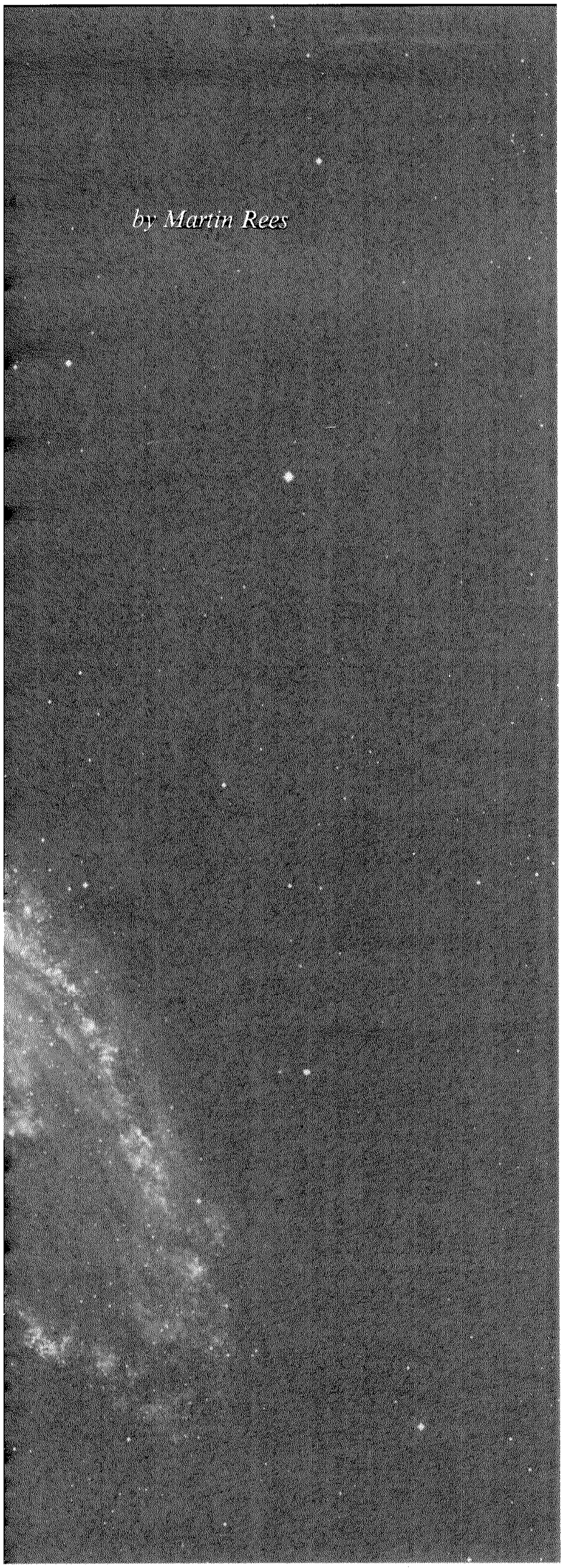
In still other cases, there will be random features of lesser interest to science as such, but nevertheless important in other ways, as the fascinating material that gives individuality to the different parts of the world around us— the details in the shape of a cloud, in the individual motions of the birds in a flock, in the appearance of the crystals of various minerals in a particular rock. Those individual details may not appear significantly in scientific laws at any level, but they give richness to our experience of the world, largely through the other, non-scientific modes of apprehending the universe, such as the artistic and aesthetic modes.

No matter how we try to describe the universe, through scientific research, through artistic creation, or through appreciation of its beauties, it exhibits a wonderful interplay of simplicity and complexity. □



# Why Do Galaxies Exist?

*The great spiral galaxy in Andromeda (M31), the closest galaxy to our own, is flanked by two elliptical galaxies—the fuzzy spots above (M32) and below (NGC 205).*



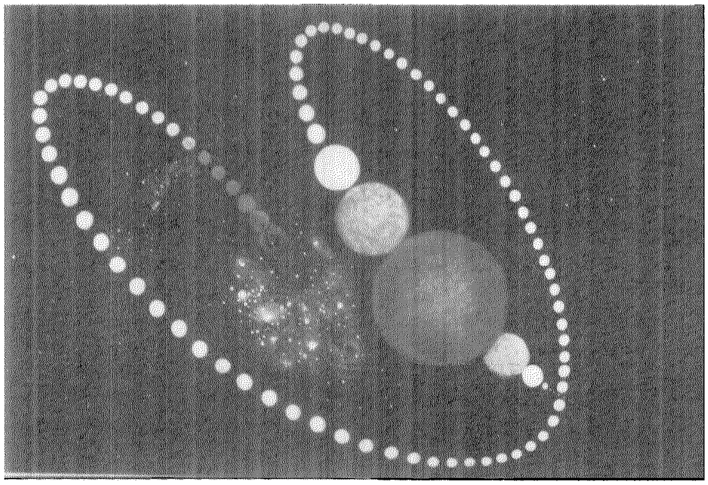
by Martin Rees

The universe has no center, but the universe of astronomers does. Ever since Hubble's time that center has been here in Pasadena, and it's therefore daunting, although an honor, to be invited from the periphery to speak to an audience here. I am further abashed because the honest answer I must give to the question of why galaxies exist is: I don't know. Nobody knows. But I'll try to describe why this isn't a presumptuous question to pose and summarize what current research programs tell us about what galaxies are made of, how they evolve and what may happen to them, and, more speculatively, what special features of the physical universe are necessary for their emergence.

In doing this I'll try to illustrate three of the intrinsic motives for doing astronomy. The first is just discovery—to find out what's there, be it in the solar system or in the remotest extragalactic realm. This vicarious exploration is something that a wide public can share. But to the astrophysicist it's preliminary to the second motive of understanding and interpreting what we see and setting our earth and our solar system in an evolutionary scheme traceable right back to the so-called Big Bang from which our entire universe emerged. Physicists have a third motive: the cosmos allows us to study how material behaves under far more extreme conditions than we can simulate terrestrially, and thereby to test the laws of nature to their limits and perhaps even find new ones.

Let's start, though, with something that's fairly well understood. The life cycle of a star like our sun begins as the sun condenses by gravitation from an interstellar cloud. It then contracts until its center gets hot enough to ignite nuclear reactions; fusion of hydrogen to helium then releases enough energy to keep the sun burning steadily. It's been going for about 4.5 billion years and has about another 5 billion to go before the hydrogen in its core is used up. It will then swell up to become a red giant, engulfing the inner planets, and ultimately settle down to a quiet demise as a white dwarf. Most stars we see are evolving in this way. Stars are so long-lived compared to astronomers that we only have in effect a single snapshot of each. But the fact that there are so many of them makes up for this, and we can check our theories, just as you can infer the life-cycle of a tree by one day's observation in a forest.

But not everything in the cosmos happens all that slowly. Stars heavier than the sun



*The life cycle of a star like our sun is illustrated here as a series of time-lapse pictures with 100 million years between successive frames. When the hydrogen in the core is used up, it will swell into a red giant and then die away quietly as a white dwarf.*

evolve faster, and some expire violently as supernovae. Supernova explosions signify the violent end point of stellar evolution, when a star too massive to become a white dwarf exhausts its nuclear fuel and then faces an energy crisis. Its core implodes, releasing so much energy gravitationally that the outer layers are blown off. Nearby supernovae are rare, and the astronomical event of 1987, which rated an eight-page cover story in *Time* magazine, was a supernova in the southern sky, the nearest and brightest by far of modern times. Its evolution is at the moment being closely monitored by all observational techniques.

Supernovae, even the nearest ones, may seem remote and irrelevant to our origins. But, on the contrary, it's only by studying the births of stars and the explosive way some of them die, that we can tackle such an everyday question as where the atoms we are made of came from. The respective abundances of the chemical elements can be measured in the solar system and inferred spectroscopically in stars and nebulae. And the proportions in which the elements occur display regularities from place to place—a fact that demands some explanation. Complex chemical elements are an inevitable by-product of the nuclear reactions that provide the power in stars. In fact, a massive star develops a kind of onion structure, where the inner, hotter shells are "cooked" further up the periodic table. The final explosion then ejects most of this processed material. All the carbon, nitrogen, oxygen, and iron on the earth could have been manufactured in stars that exhausted their fuel and exploded before the sun formed. The solar system could have condensed from gas contaminated by this ejected debris, and this process can account for the observed proportions of the different elements—why oxygen and iron are common, but gold and uranium are rare—and how they came to be in the solar system.

This concept of stellar nucleosynthesis originated with Sir Fred Hoyle and Willy Fowler (Nobel laureate and Institute Professor of Physics, Emeritus). Its detailed development is one of the outstanding scientific triumphs of the last 40 years. The work was spearheaded here in the Kellogg Lab, so it's perhaps appropriate to celebrate it on an occasion dedicated to the Lauritsens. This idea sets our solar system in a kind of ecological perspective involving the entire Milky Way Galaxy. The mix of elements we see around us isn't ad hoc but the outcome of transmutation and recycling processes, whose starting point is a young galaxy containing just the lightest elements. Each atom on earth can be traced back to stars that died before the solar system formed. Imagine a carbon atom, forged in the core of a massive star and ejected when it explodes as a supernova. This atom may spend hundreds of millions of years wandering in interstellar space before finding itself in a dense cloud that contracts into a new generation of stars. Then once again it could be in a stellar interior, or it could be out on the boundary of a new solar system in a planet, and maybe eventually in a human cell. As Willy Fowler likes to remind us, we are quite literally the ashes of these long-dead stars.

Theoretical studies of stars and their life cycles were stimulated by the challenge of observations. It's interesting that the properties of stars could have been deduced by a physicist who lived on a perpetually cloud-bound planet—or indeed by an *English* astronomer. He could have posed the question: Can one have a gravitationally bound fusion reactor, and what would it be like? And he'd reason as follows.

Gravity is extremely feeble on the atomic scale. In a hydrogen molecule, for instance, consisting of two protons neutralized by two electrons, the gravitational binding energy between the protons is feebler than the electrical energy by a factor of $10^{36}$. But any macroscopic object—an asteroid or a lump of rock—contains almost equal numbers of positive and negative charges, so that the electrical forces tend to cancel out. But there's no such cancellation of gravity. Everything has the same gravitational charge and attracts everything else, so gravitation becomes more significant for larger objects. Gravitational binding energy rises as mass divided by radius, and that means it rises a hundredfold for each thousandfold increase in mass. So gravity wins out over electrical energy on sufficiently large scales.

How large? Imagine that we were to assemble a set of bodies containing successively 10, 100, 1,000 atoms, and so on. The 24th of these would be the size of a sugar lump—about one cubic centimeter. The 39th would be like a kilometer of rock. Gravity starts off with a handicap of $10^{36}$; it gains as a two-thirds power, and when we get to our 54th object (54 being three halves of 36), gravity will have caught up with electrical energy. We then have an object the mass of Jupiter, and anything bigger than Jupiter will start getting crushed by gravity. To be squeezed by gravity and heated to the point where nuclear fusion could ignite, a body would have to be well over $10^{54}$ atoms.

So gravitationally bound fusion reactors must be massive because gravity is so weak. And having inferred this, the physicist could in principle calculate the entire life cycle of stars. In fact, Sir Arthur Eddington was the first person to express this argument clearly. He then said that "when we draw aside the veil of clouds beneath which our physicist is working and let him look up at the sky, there he will find a thousand million globes of gas, nearly all with masses [in this calculated range]."

Let's now enlarge our horizons to the extragalactic realm. It's been clear since the 1920s that our Milky Way is just one galaxy similar to millions of others visible to large telescopes. Galaxies are held in equilibrium by a balance between gravity, which tends to make the stars hold together, and the countervailing effect of the stellar motions, which, if gravity didn't act, would make the galaxies fly apart. In some galaxies, our own among them, the stars move in nearly circular orbits in giant disks. In others, the less photogenic ellipticals, we see stars swarming around in more random directions, each feeling the integrated gravitational pull of all the others.

Galaxies are the most conspicuous features of the large-scale cosmic scene. Self-gravitating assemblages tens of thousands of light years across, they typically contain about a hundred billion stars. Unfortunately we don't yet have an accepted explanation of what's special about their dimensions in the same sense that we do for stars. But there is a scenario that accounts qualitatively for why there are two basic types of galaxy—disks and ellipticals. Let's suppose that a galaxy starts life as a huge, turbulent, clumpy, slowly spinning gas cloud, contracting under its own gravitation and gradually fragmenting into stars. The collapse of such a gas cloud is highly dissipative in the sense that any two of the clumps that collide will radiate their relative energy by shock waves and will merge. The end result of the collapse of a rotating gas cloud will be a disk—the lowest energy state it can get to if it conserves its angular momentum.

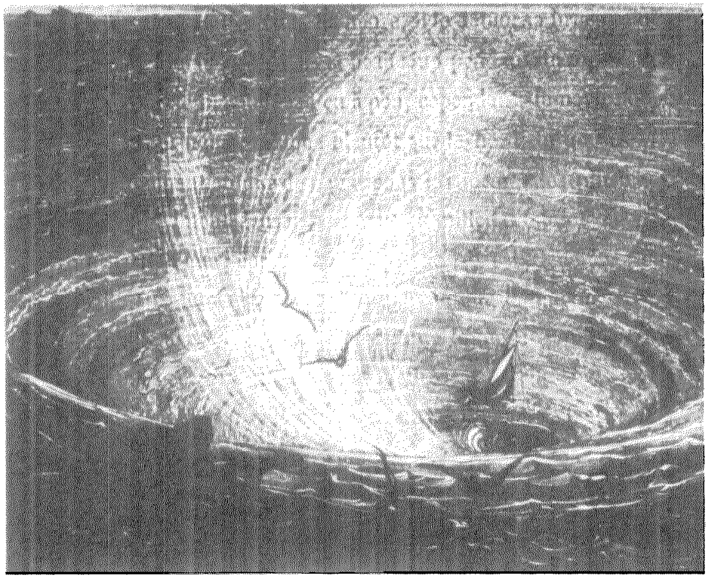
Stars, on the other hand, don't collide with each other, and can't dissipate energy in the same way as gas clouds. This suggests that the rate of condensation of gas into stars is the crucial feature determining the type of galaxy that results. Ellipticals will be those in which the conversion is fast, so that most of the stars have already formed before the gas has a chance to form a disk. The disk galaxies are those of slower metabolism, where star formation is delayed until the gas has settled into a disk. The origin of these giant gas clouds is a mystery—a cosmological question. But given these clouds, the physics determines that galactic morphology is nothing more exotic than Newtonian gravity and gas dynamics.

Some peculiar galaxies, though, which harbor intense superstellar activity in their centers, are much more than just a pile of stars. The most extreme are the so-called quasars, in which a small region no bigger than the solar system outshines the entire surrounding galaxy. In these objects the central power output exceeds a million supernova explosions going off in unison. It seems that gas and stars have accumulated in the center until some kind of runaway catastrophic collapse occurs. Gravity overwhelms all other forces, and a black hole forms. Here we do need somewhat more highbrow physics to know what's going on, in particular Einstein's theory of general relativity—that matter tells space how to curve and space tells matter how to move. Indeed, ever since such active galaxies were discovered, relativity specialists have been (in the words of Cornell cosmologist Tommy Gold) "not merely magnificent cultural ornaments, but actually relevant to astrophysics."

The rate of research progress over the 25 years since the phenomenon of active galactic nuclei was first recognized seems disappointingly slow. Sometimes we've had the illusion that it's rapid, but it's really been a rather slow advance with "saw-tooth" fluctuations imposed on it as fashions have come and gone. But there is now a fair consensus that the central prime mover in active galaxies involves a spinning black hole, as massive as perhaps a hundred million suns, fueled by capturing gas or even entire stars from its surroundings. This captured debris swirls in a flow resembling a whirlpool down into a central hole, carrying magnetic fields with it and moving at nearly the speed of light. At least 10 percent of the rest-mass energy of the infalling material could be radiated, and still more power could be extracted from the hole's spin. Some of us are hopeful that these ideas can be put on a firm basis just as our theories of stellar evolution have been, but we still have a long way to go.

If we can do this, we would have an opportunity to learn from a safe distance whether black holes really behave as theory predicts. In the vicinity of black holes space and time are thought to behave in highly nonintuitive ways. Time would stand still for an observer who managed to hover or orbit just outside a hole, and that observer could see the entire future of the universe in what was to him quite a short time. Even stranger things might happen inside the hole, but anyone who ventures there is trapped. So keep your distance unless your Faustian urge is overwhelmingly strong. No one inside the hole can transmit signals, so you would learn nothing by sending a student, even if you had an expendable one. If you really want to explore a black hole, then you should at least pick one of the monster ones in galactic nuclei. They are as large as an entire solar system and so, having passed inside, you'd at least have several hours for leisured if not relaxed observation before being discomforted by tidal forces and crushed in the central singularity.

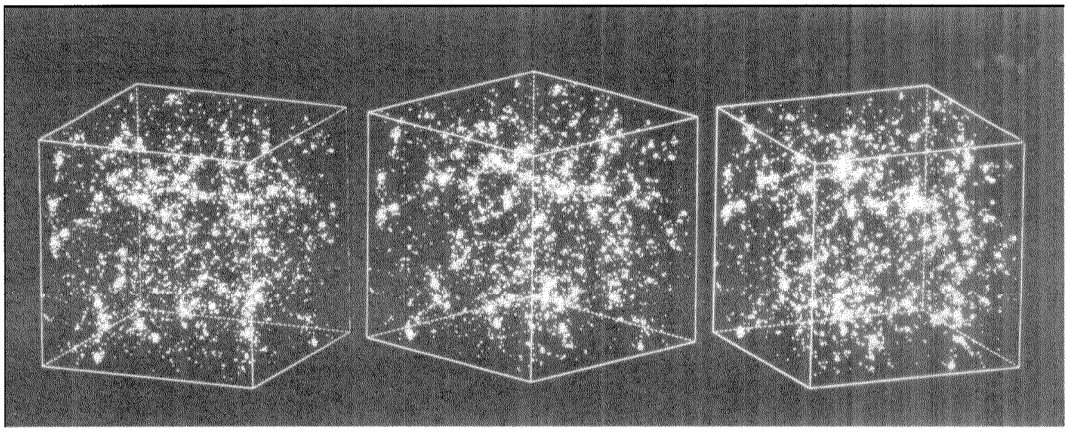
*The flow swirling into a black hole resembles a whirlpool like this illustration to Edgar Allen Poe's "Descent into the Maelstrom." As scientists grope for the right theory for galactic nuclei, they also have only a crude cartoon of what conditions are really like.*



Active galaxies are a bafflingly varied zoo, and we need more data on lots of samples to clarify their taxonomy. Violent central activity, whether it's a quasar or a strong radio source, is thought to be a relatively brief phase in a typical galaxy's life history. Dead quasars, massive black holes now starved of fuel, may lurk in the nuclei of many nearby galaxies. Recently the inner parts of some of these, including the Andromeda galaxy, have been studied accurately enough to infer that the stars very near the center are orbiting around a dark compact object, which at least answers the description of a black hole. As such it would be almost quiescent, but not quite. Now and again a star would wander so close to it that the tidal forces would rip the star apart. You would then see a flare persisting for as long as it took the debris from the star to be swallowed or expelled from the hole.

Let's turn now to cosmology, the description of our universe as a single dynamical entity. Cosmology is the study of a unique object and a unique event, by definition. No physicist would happily base his theory on a single unrepeatable experiment, and no biologist would formulate theories of animal behavior by looking at just one rat. But we can't check our cosmological ideas by applying them to other universes. Despite having all these things stacked against it though, scientific cosmology has proved possible because the observed universe in its large-scale structure turns out to be simpler than we had any right to expect.

It's natural to start off by making simplifying assumptions about symmetry, etc. And cosmologists did this. But what is surprising is that these models remain relevant and the simplifying assumptions have been vindicated. The intergalactic scales of distance are vast. To the cosmologist even entire galaxies are just markers or test particles scattered through space, which indicate how the material content of the universe is distributed and is moving. Galaxies are clustered; some are in small groups, like our local group of



*On a large scale the universe seems roughly homogeneous. A box with sides 100 million light years in length would hold quite similar contents no matter where in the universe it is plunked down.*

which the Milky Way and Andromeda are the dominant members. Others are in big clusters with hundreds of members. But on the really large scale the universe genuinely does seem smooth and simple. If you imagine a box whose sides are a hundred million light years, then the contents will be more or less the same wherever you plunk the box down. In other words, there's a well-defined sense in which the observable universe is roughly homogeneous above this scale.

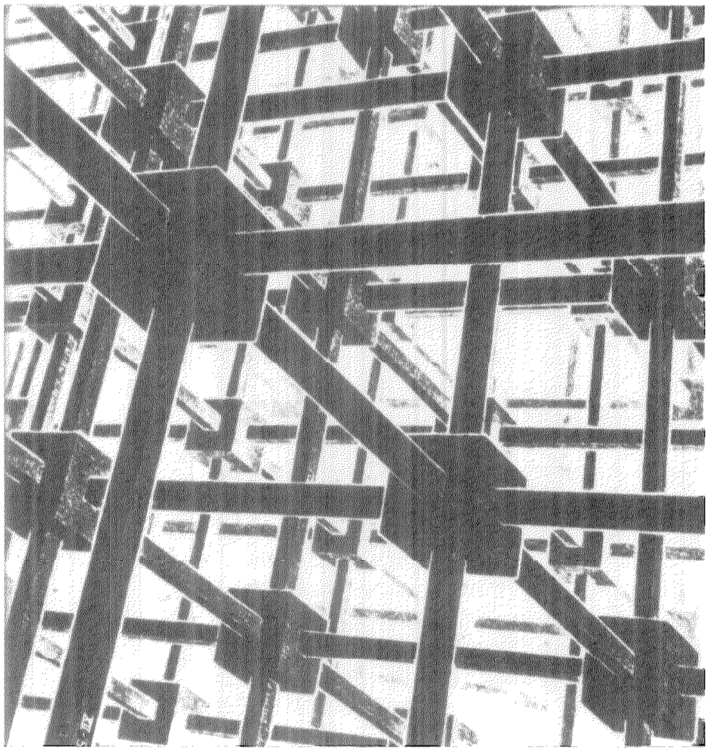
When we look out at the nearest 2,000 galaxies (that's out to a distance of 2 or 3 hundred million light years), they appear fairly uniform over the sky. And as we look at still fainter galaxies, probing greater distances, clustering becomes even less evident. This tells us that we are not in the kind of universe with clusters of clusters of clusters ad infinitum. Such a universe would look equally lumpy over the sky whatever depth you probed it to. So unless we are "anti-Copernican" and assign ourselves some sort of central position, the isotropy all around *us* implies that the universe must be roughly isotropic around *any* galaxy, that the universe is homogeneous, and that all parts have had more or less the same history.

The fox knows many things, but the hedgehog knows one big thing. Cosmologists are the most hedgehog-like of all scientists because their subject boasts very few firm facts, though each has great ramifications. The first such fact emerged in 1929 when Hubble enunciated his famous law that galaxies recede from us with speeds proportional to their distance. We seem to inhabit a homogeneous universe where the distances between any two widely separated pairs of galaxies stretch as some uniform function of time. This doesn't imply that we are in some central "plague spot," because an observer sitting in any other galaxy would see the same uniform expansion around him.

Hubble's work suggested that galaxies must have been crowded together at some time in the past, 10 or 20 billion years ago. But he had no direct evidence for a "beginning." The clinching evidence that there was a so-called Big Bang came in 1965 when Arno Penzias and Robert Wilson of Bell Telephone Labs detected the cosmic microwave background radiation. This was an accidental discovery. Their prime motive was a practical one—to communicate with artificial satellites. At first they didn't realize what they had found, but the excess background noise in their instruments could only mean that even intergalactic space wasn't completely cold. It's about 3 degrees above absolute zero. This may not sound like much, but it implies that there are about 400 quanta of radiation (photons) for every cubic centimeter. Indeed, there are about a billion photons for every atom in the universe.

There's no way of accounting for this radiation, its spectrum (roughly that of a blackbody), and its isotropy except on the hypothesis that it is indeed a relic of a phase when the entire universe was hot, dense, and opaque. Everything must have once been a very compressed and hot gas, hotter than the centers of stars. And although the intense radiation in this primordial fireball was cooled and diluted by the expansion, the wavelengths being stretched and redshifted, the radiation would still be around. After all, it fills the entire universe and has nowhere else to go.

This microwave background radiation is a relic of an era long before any stars or galaxies existed. We've come to believe that another such relic is the element helium, which would have been made from protons



A good analogy to the expanding universe is M.C. Escher's inifinite lattice, which would expand if all the rods lengthened at the same rate, and which has no center.

and neutrons during the first few minutes when the fireball was at a temperature of a billion degrees. Helium would have been made in just the proportion that astronomers now find by spectroscopic studies of stars and nebulae. And it's extraordinary that we can extrapolate back to such an early epoch on the basis of a simple theoretical model, assuming the laws of nuclear physics were the same as they are now, and account for the extremely high and uniform cosmic helium abundance.

More detailed work, much of it done here at Caltech, has firmed up the consensus that everything did indeed emerge from the hot Big Bang. Discrepancies could have emerged in the last 20 years, but none have done so. Still, this isn't yet a firm dogma. Conceivably, satisfactory proof is as illusory as it was for a Ptolemaic astronomer who had just fitted a new epicycle. Cosmologists are sometimes chided for being "often in error but never in doubt."

But, at the moment, the hot Big Bang model certainly seems far more plausible than any other equally specific alternative. Most of us therefore adopt a cosmogonic framework that looks like this: Stars and galaxies all emerged from a universal thermal soup. It was initially smooth and almost featureless—but not quite. There were (although we don't know why) small fluctuations from place to place in the expansion rate. Embryonic galaxies were slightly over-dense regions whose expansion lagged behind the mean expansion. And these embryos eventually evolved into disjoint clouds whose internal expansion halted. These protogalactic clouds then collapsed to make individual galaxies when the universe was perhaps 10 percent of its present age. Subsequently the galaxies would have grouped into clusters, a process that can be quite well simulated by n-body dynamical computer calculations.

The galaxies that Hubble observed were all within a few hundred million light years of us—relatively close compared to the distance we can now probe. But because of the large-scale homogeneity of the universe, Hubble got a fair sample of it. His classification of galaxies has survived and stood the test of time. But Hubble was acutely aware of observational limitations, and his great book, *The Realm of the Nebulae,* concludes with these words:

> With increasing distance our knowledge fades and fades rapidly. Eventually we reach the dim boundary, the utmost limits of our telescope. There we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial. The search will continue. Not until the empirical resources are exhausted need we pass on to the dreamy realm of speculation.

This search *has* continued as more powerful telescopes and detectors have been employed. Because light travels at a finite speed, we see distant parts of the universe as they were a long time ago. So we can sample the past even if we can't repeat it. To see any cosmic evolutionary trend one must look back in time by a good fraction of the 10-billion-plus years for which the universe has been expanding. The first person to do this was Sir Martin Ryle at Cambridge in the late 1950s. He found clear evidence that conditions were different when galaxies were young. His telescopes picked up radio waves from some active galaxies (the ones that we now think harbor massive black holes) even when these were too far away to be observed by the optical techniques of the time. He couldn't determine the distance by radio measurements alone, but he assumed that, at least statistically, the ones appearing faint were more distant than those appearing intense. He counted the numbers with various apparent intensities and found that there were too many faint galaxies (in other words, more distant ones) compared to brighter and closer ones. This was discomforting to those who believed in a steady-state universe, with whom Ryle was having a running battle at the time. But it was compatible with an evolving universe, if galaxies were more prone to violent outbursts in the remote past.

Optical astronomers joined this enterprise after the discovery of quasars in 1963. Quasars are hyperluminous nuclei of galaxies, and optical astronomers have now seen some so far away that the light set out when the universe had less than a fifth of its present scale. And it's also clear from quasars, as it was first from Ryle's data, that the cosmic scene was much more violent when galaxies were young. Most of the runaway catastrophes, the formation of great black holes, happened early in galactic history, when less gas was locked up in stars and more was still available to fuel the central monster.

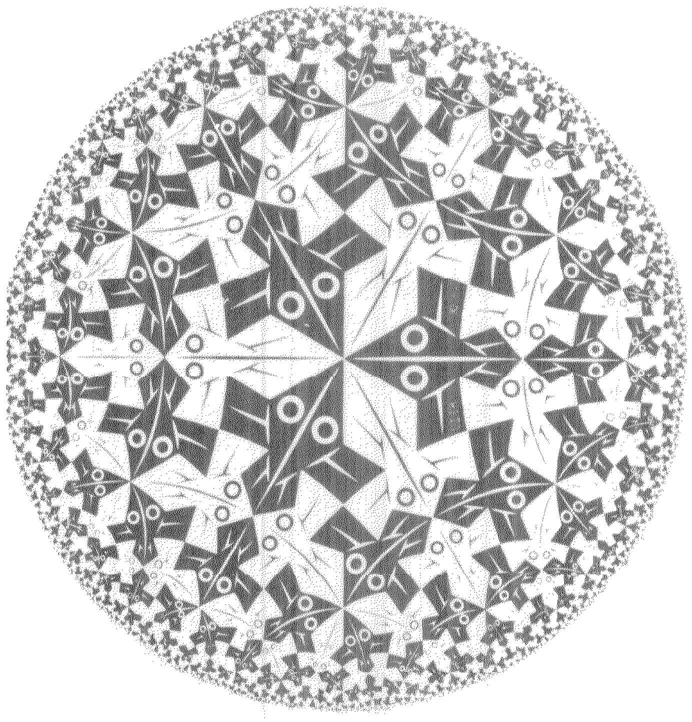
Ordinary galaxies, those without these hyperluminous quasar nuclei, would be almost invisibly faint at these great distances. But the latest sensitive detectors, such as charge coupled devices (CCDs), have recently revealed huge numbers of objects, closely packed over the sky, which are probably young galaxies at the stage of a protogalactic cloud contracting to form a disk. We must await the next generation of telescopes, of which the 10-meter Keck Telescope will be the first, to image these objects brightly enough to reveal their shape and form with any clarity. We shall then be able to obtain "snapshots" of groups of galaxies at different distances (and therefore different evolutionary stages) and trace directly how galaxies emerged from amorphous beginnings at high red shifts.

One stumbling block in understanding galaxies is the rather embarrassing fact that 90 percent of their mass is unaccounted for. When we study the orbital speeds of gas in the outer parts of galaxies, we find that the gas a long way out is still moving surprisingly fast and indeed would be escaping from the system were its centrifugal force not counterbalanced by the gravitational pull of more stuff than we see. We get this evidence also from the motions of galaxies in groups and clusters.

There's no reason, really, that we should be amazed by evidence of this "dark matter." There's no reason why everything in the universe should shine brightly, but it's still a mystery what this dark matter actually is. It could be a huge population of faint stars, too small to have ignited their nuclear fuel. Or it could be the remnants of massive stars that might have been bright in the early phases of galactic evolution but now have all died. A third idea, much discussed in recent years, is that the primordial fireball might have had extra ingredients apart from the ordinary atoms and radiation we observe. Elementary particles of some novel type could collectively exert large-scale gravitational forces.

There are various observational ways of deciding among such varied options. We might look for very faint infrared stars with high motions or for gravitational lensing due to compact stars or black holes. If there are some mysterious particles filling our galaxy, we might even (though their interaction with matter would be very small), be able to detect them by laboratory experiments. It would be especially interesting if we could learn by astronomical methods more about neutrinos, ghostly and elusive particles that hardly interact at all with ordinary matter; or, better still, if we could discover some new fundamental particle—the photino, for instance, which has been predicted by some theorists.

If such particles turned out to account for dark matter, we would then have to view the



*Another Escher drawing illustrates what we actually see as we look out from our "center" at the light from distant galaxies crowded together in earlier epochs.*

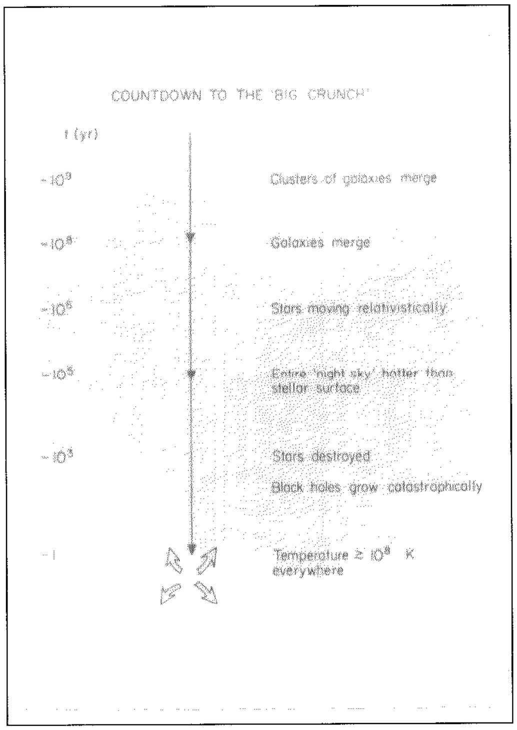
galaxies, the stars, and ourselves in a downgraded perspective. Copernicus, more than four centuries ago, dethroned the Earth from any central position. Early in this century, Shapley and Hubble demoted us from any privileged location in space. But now even *particle chauvinism* would have to be abandoned. The protons, neutrons, and electrons of which we and the entire astronomical world are made could be a kind of afterthought in a cosmos where neutrinos or photinos control the overall dynamics. Great galaxies could be just a sort of puddle or sediment in a cloud of invisible matter, 10 times more massive and extensive.

The amount of dark matter in the universe, important for galactic structure, is even more crucial for the very long term future of the universe. Will it go on expanding forever so that the galaxies fade and disperse into an ultimate heat death? Or will it collapse so that our descendants all share the fate of someone who falls into a black hole, the firmament falling on their heads to recreate a fireball like that from which we believe the universe emerged?

To answer this question we need to know the amount of gravitating matter tending to brake or slow down the expansion. We're now expanding; we don't know whether we're decelerating a lot or only a little, but it's easy to calculate how much gravitating matter is needed to bring the expansion to a halt. This critical density works out at about three atoms per cubic meter. It doesn't sound like very much, but even if we include the galaxies we see, plus all the dynamically inferred dark matter in galaxies and clusters, the mean density still falls short of this critical value by a factor of about five. There could still, however, be some more elusive material between clusters of galaxies. Absent evidence is not evidence of absence, and our knowledge of dark matter is still very biased and incomplete. That being so, it is at least amusing to consider both of the eschatologies suggested by our simple theories.

What would happen if our universe recollapsed? The red shifts of distant galaxies would be replaced by blue shifts, and galaxies would crowd together again. Space is already becoming more and more punctured as isolated regions—dead stars, and galactic nuclei—collapse to form black holes, but this would then just be a precursor of a universal squeeze to the Big Crunch that would eventually engulf everything. Galaxies would merge; stars would move faster, just as the atoms in a gas move faster as you compress the gas. Stars would eventually be destroyed, not by hitting each other, but because the night sky had become hotter than their centers. The final outcome would be a fireball like that which initiated the universe's expansion—though somewhat more lumpy and unsynchronized, and with extra entropy from starlight. When might this happen? The earliest would be 50 billion years from now—at least 10 times the future lifetime of our sun.

What about the other case? What happens if there isn't enough gravitating stuff ever to halt the universe's expansion? Gravitational binding energy is being released as stars, galaxies, and clusters progressively contract. This inexorable trend is delayed by rotation, nuclear energy, and the sheer scale of astronomical systems, which makes things happen slowly and staves off gravity's final victory. But if the universe expands indefinitely, even the slowest processes can run their full course, and the universe then has enough time to run down to a final heat death. If protons don't live forever, ordinary stars may eventually decay. If protons do last forever, then the final heat death will be spun out over a much longer period, as neutron stars tunnel quantum-mechanically into black holes. The length of time it would take for this to happen is up to $10^{10^{76}}$ (seconds or



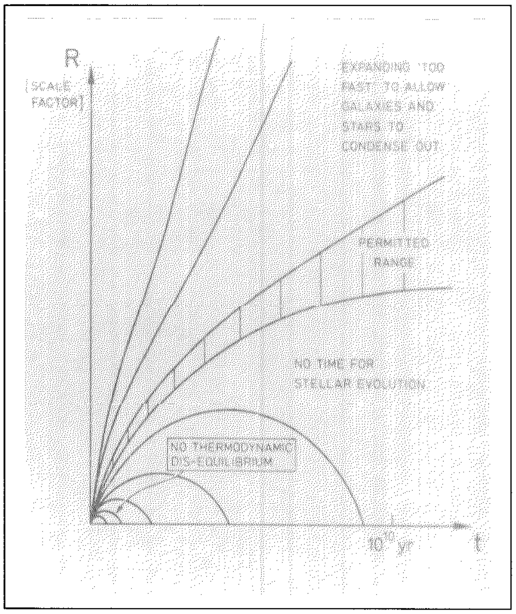
years; it doesn't matter), or 1 followed by about as many zeros as the number of atoms in the observed universe. Even if the universe were made of ink, you couldn't write this number down.

In an article written some years ago in *Reviews of Modern Physics*, Freeman Dyson discussed the future of the universe in great detail. He doesn't say much about the Big Crunch and the collapsing universe (I think that idea gives him claustrophobia), but he does address in detail some of the other points that I've summarized here, and he goes on to contemplate the outcome for intelligent life in this universe. Can it survive and develop intellectually on finite energy reserves forever, thinking infinite thoughts and storing or communicating an ever-increasing body of information? He shows, comfortingly, that in principle this can be done: As the background temperature falls, you must keep cooler, think progressively more slowly, and hibernate for very long periods. Will our descendants need to follow Dyson's conservationist maxims to survive an infinite future, or will they fry in the Big Crunch a few tens of billions of years hence? We need a more complete inventory of what's in the universe by observing it in all wavebands, searching for black holes, and understanding all sorts of exotic particles before we can pronounce a long-term forecast for the next hundred billion years.

THE FAR FUTURE OF AN EVER-EXPANDING UNIVERSE

| | |
|---|---|
| $10^{14}$ yr | Ordinary stellar activity completed |
| $10^{17}$ yr | Significant dynamical relaxation in galaxies |
| $10^{20}$ yr | Gravitational radiation effects in galaxies |
| [$10^{31}$–$10^{36}$ yr | Proton decay] |
| $10^{64}(m/m_{\odot})^3$ yr | Quantum evaporation of black holes |
| $10^{1500}$ yr | White dwarfs → iron* |
| $10^{10^{26}}$–$10^{10^{76}}$ | Neutron stars undergo quantum* tunnelling to black holes, which then "quickly" evaporate |

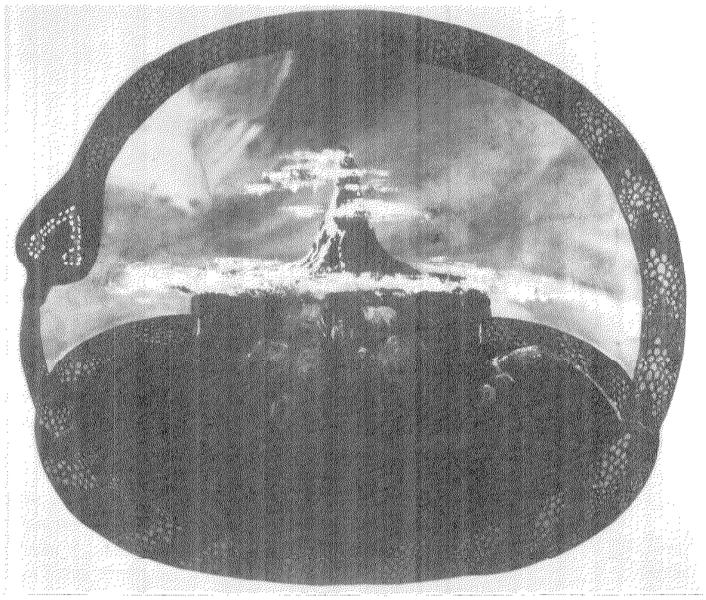
*If proton decay does not occur



*The dynamics of the early universe must have been finely tuned to allow stars and galaxies to form in the "permitted range" here. If it had re-collapsed sooner, there would have been no time for stellar evolution. It it had expanded much faster, the kinetic energy would have overwhelmed gravity, and the clouds from which galaxies are born could not have coalesced.*

These two alternative long-range futures, which seem very different, present a puzzle, because the initial conditions that could have led to anything like our present universe are very restrictive compared to the possibilities that might have been set up. We know that our universe is still expanding after 10 billion years. Had it recollapsed sooner, there would have been no time for stellar evolution, possibly not even time for it to have gone through anything other than the fireball state, precluding any thermodynamic disequilibrium. On the other hand, the expansion could not have been much faster than the critical rate; otherwise the kinetic energy would have overwhelmed gravity, and the clouds that developed into galaxies wouldn't have been able to pull themselves together. That's equivalent to saying that the density of the universe can't be far below the critical density. So the dynamics of the early universe must have been finely tuned in order to end up in the shaded region on the graph above. In Newtonian terms, the fractional difference between the initial potential and kinetic energies of any spherical region must have been very small.

So why was the universe set up to expand in this rather special way? There are other issues that baffle us similarly. In particular, why does the universe contain small-scale initial fluctuations that are necessary as "seeds" for galaxy formation, while still remaining so homogeneous overall? We can't answer these questions, even though we can trace in broad outline the course of cosmic evolution back



*Ancient Indian cosmologists envisaged the Earth as supported by four elephants standing on a giant turtle. But what held up the turtle remained a mystery, as do the initial conditions of the universe to scientists today.*

to when galaxies first formed and even all the way back to a universal fireball a few seconds old.

The ancient Indian cosmologists envisaged the earth being supported by four elephants standing on a giant turtle, but they weren't sure what held up the turtle. Conceptually we still end up in similarly bad shape with an appeal to initial conditions, saying things are as they are because they were as they were. Key features of the universe must have been imprinted before the first second had elapsed. So what happened during the first second?

The further back we extrapolate, the less confidence we have in the adequacy or applicability of known physics. For instance, the material will be squeezed above nuclear densities for the first microsecond. But if you think of time on a logarithmic scale, it seems a severe omission to ignore these early eras. And theorists differ on how far back they are prepared to extrapolate with a straight face. Some have higher credulity thresholds than others. In particular, those whose intellectual habitat is the gee-whiz fringe of particle physics are interested in the possibility that the early universe might once have been at colossally high temperatures. The goal of such physicists is to develop a so-called grand unified theory of all the forces governing the microphysical world. But they are faced with a stumbling block: the critical energy at which the so-called symmetry breaking is supposed to have occurred is about $10^{15}$ giga electron volts (GeV), which is a million million times higher than experiments on Earth can reach. It's hard, therefore, to test these theories, because only tiny effects are predicted in our low-energy world. For instance, protons may decay very slowly. But if we are emboldened to extrapolate the Big Bang theory back not just to one second but to $10^{-36}$ seconds, then, but only then, all thermal energies would exceed $10^{15}$ GeV. So perhaps the early universe was the only accelerator where the requisite energies for unifying the forces could ever be attained.

But the snag is that this accelerator shut down 10 billion years ago. So we can't learn anything about its activities unless the $10^{-36}$ second era left behind some fossils, just as helium is the fossil left from the first few minutes. Physicists would enthusiastically seize at even the most trifling vestige surviving from this ultra-early phase. An especially exciting possibility raised by these theories is that the particular mix of matter and radiation in our universe, a billion light quanta for every atom, may result from a small fractional favoritism of matter over antimatter established at that time.

Unified theories bring a new set of questions, such as the origin of matter, into the scope of serious discussion. The realization that protons aren't strictly conserved suggests furthermore that our universe may possess no conserved quantities other than those that are actually zero—such as total electric charge. This, combined with the concept of a so-called inflationary phase, in which our universe could have emerged from a single quantum fluctuation, allows us to envisage a sort of *ex nihilo* creation of the entire universe.

These concepts are still very tentative of course. Their present status resembles that of the theory of element synthesis in the Big Bang when Gamow and Lemaitre first discussed it 40 years ago. And just as the ideas of those pioneers were put on a surer footing by later developments, so we can hope that the concept of the ultra-early universe will also firm up. Indeed, we may not have to wait as long: In earlier decades only a few physicists took cosmology seriously, but now these ideas engage the interest of many leading mainstream theorists. And these developments certainly offer cosmologists a psychological boost, creating a symbiotic rather than a parasitical relationship with their physicist colleagues. It also makes me feel, in comparison with some of my colleagues, like a cautious empiricist, very reluctant to stray far from the data. That's an unusual feeling for an astrophysicist to have.

With phenomena such as ordinary stars we feel fairly confident that we know the relevant physics. When conditions get more extreme (in galactic nuclei, for instance) we're less confident, although it's astounding how far we can go without running against a contradiction. One theme that has emerged is the interdependence of different phenomena. The everyday world is determined by atomic structure, the stars are probably determined by atomic nuclei, and galaxies may be held together by some kind of subnuclear particles that are relics of a high-energy phase.

But in the early Big Bang or in gravitational collapse inside black holes we're confronted by conditions so extreme that we know for sure that we *don't* know enough physics. Above all, physics is conceptually unsatisfactory in that we lack an adequate theory of quantum gravity. Two great foundations of physics are the quantum uncertainty principle and Einstein's general relativity. The theoretical superstructures erected on these foundations are disjoint. There's normally no overlap in their domain of relevance because quantum effects are important on a microphysics scale, gravity only on the astronomical scale. But when the universe was squeezed to colossal densities (at $10^{-43}$ seconds, the Planck time), gravity could be important on the scale of a single particle, a single thermal quantum. Even the boldest physicists can extrapolate back no further.

Despite these difficulties some theorists believe that it's no longer premature to explore physical laws prevailing at the Planck time. They've come up with many fascinating ideas. There's no consensus about which concept might really fly, but it's certainly no longer just cranks who try to consider all physical forces in one go. We may have to jettison commonsense notions of space and time, the dimensionality of our world, and many other things.

What about gravity? Two features of this peculiar force that holds together individual stars and entire galaxies are quite crucial for cosmogonic processes. The first feature is that gravity drives things *further from equilibrium*, not toward equilibrium. When gravitating systems *lose* energy they get *hotter*; for example, an artificial satellite speeds up as it spirals downward due to atmospheric drag. Another example is the sun. If its radiative losses were not compensated by nuclear fusion, the sun would contract and deflate but would end up with a hotter interior than before. It needs more pressure inside it to balance the stronger gravity when it's more compressed. So, from the initial Big Bang to our present solar system, this antithermodynamic behavior of gravity has been amplifying density contrast and creating temperature gradients—prerequisites for the emergence of any complexity.

The second key feature of gravity is its *weakness*. The gravitational force within an atom is almost 40 powers of 10 weaker than the electrical forces that bind it. As I explained in discussing stars, gravity holds sway on sufficiently large scales, but those scales are vast because gravity is weak. If gravity were somewhat stronger, say 30 rather than 40 powers of 10 weaker than electromagnetism, then a small-scale speeded up universe could exist, in which stars, gravitationally bound fusion reactors, had $10^{-15}$ of the sun's mass and lived for less than a year. This might not allow enough time for complex systems to evolve. There would be fewer powers of 10 between astrophysical time scales and basic microscopic time scales for physical or chemical reactions. Moreover, complex structures could not get very large without themselves being crushed by gravity. Our universe is large and diffuse and evolves slowly *because* gravity is so weak. Its extravagant scale, billions of light years, is necessary to provide enough time for the cooking of elements inside stars and for interesting complexity to evolve around even just one star in just one galaxy. So a force like gravity is essential if structures are to emerge from amorphous starting points; but, paradoxically, the weaker it is, the greater and more complex are its consequences.

The evidence for apparent fine-tuning in the initial expansion rate (in Dyson's words, "The universe seems to have known we were coming") has led some physicists to highlight other coincidences in the physical laws. All key features of the everyday world and the astronomical scene are determined by a few basic physical laws and constants—the masses of elementary particles and the strength of the basic forces between them. And in many cases a rather delicate balance seems to prevail. For example, if the nuclear forces were slightly stronger relative to electromagnetism, the diproton would be stable, ordinary hydrogen wouldn't exist, and stars would evolve quite differently. If nuclear forces were slightly weaker, no chemical elements other than hydrogen would exist and chemistry would be a trivially simple subject.

The details of stellar nucleosynthesis—the nuclear transmutations inside stars that forge the elements we are made of—are sensitive to other apparent accidents. For instance, Fred Hoyle showed that carbon and oxygen can both be readily synthesized only because there's a sort of specially tuned resonance in the carbon nucleus.

What shall we make of all this? It shouldn't occasion any surprise that we've evolved to fit our local environment around a star. But what surprises some of us is that the physical laws should permit any complexity to evolve anywhere. Some physicists don't take this very seriously, but others envisage a kind of natural selection among an ensemble of universes governed by different laws. Most universes would be still-born in the sense that no complexity could develop within them. But some, including ours, could perhaps exist with any requisite tuning of the parameters. In other words, given that we know that our cosmic environment permits observers to exist, maybe we shouldn't take the Copernican principle too far. We wouldn't feel justified in assigning ourselves a central position in the cosmos, but it may be equally unrealistic to deny (or to be surprised) that our situation can be privileged in any sense.

The eventual status of this so-called "anthropic principle" will depend, I think, on what the laws of nature are really like. If some fundamental theory yields unique values for all the ratios, then it may be inconceivable to envisage a universe with different constants. We then have to accept it as coincidental, or even providential, that these constants happen to lie in the restricted range that allow complexity and consciousness to evolve in the low-energy world we inhabit. The intricacy implicit in these unique laws may astonish us, but our reaction would be no less subjective than a mathematician's surprise at the rich intellectual structures that can stem from simple axioms.

But if, contrariwise, the basic laws turned out to involve some random elements, then the ensemble idea could be put on a serious footing. Some cosmologists suggest that different parts of an infinite universe could have cooled down after the Big Bang with different constants. There could be different domains in which the physics could be different, and complex evolution could occur only in oases where the laws of nature were of propitious dimensions.

Our oasis must be at least 10 billion light years across, because the physical laws seem the same everywhere we can observe. But the desert, or still-born, regions may in principle be observed within the distant future (maybe $10^{12}$ years hence) when our horizon is expanded sufficiently for light from more remote domains to reach us. This time delay is, to be sure, an impediment to practical empirical tests, but conceptually the situation is no different from the conjectures of early "cosmographers" about continents beyond the limits of the then-known world.

Einstein said, "The most incomprehensible thing about the universe is that it is comprehensible." The physical laws that our brains are somehow attuned to understand apply not just in the lab but in the remotest quasar and even in the early instants of the Big Bang. Were this not so, were there not a firm link with local physics, cosmology could never rise beyond ad hoc explanations on the level of the *Just So Stories*. Some optimists indeed believe that a comprehensive and comprehensible theory for all the fundamental forces may emerge from a symbiosis between cosmology and particle physics.

This would mean in a sense, as some physicists have emphasized, the end of fundamental physics. But it would emphatically *not* mean the end of challenging science. I first heard the following metaphor for what the physicist does from Dick Feynman.

Suppose you were unfamiliar with the game of chess. Then, just by watching games being played you could infer what the rules were. The physicist likewise finds patterns in the natural world and learns what dynamics and what transformations govern its basic elements. But in chess, learning how the pieces move is no more than a trivial preliminary to the absorbing progression from novice to grand master. The whole point and interest of that game lie in exploring the complexity implicit in a few deceptively simple rules. Likewise, all that's happened in the universe over the last 10 billion years—the emergence of galaxies, the formation of their constituent stars, and the intricate evolution that, on a planet of at least one star, has led to creatures able to wonder about it all—may be implicit in a few fundamental equations of physics. Exploring and trying to understand all this offers an unending quest and a challenge that has barely begun. □

# Interesting Times in Geophysics

*by Robert Finn*

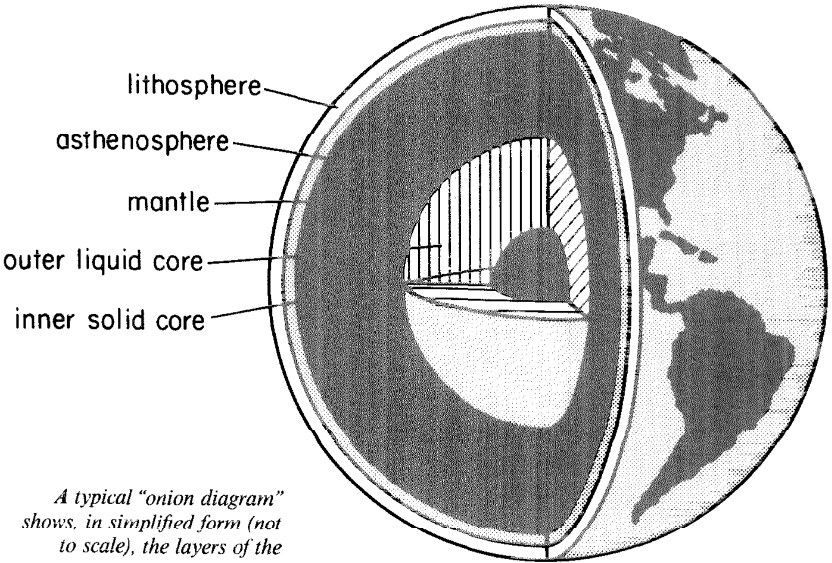
There's an old Chinese curse that goes, "May you live in interesting times." Someone must have laid this curse on the current generation of Earth scientists. Still reeling from the monumental fight over plate tectonics (the plates won), geophysicists are being confronted by new techniques and new data bearing on the structure of the Earth's deep interior. The varying interpretations of this new data are the subjects of deep disagreements in the geophysical community, and some of the data itself has been called into question. What is certain, though, is that the interior of the Earth is far more complex and heterogeneous than was previously recognized.

If you look at any basic geology text, you'll find an illustration showing the concentric layers of the Earth's interior that makes the Earth look something like an onion with a wedge cut out of it. On top is the *crust*, about 40 kilometers thick under the continents and up to 10 kilometers thick under the oceans. The crust floats on the *lithosphere*, which extends to depths of about 70 kilometers. Under the lithosphere is the partially molten *asthenosphere*, occupying a shell 70 to 250 kilometers in depth. Next comes the solid *mantle*, which contains about 70 percent of the Earth's mass. The mantle is sometimes divided into the upper mantle, a shell about 650 kilometers in depth, and the lower mantle, which extends from 650 kilometers down to 2,900 kilometers. Below the mantle is the molten *outer core*, extending from 2,900 kilometers to 4,980 kilometers. Occupying the very center of the Earth is the solid *inner core*. With a radius of about 1,400 kilometers, it is roughly the same size as the moon.

This onion diagram carries with it certain implications that are turning out to be either oversimplifications or simply incorrect. It implies, for example, that the transitions between the layers are both smooth and abrupt and that each layer is internally homogeneous. Geophysicists are now discovering that the transitions between layers are occasionally bumpy, and that within some of the layers there may be a great deal of heterogeneity. "To 99 percent accuracy, the Earth *is* an onion," says Robert Clayton, associate professor of exploration geophysics. "But what's left is a very important 1 percent."

The problem is: How do you get at that important 1 percent? Geophysics is unlike most other scientific disciplines in that its main subject—the interior of the Earth—is almost completely hidden from view. An astronomer can look at distant galaxies through a telescope, a biologist can view cells through a microscope, and a physician can visualize internal body structures with x-rays. But until recently there has been no comparable technique in geophysics.

Surprisingly, it was a medical technique—the CT (computerized tomography) scan—that gave geophysicists the clue they needed to develop a means for imaging the Earth's interior. In the CT scan x-rays crisscrossing through the body are sensed by a circular array of detectors. The information from these detectors is integrated by a computer into a three-dimensional image based on the density of different materials within the body. Clayton, together with several students (John Fawcett, Tom Hearn, Eugene Humphreys, Olafur Gudmundsson, Hua-Wei Zhou, and Huw Davies) realized that a similar technique could be used to image the Earth's interior. X-rays don't penetrate the Earth, but the pressure waves (P waves) and the shear waves (S waves) produced by natural earthquakes do. If the earthquake is



*A typical "onion diagram" shows, in simplified form (not to scale), the layers of the Earth's interior.*

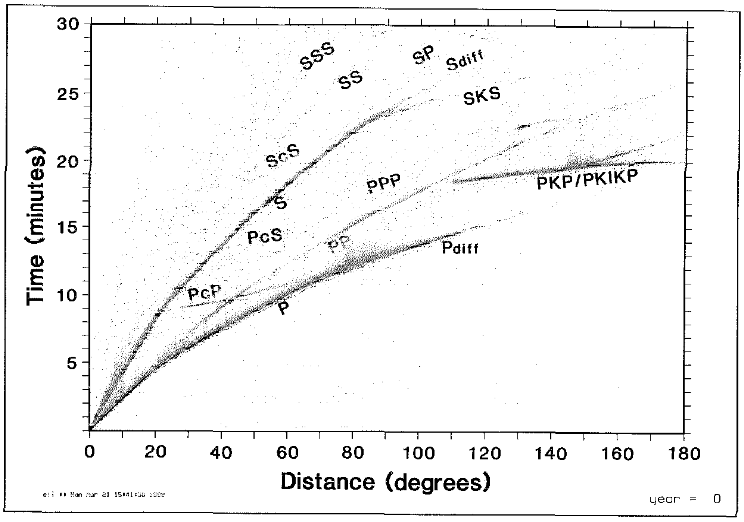
large enough—above a magnitude of 4.5 or so on the Richter scale—these waves will be detected at distant seismographic stations after being reflected and refracted by structures deep within the Earth.

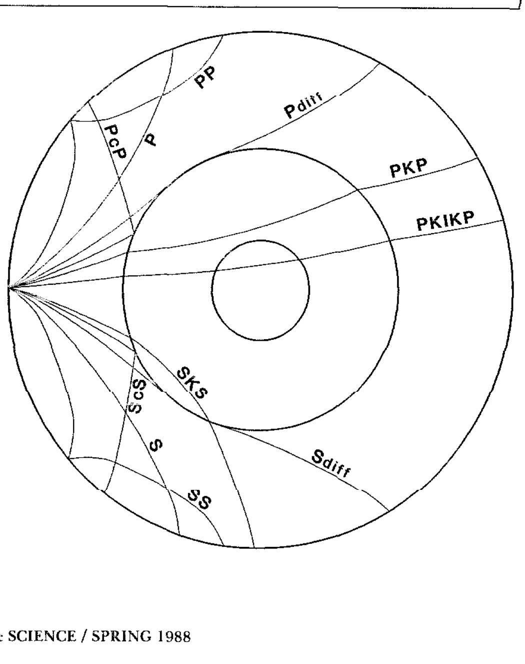
Consider, for example, two seismometers in two different locations, each detecting a single earthquake. The quake produces P waves that descend into the mantle and are continually refracted until they return to the surface. The ascending P waves will first reach the closer of the two seismometers, then the more distant one, and the expected travel times can be calculated. Sometimes, though, the P wave will arrive at a seismometer slightly ahead or slightly behind the time predicted by a model that assumes a homogeneous, onion-skin mantle. One way to account for these anomalies is to postulate that the mantle is *not* homogeneous, that there is something somewhere on the P wave's path that speeds it up or slows it down. But with a single earthquake there's no way to tell exactly where along that path this anomaly might be.

Seismic tomographers look at the P waves produced by many thousands of earthquakes, each detected at about 3,000 surface stations. This produces literally millions of data points, each representing the time it takes for a P wave to reach a single seismometer. Since the paths of all these millions of P waves are known, and since they crisscross each other many times, the locations of the travel-time anomalies can be pinpointed.

And seismic tomographers don't restrict themselves to a single type of P wave. They have quite a menagerie of P waves from which to choose, and each of them travels around the Earth's interior in a different way. PcP waves, for example, descend so deeply into the mantle that they bounce against the core-mantle boundary before being refracted to the surface. PKP waves actually penetrate the liquid outer core and are refracted there before re-entering the mantle and finally ascending to the surface. PKIKP waves penetrate the inner as well as the outer core. Each of these waves can be distinguished and each provides different information about the Earth's internal structure.

Another type of tomography—surface-wave tomography—was also developed at Caltech by former postdoc Ichiro Nakanishi; Don L. Anderson, professor of geophysics and director of the Caltech seismological laboratory; and Toshiro Tanimoto, assistant





*Earthquakes produce shear (S) and pressure (P) waves that are reflected and refracted by the Earth's internal structures. These diagrams show that S and P waves are received at different times, depending on the distance of the seismographic station from the quake's epicenter and the paths taken by the waves.*

professor of geophysics. These waves, as their name implies, travel over the surface of the Earth, but also penetrate deep into the mantle and can provide useful information on the Earth's interior.

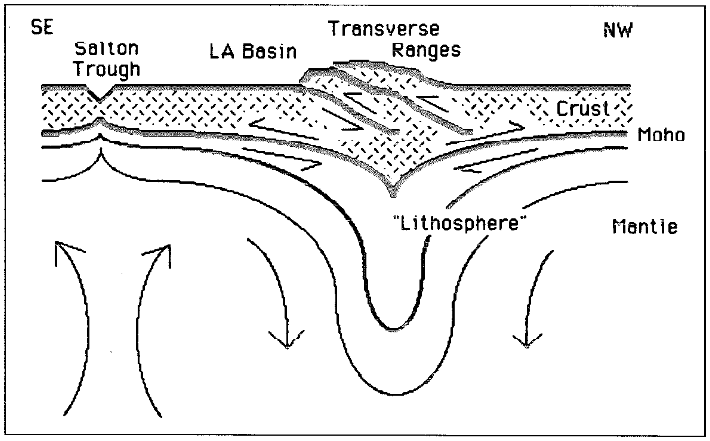
Using arrival-time data from the various types of P waves, geophysicists have built up three-dimensional images of the mantle that map the points where seismic waves travel faster and more slowly than normal. The next question is: Just what is causing these differences in travel time? Usually, the denser the material they pass through, the faster seismic waves travel. (This is also true of sound—a more familiar type of pressure wave. Sound travels faster in water than in air, and faster in steel than in water.) Density differences in the mantle are generally ascribed to temperature differences; seismic waves move faster in cold areas and more slowly in hot areas.

## Convection

These temperature differences arise from the mechanisms that have generated heat in the mantle by radioactive decay and have brought heat to the surface from the core throughout the Earth's history. It's extremely important to understand these mechanisms since heat coming to the surface ultimately controls phenomena such as volcanoes, earthquakes, continent formation, mountain building, and the large-scale movement of tectonic plates.

It has long been known that the movement of heat from the interior occurs too rapidly to be accounted for by mere conduction. A far more rapid method of heat transfer—convection—must play an important role. Convection takes place in materials that are sufficiently hotter in one place than in another and have the ability to flow. In such a situation, the heated material expands, becomes less dense, and rises to the top. Once it does so, it cools, increases in density, and falls back to the bottom. We are all familiar with convection in liquids—boiling soup is a well-known convective system. Although it may seem counter-intuitive, convection is also possible in solid materials like the rock of the Earth's mantle. Mantle rock heated at the core expands and rises, albeit very slowly. Cooler rock closer to the surface sinks back down into the deep mantle. Techniques to simulate convective flow in the mantle have been developed by Bradford Hager, associate professor of geophysics, graduate students Scott King and Walter Kiefer, and research fellow Michael Gurnis.

Clayton, Hager, and Humphreys used seismic tomography to reveal a convection cell in the upper mantle directly beneath southern California. The hot, upwelling segment of the convection cell is centered near the Mexican border, and the cold, downwelling segment is located directly beneath the Transverse Ranges—the east-west string of mountains (including the San Gabriels just north of Pasadena) running along both sides of the San Andreas Fault. The seismic velocities in the downwelling are 3 percent faster than its surroundings, which translates to a temperature difference of about 400 degrees. A narrow, cold, slab-like protrusion, this downwelling probably provides the buttressing for the Transverse Ranges. But this is a relatively small convection cell in the upper mantle, a mere eddy of the much larger convection cells circulating throughout the body of the mantle. Some of these larger cells have upwellings at spreading mid-ocean ridges and downwellings at subduction zones. This is how convection controls the movements of large surface plates. On a more global basis, former postdoc Henri-Claude Natof, Nakanishi, and Anderson found giant upwellings in the central Pacific and under northeast Africa—the Afar Triangle region. Tanimoto has now used surface waves to map upwellings in the lower mantle as well.



*This idealized cartoon represents a cross section of the crust and upper mantle cut approximately parallel to the San Andreas fault in southern California. Caltech geophysicists have detected a local convection cell with upwellings associated with crustal extension beneath the Salton Trough, and downwellings underneath the Transverse Ranges.*

## Discontinuities in the Mantle

The nature of large-scale convection within the mantle is still the subject of great debate. At issue is whether the entire mantle is part of one convecting system, or whether there are barriers within the mantle through which no convection can occur. The most important of these possible barriers, called the 650-kilometer discontinuity, was discovered at Caltech in the 1960s, and it forms the dividing line between the upper and the lower mantle.

The exact nature of the 650-kilometer discontinuity is unknown. The most important unanswered question about it is whether the materials above and below it are distinct chemical compositions or whether it represents a single material undergoing a phase transition—to a more densely packed crystalline structure that is caused by increased pressure below the discontinuity.

If the 650-kilometer discontinuity is a chemical barrier, then convection cells originating from lower levels would stop there. Geophysicists argue that if convection penetrates the discontinuity, the upper and lower mantle would eventually mix, obliterating any chemical distinction. Only conduction would operate across the discontinuity, but this conduction could set up a smaller set of convection cells operating exclusively at higher levels and controlled by heat coming out of the lower mantle. A careful study of convection patterns near the discontinuity would settle the question of its nature once and for all—if rising and falling convection currents penetrate the 650-kilometer discontinuity, then it must be a phase transition; if the convection currents are discontinuous at 650 kilometers, then it must be a chemical barrier.

While this seems straightforward enough, there are both technical and theoretical considerations that make settling the nature of the 650-kilometer discontinuity an enormous challenge. Seismic tomography as it is currently practiced gives relatively low-resolution images of the mantle, and it is particularly poor in resolving horizontal features. This means that if data from seismic tomography should reveal a column of rising material that appears to penetrate the 650-kilometer discontinuity, one could not conclude that a convection cell is indeed penetrating it. An alternative explanation would be that the convection cell stopped at the discontinuity, that heat conduction set up a separate convection cell above the discontinuity, and that the resolution of the seismic tomography data was too poor to reveal either the horizontal components of the convection cells or the break between the convection cells above and below the discontinuity.

But even if the resolving power of seismic tomography could be greatly improved, the issue would not necessarily be settled. According to Hager, the 650-kilometer discontinuity could be a simple phase transition and still seem to have separate convection regimes above and below. And according to Don Anderson, not only is it possible for convection cells to penetrate a chemical discontinuity without homogenizing everything, but there is evidence that such a mechanism actually operates in the mantle.

Hager has run computer simulations of the convective movements in the mantle to find out what would happen if there were no chemical barrier—just a phase transition at 650 kilometers that results in material 100 times more viscous below the discontinuity than above it. In such a situation, which Hager refers to as "mechanical stratification," convection above the 650-kilometer discontinuity is faster and far more vigorous than below, and the transition between the layers remains very sharp. Yet material from below does penetrate the barrier, although very slowly. What this means is that material in the upper mantle would be very well mixed, while material in the lower mantle would not be as well mixed. Speaking about the controversy between geophysicists who believe in a chemical barrier at 650 kilometers and those who believe in a phase transition, Hager says, with tongue in cheek, "This is almost a religious issue, but I'm no longer religiously involved because I have seen the truth."

Anderson, on the other hand, believes that in the argument between those who believe that the mantle is homogeneous and those who believe that it is stratified *both* sides are wrong. In Anderson's view, the mantle is neither homogeneous nor is it stratified. He believes that convection can be penetrative without being homogenizing. In fact, says Anderson, convection can actually dehomogenize things. Convection can transport light material from the depths to the surface, and it can transport dense material from the surface to the depths. These materials can then drop out of circulation and accumulate—light materials on the surface and dense materials as far down as the core-mantle boundary.

Split-pea soup is a good example of this effect of convection. If you let a pot of split-pea soup boil for a little too long, a frothy scum of low-density material will form on the top. Likewise, the heavier solids will accumulate at the bottom of the pot. In fact, it's well accepted that convection did just this during the formation of the Earth. The lighter materials that formed the crust ended up as a thin scum on top and the heavier materials, most notably the largest proportion of the Earth's iron, sank to the core. Anderson claims that this kind of dehomogenization, occurring during accretion is, by and large, irreversible, and it also made the lower mantle different from the upper mantle.

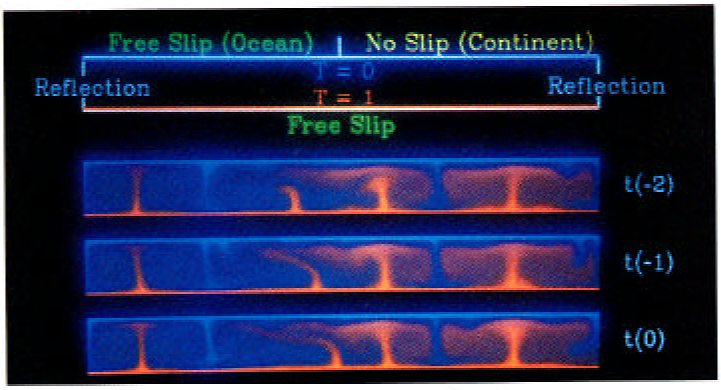
Concentrating on another discontinuity—this one at 400 kilometers—Anderson's studies have convinced him that material from the middle mantle (400 to 650 kilometers) has penetrated the upper mantle without any substantial mixing. Evidence for this comes from the isotopic composition of ocean-island basalts. These basalts have a different isotopic composition than does regular ocean crust, and Anderson interprets this in the following way: When a convection cell originating in the middle mantle (or below) first penetrates the upper mantle and comes to the surface, it is contaminated with upper-mantle material and it forms ocean-island basalts. Later, the convective upwellings punching through the upper mantle become broader and less contaminated, forming regular ocean crust. Likewise, the downwelling parts of the convective cells can penetrate through the upper mantle, contaminating it with sediments, and taking the bulk of the oceanic lithosphere down to the middle mantle. Anderson is tantalized by evidence that indicates that a layer called D″ (pronounced "dee double-prime") at the core-mantle boundary may have formed from material that was once on the surface of the Earth. The material in the middle mantle (400 to 650 kilometers) appears to recycle between the surface and the middle mantle.

Leon Silver, the W.M. Keck Foundation Professor for Resource Geology, thinks things are far more complex than that. A pioneer in geochronology, Silver has been able to determine the dates of formation of continental rocks with exquisite precision—better than two parts in a thousand even for rocks that are more than a billion years old. Using this geochronological data, Silver has built up a detailed history of the formation of the North American continent. He finds that even within granites that formed in a single geological generation there are a number of different isotopic signatures. This must mean that there are a number of isotopically distinct reservoirs in the upper mantle.

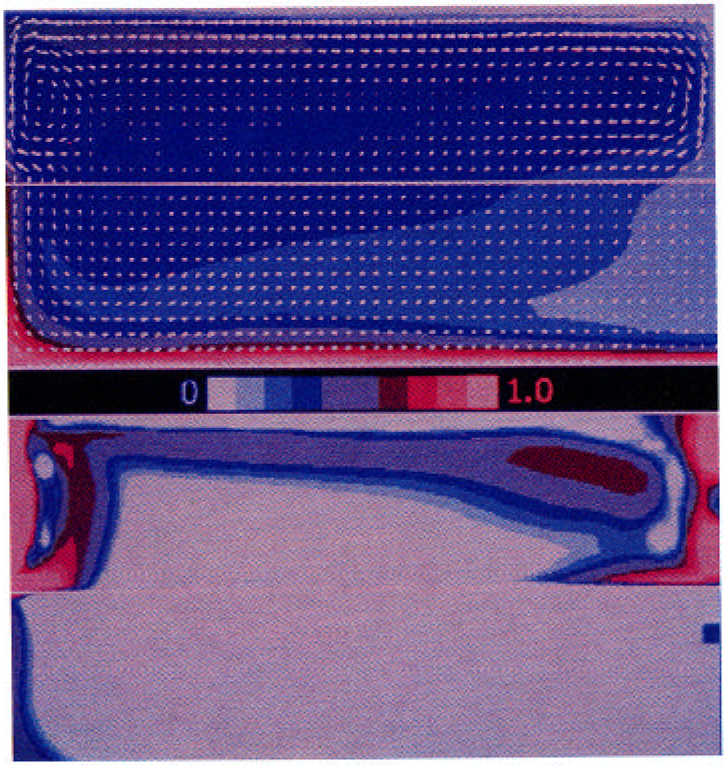
"The problem with geophysical observations is that they lack historical perspective," says Silver. "Geophysicists only look at a slice of geological time. For a historical perspective you've got to look to geology and geochemistry. Continents are ultimately extracted from the upper mantle, so they are the principal recorders of the evolution of the Earth's upper mantle reservoirs. If continents have a complex history—and my studies show that they do—then the mantle must have a complex history."

### Descending Slabs

Not only is the formation of continental crust complex, but its destruction is complex as well. Continental crust is destroyed at subduction zones—areas in which huge crustal slabs dive into the mantle. These areas are thought to correspond to the downwelling



*Above: Simulations of convection within the mantle reveal differences between areas lying beneath continental and oceanic crust.*



*Below: Hager has run computer simulations of convective movements in the mantle that assume no chemical barrier—just a phase transition at 650 kilometers (at the panel center) that results in a hundredfold increase in viscosity. The simulations reveal that convection above the discontinuity is faster and far more vigorous than below, and that the transition between the layers remains very sharp. Yet material from below does penetrate the barrier, although very slowly.*

arms of convection cells, and at issue is whether the slabs descend all the way to the core-mantle boundary or whether they stop at the 650-kilometer discontinuity.

Using seismic tomography, Clayton and graduate student Hua-Wei Zhou have recently seen cold, slab-like features at a depth of 650 kilometers in the upper mantle under Asia. These appear to be remnants of the Pacific plate that have slipped under the Asian continent. According to Clayton and Zhou, instead of diving into the lower mantle, the slabs appear to sink initially, then they move horizontally after reaching the bottom of the upper mantle.

These findings would seem to support the chemical barrier hypothesis, but the nature of the 650-kilometer discontinuity is still open. The deep slabs broaden as they descend and this may mean that they're being deformed as they push against a barrier. But the barrier doesn't have to be a chemical one; if Hager is correct and the phase transition results in a hundredfold increase in viscosity, you would expect such broadening. In fact, research fellow Michael Gurnis, working with Hager, has done computer simulations that show that when slabs hit this type of mechanical barrier they will first broaden and then break through. This will also happen at a chemical barrier.

Hiroo Kanamori, professor of geophysics, thinks it's significant that earthquakes are never seen at depths below 650 kilometers. "If plates just become mixed with the upper mantle, you'd see earthquakes gradually decreasing with depth," says Kanamori. "In fact, you see increasing activity near 650 kilometers, indicating that something may be hitting against something else. Another possibility is that the slab is going through a phase transition and, as it does so, it weakens, causing earthquakes."

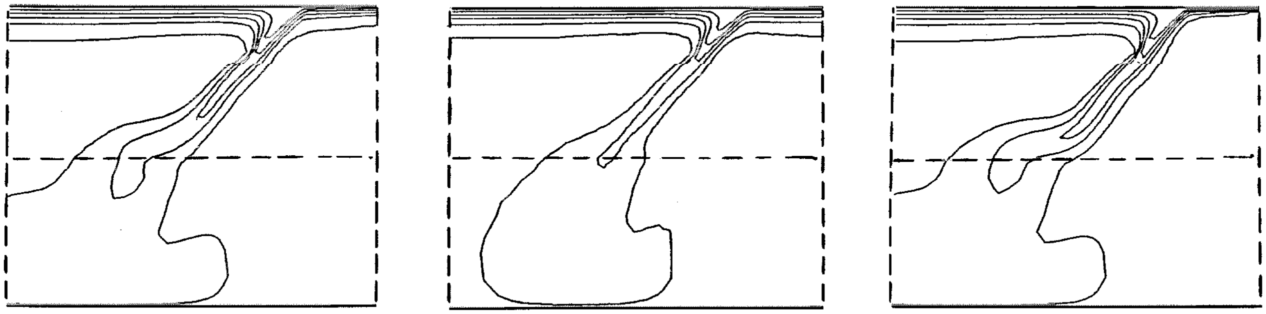
## The Core-Mantle Boundary

If slabs do descend past 650 kilometers, they probably go all the way down to the core-mantle boundary. This is a region that is turning out to be extremely interesting in its own right. Last year Clayton, Anderson, and graduate student Olafur Gudmundsson announced that studies of three types of pressure waves—PcP (reflected by the boundary), PKP (refracted by the outer core), and PKIKP (refracted by both inner and outer cores)—revealed the presence of high "mountains" and deep "valleys" at the core-mantle boundary. There are mountains (upward-going deflections) as much as five kilometers high under Australia, the Labrador Sea, and off the Pacific coast of South America. Valleys (downward-going deflections) of similar depth were found under the southwest Pacific, the East Indies, and southern Europe.

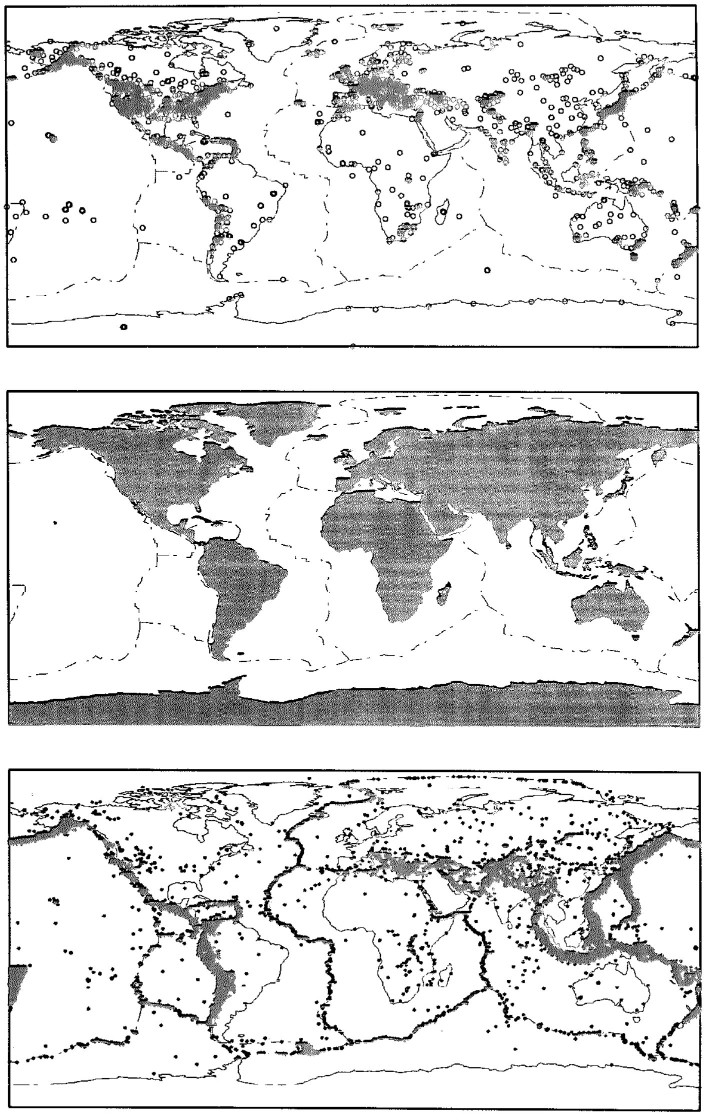
These contour images of the core-mantle boundary are still of comparatively low resolution, but they may have a great deal to say about convection patterns in the mantle. Most geophysicists believe that the mountains are the starting points of upwelling convection currents and that the valleys are the end points of downwelling currents.

The mountains and valleys reside within the D″ layer at the core-mantle boundary. This layer is turning out to be extremely heterogeneous and may, in fact, be composed of different materials than the rest of the mantle. Recent studies of the melting point of iron at the intense pressures—over 3.5 million atmospheres—in the core suggest that the core's temperature may be thousands of degrees higher than was previously believed. These studies, conducted by Thomas Ahrens, professor of geophysics, and Raymond Jeanloz of the University of California, Berkeley, who's now a Sherman Fairchild Distinguished Scholar at Caltech, revealed that the temperature of the solid inner core is about 6,900 K, and the temperature at the core-mantle boundary is about 4,800 K.

"D″ must be a chemically distinct layer," maintains Hager. "The temperatures in the



*These simulations by Michael Gurnis show that when crustal slabs descending from an oceanic trench hit a mechanical barrier—in this case a thirtyfold increase in viscosity—they will first broaden and then break through. The contours represent "isotherms"—lines of equal temperature. The first panel simulates a time 50 million years after the start of the descent, the middle panel is 8 million years later, and the last panel is 7 million years after that.*



*The top panel shows the worldwide distribution of seismic stations, and the bottom panel shows the worldwide distribution of earthquakes. Locations of continents and plate boundaries (dashed lines) appear in the center panel.*

core are much higher than at the base of the mantle. The only way to have such a mismatch would be to have an insulating layer of chemically distinct material. D″ may be old oceanic crust that has sunk to the core-mantle boundary. Or it may be a mixture of stony mantle material and metallic material from the core that makes D″ too dense to participate in convection." Another possibility, proposed some years ago by Anderson and graduate student Larry Ruff, is that D″ is the high melting-point residue of the mantle and core that formed during the Earth's accretion.

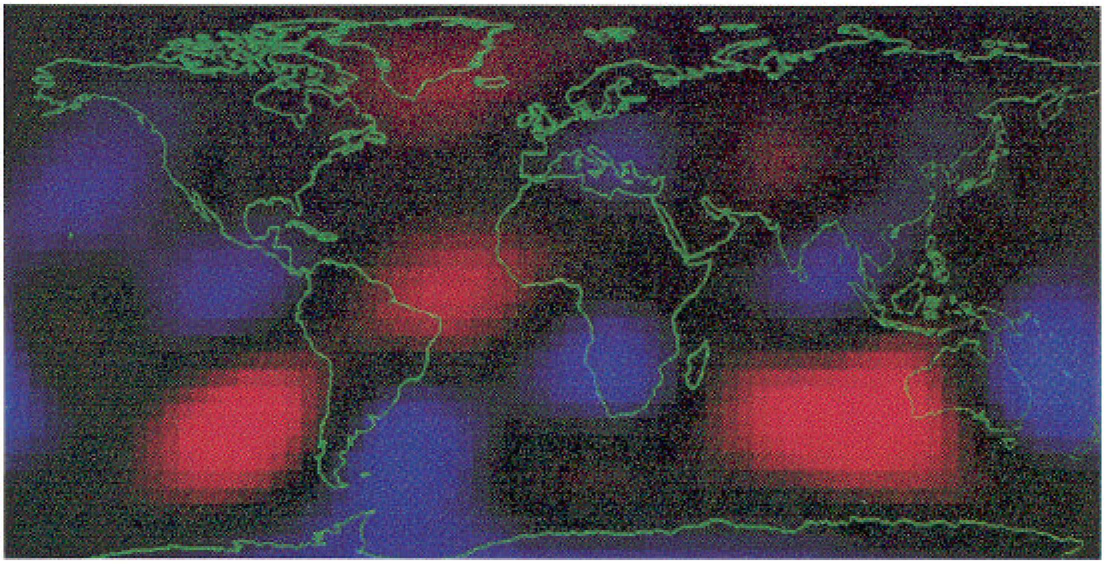
Toshiro Tanimoto has mapped D″ and has concluded that it is a highly irregular structure—as much as 300 kilometers thick in some places and as little as 100 kilometers thick, or possibly even absent, in others. These variations make D″ seem similar to the crust, and like the crust it may be forming, reforming, and shifting. In fact, some geophysicists refer to "anti-oceans" and "anti-continents" existing there.

In the course of the Earth's rotation there must be some torque produced at the core-mantle boundary as the molten core sloshes against the mountains and valleys. Last year Clayton, Hager, Mary Ann Spieth of JPL, and others announced the results of calculations indicating that this torque may account for a long-known jerkiness in the Earth's rotation that causes the length of the day to vary by about five milliseconds over a decade. More recent calculations, however, reveal that five-kilometer depressions would cause more jerkiness than is actually observed. Some seismologists now believe that upward-going dimples in the core-mantle boundary may be filled with huge inverted lakes. These lakes would be made up of a lower density layer of molten silicates, floating on top of the rest of the molten core. Such lakes would shield the mantle from motion in the core just as the oceans shield the sea floor from the effects of winds. This hypothetical new layer, called E′, will be hard to visualize by direct seismic methods, but its presence may be needed to reconcile various types of geophysical data.

## Anisotropy in the Outer Core

And it's turning out that the outer core may itself be more than just a uniform liquid. Gudmundsson, Clayton, and Anderson have found that waves traveling near the center of the Earth traveled faster if they paralleled the Earth's axis (that is, moved north and south) than if they traveled across the equatorial plane. Scientists from Harvard University showed last year that waves traveling through the solid inner core showed this "anisotropic" behavior, but the Caltech group has now shown that this behavior extends unexpectedly into the molten outer core and possibly into the base of the mantle.

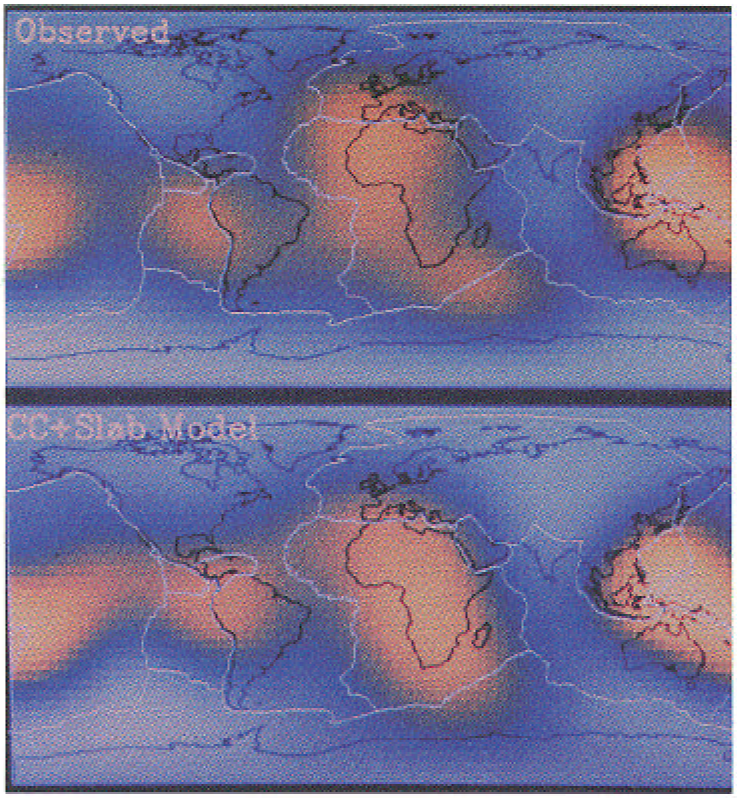
There are at least four possible explanations for this anisotropy. According to Anderson, the most likely explanation is that part of the liquid core is actually solid, like a slurry. In physical terms, this means that the molten iron alloy of the outer core may be the site of "rainstorms" in which the "raindrops" are iron filings. Part of the molten core does not behave entirely as a liquid, but has some crystal-like properties. The iron particles are freezing out in the colder



*The red blobs on this map represent upward-going deflections ("mountains") on the outer core, and the blue blobs represent downward-going deflections ("valleys").*

downwelling parts of the core and are remelting in the warmer upwellings. Some of the solid iron plates out on the inner core, causing it to grow with time.

A second possible explanation of the anisotropy could be the existence of a previously unknown supermagnetic field in the core, which could slow down seismic waves moving parallel to the equator. No evidence of such a magnetic field has ever been found, however. Extremely fast fluid motions within the core form the third possible explanation. If the motions were in just the right direction and at just the right velocity, they would cause seismic waves to speed up parallel to the axis, just as the wind sometimes carries sounds. Anderson regards this explanation as highly improbable.



*Hager used P-wave data to calculate regional variations in the density of the Earth. From these he modeled the Earth's geoid (the hypothetical shape of a rotating, fluid-covered Earth) and calculated regional variations in the gravitational field. The calculated gravitational field showed more than 90 percent agreement with the measured gravitational field.*

Hager favors a fourth explanation—that the core is about one kilometer more ellipsoidal than the generally accepted standard value. "I think it's unlikely that showers of crystals are continually being produced in the outer core," says Hager. "For this to happen you'd need a constant flux of heat from the core to cool it down." But Anderson believes that iron is constantly freezing and melting in the core, depending on location. The net freezing rate, which can be calculated from the size of the solid inner core, is just about what is expected from heat flow from the core. Anderson points out that the inner core is solid, and therefore the bottom part of the outer core must be near the melting point.

## The Quality of the Data

Interpretations of seismic tomography data are not the only things geophysicists argue over. The quality of the actual data has frequently been called into question. One problem is that earthquakes and seismographic stations are not distributed uniformly around the globe. Relatively high resolution can be obtained only from areas where there are many earthquakes and many seismometers. Unfortunately, some of the most interesting regions in the world—notably the mid-Pacific—are subject to the lowest resolution.

In addition, body-wave seismic tomographers do not get to use raw data from the thousands of earthquakes that are detected at the thousands of seismographic stations around the world. (Surface-wave tomographers do use raw waveforms.) Body-wave tomographers get a single figure—the arrival time of the P wave—that a local observer has determined from measurements of an analog seismograph recording. These data can be compromised in several ways.

First of all, seismograph quality varies enormously. Some seismometers, for example, are in locations that are subject to a great deal of background activity, and this makes determining exact travel times difficult. Secondly, the local observers themselves certainly vary in their skill at seismograph-reading. Since there are millions of individual data points, random errors in the data will tend to cancel themselves out. But systematic errors are a much greater problem, since they are a problem of unknown magnitude.

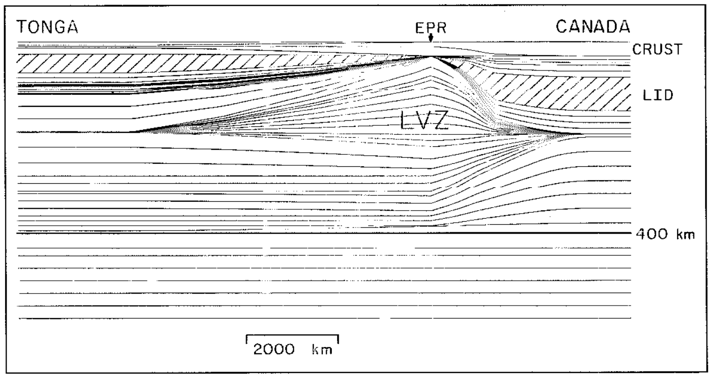
For this reason, Hiroo Kanamori is skeptical about all results that are based on P-wave arrival times. And in his view, the results become less believable the farther down one goes. "We have a reasonably good picture of the crust," he notes. "In the past decade we've gathered a lot of good data, and our computer power has increased. Our knowledge is obviously still too sparse, but at least the data quality is good. Our picture of the upper mantle is OK—large, long wavelength features are known. Qualitatively, this is not very different from 20 years ago, though our knowledge is more objective now. But it's far more difficult to understand the structure in the lower mantle, because in order to do so we must first understand the structure of the upper mantle very well. We have a great deal of P-wave data, but in my opinion the quality is very poor."

But Hager defends the quality of the data used by seismic tomographers. He points to a study in which he used the P-wave data to calculate regional variations in the density of the Earth. From these he modeled the Earth's geoid (the hypothetical shape of a rotating, fluid-covered Earth) and calculated regional variations in the gravitational field. The calculated gravitational field showed more than 90 percent agreement with the measured gravitational field and this, says Hager, tends to validate the P-wave data, at least for long-wavelength features.

## New Methods for the Future

"In order to resolve all these conflicting interpretations we need finer detail," says Kanamori. "For example, how thick is the 650-kilometer discontinuity? Is its depth the same from place to place? We need more data from broad-band digital seismometers, where operator error is much less of a factor. But there are fewer than 50 digital seismograph stations worldwide." This situation may soon improve, however. The Caltech Seismological Laboratory is trying to raise $4.2 million to add 10 broad-band digital seismometers to the 300 analog instruments in the Southern California Seismic Array.

In addition, Kanamori believes that one can gather higher-quality results by looking at S waves, as do Tanimoto and Donald Helmberger, professor of geophysics. Aside from looking at a different type of wave, both researchers differ from those who study P waves in that they examine the entire waveform, not just its arrival time.



*By studying interference patterns in S waves that take different pathways from source to seismometer, Helmberger is able to build up far more detailed images of the Earth's internal structure than is possible using P-wave arrival-time data. This diagram shows the results of his approach—a relatively detailed picture of a slice of the Earth running from Tonga in the South Pacific to northeastern North America. (EPR is the East Pacific Rise in the Gulf of California, LID is the lithosphere, and LVZ is the low-velocity zone in the mantle.)*

Helmberger, for example, is actually able to detect interference patterns in S waves that take different pathways from source to seismometer. In this way he builds up far more detailed images of the Earth's internal structure than is possible using P-wave arrival data.

"My belief is that geophysics is at a turning point," says Kanamori. "We have really powerful computers and we have good techniques. But the quality of the data is simply falling behind. The reason there are so many different views about the Earth's internal structure is that it's hard to interpret low-quality data. With a new generation of higher quality data we may be able to resolve these issues. It may be an exciting time to be a geophysicist, but the real excitement will come when we can make definitive statements based on high-quality data." □

# John F. Benton

## 1931-1988

JOHN F. BENTON, the Doris and Henry Dreyfuss Professor of History, died unexpectedly at his Pasadena home Thursday, February 25.

Born in Philadelphia in 1931, Benton attended Haverford College, earning his BA in 1953. His MA (1955) and PhD (1959) are from Princeton. After teaching at Reed College and the University of Pennsylvania, he joined the Caltech faculty in 1965 and became professor of history in 1970. Benton was honored with the Dreyfuss professorship just this past winter. He was well known in the academic world as a medieval scholar and in the local community as an active proponent of civil rights. Although Benton had suffered from arthritis for more than half his life, he never let his handicap dominate his personal and professional relationships; Benton riding his three-wheeler was a familiar jaunty sight around campus.

Benton's main scholarly interest (for more than 30 years) was the court of Champagne in the late 12th century. He combed the French archives for, and then edited, 750 charters issued between 1152 and 1197 by Counts Henry I and Henry II of Champagne and Marie of Champagne. Another long-term interest was the correspondence between the famous 12th-century lovers, Heloise and Abelard. He suggested several years ago that neither one had written the letters attributed to them but recently concluded that Abelard had probably written them all. Benton's course, "Love in the Western World" from antiquity to modern times, was an extremely popular one.

Benton was also known for his innovative application of image-enhancement techniques, developed at JPL for the space program, to make faint manuscripts legible. He suspected that it was this unusual blend of art and technology that won him a MacArthur Foundation fellowship—more than $50,000 a year for five years with no strings attached. He was in the third year of his prize fellowship when he died.

When he won the MacArthur

award, he was quoted in the *Los Angeles Times* on why he chose to stay at Caltech: "I'm more interested in giving a sense of historical perspective to a future member of the Atomic Energy Commission than in teaching a future historian how to read documents. . . .What scientists need most is a sense of historical perspective. They can get a sense of paradigms of thought when they learn how intelligent people could have held quite different ideas in different cultures."

A memorial service (featuring the Golden Eagle Jazz Band to commemorate Benton's love of jazz) was held March 14 in Dabney Lounge. Three of his Caltech colleagues were among the speakers.

**Eleanor M. Searle**
The Edie and Lew Wasserman Professor of History

My intellectual life and my joy at Caltech will be so diminished that I almost forget to be grateful that John has been around. He was a wonderful scholar and in nothing more wonderful than in his delight in the technicalities of scholarship. That's what the real fun is in medieval scholarship—the technicalities.

On the day before he died, John came into my office and said, "I've got these wonderful pictures that Peggy Brown has sent me." (They were photographs of charters of the early 12th century that had found their way to Leningrad.) "Let's go off campus," said John, as he so often did, "and have lunch." "Good," said I. "If this is a real feast, let's 'pig it' and go to Hamburger Hamlet." (This was our idea of really pigging it.) And so John and I went and we had our great lunch (hamburgers and milkshakes) and pigged it for two hours over the technicalities of those charters. How could this date have got to be this way? Who is this scribe? Is this the same scribe? We spent a wonderful two hours, and it was the essence of John—hard work and real joy. I shall always think of John in this way. He will always seem to me also to be walking that high wire that he always did walk, balancing above us with no net underneath him, with a merrily striped umbrella in one hand and charters and jokes, scattering them down upon us.

**J. Morgan Kousser**
Professor of History and Social Science

John Benton was a very disconcerting person. He refused to behave as one expected him to. Before I met John I hadn't known anybody very well who had been brought up as a Quaker. Even so, I had some stereotypes—moral, selfless, and most of all, solemn. John was certainly moral; he often pointed out to me issues of principle that I'd been too obtuse to see, and his activism on social questions is well known. If selfless means generous to others, generous with his time, wisdom, and concern, then John was selfless. But he was almost never solemn. For one thing, he giggled a lot, especially when he and Elspeth were together. How many times have I gone into that chaotic office of his and received a cheery, "Come on in. Do you have time to sit down and talk for a minute? Look what I got in the mail." John would then regale me for 15 minutes or so with some crazy invitation from a French committee to honor a scholar with a jewel-encrusted sword; or some obscene verses of 11th-century Icelandic songs that had only recently been translated into English; or some humorously bitter letter he'd gotten attacking him for what he'd said about Abelard and Heloise. The joy, the verve, with which he'd explain these arcane matters was very infectious. I always left John's office happier than when I'd come.

Despite all his numerous ailments, John never seemed to me to be self-pitying, and he somehow made one feel unselfconscious about his physical problems. One made allowances for his arthritis, opening the door for his three-wheeler, walking slowly downstairs; but it seemed very natural, just as one seats left-handed people at the end of the dinner table.

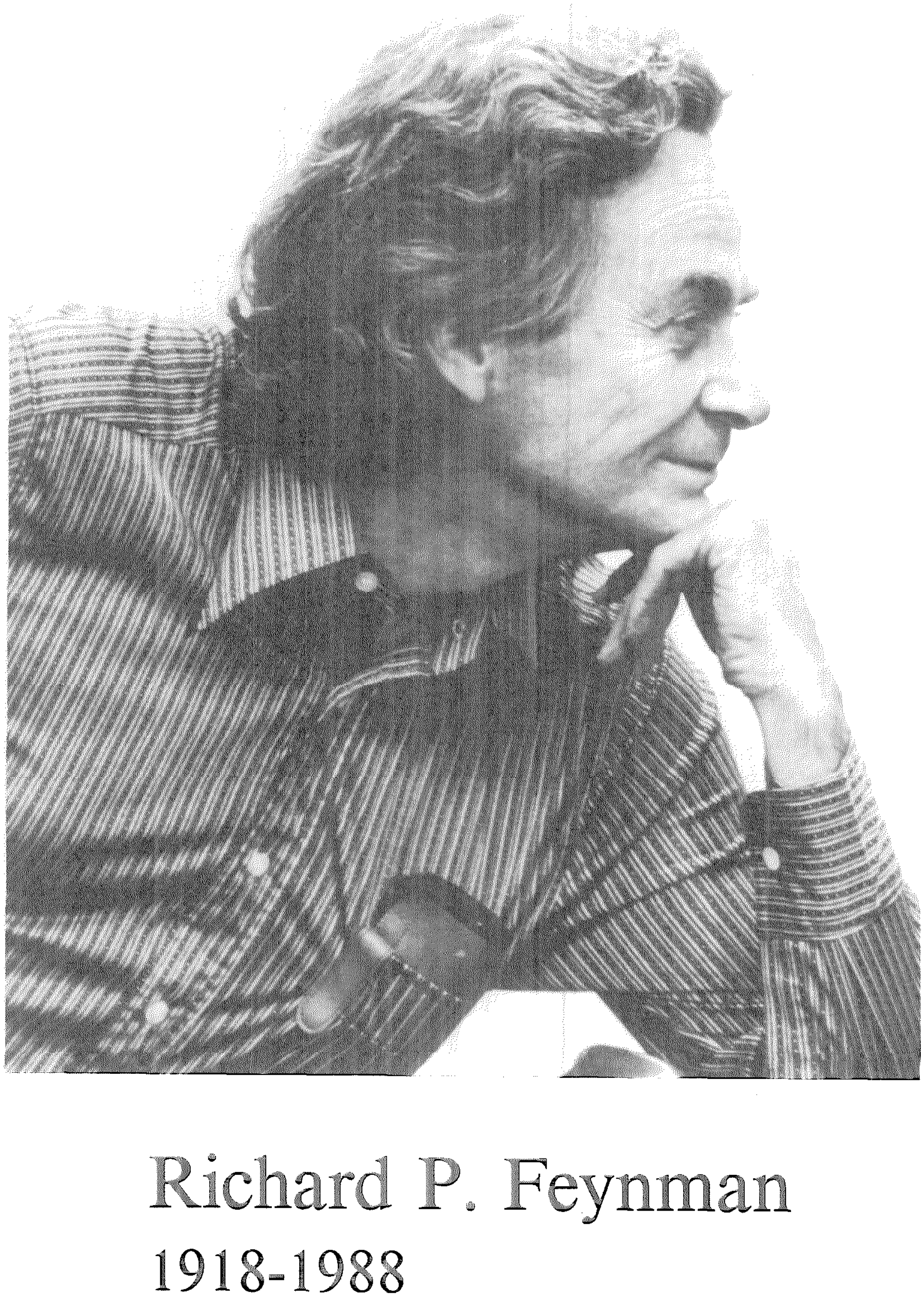
Among the great many emotions that flow over the survivors when a friend or family member dies is a sort of heartrent joy, a renewed inspiration from a life only now fully appreciated, the realization that, in the face of transience, we must enjoy friends and moments and not just mechanically drift through them. John Benton lived fully and joyfully, and remembering him fondly as we do, we should do so as well.

**George W. Pigman III**
Associate Professor of Literature

When I arrived here ten years ago John was, I believe, the very first member of the faculty to take an interest in my work and to seek me out and ask me what I was doing and show me what he was doing. Since we shared an interest in Latin literature he often shared with me manuscripts that he had found—could I help him read this little bit? And I would take my similar questions to him. He meant very much to me in turning me in a professional direction. In fact, it's appropriate that I should be speaking to you today in public because I wouldn't have spoken in public the first time without his—I won't say *gentle* urging—but urging that I give a paper at a certain conference.

I remember the moments all throughout my years here when I felt very grateful to John for his help, for his friendship. In particular I recall the many times we spent together during my first two or three years here, meeting every week to read medieval Latin poetry, which was a discovery to me because I had only read ancient poetry. Since that was the primary bond between us (and also because John and Elspeth met in a Latin class many years ago) I thought I would share with you a very brief Latin poem by one of John's favorite poets, Catullus. As a historian John was always deeply interested in the inner life of individuals in addition to broader social, institutional concerns. He was deeply moved, as I am too, by that peculiar inner vision that Catullus has. One poem that was a favorite of his is a very short poem on the death of Catullus's brother. Catullus visited the grave, which was in Asia Minor near the site of Troy, and wrote a poem about it which is very difficult to translate because it's very simple. It just says, "I've come many many miles, and I've performed this last rite, and farewell forever." And so it's my way of saying farewell to John.

*Multas per gentes et multa per aequora uectus*
  *aduenio has miseras, frater, ad inferias,*
*ut te postremo donarem munere mortis*
  *et mutam nequiquam alloquerer cinerem.*
*quandoquidem fortuna mihi tete abstulit ipsum,*
  *heu miser indigne frater adempte mihi,*
*nunc tamen interea haec, prisco quae more parentum*
  *tradita sunt tristi munere ad inferias,*
*accipe fraterno multum manantia fletu,*
  *atque in perpetuum, frater, aue atque uale.*



# Richard P. Feynman

## 1918-1988

*By Jacqueline Bonner*

NOBEL LAUREATE RICHARD PHILLIPS FEYNMAN died in Los Angeles on Monday, February 15, after a long illness. One of this century's most brilliant theoretical physicists and original thinkers, Feynman was the Richard Chace Tolman Professor of Theoretical Physics at Caltech, where he had been on the faculty since 1950.

Feynman was born in Far Rockaway, New York, in 1918. His father, a clothing salesman, determined that young Richard would be a scientist, and made a continuing effort to help him in that direction. He began by teaching him elementary mathematics when he was still in his high chair, used a toy wagon and a ball to explain inertia to him, and read aloud to him the science articles from the *Encyclopaedia Britannica.* He also helped him understand their implications—"translating" them, Feynman said. Another lesson was that names don't constitute knowledge. "I learned that when you know the name of a bird in every language, you know nothing, but absolutely nothing, about the bird," Feynman recalled.

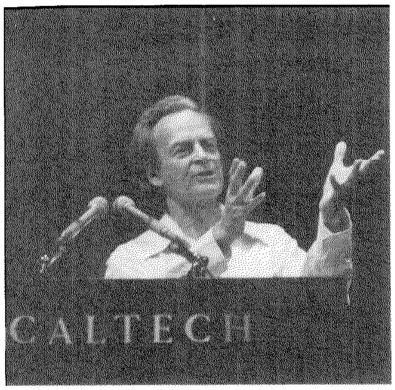
After graduating from Far Rockaway High School, Feynman attended the Massachusetts Institute of Technology where he graduated with a BS in 1939. From there he went to Princeton to work with John Wheeler, and received his PhD in 1942. After wartime work at the Los Alamos Scientific Laboratory—where he divided his time between trying to solve the secrets of the atom and of cracking safes—Feynman became professor of theoretical physics at Cornell, where he worked with Hans Bethe. It was there in a period of about four years that he did the work that led to his sharing the Nobel Prize in Physics in 1965 with Shinichero Tomonaga of Tokyo and Julian Schwinger of Harvard. They had worked independently on problems in the existing theory of quantum electrodynamics; Feynman basically rebuilt the theory from the beginning.

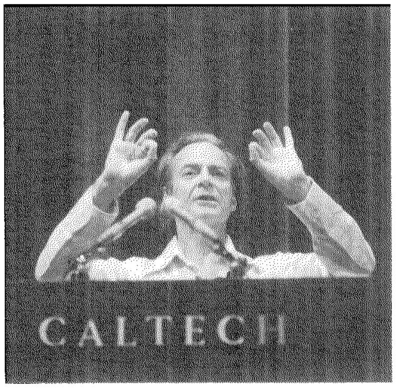
Quantum electrodynamics was born in the late 1920s when Dirac, Fermi, Heisenberg, and Pauli applied the new quantum mechanics to the old equations of Maxwell's classical electrodynamics. The new theory, by quantizing the fields and physical quantities involved, was able to describe the standard radiation processes occurring in atomic physics, but it was, nevertheless, not able to provide precise answers to some questions. Thus, when an electron moved into a lower energy orbit and emitted a photon, the theory could predict only a first approximation of the wavelength of the photon. Correction terms in the equations, which should have yielded more precise answers, diverged and gave infinite values, which were physically meaningless.

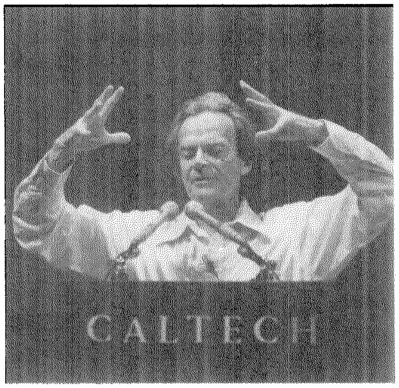
In 1946 experiments were already being conducted with much improved accuracy, made possible by the development of microwave techniques, and the weaknesses of the existing theory became glaringly evident. Feynman's radical approach to correcting the theory was to reconstruct almost the whole of quantum mechanics and electrodynamics from his own point of view. He treated all events in terms of particles, simplifying the interaction calculations largely through developing his famous diagrams of the interaction trajectories. By 1965, modern quantum electrodynamics had brought order to that vast part of physics lying between gravity and nuclear forces, and his simplified rules of calculation had become standard tools of theoretical analysis in both quantum electrodynamics and high-energy physics.

Feynman was a visiting professor at Caltech in the early part of 1950, and later that year accepted a permanent faculty appointment. He became Richard Chace Tolman Professor in 1959. Over the years at the Institute he worked with Nobel laureate Murray Gell-Mann on a theory for weak interactions; he formulated a mathematical theory that explained a whole range of properties of liquid helium at very low temperatures; and he did theoretical work on how the structure of the proton is revealed in bombardment by high-energy electrons.

He became something of a legend







for other reasons as well, known not only for his science but also for his extraordinary ability to communicate its meaning to audiences at all levels. Students appreciated his efforts in their behalf, voting him an award for teaching excellence in 1982. These awards are made on the basis of student evaluations of the instructors' clarity, enthusiasm, command of the subject, rapport with the class, and interest in the students as individuals. On the morning after his death they expressed their feelings more directly by hanging a huge banner that said, "We love you, Dick," from the top of the tallest building on campus.

A concrete expression of the respect and admiration the Caltech community felt for him occurred a few years ago when word reached the campus that Feynman needed massive transfusions after major surgery. Within hours Caltech students and faculty had donated over 100 pints of their own blood to the appropriate blood banks in his behalf.

Other manifestations of the Feynman/student rapport showed up when he appeared in full academic regalia for commencement whenever it was physically possible for him to do so, and one year he gave the commencement address. He attended Freshman Camp now and then, made appearances in several of the annual musicals (once in *South Pacific* dressed as a South Sea islander playing the bongo drums; another time in a production of *Guys and Dolls*, for example), and he regularly gave a lecture to the freshman physics class, never talking down to them and always challenging them to the limits of their abilities. He continued to meet his classes until just two weeks before he entered UCLA Medical Center for the last battle in his eight-year struggle with a rare form of abdominal cancer.

Appreciation was also manifested by the faculty. Whenever it became known that he was going to lecture on any topic, the largest lecture hall available was made ready for what was sure to be an overflow crowd. Seating on such occasions was so valuable, in fact, that the room filled up long before Feynman appeared on the platform. "I always come to Feynman's lectures," said an old-time faculty member, "because I'm sure there will be at least one good surprise."

Sometimes that surprise was a new idea, and sometimes it was also extraordinarily good theater. In 1973 British audiences saw a Yorkshire Television interview with Feynman called "Take the World from Another Point of View." The title was a capsule statement of Feynman's outlook, and television viewers all over the world got to see an example when, as a member of the President's Commission on the Space Shuttle Challenger Accident, he performed his "little experiment." While an expert from NASA was testifying, Feynman demonstrated what happened to a synthetic rubber O-ring dipped in a glass of ice water. It was no surprise at all when he issued his own explanatory addendum to the commission report. One faculty member with long experience on boards of inquiry asked the pertinent question when his appointment was announced. "Do they realize," he wondered, "that Feynman asks questions—and that he keeps asking them until he gets answers?"

The biggest surprise of all—to those who knew him—was that he accepted the appointment. He liked to describe himself as "actively irresponsible," and had a highly developed distaste for the bureaucratic mind-set and the pointless activities of most committees. He needed lots of solid time to think, and he made sure he had it. Time-wasters got short shrift from him. He also hated formality, and considered declining the Nobel Prize because of his aversion to pomp and circumstance.

In addition to the Nobel Prize, Feynman had been awarded the Albert Einstein Award from Princeton and the Einstein Award of Albert Einstein College of Medicine, the E.O. Lawrence Award of the Atomic Energy Commission, the Oersted Medal for Teaching, and the Niels Bohr International Gold Medal. He was also a foreign member of the Royal Society.

Much as science interested him, it was not his whole life, and his well-known playing of bongo drums was not his only outside interest. It was, for example, a point of pride with him to deliver his lectures in the language of the country in which he was speaking, and fortunately he had a facility for learning new ones. He thus spoke several, including both Spanish, which

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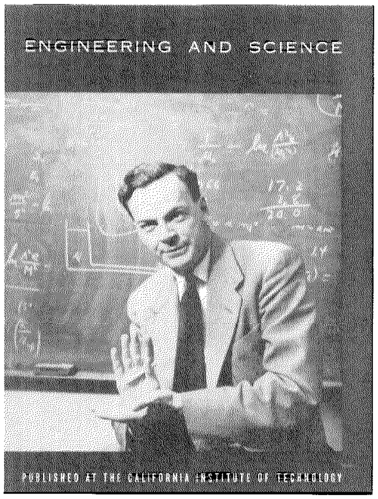


# An Edito

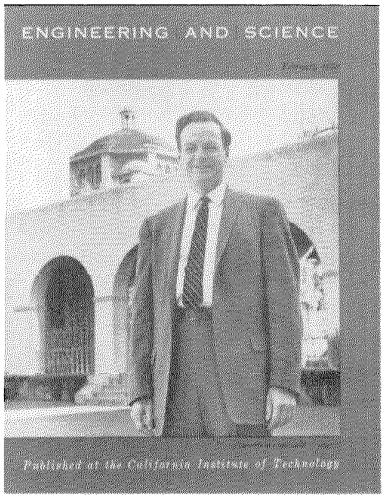
IN A CERTAIN SENSE, we all knew different Richard Feynmans. His colleagues knew the brilliant theoretical physicist; his students knew the electrifying teacher; Caltech's drama coach, Shirley Marneus, knew the earnest actor; his art teacher, Tom Van Sant, knew the apprentice artist.

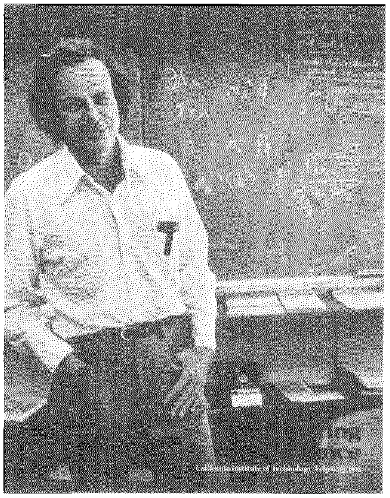
The Feynman I knew was the writer. Not that he ever wrote. Well—*hardly* ever. But he *talked.* How he talked. To his colleagues. To his students. To his friends. To whoever sat near him in the campus cafeteria. In a pinch—to himself.

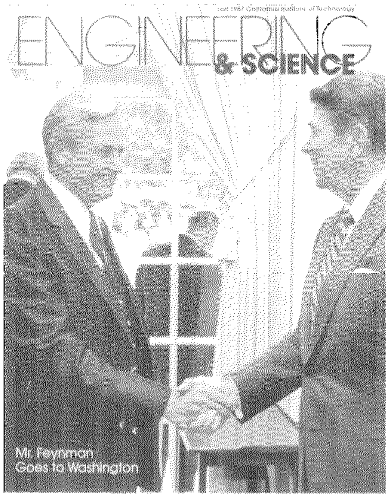
But *write*, he did not.

When Feynman first came to Caltech in 1950, I was editor of *Engineering & Science.* Our articles were written for the most part by faculty members or distinguished visitors to the campus. Sometimes we would get a man to revise a technical paper he had presented at a scientific meeting —scaling the paper down to more general understanding. And sometimes we would work over a talk written out to be read at a departmental seminar. Or, after reading an official report on a research project, we would ask a faculty member to write up a more general account of his work. And sometimes, miraculously, he would say yes.

With Feynman we had to resort to







# Remembers Feynman, the "Writer"

*By Edward Hutchings Jr.*

the tape recorder. The tape recorder was just a pup in the early fifties. Before tape, there was a monstrous machine known as the wire recorder, which had a mean habit of doggedly unreeling mile after mile of snarled wire onto your office desk when you started it up.

Even in his first days at Caltech, there were constant demands on Feynman's time. Later, and particularly after he won the Nobel Prize, he became very skillful at protecting himself. But in those early days he was saying yes to everything— including giving talks to everyone from the American Physical Society to an undergraduate student assembly.

As soon as *E&S* discovered that Feynman had agreed to give a public talk, we would call him up. If he answered his phone at all (and he was already beginning to go to a lot of trouble to keep from doing this), he was quite likely to start the conversation, not with "hello," but with, "*now* what?"

Undaunted, we would foolishly ask if he intended to write out his talk. "*Write?*" he would say scornfully. "I won't even know what I'm going to *say* until I say it."

Then how about making a tape of the talk?

A tape? If we wanted. It would make no difference to him.

So we would tape the talk. And transcribe it. And send him a copy of the transcript. His reaction was the same (well, as with everything about Feynman, it was perhaps a little heightened) as that of most people faced with a direct transcript of what they have said in public. He was appalled.

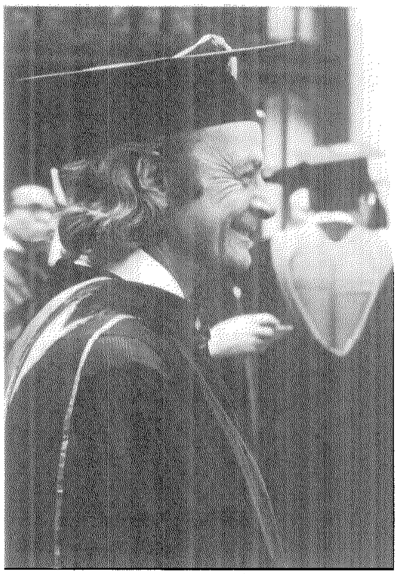
The fact is that verbal communication—including extemporaneous talks or lectures—has very little in common with written communication. When most of us speak, grammar goes out the window, sentence structure is violated, sentences are rarely completed, and repetition is rampant. By writing standards it's a mess.

So, to regain his self-respect, Feynman would gladly work with us to turn his chaotic transcript into a publishable article. And I must say that he always took as much satisfaction in the end result as we did. *E&S* and Richard Feynman soon became a mutual admiration society, and Feynman got to calling me "my publisha."

We did manage to publish almost a dozen of his talks over the years—talks that covered some of his more general interests, aside from physics. All of them were enormously popular—partly I think because we went to a great deal of trouble to not make too many changes, so that they still, in writing, sounded like Feynman speaking. And, as we all know so well at Caltech, Feynman speaking was pure gold—especially in a Far Rockaway accent that could lure you even into thinking that you were finally beginning to understand physics for the first time.

One of my encounters with Dick Feynman in the early fifties occurred in the newly opened Alumni Pool. A dedicated swimmer, I was huffing and puffing after doing my daily quota of laps in the pool, when Feynman lowered himself gingerly into the water beside me and stood there glowering at the prospect before him. Finally he set off, swam briskly to the far end of the pool, then turned around and swam back to where I was still standing. He rose up out of the water with a look of surprise on his face. "*This*," he said, succinctly, "is *boring*." And he got promptly out of the pool—never, to my knowledge, to return.

So I learned early: If it was boring, Feynman wouldn't do it. We may all have known different Feynmans, but we all knew the one to whom life was an adventure. To be in his company was to share some of that sense of adventure, to catch some of his excitement, to feel some of his enthusiasm. It was a very great privilege. □



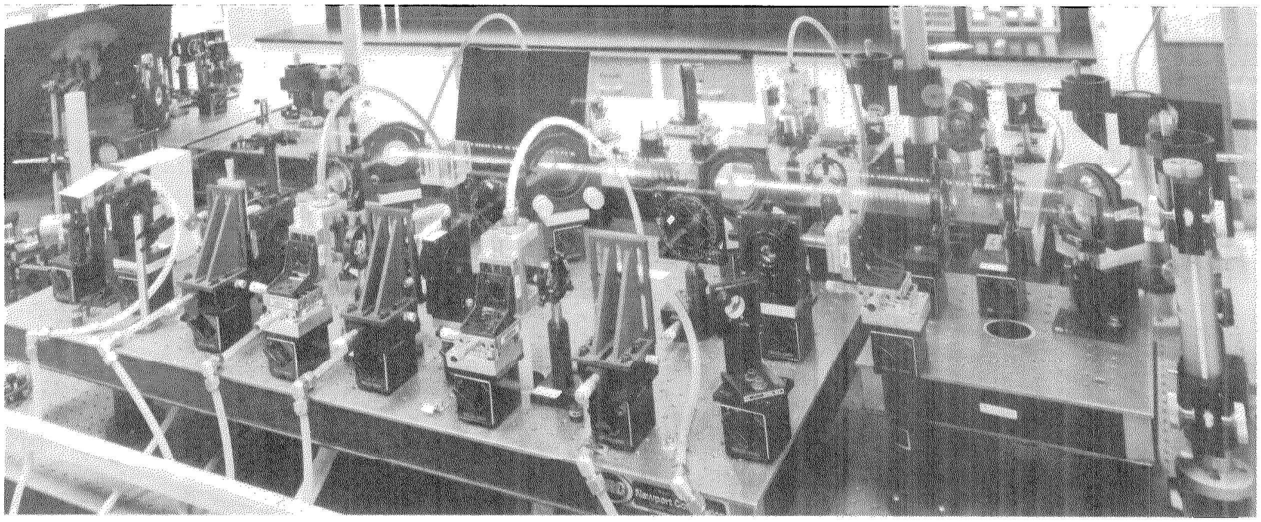
he learned in preparation for a visiting professorship in Brazil—and Portuguese, which he quickly acquired when he discovered that it (not Spanish) was the language of Brazil. He enjoyed drawing and painting and worked with professional artists to develop his technique. Archaeology was another subject of investigation for him, particularly the challenge of trying to decipher Mayan hieroglyphics.

Of his publications, the most recent was *QED: The Strange Theory of Light and Matter*, which was published in 1986. In it Feynman undertook to explain quantum electrodynamics to the general reader—without using a single equation. His 1985 *Surely You're Joking, Mr. Feynman*, which spent 14 weeks on the *New York Times* best-seller list, was the result of taped conversations with his friend Ralph Leighton. His earlier textbook, *The Feynman Lectures on Physics*, co-authored with Robert B. Leighton and Matthew Sands and published in 1963, has become one of the world's most popular physics books, and a best-seller in its own right. A footnote in Volume 1 of the three-volume set displays the poet and mystic in Richard Feynman and his profound awe at the wonders of the universe:

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

# Research in Progress

## Perfect Timing



*A portion of the optical bench in the femtosecond lab.*

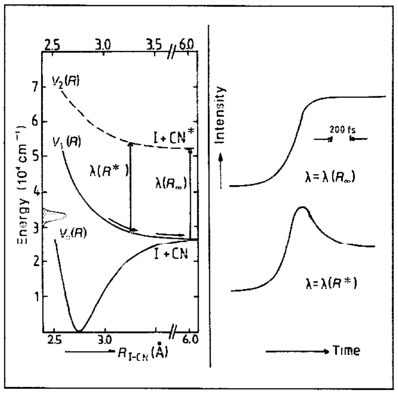
For the first time ever, scientists are watching the birth of molecules. Professor of Chemical Physics Ahmed H. Zewail's group uses ultrashort laser pulses to watch reacting molecules pass through so-called "transition states" before splitting apart into new combinations of atoms. Transition-state molecules are no longer reactants and not yet products—they are ephemeral moments of partially formed bonds. While transition states have been used to describe chemical reactions for decades, the states themselves are so fleeting (lasting for $10^{-12}$ seconds or less) that they had never been observed directly.

Zewail's group records molecular encounters in a series of "snapshots" a few femtoseconds (fs) apart. A femtosecond ($10^{-15}$ sec) is less than a hairsbreadth of time. Light zips from the earth to the moon in about 1¼ seconds, but travels only one percent of the width of a human hair in a femtosecond. Previous work with the fastest techniques then available produced blurry, time-averaged results for the transition region—like old photographs of a busy street.

The group works in Caltech's laser facility, where their optical bench—a forest of lenses, prisms, mirrors, filters, and other components on stalklike mountings—is enclosed in sliding plastic panels in a dust-free lab. (A couple of good-sized dust particles could scatter the 0.5- to 0.1-mm-diameter beams.) The enclosure prevents air currents from disturbing the beams, and gives them the exacting degree of stability needed to record femtosecond chemistry (dubbed femtochemistry).

Zewail's technique uses two laser pulses, each about 40-100 fs long. The first pulse—the pump—initiates the reaction and starts the clock. The second one—the probe—"photographs" the molecule after a preset interval.

"We cannot use electronics to get femtosecond time resolution," Zewail says. Time may be money in most places, but in Zewail's lab, time is distance. A partially transparent mirror splits the laser light, sending the pump, or time-zero ($t_0$), portion directly to the reaction chamber and detouring the rest through a variable-length path. A mirrored prism on a stepping motor controller sets the second path's length to within 100 nanometers ($10^{-9}$ m). The mirror is adjusted until the pulses overlap. "The overlap defines $t_0$ very accurately, and we take a snapshot of what's happening," Zewail says. "Then we start separating the pulses. If we delay the second pulse by three microns distance, say, that's ten femtoseconds in time, and we take another snapshot. We delay six microns and take another snapshot, and so on." The snapshots assembled in sequence form a "movie" showing the rapid



*Dissociating ICN. (left) Three electronic states [$V_0(R)$, $V_1(R)$, $V_2(R)$] of I–CN. Energy varies with I–CN separation (R). A probe at wavelength $\lambda(R^*)$ corresponding to an intermediate separation gives a transient signal (bottom right); the full separation signal $\lambda(R_\infty)$ appears later (top right).*

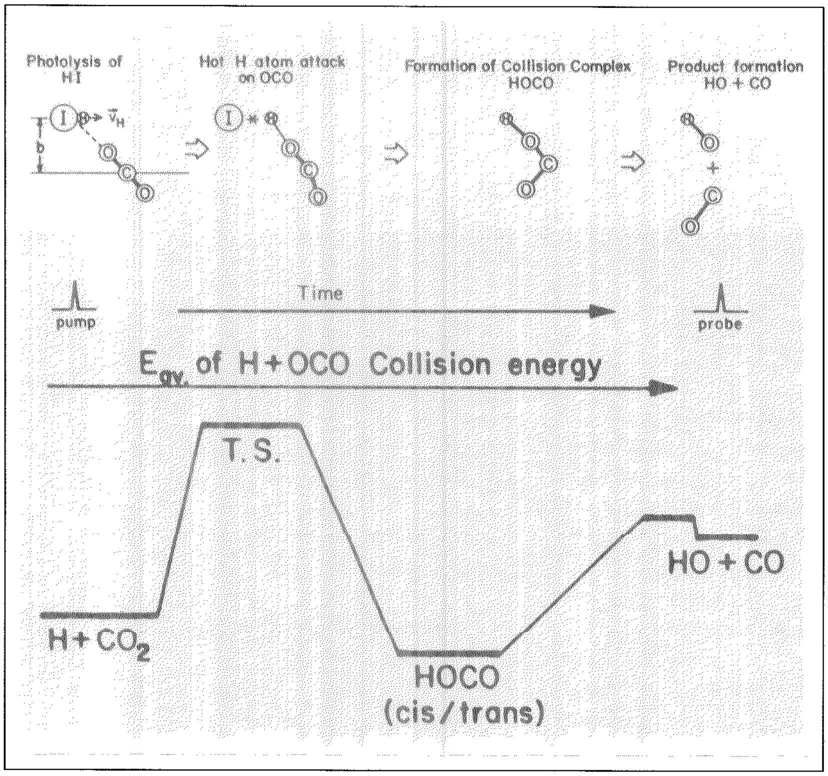
motions of atoms within the molecule, a feat never done before.

As a reacting molecule comes apart, its fragments absorb light at specific wavelengths depending on the atoms involved and the distances between them. The probe's snapshot monitors this absorption, so by adjusting the probe to a wavelength corresponding to a particular separation and then varying the delay time, the femtochemist can see exactly when the fragments pass through that configuration on their way to forming products. In a typical experiment, 20 pulses shoot through the reaction chamber every second. Five readings are taken at each delay, 150 delay times in all, yet the run takes less than a minute to complete.

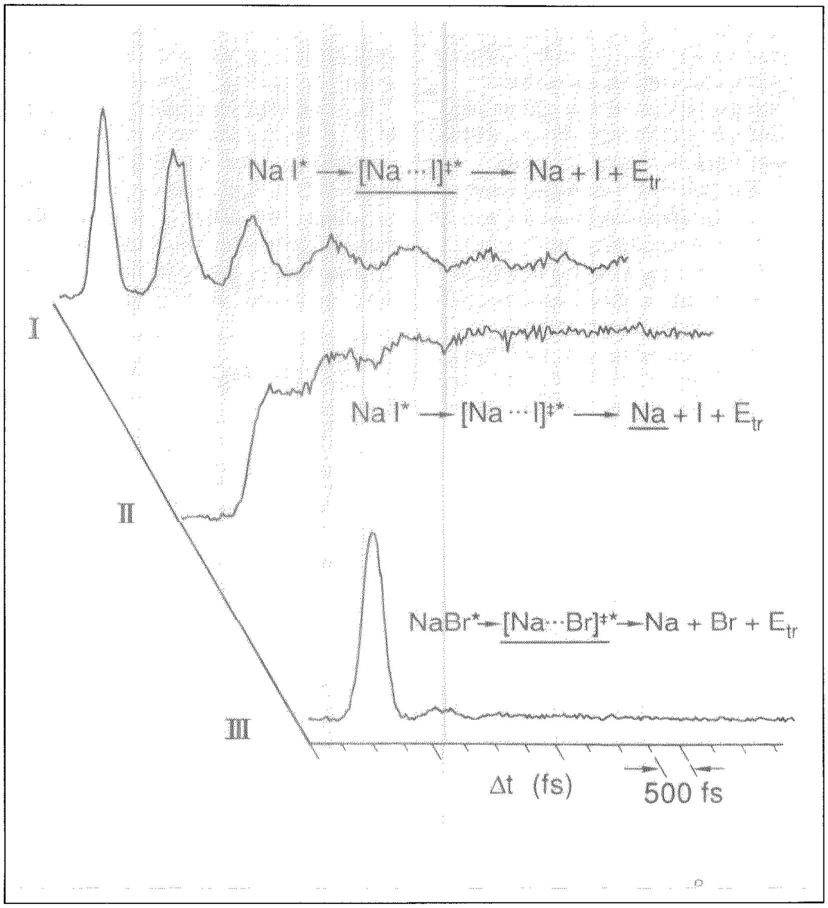
The group has published work on two reactions. Zewail, postdoc Mark Rosker, and graduate student Marcos Dantus are studying the decay of cyanogen iodide (ICN) into iodine (I) and cyanide (CN). Zewail—in collaboration with Richard Bernstein, a Sherman Fairchild Distinguished Scholar from UCLA—and graduate students Norbert Scherer and Lutfur Khundkar are looking at the reaction of hydrogen (H) and carbon dioxide ($CO_2$) to form carbon monoxide (CO) and hydroxyl (OH). These reactions were chosen because they represent two fundamental chemical processes.

Decomposing cyanogen iodide is what chemists call a unimolecular reaction—only one molecule is involved. Therefore, studying it with the new technique is conceptually quite straightforward. Zap an ICN molecule at the right energy, and it just falls apart—in a mere 200 fs, as it turns out.

Coordinating $t_0$ on the second reaction is a bit trickier, as the reaction is bimolecular—H and $CO_2$ start as separate entities. Not only do they have to be properly oriented and close enough to react on cue, but mon-



*Top panel: hydrogen reacting with carbon dioxide. The reaction sequence is shown schematically, with the corresponding energy level shown below each step. (T. S. stands for transition state.) The timing of the pump and probe pulses is also shown.*



*Bottom panel: salt dissociating. I. The Na–I bond resonating. II. Full separation. III. The Na–Br bond resonates once.*

atomic hydrogen is too reactive to wait quietly until needed. Both dilemmas are solved by starting with a carbon dioxide-hydrogen iodide complex, loosely held together by intermolecular attractions between hydrogen and oxygen (hydrogen bonds). To make the complex, the group uses a supersonic molecular beam expansion method developed at the other end of the Pasadena Freeway, by Curt Wittig's group at the University of Southern California. The beam cools as it expands, causing its molecules to lose energy and stick together.

The $t_0$ pulse breaks the H–I bond and simultaneously smacks hydrogen against oxygen as the hydrogen bond compresses; orientation and availability are guaranteed. The researchers could watch the collision complex pause for up to five picoseconds ($10^{-12}$ sec), gathering its forces to go over the energy hump—through the transition state—and form the O–H bond. Once the bond forms, the complex clings together a bit longer to redistribute its energy before the HO–CO bond breaks and the newborn HO and CO molecules fly apart.

In a more recent experiment by postdocs Todd Rose and Mark Rosker, the Zewail group has observed "resonances" as salt molecules react in real time. As molecules of sodium iodide (NaI) start to come apart, the Na–I bond doesn't simply stretch until it snaps. Instead, the bond stretches and compresses (resonates) a half-dozen times or more before coming unglued. On the other hand, sodium bromide (NaBr) stretches only once before final separation. Neither phenomenon had ever been observed in real time before. The work is described in the May 1988 issue of the *Journal of Chemical Physics*, now in press.

"When Linus Pauling was at Caltech 34 years ago, he taught us about the structure of the chemical bond," Zewail says. "Now we are seeing its dynamics in real time." The 1986 Nobel Prize in chemistry went for time-integrated studies of reaction dynamics— using the "before" and "after" molecular states to deduce what must have happened in between. This new work, which looks at the hitherto inaccessible "in-between," opens up "a new era in chemistry," according to Bernstein. "It's a milestone."□—*DS*

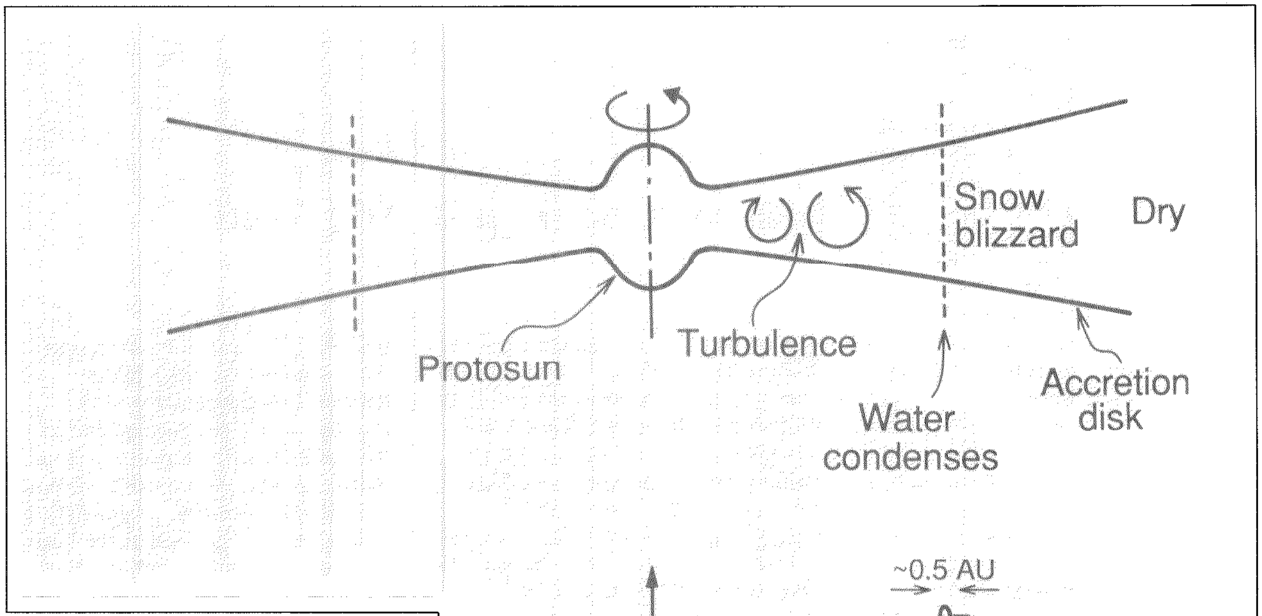
# Instant Jupiter: Just Add Water

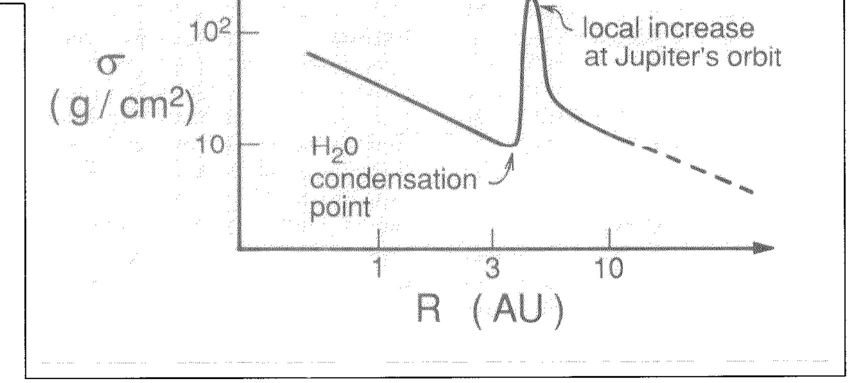
HOW JUPITER CONDENSED from the roiling gas and dust of the primordial solar system is a mystery, according to Professor of Planetary Science David Stevenson. Not that a giant gasball forming from a gas cloud is baffling—but that swaddled deep within the hydrogen and helium lies an inner core of rock or ice. This core is believed to have formed first, then cloaked itself with the lighter elements. "The cloud heats up as it collapses, and its interior soon reaches a temperature where water and rock are soluble in hydrogen," Stevenson explained. "If you try to make the whole planet all at once, there is a tendency for it all to get mixed up together." The core, 10 percent of Jupiter's radius or approximately Earth's size, has roughly ten times Earth's mass. It would take somewhere around 10 million years to form the way Earth did. (The solar system is about 4.6 billion years old.) But observations of T Tauri objects—gestating sun-sized protostars— imply that the sun lit up at around 1 million years of age, sweeping away the interplanetary cloud. If Jupiter's core finished aggregating 9 million years later, the gas would be long gone. So how could Jupiter form fast enough to capture it?

According to standard theory, a planetary system forms from an interstellar cloud of gas and dust called a presolar nebula. Mutual gravitation collapses the cloud; conservation of angular momentum sets it spinning. The nebula flattens into a disk, perhaps 100 to 200 astronomical units across and one tenth as thick at the periphery. (An astronomical unit, or AU, is the mean distance from Earth to the sun: 93 million miles or 150 million km.) The central accumulation of mass becomes the protosun. Small, solid bodies called planetesimals form elsewhere in the disk. A gravitational shoving match ensues, gradually pushing losers into collision courses—orbits crossing the disk's plane. Shipwrecked planetesimals stick together, or accrete, because part of their kinetic energy turns to heat on impact, and what's left can't overcome the aggregate's gravity. A gravitational truce eventually emerges as the largest survivors settle into stable, coplanar orbits.

The planetesimal casualty rate depends on the accretion disk's local surface density. "If you take all the matter at a given radius, smear it evenly in two dimensions, take a one-centimeter-square cookie cutter, and ask yourself how much material you cut out," Stevenson explained, "that's the surface density." The surface density where Jupiter formed is usually estimated at 5 gm/cm$^2$. A 20-fold increase would spark runaway accretion. "One object gets just a little bit larger than the others, and its gravitational field focuses the orbits of objects going by it," Stevenson said. "There are no antitrust laws in gravitational physics—one company gobbles up all the others." Instead of nudging its prey into a crossing path over thousands of orbits, a planetary robber baron could engulf the competition in a few passes. Other scientists saw the possibility, but had no plausible story to explain a local increase in density.

Stevenson's tale hangs on the (roughly) inverse relationship between temperature and orbital radius. Jupiter's birthplace was bitterly cold, about 160 K (-170° F), which happens to be water's freezing point at the then-ambient pressure of $10^{-6}$ atmospheres. Outbound water vapor would turn to snow as it crossed Jupiter's orbit, forming a permanent blizzard in the void. But could enough water cross the orbit in time? And if it could, would a sufficiently dense snowdrift accumulate? The storm's turbulence would have to pack flakes





*Top: a cross-section through the accretion disk. Turbulence carries water across the condensation point, where it turns to snow. Bottom: a plot of surface density (σ) vs. distance from the protosun (R), showing the local increase due to the blizzard.*

into snowballs big enough to ride out a 100-meter-per-second gale (about 210 miles per hour, the equivalent of Earth's jet stream at 45,000 feet). Otherwise the snow would blow back across the blizzard line to melt, or worse, disperse out of reach beyond Jupiter's orbit.

Stevenson and Jonathan Lunine, who earned his doctorate under Stevenson before joining the University of Arizona's faculty, worked out the calculations. They have shown that a water molecule starting near the protosun—but outside its accretion zone—could wander out to the blizzard line in 10,000 to 100,000 years via random diffusion. (Water heading directly for Jupiter would take only 100 years for the 5-AU voyage.) Ten Earth masses are needed for Jupiter's core. Stevenson and Lunine estimate the disk held as much as 50 Earth masses of water within Jupiter's orbit. The molecules wouldn't be drifting singly, either, but in gas parcels 100 times Earth's size. Parcels collide and intermix, creating that 100 m/sec gale. This windstorm is the key to the whole problem: the theory needs it to move so much gas so fast; conservation of angular momentum provides it automatically to counterbalance material accreting onto the protosun.

When a gas parcel becomes a blizzard, snowballs form instantaneously. (Relatively speaking, of course— astrophysicists have calculated that a meter-sized snowball could form in as little as 1,000 years.) Snowballs perhaps 30 m across would be big enough to stay put, Stevenson believes, and would only take a few thousand more years to form. The runaway accretion zone's area of influence would be about 0.5 AU wide, so snowballs would be unlikely to drift beyond it before dropping anchor. Ten Earth masses of snow could accumulate in 100,000 years, leaving ample time for the core to acquire the gas which, compressed by its own weight, would eventually form the dense layers of metallic hydrogen, liquid hydrogen, and gaseous hydrogen and helium that make up most of Jupiter.

Although there is some indirect evidence for it, the theory will be difficult to verify in the near future, Stevenson said. "We do know there's a core. It could be mostly rock or mostly ice. Unfortunately, we don't have any way of deciding by observation. In my story it's ice, which is the most abundant substance in the universe capable of condensing in the right temperature and pressure range. We can see water ice on Jupiter's satellites— Ganymede, Callisto, and others—and there's lots of it in the outer reaches of the solar system. We could do an indirect test by looking for chemical gradients in the disks around nearby objects like HL Tau, a T Tauri star. Caltech's Millimeter Interferometer in Owens Valley or the Submillimeter Observatory in Hawaii have sufficient spectroscopic and spatial resolution. We might do that in five to ten years, and that's very exciting."□—*DS*

# Random Walk

## Honors and Awards

Don Anderson, professor of geophysics and director of the seismological laboratory, received the highest honor that Britian's Royal Astronomical Society can bestow, its Gold Medal. Anderson was cited "in recognition of research and leadership in the field of seismology, in particular for investigation into the structure and physical parameters of Earth's deep interior."

Sunney Chan, professor of chemical physics and biophysical chemistry, has been elected a Fellow of the American Physical Society for his work on applying the resonance methods of physics to a wide variety of biological and chemical problems.

Leroy Hood, Ethel Wilson Bowles and Robert Bowles Professor of Biology and chairman of the Division of Biology, has received the Miami Biotechnology Winter Symposium's Distinguished Service Award for 1988. The Symposium is sponsored jointly by the University of Miami's Department of Biochemistry and the Papanicolaou Comprehensive Cancer Center. The award honored Hood's contributions to synthesis and sequencing technology for genes.

John Hopfield, Dickinson Professor of Chemistry and Biology, won the 1988 Michelson-Morley Award, presented annually by Case Western Reserve University in Cleveland, Ohio. The award recognizes research that has contributed significantly to the advancement of knowledge and to human welfare. The award includes a plaque and a $5,000 prize.

Assistant Professor of Astronomy Shrinivas Kulkarni has been awarded the Booker Prize. The award, which is given every three years by the U.S. National Committee of the USRI (International Scientific Radio Union) for outstanding work in radiophysics, includes a $2,000 prize.

Robert Leighton, the William L. Valentine Professor of Physics, Emeritus, has been granted the 1988 James Craig Watson Medal. The National Academy of Sciences established the medal in 1887, and awards it every three years for contributions to astronomy. Leighton's contributions include creating and exploiting "new instruments and techniques that have opened new areas of astronomy to us all—solar oscillations, infrared surveys, spun telescopes, and large millimeter-wave reflectors." The bronze medal also includes a $15,000 prize.

The tenth year of Caltech's Summer Undergraduate Research Fellowship (SURF) program has been dedicated to Professor of Biology, Emeritus Ray Owen in recognition of his outstanding commitment to undergraduate education.

Professor of Mathematics, Emeritus Olga Taussky-Todd will be granted an honorary Doctor of Science degree by the University of Southern California on May 6.

Professor of Mathematics Hugh Woodin has been named co-recipient of the 1988 Carol Karp Prize by the Association of Symbolic Logic. The prize is presented every five years in recognition of a connected body of research. Woodin's work "establishes from the existence of a supercompact cardinal that the Axiom of Determinacy holds in the smallest transitive model of ZF containing all reals and all ordinals."

## Feynman Memorial Fund Established

In recognition of of Richard Feynman's 38 years on the Caltech faculty, the Institute has established a memorial fund in his name. In addition, Feynman's family has expressed gratitude for the life-prolonging care provided to the late physicist by Dr. Donald Morton, who directs cancer research at UCLA. Checks payable to Caltech may be sent to the Richard P. Feynman Memorial Fund, Caltech 105-40, Pasadena, CA 91125. And contributions may also be sent to the Richard Feynman Memorial Fund at the UCLA John Wayne Cancer Clinic, Village Station, Box 24177, Los Angeles, CA 90024.

## Programming Team Wins Competition

A team of Caltech students has won the Association of Computing Machinery (ACM) Scholastic Programming Contest for the second time in three years. This year's contest was held in Atlanta, Georgia, on February 24, and pitted teams from 24 schools against eight problems to be solved within six hours. The Techers were the only team to solve all six problems correctly in the allotted time—in five hours, 17 minutes, to be exact.

The team consisted of David Gillespie (a graduate student in computer science and team captain), Scott Hemphill (graduate student, computer science), Adam Greenblatt (senior, biology), and Ron Goodman (junior, computer science). Professor of Computer Science Charles L. Seitz was faculty advisor.

The team had previously won the southern California regional competition on November 14, 1987. Only the top two teams from each region advanced to the finals. The other southern California finalist was UCLA, who finished sixth.

Caltech began fielding teams in 1986, winning that year and finishing fourth in 1987.

# Random Walk (continued)

*On a recent trip east, President Everhart spoke on technology and national competitiveness at the National Press Club in Washington, D.C. Everhart also addressed 170 alumni and guests of the Alumni Association's just-organized Boston chapter. He later met 100 alumni and guests of the D.C. chapter at a reception at the National Academy of Sciences.*

## Ramo's AAES Award Donated to Caltech

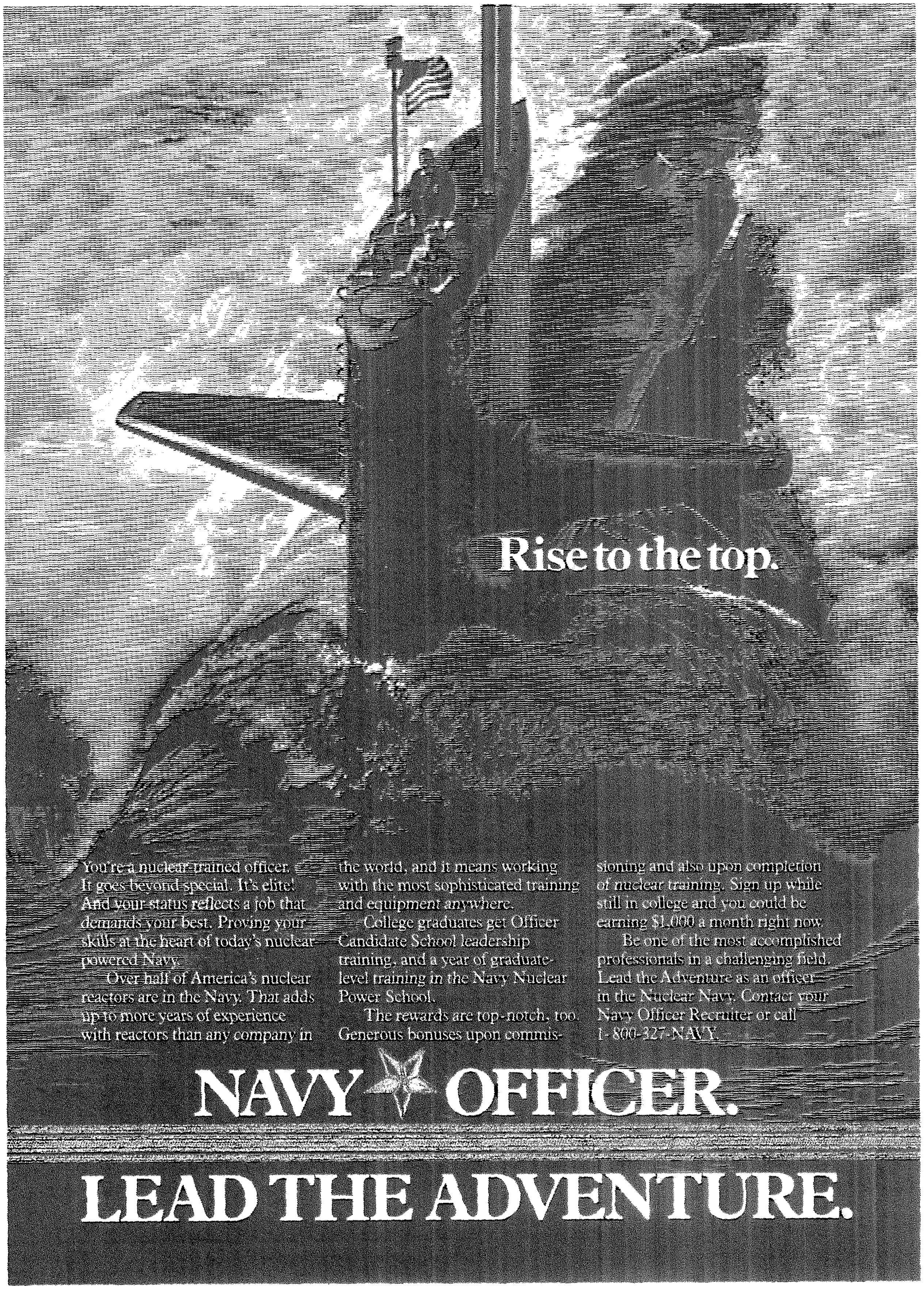
SIMON RAMO, PhD '36, a Life Trustee and visiting professor of management science at Caltech, has been given the National Engineering Award by the American Association of Engineering Societies (AAES). The award, one of the profession's highest honors, was presented at the AAES's annual awards luncheon in Washington, D.C., on April 6. The award includes a $5,000 honorarium, which Ramo is donating to the Institute.

Ramo graduated from the University of Utah with highest honors before coming to Caltech, where he earned a PhD magna cum laude in electrical engineering. He began his engineering career at General Electric, accumulating 25 patents before he was 30. Ramo moved to the budding aerospace industry, where he organized Hughes Aircraft Company's electronics and missile operations. In 1953, he co-founded The Ramo-Wooldridge Corporation (later TRW Inc.), and served on its board of directors until his retirement. Ramo became one of the nation's top experts on guided missiles, and was the chief scientist for the development of the Intercontinental Ballistic Missile (ICBM) system. Ramo is a founding member of the National Academy of Engineering, has received the National Medal of Science, and has been a key advisor to the nation's government on science and technology.

## Cram to Give Beckman Lecture

DONALD CRAM, winner of the 1987 Nobel Prize in Chemistry for his research in host-guest chemistry, will give the Beckman Lecture for 1988. The lecture is open to the public, and will be at 4:00 PM, Wednesday, May 4, in Gates Laboratory. Cram, a faculty member at UCLA, will speak on "Organic Container Compounds."

The Beckman Lectureship was established in 1985. Past Beckman Lecturers include Elias James Corey of Harvard (1985), Jerrold Meinwald of Cornell (1986), and Ronald Breslow of Columbia (1987).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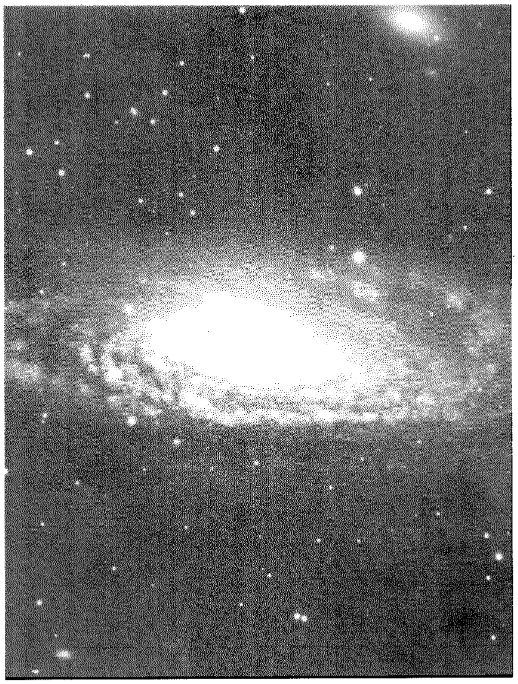

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