ENGINEERING & SCIENCE

California Institute of Technology

SEPTEMBER 1982

In This Issue

Memories

On the cover — a human brain against some detail of a portion of a computer chip. Superficial similarities have made comparison of computer and brain tempting. Even though they operate on entirely different principles to process information and store and retrieve memories, an understanding of the way each functions in these tasks may aid comprehension of the other as well.

To try to determine how the brain functions as a physical system, John Hopfield, the Roscoe G. Dickinson Professor of Chemistry and Biology, constructs mathematical models of collections of neurons. Hopfield came to chemistry and biology via physics, the field in which he earned his PhD from Cornell in 1958. Before coming to Caltech in 1980, he was professor of physics at Princeton for 16 years.

During that time, however, his research veered from solid state physics to the physical basis of molecular biology. The long-term goal of his research is understanding the relation between structure and function in biological systems, but he considers that he is still doing solid state physics — only on rather more complicated material.

In his recent Seminar Day talk, which generated much enthusiasm and many questions, Hopfield described how a simple physical system can underlie the complex memory retrieval function of neurons. "Brain, Computer, and Memory," adapted from that talk, begins on page 2.

Commencement 1982

This year's commencement speaker, Hans W. Liepmann, is a man who knows and cares about students — a fact that is recognized and appreciated by them. In 1976, for example, ASCIT gave him an award for excellence in teaching; in 1978 the campus chapter of Tau Beta Pi honored him with the title Eminent Engineer; and in 1981 he was elected an Honorary Alumnus by the Alumni Association. His talk, "To Know, To Understand, To Do," was addressed very directly to those who were graduating and appears on page 8 almost word for word as he delivered it.

Liepmann is actually an alumnus of the University of Zurich, where he received his PhD in 1938. He came to Caltech in 1939 as a research fellow and has been at the Institute ever since, becoming a full professor in 1949, director of the Graduate Aeronautical Laboratories in 1972, and Powell Professor of Fluid Mechanics and Thermodynamics in 1976. Over the years his research has included work on laminar instability, transition and turbulence, shock wave boundary layer interaction, transonic flow, aerodynamic noise, and the fluid mechanics of helium II.

This has been distinguished research, and Liepmann has been honored for it by his peers. He is a member of the National Academy of Engineering, the National Academy of Sciences, and the American Academy of Arts and Sciences. He is an honorary fellow of the American Institute of Aeronautics and Astronautics, for which he was First Dryden Research Lecturer. The German Society for Aeronautics has awarded him the Ludwig Prandtl Ring, and he holds the Worchester Reed Warner Medal of the American Society of Mechanical Engineers, the Monie A. Ferst Award of Sigma Xi, the Michelson-Morley Award from Case Institute of Technology, and the Fluid Dynamics Prize of the American Physical Society, of which he is a fellow.

Clearing the Air

Roger Noll, Institute Professor of Social Sciences, is a Caltech alumnus who received his BS in 1962 and then went off to Harvard to do his graduate work. He came back to Caltech as a member of the faculty in 1965, and has been here ever since except for stints as a senior economist at the President's Council of Economic Advisers in 1967-68 and a senior fellow at the Brookings Institution in 1970-73.

Noll is the author of three books and of more than a hundred articles on such subjects as safety and environmental policies, public utility regulation, the broadcasting industry, the economics of professional sports, the application of economics in political science, medical care policy, and bureaucratic decision-making. One of his current research interests is the development of a practical method for implementing tradable emissions rights as a means of dealing with air pollution.

On Seminar Day last May, Noll talked about some aspects of this research. "Leasing the Air: An Alternative to Regulation?" on page 12 is adapted from that talk.

STAFF: *Editor* — Jacquelyn Bonner
Managing Editor — Jane Dietrich
Photographer — Chris Tschoegl
PICTURE CREDITS: Inside front cover, 8-11, 18, 19, 28, 30 — Chris Tschoegl/13, 17 — Gregory McRae/19 — Mount Wilson and Palomar Observatories/23-24 — Jane Dietrich/29 — Richard Kee/32 — Gordon Glattenburg, BS 58.

Engineering & Science (ISSN 0013-7812) is published five times a year, September, November, January, March, and May, at the California Institute of Technology, 1201 East California Boulevard, Pasadena, California 91125. Annual subscription $7.50 domestic, $15.00 foreign, $20.00 foreign air mail, single copies $1.50. Controlled Circulation postage paid at Pasadena, California. Published by the California Institute of Technology and the Alumni Association. Postmaster: Send change of address to Caltech, 1-71, Pasadena, CA 91125.

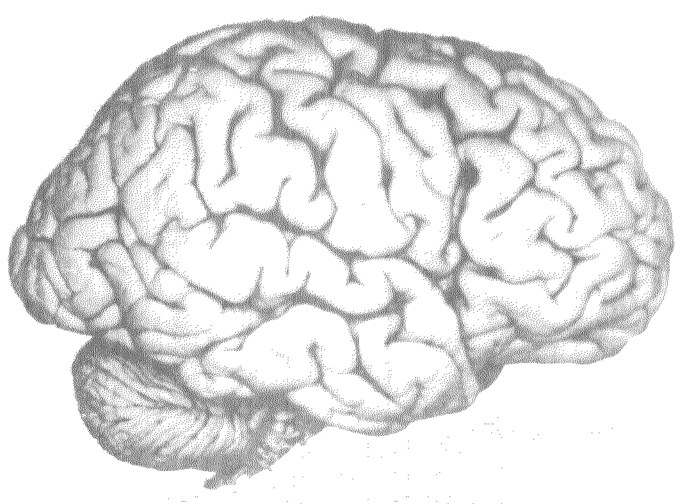
ENGINEERING & SCIENCE

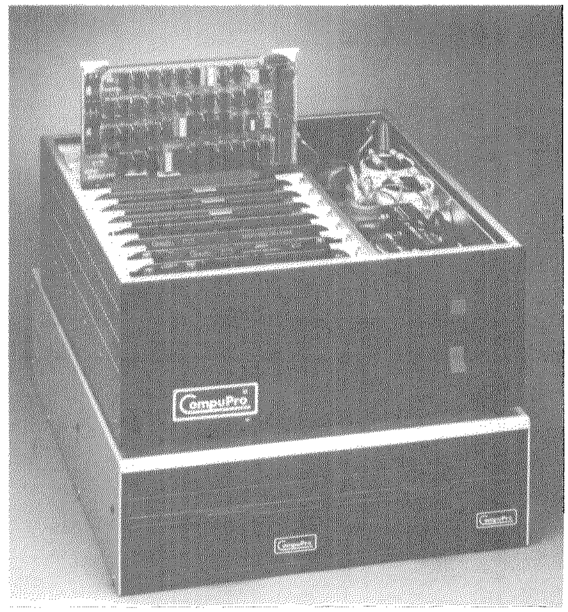
CALIFORNIA INSTITUTE OF TECHNOLOGY | SEPTEMBER 1982 — VOLUME XLVI, NUMBER 1

Departments

Brain, Computer, and Memory

by John Hopfield





BOTH OBJECTS above are computers. If you put reliable information into each of them, and if previously each has received appropriate programming, each will deliver what appear to be intelligent responses. At this macroscopic scale, however, it's impossible to determine whether the microprocessor and the human brain store and retrieve memories and make decisions on the same principles or on different ones.

While it isn't obvious from looking at their architecture whether or not the brain and the computer work on the same principles, it is clear that they don't carry out all tasks equally well. If you want to remember a million things accurately, it is better to do it on a computer than to trust your brain. On the other hand, your brain is capable of recognizing the face of somebody you haven't seen in ten years, even though both the face and the context may have changed considerably. It is *very* hard to write a computer program to make such a recognition, and these routine abilities of animals are astounding by comparison.

A closer look at their processing elements — a processing chip and a stained section of a brain (opposite page) — reveals more about how they work. This chip, which is one-quarter inch on a side, contains about 5,000 individual devices called gates. This is small compared to modern chips, which can have 50,000 or 100,000 individual devices on them. There are also many input and output leads to a chip — so many that you can't figure out from the circuit diagram of the chip itself how to use it. There are too many different ways of applying inputs to be able to try them all. If you don't know what the designer intended you won't find a useful function for a processor chip.

The human neural system also has processing elements — the individual nerve cells (or neurons), each with long branching arms. These branches have still finer branches, where connections are made from other cells. There are about 1,000 to 100,000 connections, or synapses, for each neuron.

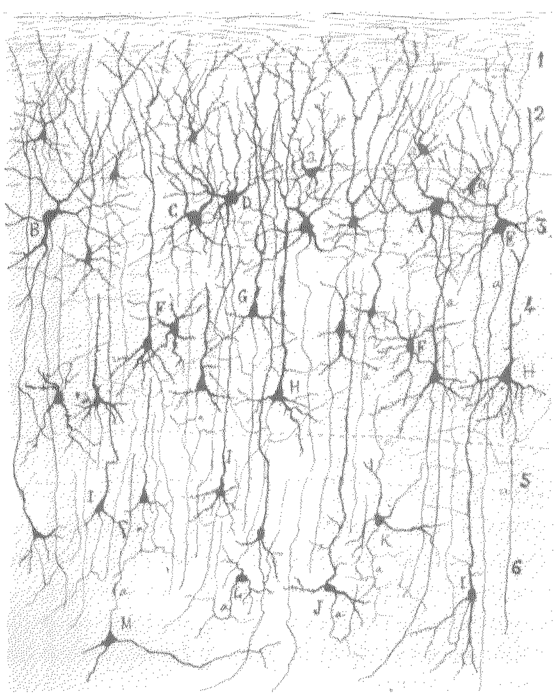
A modern computer has about ten million individual silicon gates or processing elements, each typically connected to three or four other elements. In comparison, a human brain has about 1,000 times as many cells as the modern computer does computer elements, and each cell has about 1,000 times as many synapses. So the brain is about a million times more complex than a large computer, though the computers are growing rapidly and will eventually rival a brain in complexity.

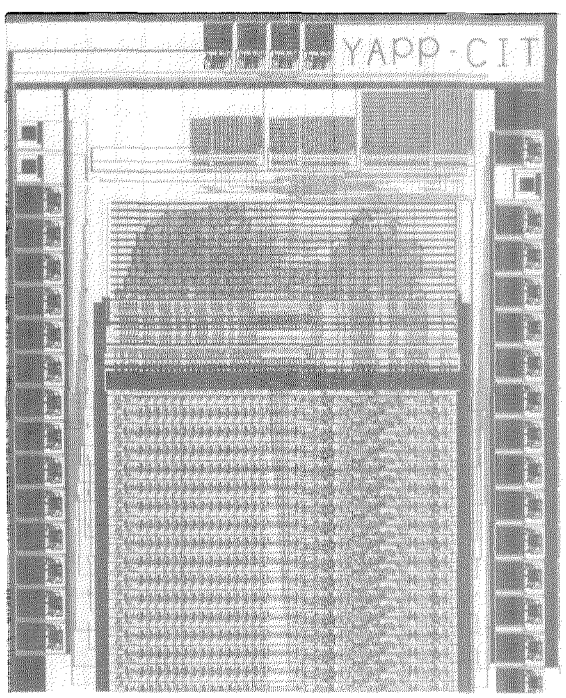
There is a major difference in the importance of the individual computing element for these systems. This difference is most visible in the sensitivity of these two computers to the failure of individual elements and suggests the occurrence of differing modes of operation. The brain of a 12-year-old child has a certain number of cells in it. By the time that child reaches 50, a few percent of the cells will have died. Yet his brain will still work very well, perhaps even better than it did at 12. In contrast, if one percent of the transistors in a computer go bad, it won't do anything at all. The reason for this difference is that the layout of the electronic computer is carefully planned. There isn't a transistor in it that wasn't put there with a purpose in mind. If that transistor goes bad, that purpose doesn't get carried out. The brain had no such grand overall planning done for it. Evolution didn't figure out ahead of time that if you build a brain exactly one certain way it will all work. Fortunately, since the biological computer must operate in a somewhat more holistic fashion than an electronic computer, it's also more fail-safe. How the brain actually manages to achieve such a mode of operation is among the most interesting problems of biology.

In physical science the customary and best way to study the fundamental interaction between simple objects is to put a few of them together and observe what happens. But new properties emerge as a result of having a very large number of those simple objects or elements. Take as an example the collision of molecules. To study simple collisions we can put two molecules in a large box. Every once in a while they collide, and that's an exciting event in the life of someone studying molecular collisons. After a while it gets boring waiting for them to collide, so we'll put in ten molecules or even 1,000. All that happens then is more frequent collisions between two objects, and the collisions will look the same as they did when there were only two molecules present.

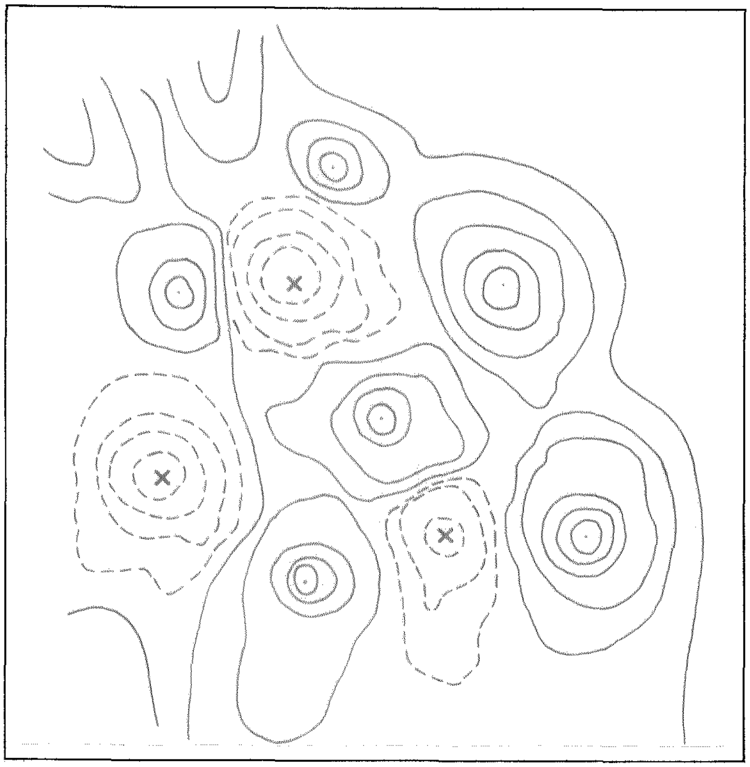
But if we put a billion billion (10^{18}) molecules in the box, there's a new phenomenon — sound waves. Sound waves wouldn't exist without collisions, which keep the sound waves organized. There was nothing in the behavior of two molecules in the box — or ten or 1,000 molecules — that would suggest to you that a billion billion molecules would be able to produce sound waves. Sound waves are a collective phenomenon, which takes place only when there are huge numbers of molecules present. Many of the laws of physics are collective in nature, including thermodynamics, hydrodynamics, magnetism, and the fact that materials have solid, liquid, and gas phases.

The brain has a huge number of elements — about 10^{13}. Do large collections of neurons have collective properties like other large physical systems? And if they do, are these collective effects used in the computations that a brain can do? One thing that the brain can do is keep memories intact. For instance, we all remember dozens of telephone numbers, with names, faces, places, and sets of experiences associated with each one. How do those telephone numbers and personal associations remain distinct without getting scrambled? Could a collective property keep a memory as an entity, unmixed with other memories?





Staining one neuron in 100 produces this picture (far left) of the brain's individual cell bodies with their branching arms that connect to other neurons. Each neuron has between 1,000 and 10,000 such connections. If the other 99 percent of the neurons were stained, this picture would be completely black. The 18-bit microprocessor (left) designed by graduate student John Wawrzynek (YAPP stands for "yet another processor project") is a one-quarter inch silicon chip containing about 5,000 individual devices, or gates. Modern chips can have 20 times this number.



A content-addressable memory can be likened to a simple physical system such as this contour map, which describes a terrain in terms of altitude. Mountain peaks are represented by dots, valley bottoms by Xs; the solid lines describe high altitude contours and the dotted lines, low contours. The valleys are like salt lakes with no connections with other valleys or escape routes worn by water. Another interpretation of this terrain appears on the following page.

A computer keeps memories distinct and held together in a way that we can liken to a very tall, very skinny library — 100,000 stories tall — with one book stored per floor. If we write the information we want to keep connected together in one book, and store the book on one particular floor, all we have to know to get that information out is the floor it's stored on. The information has obviously stayed together because it's all in one book.

That kind of memory doesn't work in biology. For one thing, as far as we know, there is no such thing as the address of a memory in the sense that there is a particular book on a particular floor. For another, a biological memory is content addressable; that is, a big memory — of a telephone number, a name, a person, the experiences you've had with that person, some places you've been together, and so on — holds together. Any part of that memory can be used to try to retrieve the whole thing. If you're reminded of any bit — the telephone number, or the name, or a common experience — all parts of the memory come together and can be retrieved. There is no one single part of the memory that plays the role of the library floor number and can be used to reach the memory. Rather, the memory can be retrieved by *any* reasonable part of the content.

Another difference between computer memory and biological memory is the locality of storage. It is generally believed that memories in our heads are much less locally stored than those in computers. What is "local" or "nonlocal" storage of memory? If I want to remember the word "Caltech," I can write "Caltech" on one page of a book. That's a local memory. If I rip the page out, the memory is not in the book any longer. If I had ripped out some other page, the memory would still be there. There is, however, another way of storing "Caltech" in a book. If I write it across the fore edge of the book (across the edges of the pages), ripping out one page or *any* particular page doesn't degrade the memory of "Caltech" written across the edge. Even if I ripped out 5 percent of the pages, I would still be able to retrieve that memory. This is nonlocal storage of information.

The trouble is, a book doesn't have many edges. If I want to store a lot of memories that way, I'm going to have to write one over another. If I do that and then try to recall a particular memory, it's going to be difficult to pull it out accurately and unmixed with others because it has many other memories written on top of it. Holding memories together in nonlocal storage is, I think, one of the fundamental problems that biological memories have had to solve.

Essential to the properties of content addressability and nonlocal storage is the fact that biological memory is not a linear system. Relations between input signals and output responses can be either linear or nonlinear. A great deal of physics and engineering is done with linear systems, and usually linear systems are easier to analyze than are nonlinear systems. But they do not always generate the desired outcome. For example, if I give a particular name to a linear memory system storing telephone numbers and names in memory, it will evoke the corresponding telephone number. If I give it a different one of its remembered names, it produces a different corresponding phone number. But if I give it a confusion of names, say, a 50-50 mixture of the two names, it will produce a 50-50 mixture, or an average of the two outputs. Since an averaged telephone number is of little use to anyone, it is fortunate that our brains don't work this way.

The essence of a content-addressable memory can be described in terms of the spontaneous behavior of appropriate simple physical systems. As an example we can use a contour map of a simple terrain, perhaps a lunar terrain, with mountain peaks and with valleys that don't connect with one another or lead down toward the ocean as they would on earth. A contour map defines a terrain in terms of altitude, but there is also another way to describe it — by a flow map showing which paths raindrops landing at any point would follow downhill, eventually to accumulate at the lowest places.

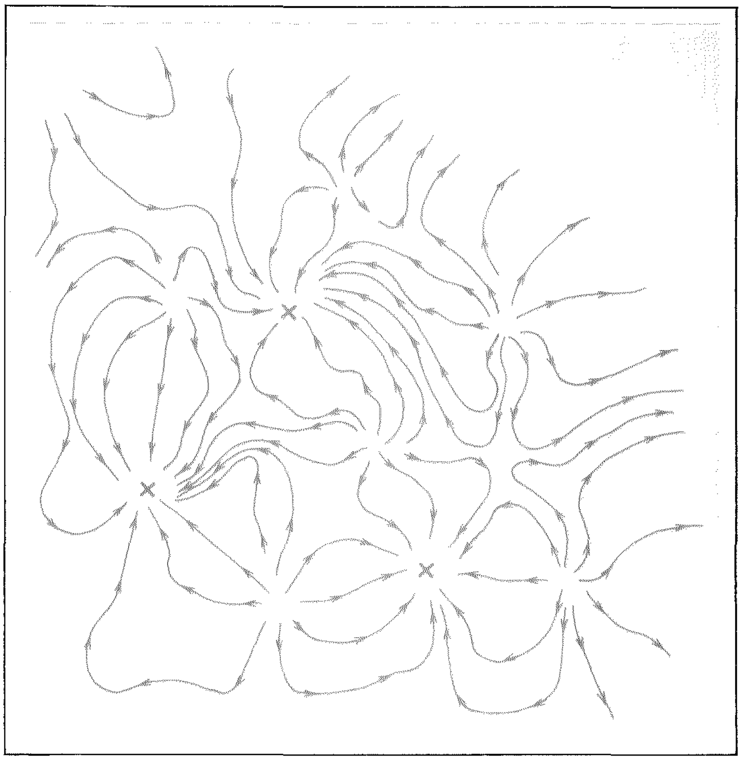
A flow map has all the information that the contour map contains but in a different representation. In looking at the flow map by itself without any knowledge of altitude differences, you would think that the raindrops were motivated by some miraculous laws of forces of attraction to specific locations. But knowing that there's a contour map behind it you know the secret — that this map doesn't come from mysterious forces. It comes from the flow pattern of water flowing downhill, and there is a terrain underneath causing the particular flow pattern.

In some sense this flow map is like a content-addressable memory. Just as a water droplet falling somewhere near the position of a valley bottom will flow to exactly the bottom position, so partial information can ultimately generate total information. Think of a particular valley location as being precise information. If you start anywhere vaguely near that position (having been given only partial information about the location of the valley) and simply follow the raindrops along, you'll come to the precise valley location. Then you'll stop moving because you've reached the lowest point around. Any one of these lowest points might be thought of as memory.

We can also describe a content-addressable memory in a computer or brain in such a way as to be able to understand it by a flow map of this sort. A computer is basically a large number of switches. At any moment each switch is either on or off. Each switch can be represented as a one, if it's on, or as a zero, if it's off. The present state of the computer can be represented by a long string of ones and zeroes, simply listing what its switch positions are at the moment. With time, the computer changes the switches around, but at any particular time you can represent what the computer is like by how the switches are set.

The same is presumably true of a set of neurons, though neural switches are more complicated — for example, they are not simply on or off. But conceptually the idea in brains is very similar. What your brain is like at any moment is described both by its connections and by which of the neurons are at the moment active (ones) and which are inactive (zeroes).

A particular memory state in a computer can be thought of as a long string of ones and zeroes — a long word in an alphabet with only two symbols. Different memories are simply different strings of ones and zeroes. In a content-addressable memory, an initial clue to a memory that somewhat resembles a particular one of the memories, say a slight "misspelling" of the ones and zeroes, will be able to change the "wrong" ones and zeroes to achieve exactly the desired



The information of the contour map on the preceding page can also be described by a flow map. The arrow paths indicate how a drop of water would flow from higher ground ending up at an X, which marks a valley bottom. Without knowing the "secret" that the flow is downhill, it would be easy to conclude that the flow is motivated by some mysterious force.

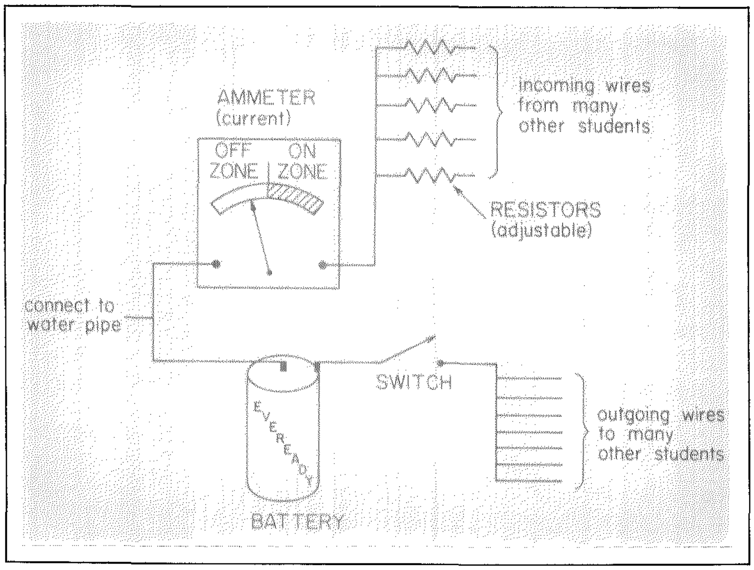
memory. For example, the two states below differ in the five places indicated by arrows.

```
memory state . . . 11010110110001 . . .
initial clue   . . . 11100110101000 . . .
                      ▲▲      ▲▲   ▲
```

If the computer starting in a state represented by the initial clue could change these five ones to zeroes (or zeroes to ones) to match the first state, it would be behaving as a content-addressable memory.

In order to turn this description into a kind of physical map, we could say that these two states are five units apart in distance. We could then draw a picture of a space in which every point represents a possible state of the computer, a possible computer word, and some particular ones of those states are the things that we have stored as memories. What we need for a content-addressable memory is for initial states of the computer near one memory but distant from others to change with time to become the nearby memory.

If we think of a content-addressable memory in these terms, we end up with a flow map like the one generated by raindrops flowing downhill. The flow in state space tends to accumulate at the points representing the memories. If you start with information somewhat like the memory, you will be able to retrieve the whole thing. If you start halfway between two points, you will end up at one or the other, but not in a linear combination of the two.



In the "Caltech neuronal computer," a model representing 1,000 neurons as 1,000 Caltech students, each student would have on his desk an apparatus similar to this. Each has many wires coming in from and going out to other students, but it does not matter which students are connected to each other. Switches are opened and closed according to the meter at random time intervals. Surprisingly, the system will quickly settle down to one of 100 stable states out of a possible 10^{300}.

We derived the flow pattern of the figure from a very simple physical system, so it's clear that real physical systems can have the kind of flow patterns necessary for a content-addressable memory. Nor did we have to plan how to obtain content-addressability. This feature arose spontaneously. In that same sense we might ask whether the physical system consisting of a collection of neurons is of such a nature that it will spontaneously produce for its states a flow pattern like this.

I've been doing mathematical modeling of such systems, trying to abstract essential features of neurons and see if this kind of flow pattern will happen. To see what sort of simple system is capable of generating this flow, we can imagine a hypothetical system representing 1,000 neurons as 1,000 Caltech students busy working on their calculus problem sets. Each is sitting at a desk, in the corner of which is a little apparatus with a battery, a switch, and an ammeter. The switch connects to wires going out *to* many other students, but no student needs to know exactly where his own wires go. And each student, of course, has wires coming in *from* many other students through resistors and through the ammeter that measures the current. It's all hooked to a water pipe to get a "ground" return current path.

Each student is given the following instructions: Every once in a while look up from your problem set and observe your meter. If the needle is pointing to ON on the dial, *close* your switch; if your switch is already closed, leave it closed. If the needle is pointing to OFF, *open* the switch, or if the switch is already open, leave it open. Then go back to your homework.

This system preserves crudely some of the essential features of interacting nerve cells. The apparatus of each student represents a neuron. The switch being *open* or *closed* corresponds to whether each neuron is making an output or not. Each of the student neurons puts out leads to many others and gets inputs from a comparable number. The input connections from the other students are the synapses in the case of neurons, and the strengths correspond to adjustments of the resistors.

What happens if you give these instructions and then simply turn the system loose? You can describe the state of the system at any moment by writing down the names of all the students and opposite each name a zero for *open* and a one for *closed* — 1,000 ones and zeroes. There are 10^{300} different states this system can be in, which is more than the number of atoms in the universe. So it's not obvious what's going to happen when the system is turned loose. It could keep going from state to state and never run out of new ones to go to.

But this does not happen. Of that nearly infinite number of states, only about 100 will be stable. The system will quickly settle down to one of 100 memories in it. Each of these memories corresponds to a particular set of students' switch settings. Each memory consists of a 1,000-bit "word" — the amount of information in 200 typewritten characters or a little more than four of these lines of type.

This memory turns out to be content addressable. You can create a particular memory state by telling the first 50 students which way to set their switches for that memory state. Then if the other students follow the usual procedure of looking up occasionally and throwing the switch, they will actually reconstruct the particular stable memory that corresponds to the switch setting of the first 50 students. Any 50 students would suffice. So this memory is content addressable and addressable by any part of the information in it.

How is it that this system (which has no particular design principles and which might conceivably wander anywhere in its huge number of states) actually goes to stable states? In the case of the pattern of water flowing, looking only at water moving across the surface produced a mystery. Understanding that there was really a hidden contour map and that the water was flowing downhill made the whole thing understandable. There was a secret in understanding the cause of flow pattern for water.

Sometimes flows in physical systems are directed by collective principles. For example, the flow of heat from a high temperature object to a low temperature object is a collective effect, and comes about only because of the large number of molecules in each object. If the objects were tiny enough, heat would no longer always flow from the hot to the cold. Similarly, when I wrote down the mathematics that describes how on the average the students will change the positions of their switches with time, I found a quantity that plays the role of the height and contour map in the water flow problem or the temperature difference in heat flow, and drives the system in a collective fashion inexorably toward stable states.

In the Caltech student "neuronal" computer system the stable memories are determined by the particular values of the resistors that lie in the connections between students. Each connection between one student and another has one of these resistors in it, just as in neurobiology each connection between a neuron and another neuron has a synapse in the pathway. Many neurobiologists think that the place where information is stored in a biological memory is in the strength of the synaptic connections between particular neurons.

In order to have a useful memory, you need to have a way of establishing what is to be remembered. If this system (with its 100 stable states) remembers an arbitrary 400 lines of type, it's not much help. You would like to be able to specify exactly which 400 lines of type are stored out of the 10^{300} possibilities. You can do this by adjusting the resistors appropriately. There turns out to be a very simple way of adjusting them that involves no global information about the memory. You need only local information. Each resistor actually participates in many of the memories but has no idea of the total memory. There are so many resistors that if you were to take one of them out, you wouldn't forget anything. If one of the students were to go to sleep, one bit of information in the 1,000-bit word (or state) would disappear, but the memory presented by the other 999 students would remain intact and correct. Because the system is based on very large numbers and is collective in nature, it is robust against failure in a way that is highly desirable in neurobiology.

The system operates through parallel processing, doing many things together. A student doesn't have to wait and see what another student does. Each student flips a switch or not according to what his meter is doing at the moment he happens to look up. Parallel processing is one of two different kinds of processing in computer science; the other is serial processing, doing things one after another. Most computers rely heavily on serial processing.

The importance of "parallel" and "serial" in computers can be illustrated by considering two problems involving the sentences in a book. If I try to find the location of one particular sentence in a book, I can do it in parallel by tearing out the pages, distributing them to a group of people, and asking each one to read his page to see if the sentence is present. That way I'll find out very rapidly where the sentence is. Each of the tasks of looking at a particular page can be done in parallel, independently of all the others.

The position of a sentence in a book can also present a different problem. I could break up the book into its individual sentences and then try to reassemble it with the help of the same group of people. Each of them is given a page number and told to pick out a set of sentences appropriate for his particular page. If you are given page 75, you will have trouble making your choice unless you have seen the contents of pages 1 to 74. This is clearly a sequential or serial task.

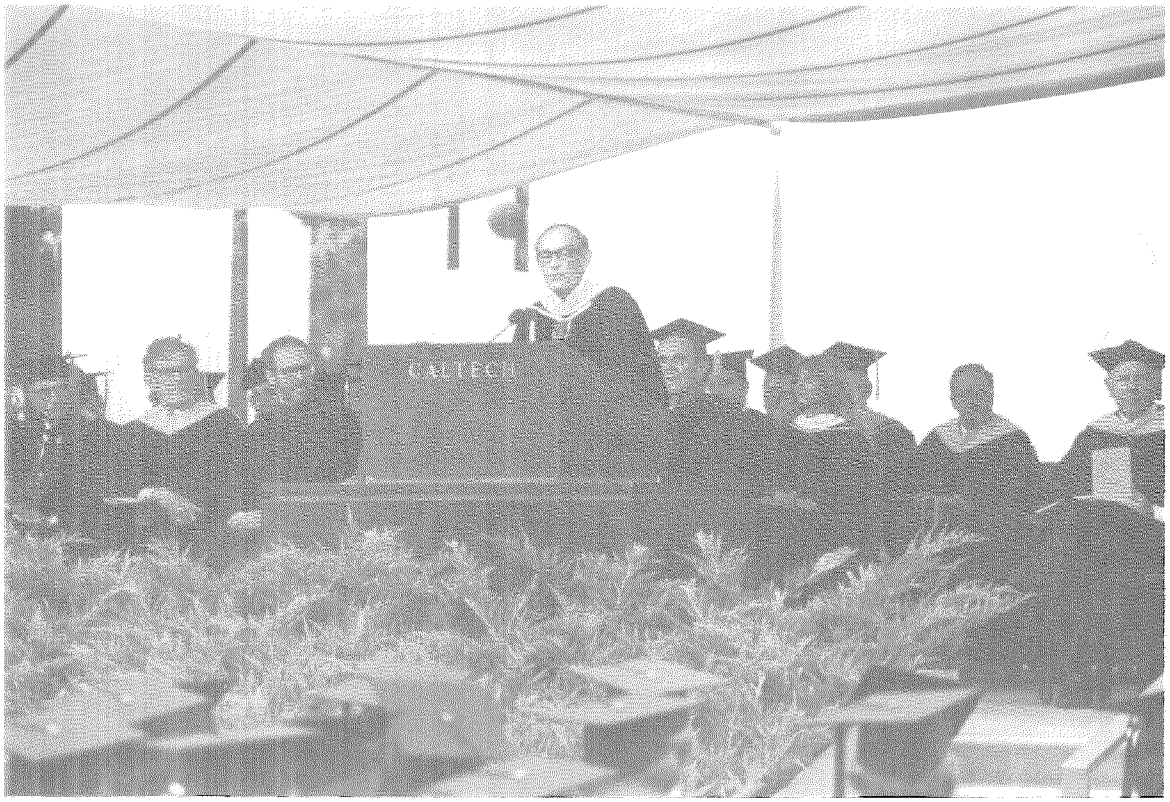
Biology is different from most modern computers in that biology heavily emphasizes parallel processing. The collective processing that my simple array of students (or neurons) did is also highly parallel in nature. It accomplishes a memory retrieval task that from the point of view of planned computers might be most readily done by a sequential operation, and yet it manages to do so effectively even though operating in parallel.

Useful computational properties, which one might expect to have to carefully design, can generate themselves (in this case, at least) as collective properties of a large system of simple elements. The fascinating intactness of memories seems to come about in a spontaneous way as a collective behavior of a system with simple elements that have the plausible behavior of neurons. All the functions of the devices needed for the student computer system algorithm could easily be duplicated with neurons (or with silicon devices!). The evolution of higher nervous function and intelligent behavior would be easier to understand if some of it is based on collective properties, rather than based on the precise design necessary to make conventional computers having the capabilities of higher nervous function.

The same principles could be used to design a silicon-based computer system very different from current ones. It would have ten times as many elements but could tolerate the failure of one percent of its devices. This design, which might be called biological design, would use parallel processing in a natural way and should have corresponding speed advantages in many tasks.

Thus, I think the two computers discussed at the beginning of this article achieve their similar computational abilities rather differently. I believe that thinking about these differences will enhance our understanding of each. □

Commencement 1982



To Know, To Understand, To Do

by Hans W. Liepmann

I HAVE BEEN asked to address this 1982 commencement convocation, probably because of my endurance at Caltech. After all, I have spent just about ten times as much time here as any of you whose graduation we celebrate today. Have I learned ten times as much as you? I would rather not answer or discuss this question but sidestep it with the excuse that I have never been on the receiving end — I left this to my sons.

You down there who are at the end of the GPA [Grade Point Average] rat race may well snicker and think that the old fool did not know what else to do but to stay here. Well, this is a possible conclusion, but there may be another. Stop and consider the possibility that Caltech is more than an expensive penal institution but has conceivably attractive, even addictive, features that are worth preserving.

You, the graduates, and I have in common that we came here to learn, to understand, and eventually to be able to use the learning and understanding to contribute to a chosen field in a chosen way. How to design an institution, a system, that enables these goals to be reached in an optimal way and still remains inhabitable, is a subject of much theory and even more experimentation.

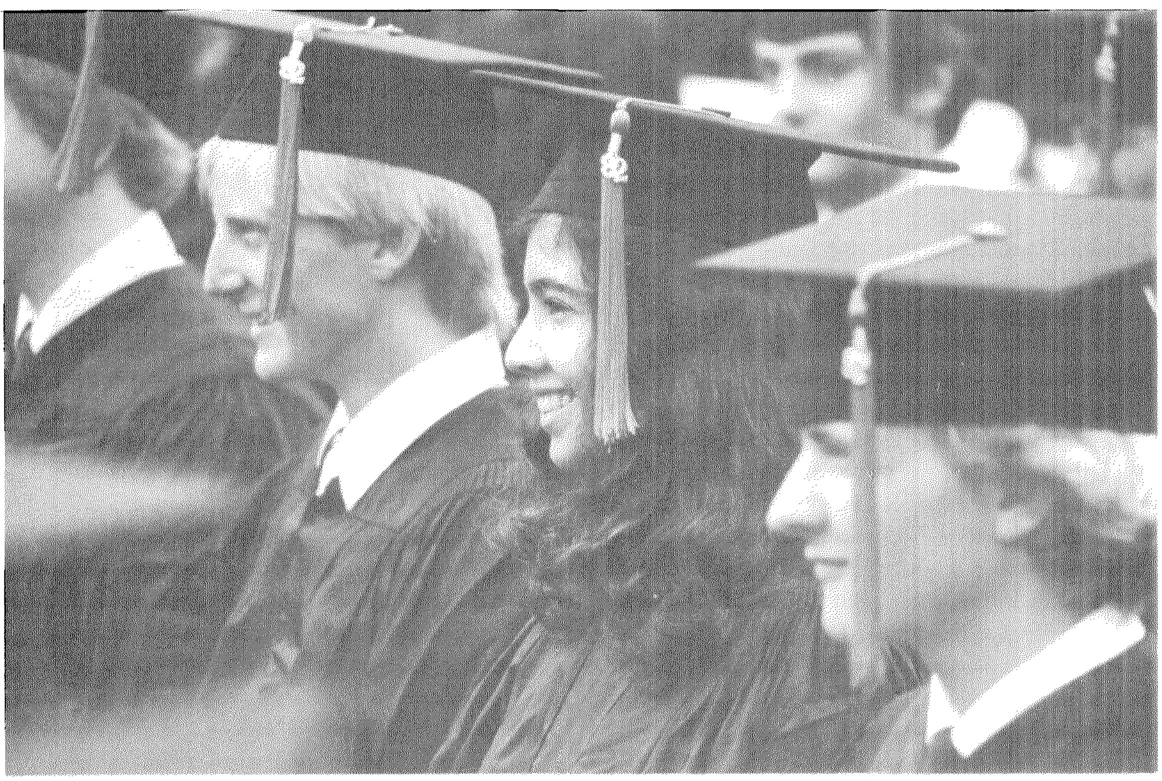
As in thermodynamics, we have to separate a system from the universe and we have to find an enclosure for this system with suitable properties. The completely closed system, the ultimate ivory tower, will not do; its entropy will surely increase, and all action will cease. A completely open system will exhibit the wild fluctuations reflecting the often chaotic state of the surroundings, an environment not particularly suited for learning and certainly not conducive to understanding. Between these limits there must be an optimum; but since people, even students, unlike atoms are still always distinguishable, the best one can hope for is an optimum for a specific set of students.

The common, rigorous, core program in the natural sciences with a strong backing in the humanities, together with the deliberate restrictions in size and the aim toward excellence in selected disciplines only, defined the enclosure since the beginning of Caltech. It was, fortunately, modified some time ago to make it permeable to an additional subset of humanity — women. (I do hope that this subset remains distinguishable from the other!)

Within this framework, which sets us apart from other larger schools, we should be able to create and preserve an atmosphere which combines intensity and rigor of study with warmth and companionship. An atmosphere in which learning and teaching facts are enjoyable challenges, with enough slack and leisure to understand old ideas and pursue new ones. An institution in which the faculty has enough time to interact with students and each other and where research at the leading edge diffuses through the whole educational process. A fraternity of scholars where ambition and striving for excellence is free of petty jealousies.

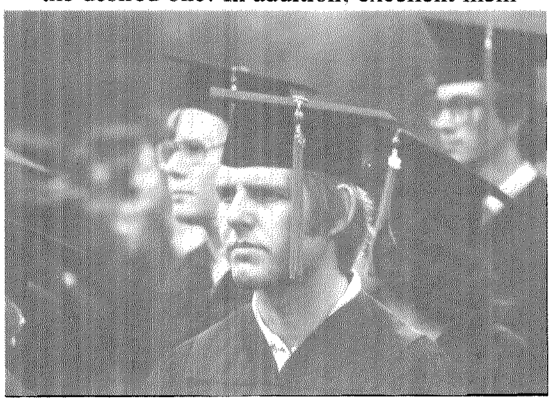
To accomplish such an aim we have to preserve not only an enclave of excellence but also of trust. This is trust between the members of such a community, openness of exchange of ideas, respect for differing thoughts. This is a very tall order and like any asymptotic state hardly fully attainable. We are fortunate that we do have a head start at Caltech. We have a crucial ingredient, a functioning honor system, based on the premise that no member of the community should take advantage of another! We still have the pick of students and faculty. We have an academic administration small enough and competent enough to do what I consider the only essential administrative job: to protect the ones who contribute most from the ones who contribute least. Add to all this a very effective board of trustees and our loyal alumni, and we should have it made. So why are we still far from the ideal? What makes the aim so difficult to achieve?

Well, we deal with people with abilities and idosyncracies not easily codeable on an IBM card. In selecting students and young faculty, we can measure the voltage, the straight I.Q. type ability, reasonably well. But the output, the ulti-



mate accomplishments, should be measured in watts. The current — that is, the ability to apply the intelligence, the necessary perseverance, power of concentration and motivation, let alone imagination — is much harder to evaluate or predict. In the tendency toward a more "democratic" form of faculty promotion and selection we have certainly successfully decreased the chance of petty tyranny and discrimination. But could we today appoint a professor with a patent office background like Einstein's, or a high school teacher like Weierstrass? Could we discover and document a candidate who publishes in the obscure proceedings of a minor academy like Gibbs? I wonder!

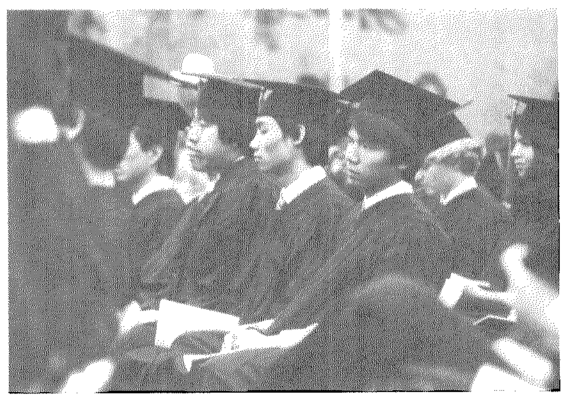
Historically a university is a nonlinear unstable system: a mediocre group will select and attract mediocre members and tends to become worse. An excellent group will tend in the other direction — the desired one. In addition, excellent members are moveable, mediocre ones less so, and hence a sudden decline of the quality of a university can and does happen. Preoccupation in the faculty with research and publishing at the expense of teaching is an age-old problem as well and, by the way, not too different from the preoccupation with GPA at the expense of learning and understanding in the student body. Evaluating successful, creative teaching is by no means as easy as it looks. The distinction between smoothness and elegance of presentation versus depth of penetration of a field is often quite difficult. Maybe you down there should contribute to a TQFR [Teaching Quality Feedback Report] again five years after graduation!



Direction of effort, choosing promising new avenues, often requires decisions whether or not an opening field is full of promise or full of propaganda, an exciting opportunity or merely a fashionable bandwagon. Missed opportunities and, even worse, choice of spectacular trivialities are bound to occur occasionally.

To these classical problems has to be added a modern dilemma. The noise level has increased throughout academia by orders of magnitude. The increase in the number of publications, meetings, and committees is at least exponential in time; even the task of *turning down* paper and proposal reviews, meeting participation, and committee memberships takes a reasonable length of time, let alone accepting, preparing for, and participating. There are times when the old ivory tower looks very attractive indeed. Still, a loose coupling with the outside world is, of course, essential to keep in tune with the times, to feel the pulse of both a rapidly changing technology and rapidly changing attitudes and needs. But within our enclave there must be room for the odd ball, not only for the entrepreneur. Intensive work and extensive show have to keep a reasonable balance.

These then are our difficulties. How well have we dealt with them? With the help of some undergraduate spies I tried to find the student reaction, an association with the word "Caltech." The result was quite positive — *hard work plus comradeship sum it up quite well.* But I realize, of course, that experiment and experimenter are not independent. There does exist discontent and resentment. I, like some or most of you, regret the apparently ever increasing problem-set syndrome — the feeling of always being behind. I also regret the increasing tendency to rigid curricula since both reduce the time for contemplation, exploration, and fertile leisure, and thus tend to eliminate or at least reduce the enthusiasm for learning as well as any cross-fertilization. There are a number of reasons for this trend but one outstanding one: the rapid explosion-like expansion of the limits of all fields in natural science and engineering.



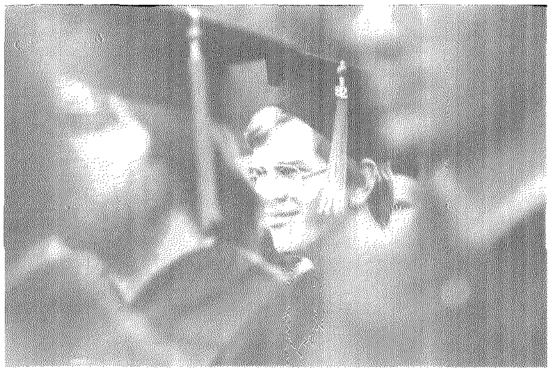
In the preface to one of the earliest monographs on relativity by von Laue written in 1911, the prerequisites are stated as "the usual mathematical tools of the theoretical physicist, calculus and vector analysis," less than what you are supposed to have mastered at the end of the freshmen or, at most, sophomore year. In engineering for many years, thermodynamics and steam tables were synonymous. From my experience in applied science and engineering, the usual way for a faculty to approach the structure of a curriculum is to begin with a question like this: What should an applied physicist, say, know today? If this knowledge is to be supplied entirely by formal classroom teaching, the result is obvious: a dense set of tough required courses that leaves little time for electives and even less for musing. This type of approach is quite difficult to avoid but it is, I believe, orthogonal to the real aim of Caltech. The aim has been and should be to turn out professionals that are not narrow specialists but on a basis of solid fundamentals are *able* to specialize and *change* specialization. Required courses, like publications, should follow Gauss's maxim — *pauca sed matura* — few but excellent!

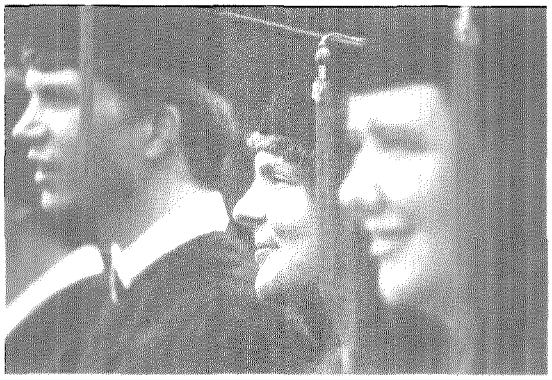
In this context I would like to repeat a modest proposal I once made, not quite in the spirit of Swift — I do not advocate the eating of faculty by the students or vice versa — that one week added to the Christmas and Spring recesses, or a free week around midterm, would go a long way in helping to regenerate and revitalize souls downtrodden from an excess of problem solving. A minor change but I think quite important for the coming crop of students, the ones who remain. Furthermore, to make the GPA race reasonable, a way has to be found to convince all universities and industry that grades here (graduate and undergraduate) mean what they say; that a Caltech C is a respectable grade and not a consolation prize for flunking out! Straight A's, a 4.0 GPA, may indicate an impressive intellect or a depressing lack of interest.

So we have not yet reached the ideal, and we will probably never quite get there. But the spirit of academic fellowship and the drive toward excellence is still alive here. Caltech remains an irreplaceable singularity among the schools in this country that we hope to preserve intact and that one does not leave lightly.

You, the graduating class, are leaving the system to meet the challenge of the surroundings — real life, as it is sometimes called. You can be proud to have finished a difficult obstacle course. But watch your pride: your way is not the only one. In your professional daily life you will meet people who know without understanding, understand without knowing, and act without understanding. All permutations are possible, and the results are by no means always bad — provided one excludes the case of acting without knowing and understanding, which happens as well.

You will have to face larger issues. Already the first practitioner of thermodynamics, Prometheus, challenged the gods, and they sent the alluring Pandora to earth. His simple-minded brother per-





mitted the fatal box filled with evil to be opened. In our times a Pandora appears every few years, alluring as ever in her guise as atomic energy, computers, lasers, or genetic engineering, each time with real promise and real danger. I do not believe that there is a way to escape the Pandora syndrome. Somebody, somewhere, is bound to open the box. This syndrome may well provoke your public reaction, but before you climb a soap box, make sure it is very solid, and remember that responsibility, exhibitionism, and vanity are often hard to distinguish. Much more difficult is the ability to say: *One* does but *I* don't!

Whether we like it or not, we struggle on under the Chinese curse, "May you live in interesting times!" Well, at least life will certainly not be dull, and hope was, after all, the good gift from Pandora's box. Leaving Caltech to face the interesting times you should have two assets: competence and confidence. What I hope you will keep throughout your lives is the pleasure of learning, the pure joy of understanding, and the urge to contribute.

Felix Bloch recalled that at a similar state in his life he proudly declared to Heisenberg that space is simply the field of linear operations! "Nonsense," said Heisenberg, "space is blue and birds fly through it!" With all the encyclopedic knowledge and techniques stored in your memory banks now, it is well to remember that there is an outside world to see and enjoy. Add a fourth dimension: to know, to understand, to do — and to dream. □

Leasing the Air:

An Alternative Approach to Regulation?

by Roger Noll

THE CONCEPT of leasing the air is one of using market processes to provide an efficient way to satisfy air-quality objectives. By a "market," I mean an organized process and set of rules for buying and selling a well-defined commodity or property — in this case, a government permit to emit pollutants. A market for emissions permits is an alternative to the present approach of dealing with air pollution by writing technical standards for every one of the millions of orifices through which pollutants pass into the atmosphere. Though the idea may seem straightforward, each year about 40 percent of the new markets that are established fail to survive, and usually for reasons that are never really understood. Simply setting up a situation in which people can engage in trade does not always mean that trades will take place or, if transactions do occur, that the market performs efficiently. Thus, to use this method to achieve the goal of more efficient air-quality control requires solving two problems — first, establishing the market and, second, making sure it performs as intended.

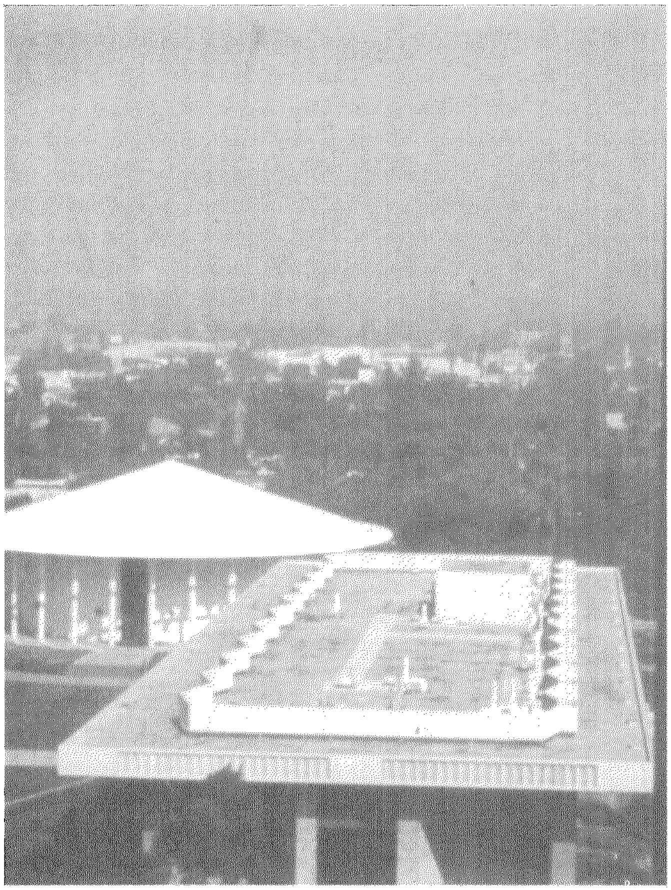
For the past three years, several Caltech faculty and graduate students have been attacking this problem for a specific case — sulfate particulates in the Los Angeles air basin. The results of this work were recently submitted in a three-volume report to the California Air Resources Board. This article summarizes our report.

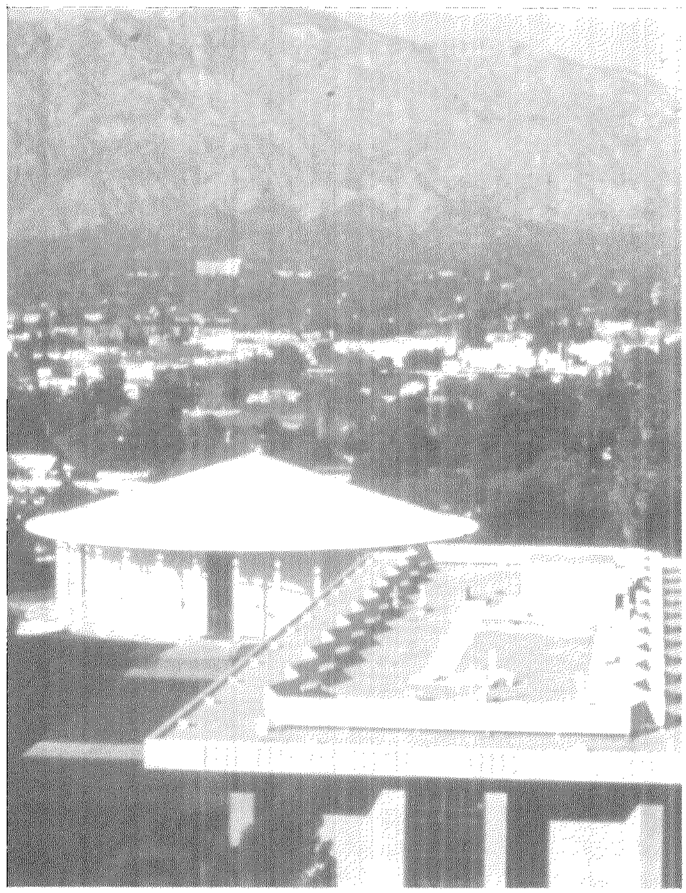
The details of how society might organize a market in emissions are as follows. First, some regulatory or legislative process would establish a limit on the quantity of pollutants that can tolerably be emitted into the atmosphere, and would create permits to emit that amount. Businesses can then purchase these rights. In doing so they will be motivated by the same incentives as they are in hiring labor, purchasing land, buying machines, and acquiring other inputs into their production processes. Among their incentives will be the desire to minimize costs, including the cost of permits to use the atmosphere. The point of establishing a market for emissions permits is to channel normal business incentives into conserving the environment and minimizing abatement costs.

The case of sulfur emissions into the Los Angeles "airshed" provides a useful setting in which to study how a market for pollution could be established. Almost all of the sulfur emitted in Los Angeles arrives in a barrel of oil and is put into the air by burning petroleum products. Most of the sulfur comes out of the combustion process as sulfur dioxide (SO_2). The federal government has set ambient air quality standards for the allowable amounts of it in the atmosphere, and Los Angeles is in compliance with this standard.

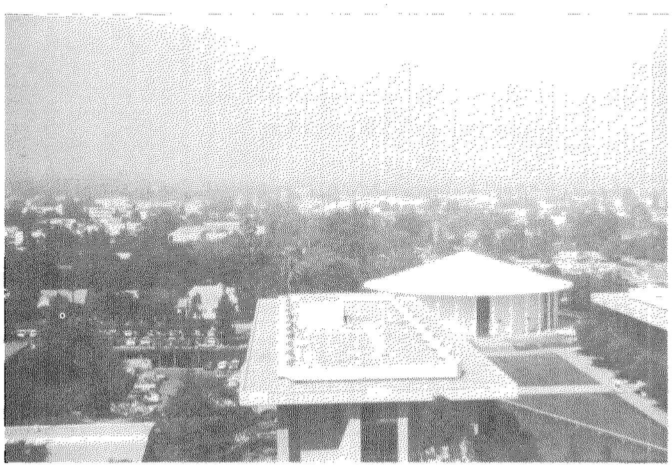
The interaction of SO_2 with sunlight and other matter in the atmosphere produces sulfate particulates, which are part of another category of pollutants called total suspended particulates. At the national level, total suspended particulates are also regulated, and once again Los Angeles is not out of compliance. Los Angeles, however, has the problem that sulfate particulates account for a very large part — probably more than a third — of the reduced visibility due to air pollution in the basin. So the California Air Resources Board has established an ambient air quality standard requiring that about two-thirds of the sulfur emitted into the airshed be removed. With the late 1980s as the current target for achieving this standard, Los Angeles is only about halfway there.

The method of environmental regulation used to get even that far along toward the goal has been an extraordinarily complicated and difficult

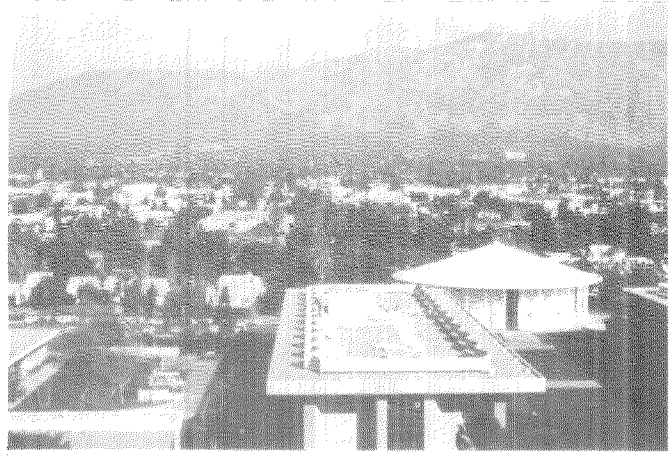




The foothills of the San Gabriel Mountains are located less than five miles north of the Caltech campus, but on smoggy days they might as well be a thousand. The two views above were photographed from the ninth floor of Millikan Library on two different days, and they provide a graphic illustration of the effects of particulate air pollution on visibility.



Two more views of the same scene. The one above was taken in October 1980, and the one on the right in January 1980.



one. According to the requirements laid out in state and federal law, the regulator holds a formal proceeding at which each specific category of sources is scrutinized. Then a regulation is established specifying what is to be done about that source. These regulatory procedures take a long time and consume a lot of resources. In Los Angeles, approximately 40 different categories of sources emit significant amounts of sulfur. These categories encompass numerous companies, and within each company there may be several sources. Because regulations are written for each hole through which something leaks into the atmosphere, there are literally thousands of specific regulations that deal with sulfur.

Because of all this, only a few industries can be in the process of having regulations for their emissions under consideration at any given time, and it takes several years from the beginning of the process to the completion of a written standard. The process starts with a proposed set of instructions to a firm to use the best technology for abatement that is economically feasible at the time, but by the time the process stops, this standard is several years out of date. Moreover, many other industries are still standing in the queue waiting to be regulated, and still others are operating with standards that were written for them more than a decade ago.

Because various firms have different vintages of technology that they have been required to use, widespread differences exist among them in the cost of achieving the current amount of pollution abatement. Naturally, a firm is very reluctant to adopt new technology, because that reopens the very long, expensive, and uncertain regulatory process. To sum up, the way regulation is done erects a barrier to technological change, either for doing a better job of abating pollution or for creating new production processes that achieve the goals of a business in a cheaper way.

These inefficiencies mean that we are achieving the current amount of reduction in air pollution at a cost that is substantially greater than the least expensive way of doing it. The main purpose of setting up a market is to convey to polluters — new and old — appropriate price signals about the social cost of emissions. Each can then select a combination of capital investments, operating practices, and emissions releases that minimize the sum of abatement costs and the cost of permits to pollute.

If markets show promise, the question remains whether that promise can be realized. Would just saying, "Let's have a market, and let 'er rip," really work?

Not necessarily. A number of potential problems could thwart the creation of a market. The first has to do with the fact that the market may not be competitive. The reason competitive markets are efficient is that the prices conveyed through them are honest signals to businesses about true costs. Only if permit prices represent the true incremental cost of abatement will each business make a decision about how much to spend on abatement that is consistent with the objective of achieving an air-quality goal at minimum total cost for the region. A monopolist would engage in strategic games to alter the price to his own benefit, thereby destroying the connection between permit prices and incremental abatement costs.

The second problem we have to worry about is market "thinness"; that is, transactions may not occur frequently enough for the market to work. A business wants to minimize the total costs of being a polluter, which includes the cost of abatement itself plus the cost of buying permits for the amount of pollution produced after abatement activities have been adopted. To make this calculation, business needs to know the price of permits. If market transactions do not occur very frequently, business will not have that information. In the past few years, the Environmental Protection Agency has sought to introduce some limited opportunities for trades of emissions permits. These have not yet proved very successful because the way the markets have been set up, combined with the limitations on allowable trades, has produced a very thin market.

A third issue has to do with the geographic distribution of emissions. Right now standards are set on a firm-by-firm basis regardless of their geographic distribution. But if all the permits to pollute were concentrated in one geographic area, the possibility of a market might be destroyed. If, for example, a permits market ended up with a situation in which one square block in Los Angeles was the sole source of all the sulfur emitted into the airshed, the people living downwind from that block would not be enthusiastic about the permits market.

Another concern is called "distributional equity" or fairness. Permits to pollute are valuable commodities, and the political system is going to be very sensitive about how they are distributed. If the value of the permits is very great, whoever sells them is going to be rich, but the businesses that have to pay abatement costs and also to buy permits are not likely to be eager to do so. After all, business now gets the permits for free from the regulatory process.

The final problem surrounding the creation of a market is long-term stability versus short-term flexibility. One of the legitimate complaints businesses have about regulation is its unpredictability. In order for businesses to make rational decisions, they need to have long-term stability in permits; that is, they must have some confidence that, if they make a capital investment, the strategy for environmental regulation on which it is based will be constant long enough to give them some chance of amortizing the cost.

Equally legitimately, society wants to have flexibility in the regulatory process. As society learns more about the effects of air pollution and the technologies for abating it, it will want to have the freedom to change air pollution policies.

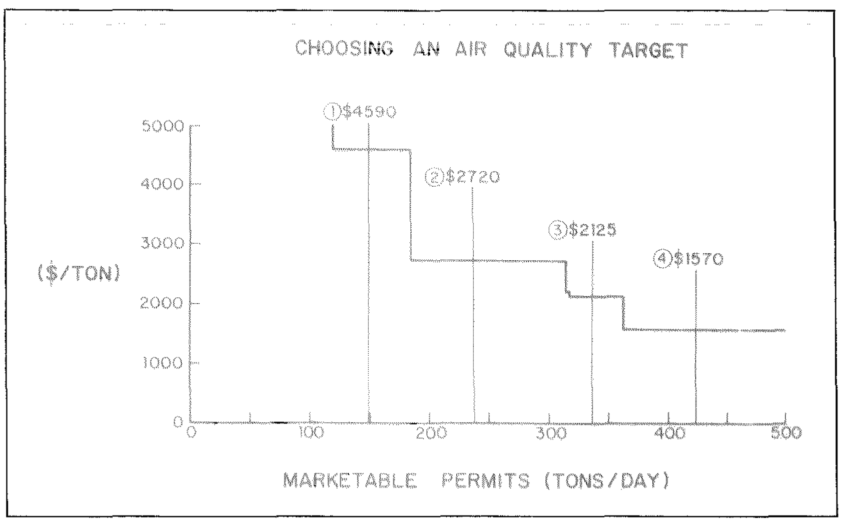
With this as background, let us now review the Los Angeles sulfur problem and see how we might characterize and then attack each of the obstacles to setting up a market. The table above shows the amount of emissions in tons that would be allowed each day in Los Angeles to satisfy four different targets for air pollution. The first is the one that would allow us to achieve the current California ambient air quality standard. Number 2 is a slightly more relaxed version that would satisfy the standard all but two weeks a year. The third item is slightly better than where we are today. It assumes current controls and relatively accessible supplies of natural gas. Number 4 is where we were in the late 1970s when the regulation and resulting shortage of natural gas made it extraordinarily difficult to purchase as an alternative to oil as a fuel.

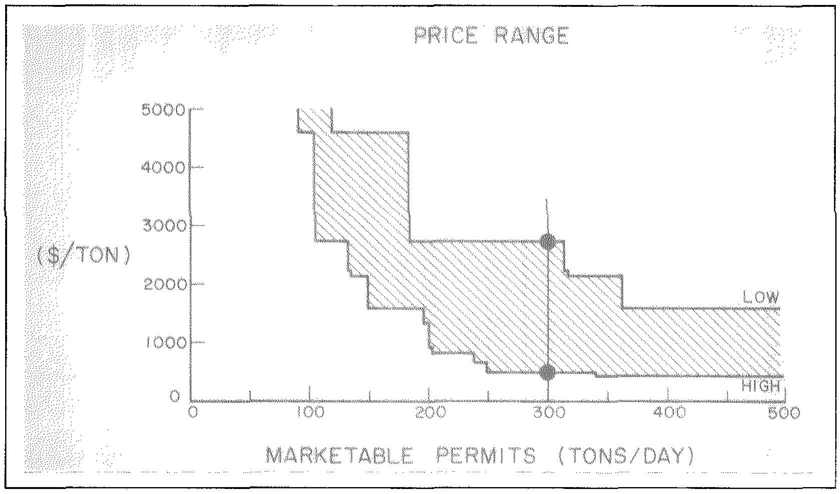
One aspect of the work at Caltech has been to use simulation methods to examine how the market would work under these and other possible standards and under different conditions of natural gas availability. These simulations can be used to estimate the distribution of emissions among sources that would result in a market. In order to undertake this analysis, several research projects were needed. The first, undertaken by Glen Cass, assistant professor of environmental engineering at Caltech, was to construct a model of the relationship between emissions and air pollution. The second was to estimate the abatement-cost functions for every single source category in Los Angeles. This information was then used to construct a model of how cost-minimizing companies would behave in a permits market, a task that was successfully undertaken by Robert Hahn, PhD '81, as part of his doctoral dissertation work in social science. The Hahn model was used to estimate the distribution of emissions among sources for several different ceilings on total emissions, three assumptions about the availability of natural gas, and both a competitive market and a "monopsony" (a situation in which one firm accounts for all purchases of permits). The figure below shows one output of this analysis — the "demand" for permits in a competitive market under conditions of low natural gas supplies. The curve shows, for each possible ceiling on total emissions, the price of permits to emit a ton of sulfur that would clear the market. When multiplied by 365, these prices become the amount business would pay to emit one ton per day for a year. At 150 tons per day, which is the final target of the ambient air-quality standard, this comes to about $1.7 million for a ton-a-day, one-year permit.

The first major result of the study is to show that the reform of environmental regulation with the greatest effect for the amount of money spent would be the decontrol of natural gas. Currently there is excess demand for natural gas at its regulated price. Use is curtailed by limiting the use of gas by industries and electric utilities as boiler fuel. If gas were deregulated, the price would go up and the market would clear. This would allow industry to choose to burn natural gas as one way of abating sulfur if it were a cost-effective option. Generally speaking, industry would do this even at a higher price because it is a relatively cheap

Target	Allowable Emissions
1. Achieve California Sulfate Air Quality Standard of 25 micrograms per cubic meter over a 24-hour averaging time.	149
2. Violate California Sulfate Air Quality Standard 3-5½ of the time.	238
3. No additional controls with an above average natural gas supply.	335
4. No additional controls with a low natural gas supply.	421

The allowable emissions levels shown above are in tons per day of sulfur dioxide, and the standards on which they are calculated refer to those in effect in 1977. More stringent standards are scheduled to be applied to some sources in 1985.





abatement strategy. The figure above illustrates this point. For example, at 300 tons per day, the market-clearing price for the right to emit a ton of sulfur into the Los Angeles airshed would be about $600. At low natural gas availability, the price would be about $3,000.

One of the problems in setting up a market for air pollution permits would be the potential for creating a monopoly. The table below shows the most important sources of sulfur pollution in Los Angeles. Mobile sources are cars, trucks, and the like, and the best way to deal with sulfur coming from them is to have less sulfur in fuel. If a permits market is set up so that oil companies must have the permits for the sulfur in vehicle fuels, the percent of total emissions from mobile sources would be distributed among the oil companies shown in the table. Adopting this approach, the two most important source categories are oil refineries and electric utilities, which account for approximately 40 percent of the sulfur emitted in Los Angeles. One of the utilities emits almost a third of the total amount of sulfur in the airshed. With a single pollution source of that size, maybe

The actual 1980 figures for sources of sulfur emissions in Los Angeles differed somewhat from those projected in this table. This is because natural gas was more available then than it was for most of the 1970s.

1973 Emissions		1980 Projection Low Natural Gas Scenario	
SOURCE TYPE	½ OF TOTAL EMISSIONS	SOURCE TYPE	½ OF TOTAL EMISSIONS
Utility	28	Utility	31
Mobile Sources	16	Mobile Sources	27
Utility	11	Utility	10
Oil Company	8	Oil Company	4
Steel Company	7	Coke Calcining Company	4
Oil Company	3	Oil Company	4
Coke Calcining Company	3	Steel Company	3
Oil Company	3	Oil Company	3
Oil Company	2	Oil Company	2
Oil Company	2	Oil Company	2

the market is not going to be as competitive as we might hope.

Actually, the situation is worse than this. Suppose we allocate the permits initially by "grandfathering"; that is, we give permits to everyone in a number equal to the amount of their current regulated emissions. In that case the largest electric utility would end up with 31 percent of the permits. Our calculations indicate that it would be the only firm that would want to buy more permits. Everybody else would want to sell them. Private electric utilities are by far the most heavily regulated of all businesses, and they over-abate relative to everyone else, so the cost-minimizing way to achieve current emissions would be to increase emissions at utilities and reduce them everywhere else. This creates the opposite of a monopoly — a monopsony, or a situation in which a single buyer faces a large number of sellers.

Economic theory enables us to predict the outcome of a permits market if a monopsony exercised its full power in manipulating the market to its own advantage. The best strategic behavior for a monopsonist would be to understate the intensity of its desire to hold permits, thus depressing the price in order to get them cheaper. We have simulated the outcome of a market that allowed a single firm to exercise the maximal amount of monopsony power. According to these results, at the current level of emissions, the amount of emissions by the largest source would change by only one percent if a fully monopsonized market were established. By contrast, in a competitive market the largest single source of emissions would seek to increase its total emissions by about 15 percentage points, from 30 to 45 percent of the total for the airshed. This big change is a measure of how far things are from the cost-minimizing, efficient allocation in Los Angeles. To underscore that point, 14/15 of the potential gains of switching from a regulatory-standard system to a market system would be lost if the market were monopsonized. The lesson is that in designing a market, the simple solution, which is to grandfather the permits and to let those who want to engage in trades do so, may not work because there may be no significant trading.

Another possible problem in designing a market is the sensitivity of the design to changes in geographical patterns of emissions. Here the news is good. We ran a number of complicated simulations at Caltech and concluded that the nature of the abatement problem in Los Angeles is such that we do not have to worry about the geographic pattern of emissions. The sources are sufficiently dispersed and face sufficiently similar abatement-cost opportunities that the concentration of emissions in one place would not be likely to occur.

The final problem is that of equity. If the price for the permit to put a ton of sulfur into the atmosphere in Los Angeles is $1,000 to $4,000, emissions amount to somewhere between 150 and 400 tons per day for 365 days per year, and permits are to be valid for several years, the implicit value of all permits is upwards of a billion dollars. Naturally, the state legislature is going to get very concerned about who gets such a sum. It could, for example, attack the budget problems of the schools by giving them the right to sell air pollution permits.

I have already pointed out that businesses are going to be reluctant to pay for something they now get for free, and that too is going to be an important political factor. This would seem to argue in favor of a grandfathering method of distributing the permits, but that would raise the possibility of a monopsony problem. How can we grandfather the system so it does not generate one or two billion dollars of new business taxes for the reform? How can we avoid the monopsony problem and still have a "thick" market that will provide clear price signals?

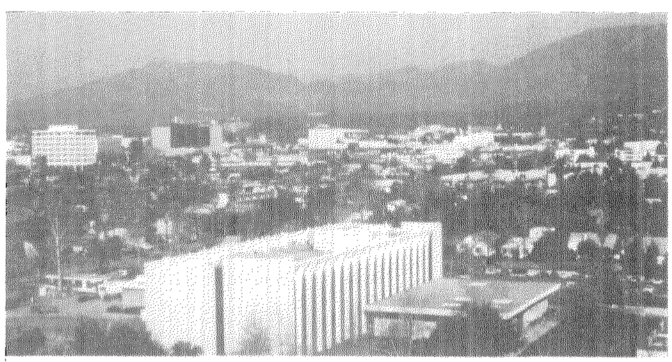
One solution is something called the "zero revenue" auction. The trouble with a standard auction is that the seller receives the amount bid for the items that are auctioned. The mechanism we have devised to prevent that is to grandfather the permits but make it mandatory for them to be sold in the market through an auction. The regulatory agency would initially allocate so many tons per day to each company in Los Angeles according to how much it is currently emitting. Then, every potential source of pollution would have to submit a bid on how many permits it would like to hold at each possible price. If the price is $4,000 per ton, for example, how many permits does a company want to buy? If it's $1,000, how many? Then the regulator would add up the quantities requested at every price for all companies, and pick the price at which the number desired exactly equals the number that are available. Each bidder then gets the number of permits requested at that price.

What then happens to a specific business? It pays into the system the base price times the number of permits it buys. It receives from the system the same price times the number of permits it was initially allocated. This means that the total revenue collected in the auction from all firms is exactly equal to the total revenue that is returned to the people who initially held the permits. But it also means that every business in this auction is on the same side of the market; they are all buyers. Consequently, there is no monopsony problem, which threatened the market based on voluntary trades from the grandfathered position.

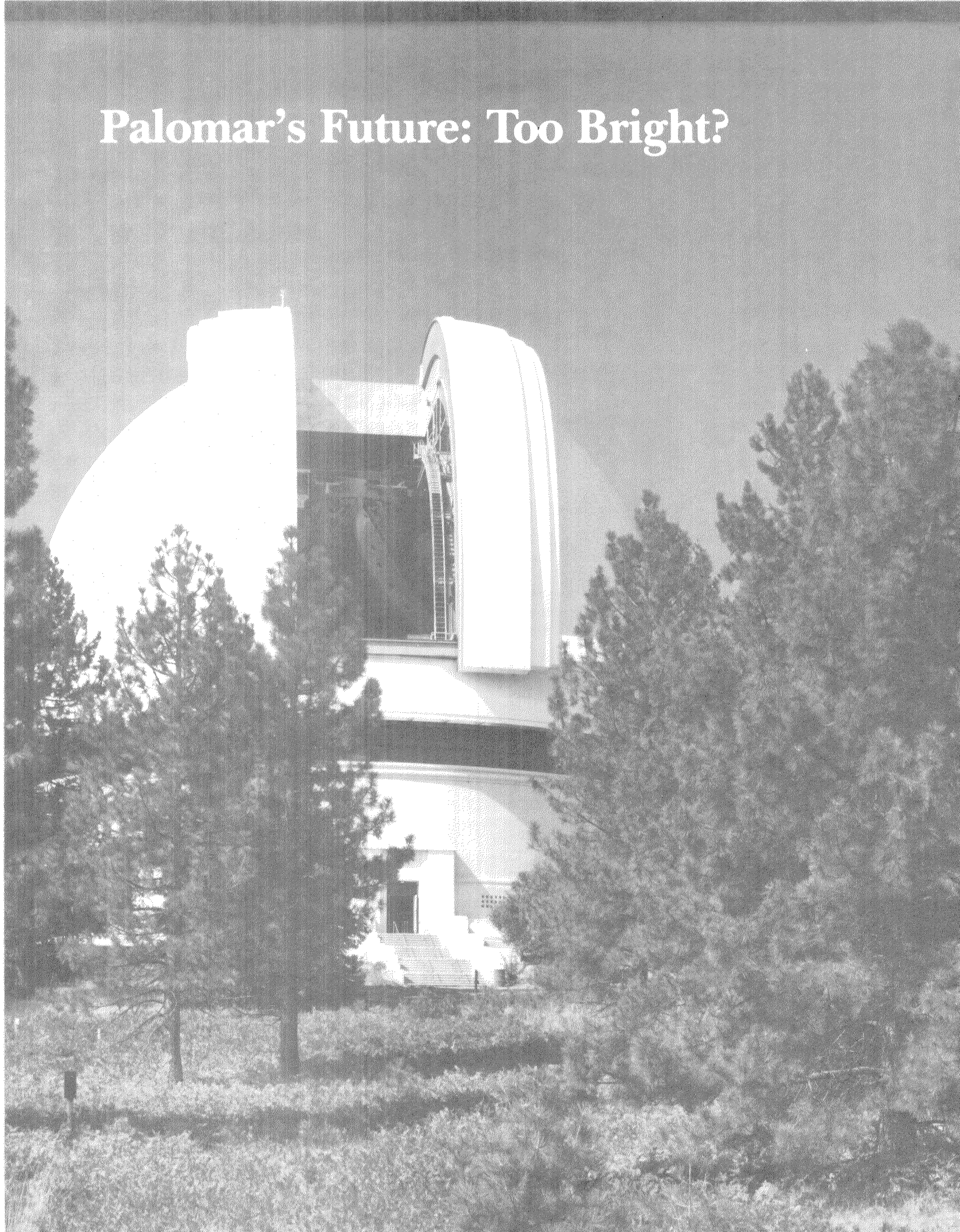
Given that it takes at least three years to write a regulation, our solution to the flexibility issue is to create permits of nine-year duration, one-third of which expire every three years. At the end of each three-year period, the regulators can define a new ratio between expiring permits and new permits. If permits for 50 tons per day are expiring, they could reduce the number available to 45 to make the air quality better, or increase it to 55 if they were willing to accept worse air quality. Under these circumstances, each firm has permits that will last long enough for it to make rational decisions about capital investment. At the same time, within the three-year planning horizon of the regulatory agency, it would be possible continually to be adjusting emissions in response to new information about air quality and its effects.

We have proposed our approach to the California Air Resources Board and to the Environmental Protection Agency in Washington, D.C. There is only one slight problem; it's illegal. The regulatory agencies would be in violation of virtually every environmental law if they were to implement it fully. Yet, with some changes from its purest form, there is hope that this kind of approach could be adopted in one market as an experiment to test the validity of the idea. We believe that there is a good chance that a market in emissions permits could reduce the cost of achieving air quality objectives, but the idea can be proved only by trying it out. □

Another pair of views from the top floor of Millikan Library. These two pictures of Pasadena were taken looking northwest on very different days.



Palomar's Future: Too Bright?



The 200-inch Hale Telescope at the Palomar Observatory of the California Institute of Technology is one of the most important scientific instruments ever built. For over 30 years, astronomers have been using it and its companion telescopes at the observatory to increase our understanding of the universe. In that period, astronomy has advanced enormously, with other fine conventional telescopes being built, and both advanced orbiting and ground-based telescopes planned or under construction. But now civilization is encroaching on the observatory, as developments spring up around it. In this interview, Gerry Neugebauer, professor of physics at Caltech and director of the observatory, discusses the current value to astronomy of Palomar's telescopes and the threat of light pollution to their effectiveness. The interview was conducted by Dennis Meredith, director of the Caltech News Bureau.

Dennis Meredith: Could you start by describing the relationship the Palomar telescopes have to other instruments today?

Gerry Neugebauer: In astronomy today, there are on the order of 20 telescopes that are bigger than 100 inches in diameter, and of these the Hale is one of the half dozen bigger than about 150 inches. The Soviets have a bigger telescope, but the Hale Telescope remains the biggest in this country. It dominated astronomy in the fifties and sixties because of both its size and its achievements. When it was built, it was twice as large as any previous telescopes, and all the others of comparable size have been built only recently.

DM: Is it still useful in astronomy?

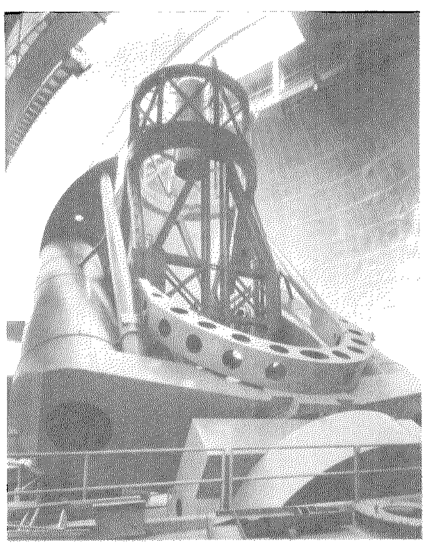
GN: Most certainly. It's a highly valuable instrument that is at the forefront of astronomical research. The telescope itself is a light-gathering device for the detectors that are placed on it, so it doesn't go out of style. And the instrumentation developed for the 200-inch Palomar telescope has always been at the front of the line. Things such as multi-channel analyzers and spectrographs that more effectively analyze the gathered light have long been used. And we were among the first, if not *the* first, to use charge-coupled devices, which are arrays of electronic elements that are far more sensitive light detectors than traditional photographic plates. Because the new detectors are more sensitive than the old photographic plates, the 200-inch can now see objects a hundred times fainter than it could when it was built. In addition, in just the last few years we have upgraded such things as control systems to point the telescope.

DM: Could you outline a few of the discoveries that have been made with the telescope over the last few years?

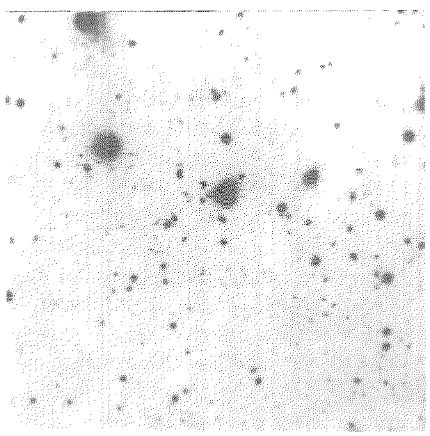
GN: The most recent has to do with quasistellar objects, or quasars, which are incredibly bright objects at the edge of the observable universe. Astronomers believed that quasars were the nuclei of galaxies of stars, but until the recent detection at Palomar of starlight around a quasar, they had no solid evidence. Now we have proof that quasars are, indeed, at the centers of galaxies.

Another fascinating study now being done at Palomar involves studying the spectrum of light from quasars to detect absorption by material in clouds between the quasars and earth. The quasars, in effect, backlight the clouds, which have been found to be perhaps the most pristine material in the universe, unchanged since its beginning.

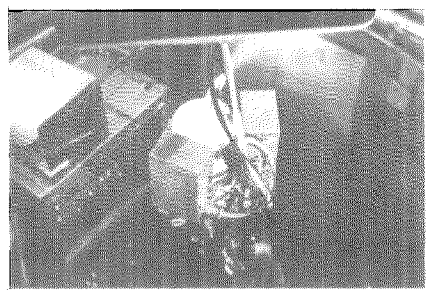
Also, very significant studies of the gravitational lens effect were done in 1979 with the 200-inch. In this effect, the light from quasars is warped by the gravity of galaxies between the quasar and earth, creating multiple images of the quasar.



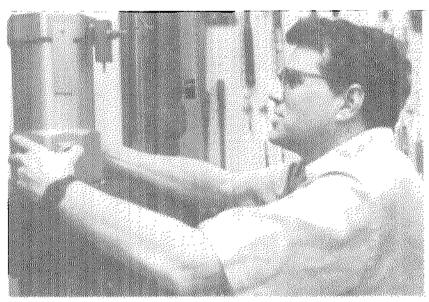
The 200-inch Hale Telescope points toward the zenith. The solid tube at the top is where the prime-focus observing cage is located.



This 6,000-second exposure of the first gravitational lens taken by a detector on the 200-inch telescope is one of the deepest pictorial looks into the universe ever taken. The field size is 12 square arc-minutes (compared to the moon's 700), and the faintest visible objects are of a magnitude fainter than 25, which is 100 million times fainter than anything visible to the naked eye. The photo was obtained by Jerome Kristian of the Mount Wilson and Las Campanas observatories and the late Peter Young of Caltech.



The PFUEI/CCD system that made possible the picture at the left is mounted in the prime-focus cage of the 200-inch. The PFUEI (Prime Focus Universal Extragalactic Instrument) was designed by James Gunn, formerly of Caltech, and James Westphal, professor of planetary science. CCD stands for charge-coupled device. The photo is courtesy of graduate student David Jewitt.



Gerry Neugebauer, professor of physics and director of the Palomar Observatory, with the infrared detector he uses in astrophysical research.

Astronomers can study the differences among these images to learn about the stars in the distant galaxies the light has traveled through and also about the precise distances to the edge of the universe.

Other discoveries farther back in time include the first measurement of the diameter of Pluto, the establishment of the distance scale of the universe, and the first discovery of quasars. All of these represent some of the most exciting astronomy ever done.

DM: Of course, the 200-inch is not the only telescope on the mountain.

GN: No, and that's important to stress. Because it's the telescope that looks at the faintest objects the farthest out in space, it's been preeminent. On the other hand, the 48-inch Schmidt telescope, which is basically a large camera, can't see as far. It has, however, a much larger field of view, so it's used for mapping big areas of the sky. There's an exact twin of it in Australia. Immediately after the Schmidt was installed at Palomar in 1949, astronomers used it to survey the entire sky, and the result has been called the Bible of astronomy. We're going to repeat that survey maybe two years from now, using the Schmidt to map the entire sky at several different wavelengths. The project will take about five years, but if the survey was done with the 200-inch, it would take about 200 years.

DM: Will this new survey be an improvement over the previous sky surveys?

GN: It's an important improvement in two ways: It will be at different wavelengths and with improved, more sensitive film, so it will show more objects; and it will show how the stars have moved in the sky over the years. Knowing such motions is very important for astronomers.

DM: How does the work at Palomar relate to studies done with such space probes as the Space Telescope, which will be launched in 1985?

GN: Well, first of all, Palomar is significantly aiding such efforts. For instance, right now we are using the 48-inch to make a survey of the sky to establish the guide stars for the Space Telescope.

More importantly, though, ground-based telescopes like the 200-inch and the 48-inch are complementary to such instruments as the Space Telescope. It's certainly not that one kind of instrument will put the other out of business. While the Space Telescope will not have to deal with atmospheric interference, ground-based telescopes are larger and we have the flexibility to change our instrumentation more often. What I think will happen is that once we have the Space Telescope, it will open up more, different kinds of problems that can be attacked with the 200-inch.

It's as if you owned a store in an area and somebody wanted to build more stores nearby. Your business won't be hurt, it will be helped, because the more stores you bring in, the more people will come to buy. In the same way, I think the more we learn about astronomy with the Space Telescope, the more use the 200-inch will see.

DM: Could Palomar then be described as a cheap space probe, because the knowledge it brings is less expensive?

GN: I wouldn't call ground-based astronomy a cheaper version of the space program. What we have learned from the ground undoubtedly cost us less, but I would like to emphasize that space yields different knowledge. That's the real answer. There are wavelengths you can look at from space you simply can't detect from beneath the atmosphere.

DM: What do you consider the major current problem facing Palomar?

GN: Right now, as far as its long-term future, light pollution is the major problem for both telescopes. Without light pollution, we should without a doubt be able to keep on using Palomar far into the next century. The only limit is our imagination in building new instrumentation, and we can keep on doing that. The limit set by light pollution, however, will soon be a fundamental limit; that is, because of it we won't be able to keep on pushing to fainter and fainter objects. We are already looking at objects that are fainter than the sky, but if the sky brightness continues to increase, pretty soon we just won't be able to make measurements.

DM: How can you look at objects that are fainter than the sky?

GN: Even at the darkest of sites on the darkest nights there is a natural glow that comes from a lot of different things. It comes from light pollution from surrounding cities, from material in the upper atmosphere, and from dust in the solar system. With our new electronic instrumentation, we can subtract out that background because it's random noise that cancels itself out. It differs from the light from the object, which builds up as we fix on it with the detector. But this subtraction can only go so far.

DM: How about replacing Palomar with other telescopes at a better site or moving the existing telescopes to a better site?

GN: According to current estimates, it would cost from $50 to $100 million to replace Palomar, which makes that out of the question. We've thought a bit about moving the telescope, but when you look at the numbers, that's impractical, too. Just as important is the fact that there aren't that many good sites left. Among the many excellent qualities that Palomar Mountain has is that the atmospheric turbulence is very low there, so the seeing is very good. We couldn't match that quality by just going out to the desert to look at the stars. So, if we can just keep the lights down, along that ridge near San Diego is a really ideal place for the telescope.

DM: What would you ask of the people who live in communities near the mountain?

GN: Well, first of all, I accept the fact that we can't have an ideal world with no lights around Palomar. And so what we want to try to do is to ask for the kinds of lights we can deal with most effectively. That's why first of all we're recommending low-pressure sodium lights for outdoor use. All the light from low-pressure sodium lamps is emitted in one narrow line of the spectrum. In effect, it's gathered up in one small area of the spectrum, and our instruments can effectively filter it out. On the other hand, incandescent, high-pressure sodium, and mercury vapor lamps emit light that's all over the spectrum, and it literally blinds the instruments. In fact, because low-pressure sodium lights emit all their energy at a usable visible wavelength, they're more efficient and cheaper to use.

The other thing we're asking is that people try to use fewer outdoor lights for less time. We hope that lights for advertising can be shut off after business hours. Beside being bad for us, they're not selling very much during that time anyway, so we're actually only asking the users to save energy and money. When lights such as security lights do have to stay on, besides asking that they be low-pressure sodium lights, we'd like to have them shielded, so they don't shine above the horizon.

DM: Are the low-pressure sodium lamps effective for security use?

GN: In every case in which the effectiveness of the lamps has been studied, there has not been an increase in crime in an area where low-pressure lighting has replaced other forms.

DM: Does the average person who lives around Palomar and has a porch light or other outdoor light really make a difference to the effectiveness of the telescopes?

GN: Absolutely! The average guy clearly does make a difference. If you just look out over the area around Palomar, you can see more than street lights and advertising lights. Street lighting probably contributes something on the order of a third to light pollution, depending on the time of night and the kind of area. But all the rest of the light is made up of little bits and pieces — porch lights, security lights, and such. If we can get people to arrange those so that they're downward-looking, and to perhaps turn them off after midnight, I think it'll be a big step forward.

Our hope is that we can convince the people who live around Palomar that the observatory is a big enough national resource that they will want to help. And so far, everybody that we've talked to has been very cooperative. We've talked to developers, industries, and governmental bodies, and they've all been very understanding. Recently, for instance, TRW agreed to install low-pressure sodium lighting in its new facility near Palomar.

DM: Do you think that light pollution will be the death of Palomar?

GN: If we're not successful in our efforts, it will be. Light pollution is the only factor that is detrimental to Palomar right now. The area right around us is a big national forest, so it won't ever be developed. And we don't see any dust or smoke clouding our images. We had a bit of a problem with airplanes flying over, but the Air Force has been cooperative and rerouted their flights so they no longer interfere with our viewing. And they don't turn on their landing lights right over our telescopes.

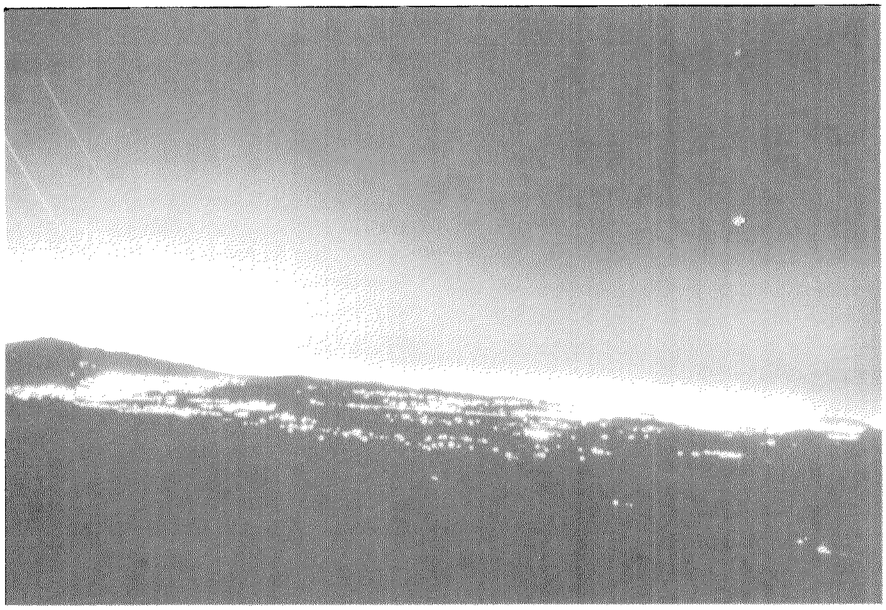
DM: Is there time to reduce light pollution?

GN: There's not as much as we hoped there would be. One reason is that the Public Utilities Commission mandated in 1978 that street and highway lighting be converted to sodium vapor for economic reasons, to save energy. Until now, the conversion has gone largely to high-pressure because the highway agencies thought that the citizens would object to low-pressure because of its yellow color. But it turns out that the people haven't objected to low pressure wherever it has been tried. We've got to try to reverse decisions to go with high-pressure sodium.

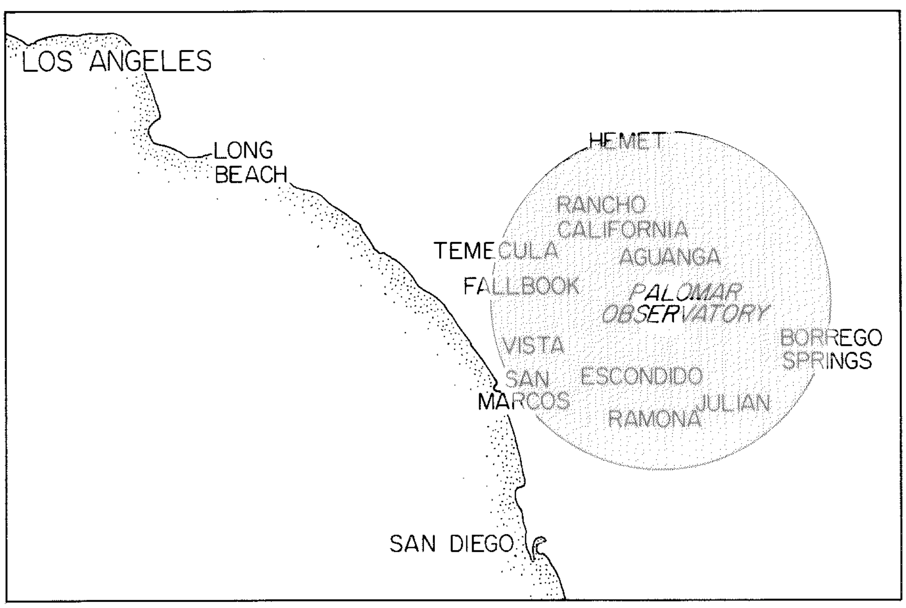
Another reason we don't have a lot of years to work on the problem is that the area right around Palomar is the fastest growing in the country. I've seen estimates that say before the year 2000 the population will have increased more than 50 percent. With that increase, unless we can persuade people to install the right kinds of lighting as we go along, it's going to be very hard to reverse the trend. So I don't feel complacent about the problem; I think we have to work with some sense of urgency.

DM: You do feel though that, even given the population increase, if the lighting is done carefully, Palomar can continue to operate?

GN: Yes, I think that it can, or else I wouldn't be investing the effort that I have and am. I think Palomar can continue, and that it will survive as an important contributor to science. □



***On** a clear night the telescopes at Palomar Observatory would be able to see almost forever if it weren't for the kind of light pollution shown above. This photograph was taken from the mountaintop looking north-northeast, and the glow is largely from Hemet, which is just inside the 30-mile radius around the mountain indicated by the shaded area on the map below. The rest of the lights are shining in Sun City, which is even beyond the 30-mile area.*

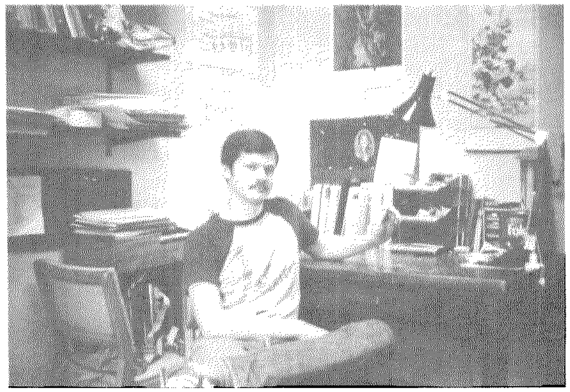


Student Life

Ditch Day Stacks Up

One Senior's Account

by Robert Lang



Robert Lang presides over his Ricketts room in quieter times before Ditch Day.

Senior Ditch Day started as a Caltech tradition in 1921 when "the seniors of the Institute took it upon themselves to strew the sands of Ocean Park with their intellectual personalities," leaving classes and campus behind. Over the years the seniors began to keep the date of their planned ditching a secret, which of course challenged underclassmen to find it out and to disrupt the day in some way – relocating the seniors' possessions while they were gone or "redecorating" their rooms. By the 1950s the seniors were shoring up their doors and windows with imaginative protection plans, and these "stacks" have grown more and more elaborate in the last 20 years or so, some involving brute force to break down while others (finesse stacks) are of a more intellectual nature and require students to be on their honor to perform the tasks. Usually the underclassmen do manage to break in, whereupon they can accept an offered bribe of food and drink or decline the bribe and "counterstack." Recent counterstacks have involved making one senior's room into a swimming pool and reassembling another's room intact on the roof.

Robert Lang (BS '82 in electrical engineering and now a graduate student at Stanford) describes the stack for his room in Ricketts House.

SENIOR Ditch Day began officially at 8:00 a.m. on Friday, May 7. That is, all seniors were required to be off campus on pain of being roped to a tree for the duration of the day. Of course, Ditch Day had really been weeks in the making, albeit covertly. My stack (created in collaboration with fellow student Camilla Van Voorhees) was conceived over a year ago when I decided on the final pun that located the key to my room. I had placed a copy of my key in its hiding place in January. The general form of the stack came together over the course of third term, as we discussed what cruel and unusual tasks we could require of the eager little underclassmen.

The stack finally coalesced the week of Ditch Day. It consisted of a trail of clues, the solution to which required building climbing, steam tunneling, and a familiarity with such things as Shakespeare, chemistry, psychology, electrical engineering, the music of Keith Emerson, and the elvish alphabet from Tolkien. Eventually the design of the stack grew so complicated that we were forced to draft a flow diagram to keep track of the branches of the path and the various cross-links. Actually laying the trail of clues took the whole night before Ditch Day.

By 7:55 the underclassmen were up and around, waiting in gleeful anticipation of the stacks they were going to assault. At 7:59 I left (not for the beach but to go to sleep somewhere) and locked my room, leaving on my door the terms of the stack:

1) You may enter only with the key to this room, which is hidden somewhere on campus.

2) The whereabouts of the key is encoded in a sequence of 29 four-digit numbers. It is not necessary to have all 29 numbers to get the message.

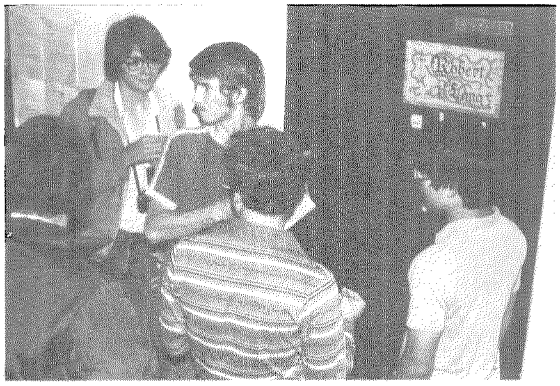
3) You must find the 29 numbers as well as crack the code. Timed clues will be provided, including an EE problem, which, when solved, will tell the secret to the encryption method.

4) More informaton will be made available to you as you work through the stack.

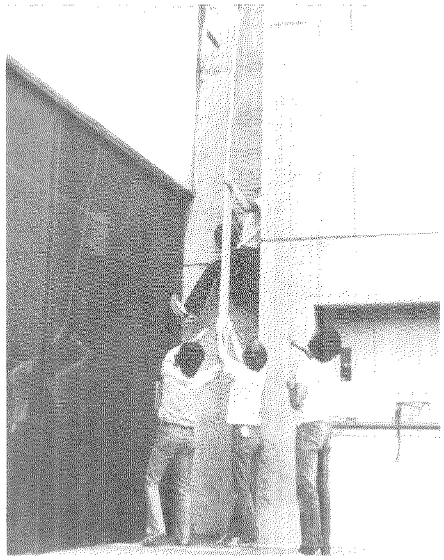
5) The first piece of information you need is located between pages 278 and 529 of *Radio Operating Questions and Answers*, a book located at window level on the second floor of Millikan Library, roughly 25 ft. south of the northernmost part of the building, and exactly 12 ft. west of the west side of the main card catalog.

To start off, the underclassmen would have to find the first piece of information as instructed in 5). If they followed the dimensions *exactly*, they would find that the book should be located about two feet beyond the interior wall of the building. Sure enough, the book was taped to the outside of the building, necessitating a climb to the second floor to retrieve it.

Inside the book was a note that split the trail into two portions. One led to an envelope in my mailbox that contained timed clues; the other portion continued in a climbing vein. Theoretically timed clues shouldn't be necessary, but they are frequently offered in case the stackbreakers get stumped. The extra hints were placed in sealed envelopes with the times they could be opened — every hour or so — on the outside.

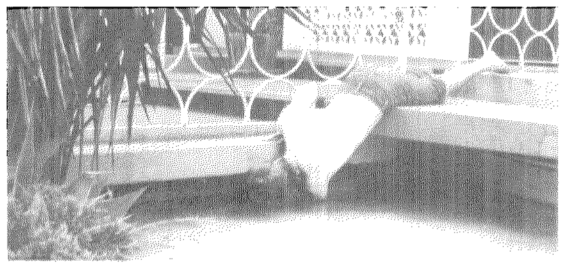


8:05 outside the door



9:10 Millikan Library

10:15 Bridge Lab



9:45 apartment house moat

Underclassmen begin their odyssey at Lang's door (top left) where the key is hidden right before their eyes. Directions in the book retrieved from a library ledge (top center) leads the stackbreakers on a merry climb after clues in a wide assortment of nearly inaccessible spots on campus (and off). Freshman Mark Hammond is the chief climber.

11:30 Kerckhoff's dome

2:10 Athenaeum window ledge

The second portion of the stack led off on a campus-building-climbing trail from Millikan Library to the wrought-iron lattice over the windows in the Athenaeum, to the concrete latticework on the back of Bridge Laboratory. From there, the trail led back to the Athenaeum (climb a tree), to Kerckhoff Lab (on top of the dome), to the North-South connector in the steam tunnels, to a balcony on the Athenaeum, a ledge outside the third floor of Crellin, and the top of the 20-foot-tall delivery doors to the Athenaeum. The trail continued to the second floor of the uncompleted Braun Lab, the metal latticework over the main entrance to Church Lab, the tiny room behind the concrete grill in the side of Gates, and finally to the overpass between Firestone and Guggenheim.

At each point in the climbing trail, the stackbreakers were directed to the next point and were given a set of clues or problems in an envelope. The solution of a particular problem provided one or more of the 29 four-digit numbers that encoded the location of the key. For example, this clue was located on the second floor of Braun:

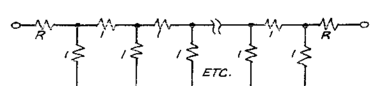
> "Because I could not stop for Death,
> He kindly stopped for me —
> The Carriage held but just Ourselves
> And Immortality."
>
> To find code number 7 of 29, square the value of the author's first name and then add 104.

The underclassmen would have to know (or find out) that the author is Emily Dickinson, whose first name (a = 1, b = 2, and so on) adds up to 64. That squared is 4096 plus 104 is 4200 — one, just one, four-digit number of the 29.

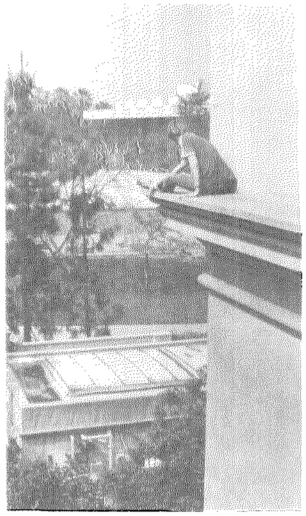
Access to some of the numbers also involved running and swimming laps, singing in the Athenaeum at lunchtime, and asking a questionable question of a staff member, whose identity was hidden in a series of clues.

The secret to the encryption method was itself encrypted in an electrical engineering problem:

> Consider the resistor network shown below, consisting of 115 $1-\Omega$ resistors and two resistors of value $R-\Omega$ (where R is a positive integer).

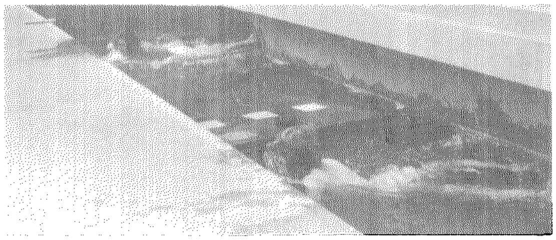


3:00 *Public Relations*

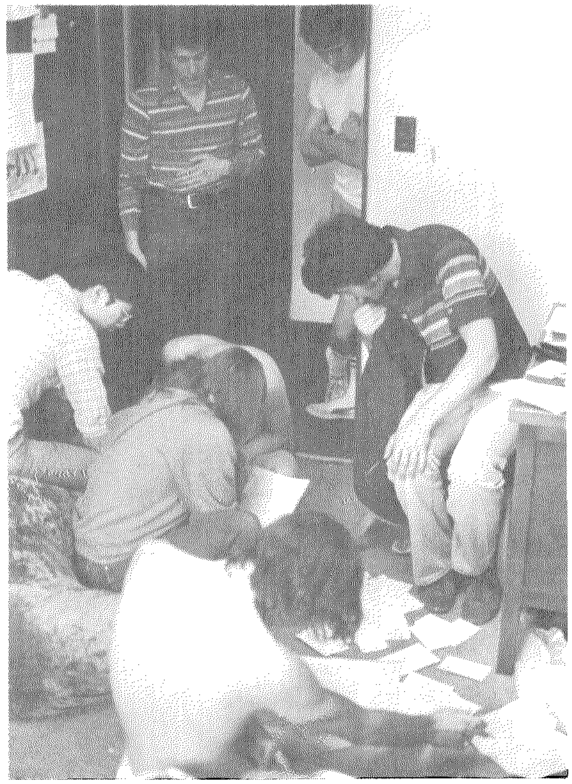


3:25 *Crellin – third floor*

Embarrassing questions, precarious perches, and swimming laps (very short ones) also yield clues. Meanwhile back in Ricketts, a growing crew assembles clues and tries to crack the code. Barry Lippey (bottom left) is the first to recognize the melody and retrieve the key.

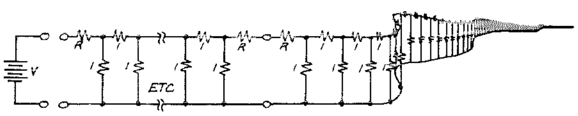


4:10 *Millikan pond*

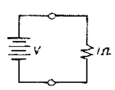


3:55 *next door*

We could string together an infinite number of these sections to form an infinite lattice, as shown below.



A battery of voltage V is connected across the two terminals of the lattice. You find that 1 Ampere of current flows. If the battery is subsequently connected in series with a $1-\Omega$ resistor (see below), an integral number of Watts of power is dissipated in the resistor.



If V is not an integral number of volts, what is the smallest possible value of R in Ω?

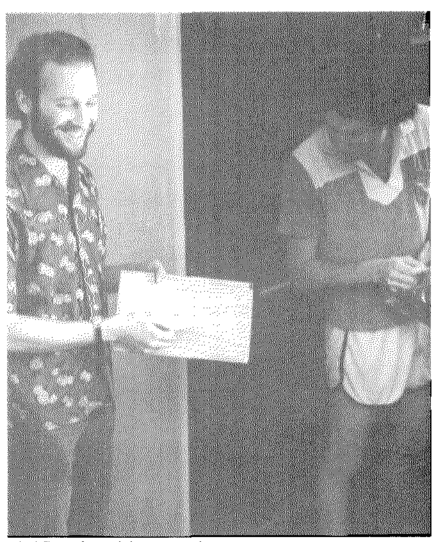
When the value of R was added to a 26-digit number and then separated into two-digit groups, substituting letters for the groups gave the answer "AUDIO FREQ." This answer might also have been arrived at without the solution to the EE problem by figuring out the mathematical relationships and patterns in the four-digit numbers. The 29 four-digit numbers were the frequencies of notes in a melody — "Auld Lang Syne." The key was hidden behind an old Lang sign — the nameplate on my door.

After a whole day's work by between three and a dozen underclassmen at various times produced 20 of the 29 numbers, and the EE problem was solved in many hours at the computer, the stack finally succumbed at 4:35, barely 25 minutes before the official end of Ditch Day. There was some discussion of counterstacking, but the allure of the bribe (ginger ale, cookies, fresh fruit, and a saucy but unpretentious rosé) proved too much after a tiring day, and the stackbreakers fell to with gusto.

Some of the clues are still waiting for some future climber to discover. If, for example, facing south you start at the lower left corner of the Firestone-Guggenheim overpass and count nine squares in and six squares up on the facade pattern, you can still see an envelope containing clue number 17. □

The solution to the EE problem is $\frac{1}{2}(f_{115}+1)$ where f_{115} is the 115th Fibonacci number. The value of R is 390,887,039,715,493,615,101,719.

4:30 *numbers become notes*



4:35 *the old Lang sign*

Far Out

FROM 300 MILES above the earth, outside the distorting and obstructing atmosphere, the Space Telescope will consider the universe from a new point of view. Its 94-inch primary mirror and six accompanying instruments will be able to respond to the entire optical spectrum from far ultraviolet to far infrared; its maximum resolution will be improved by a factor of ten over observations from earth; and it will be able to see seven times farther from the solar system.

Of these instruments, the most versatile and the one that will collect the greatest number of bits of information is the wide-field/planetary camera. James Westphal, professor of planetary science, is principal investigator for the camera and head of the investigation definition team chosen in 1977 to develop the instrument — to decide what it's to do and how it's to do it.

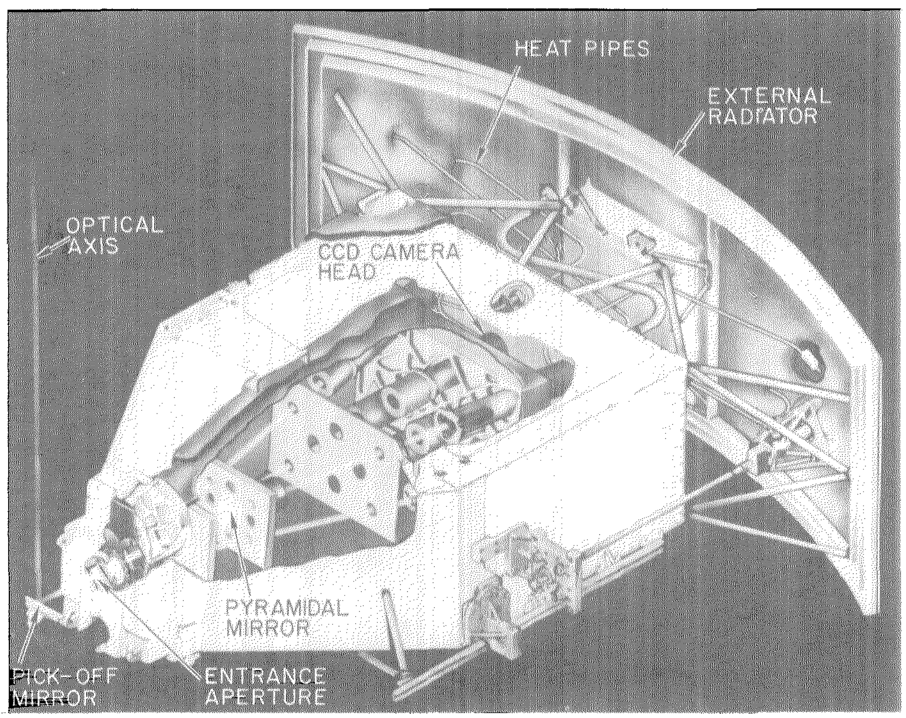
The camera is being built at JPL. Almost all the individual parts have been constructed, and the instrument is currently being assembled. After testing, calibrating, and operating with the other instruments, it will be installed in the Space Telescope and, after more testing, launched in the spring of 1985. The telescope is expected to remain in orbit at least 15 years, and probably much longer, with periodic service calls by astronauts and occasional trips home for major maintenance.

Out in space the wide-field/planetary camera, which is actually two instruments in one, will be located on the side of the telescope that will usually be turned away from the sun. Incoming light will be "folded" from the primary mirror to the secondary mirror and then back to a "pick-off" mirror, which deflects the beam into the wide-field/planetary camera. From there the beam goes through a shutter and one of 48 color filters. The beam will then be split by a four-sided pyramid mirror into the four quadrants of the wide-field position. Or the pyramid mirror can be rotated 45° to switch the four beams to the planetary mode.

With the two modes to choose from, the best tradeoff between field coverage and spatial resolution can be selected for each target, whether a large piece of the sky or a planet. That tradeoff is a factor of 2½ in resolution between the sensors of the wide-field mode, whose individual picture elements subtend an angle of 0.1 arc-second, and those of the planetary mode, which at 0.043 arc-second utilize almost all of the optical capability of the Space Telescope. Even though the planetary camera sacrifices a larger picture (it covers one-fifth as much sky as the wide-field camera) for its better resolution, it can still get all of Jupiter in on one shot — in a view similar to that from Voyager five days away.

For sensors the wide-field/planetary camera does not use photographic film but is equipped with charge-coupled devices (CCDs), tiny silicon chips that are the most sensitive and efficient detectors known. This camera's CCDs are about one-half inch square and ten microns thick and have 800 individual picture elements (pixels) on a side — 640,000 pixels for each of the eight CCDs (four for each mode). Each of the pixels is almost completely independent of all the others and can record and store, depending on the wavelength, up to 70 percent of the photons that strike it during exposure. This photon pattern is translated into a pattern of electrons and holes with a 1:1 correspondence to the photons. A numerical value can be generated proportional to the electrons, and these can be read out, pixel by pixel, back on earth. All 640,000 signals from one chip can be read out in 16 seconds, or a little over a minute for the four quadrants of the image, which can be recombined if the researchers wish.

Westphal's research team, along with the other groups developing instruments,



Incoming light is deflected by the pick-off mirror into the wide-field/planetary camera and through one of 48 filters mounted on rotating wheels. Then the pyramidal mirror splits the beam and directs it into either the four charge-coupled devices of the wide-field camera or the four CCDs of the higher resolution planetary mode. A cooling system (not visible) to reduce thermal noise in the CCDs necessitates the heat pipes and the external radiator, which forms part of the outside surface of the Space Telescope satellite.

will get first crack at observing time — more than a month's worth — as a benefit for their years of dedication to the project. The 11 members of the team have research interests that mirror the whole range of the camera's versatility; Westphal himself is interested in planets, Jupiter and Venus in particular, as well as distant galaxies. Of the other local team members, Jerome Kristian, staff member at Mount Wilson and Las Campanas Observatories, will also study distant galaxies, while Edward Danielson, member of the Caltech professional staff, will look at Jupiter and Saturn.

Other targets in our solar system for the camera's overall science program include Uranus and Neptune, which will be visible at ten times the resolution of observations from earth. Such objects as comets and the newly discovered satellite of Pluto can be studied in detail. The instrument will also search for planetary systems around nearby stars. Such a system could be identified by perturbations in a star's path.

Nearby galaxies will be visible with almost the same resolution as our own, and extremely distant quasars and radio galaxies as yet unseen from earth will also be studied. And the camera's broad wavelength response will enable it to see galaxies with different redshifts farther back in time than any now discernible and investigate such cosmological questions as the expanding universe concept itself.

The Space Telescope is a NASA project under the direction of the Marshal Space Flight Center in Huntsville, Alabama. The scientific data will be coordinated by the Space Telescope Science Institute being established at Johns Hopkins University and operated by the Associated Universities for Research in Astronomy, of which Caltech is a member. □ *–JD*

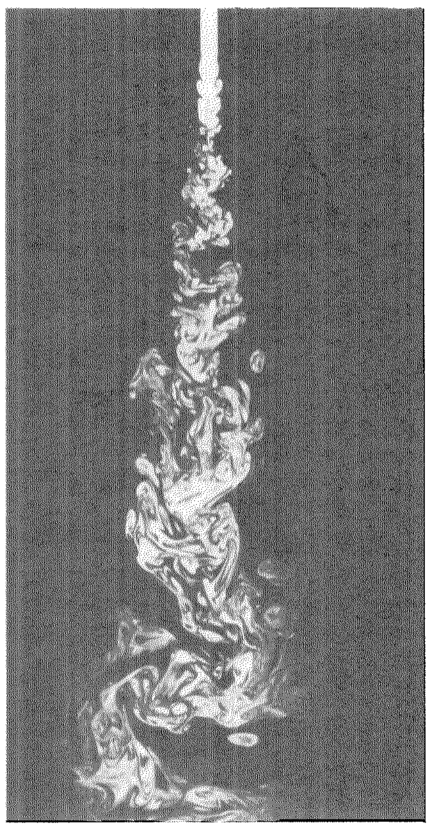
Inside Turbulence

THE STRUCTURE of turbulent flow has quite literally come to light in Caltech laboratories over the past decade. New techniques for making such flows visible have, in addition to producing pretty pictures, also overturned many of the long-held traditional views about turbulence as a more or less random behavior of fluids.

Paul Dimotakis, associate professor of aeronautics and applied physics, compares this juncture in the evolution of our understanding of turbulence with the transition, a little while ago, in our perception of the world, which was based on the ancient models of the universe constructed from Ptolemy's geocentric theory. Eventually the realization dawned that there was no way to keep adjusting the Ptolemaic model by adding more and more epicycles to fit the "predictions" with the observations. The trouble, of course, was that it was wrong in concept.

A similar conceptual revolution may be in progress today in fluid mechanics. The textbook definition of turbulence, on which almost all present engineering practices are based, assigns responsibility for turbulent entrainment and mixing to a gradient diffusion process. This is presumed analogous to the mechanism of molecular diffusion, the result of the random motion of molecules, with no particular organization, and describable only in statistical terms. In the conventional description of turbulence, it has also been assumed that there exists a relatively simple interface that separates the turbulent region from the non-turbulent region, so that a point is either inside or outside the turbulence; entrainment was understood as the "turbulent diffusion" of the non-turbulent fluid across this interface.

Work at the aeronautics department at Caltech suggests that the conventional view of turbulence is largely incorrect in concept and should be replaced by a picture in which turbulent transport is associated with coherent flow structures whose

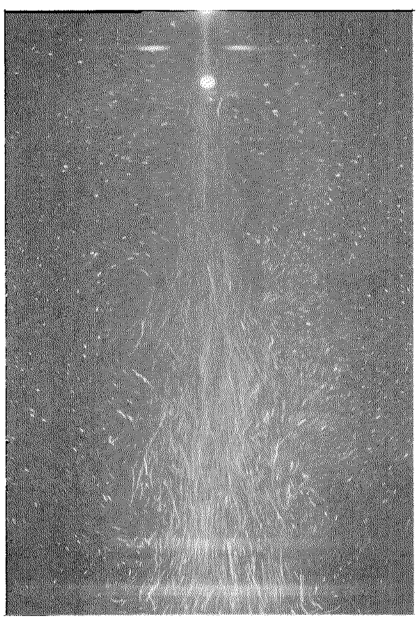


These photographs of laser induced fluorescence record the concentration of jet fluid in the plane of symmetry of a turbulent jet. The zig-zag pattern with the large regions of clear entrained fluid, which is particularly evident in the picture on the left, provides evidence for a large-scale vortical structure that in this case is probably helical. The small scales and complicated intertwining of the entrained fluid in both pictures casts doubt on the validity of a single interface between the turbulent and non-turbulent regions.

behavior can be described kinematically and thus can ultimately be predicted by solving appropriate equations of motion.

In the early 1970s, Garry Brown and Anatol Roshko, both professors of aeronautics, discovered the presence of an organized structure in shadowgraph pictures of turbulent shear flows, which are formed whenever two streams of different velocities meet. The structure was in the form of vortical "roller bearings" between the two streams. This was a complete surprise, because the experiments involved high-speed turbulent flow that should have been "disorganized," as proper turbulence is expected to behave. Subsequent experiments performed by Dimotakis and Brown confirmed the persistence of these organized structures to even higher velocities. Was it possible, however, that the shear layer was a special case, not typical of turbulent flow?

About five years ago Dimotakis and his students developed a technique using lasers to slice through the turbulence permitting a view of the interior of the turbulent region. The technique, called laser induced fluorescence, utilizes special dyes that can be selectively excited by a laser to emit light. Using appropriate optics to turn the laser beam into very thin sheets of a few hundred microns, one can monitor in this manner the instantaneous concentration of the fluid that has been labeled by the dye, in the plane illuminated by the thin laser sheet. It is also significant that dyes are available whose fluorescence properties depend on their local chemical environment. This allows monitoring the processes of entrainment and mixing down to the molecular scale, by comparing measurements in chemically reacting and non-reacting flows. Although variations of this technique have been used elsewhere, the resolution achieved in Dimotakis's experiments is considerably higher than elsewhere, allowing measurements down to the smallest length and time scales expected in the turbulent flow.



The conditions in this particle streak record of a turbulent jet flow field are identical to those in the photograph at left. Vortical structures can be seen at the edges of the jet, as well as high entrainment velocities far from the outskirts of turbulence.

The power of this new diagnostic technique was turned on to investigate the flow of a turbulent jet, surely a case of bona-fide turbulence. What the fluorescent dye revealed was that, just as in the shear layer, entrainment and mixing were not a matter of "turbulent diffusion." In the case of the jet, the structure of the flow turned out to be topologically richer than that of the shear layer, but the basic mechanisms appeared to be much the same. Large-scale vortical patterns became apparent, which in this case resembled ring vortices or helical structures, dominating the dynamics of the flow and gulping in the reservoir fluid. Reynolds number (the measure of the relative importance of inertial forces to viscous forces) also appeared to make no significant difference, with the slower moving, more viscous flow behaving in a manner similar to those with a high Reynolds number.

Dimotakis can perform various tricks with this technique, illuminating different aspects of the turbulent jet. He can arrange the chemistry of the dyes, for example, so that the fluorescence will turn on (or even change color) only when every part of the jet fluid has mixed with at least a certain amount of reservoir fluid. Conversely, the fluorescence can be turned off when the jet has mixed to a certain ratio with the reservoir.

The picture that emerges from these experiments on chemically reacting turbulent jets, conducted with Gene Broadwell, senior research associate in aeronautics, reveals a jet composed of large-scale vortical structures proceeding downstream and interacting with their upstream and downstream neighbors in almost discrete steps. It would appear that each structure passes mixed fluid on to the next downstream structure, which mixes it in turn with the fresh reservoir fluid it is entraining, and so on. This mixing mechanism is so efficient that at each step the chemical composition is very nearly the result of homogenizing the original jet fluid with all the entrained fluid up to that point.

A parallel set of experiments, in which the turbulent flow is made visible by recording time exposures of laser light scattered by small, neutrally bouyant particles in water, support the preceding conclusions. On time-exposure photographs, the particles leave streaks of light whose length and magnitude are a good indication of the local velocities of the flow. These photographs show clearly that portions of the non-turbulent reservoir fluid are set in motion and are committed to enter the "turbulence" long before they come in contact with the turbulent region, suggesting that the entrainment velocity is induced by the vorticity at some distance from the turbulence. The traditionally accepted simple interface between turbulent and non-turbulent is not apparent in these experiments.

Both the particle streak and fluorescent laser sheet pictures give a view of turbulence in which only two spatial coordinates are recorded. Even though it is possible to trade one space dimension for time using electronically scanned linear arrays of photodetectors in place of photographic film, actually all the complexities of four dimensions (three space coordinates versus time) are involved in dealing with turbulence. Efforts currently under way to analyze motion picture data would introduce time to two spatial coordinates, and other parallel efforts would also sweep the illuminated plane in the third spatial dimension synchronously with a high framing rate motion picture camera, to get at the fourth dimension. Dimotakis says that it is difficult to speculate at this time what the outcome of these experiments will be, as there are many unanswered questions at present regarding exactly how these vortices are connected to each other, or how they switch from one configuration to another. This makes the current efforts all the more exciting as they are designed to answer many of these questions.

The results of this work, and parallel efforts in other research groups in engineering, could prove to be quite important. Understanding turbulent entrainment and mixing processes could have a significant impact on such things as combustion efficiency, methods of building power plants and jet engines, and controlling pollutants. □ *–JD*

Retirements 1982

Robert P. Dilworth
Professor of Mathematics, Emeritus

AS A NATIVE Californian and a double Caltech alumnus (BS '36, PhD '39), Robert Dilworth has felt right at home being a faculty member at his alma mater for 39 years. He entered the Institute in 1932 planning to major in chemistry, but he switched to mathematics at the end of his sophomore year. His graduate work on a new algebraic theory of lattices was done under Morgan Ward. During three postdoctoral years at Yale, he continued this research and formulated a theorem that has become one of the fundamental supports of lattice theory, combinatorics, and partially ordered sets. It is so basic, in fact, that it is known in the profession as the Dilworth Theorem.

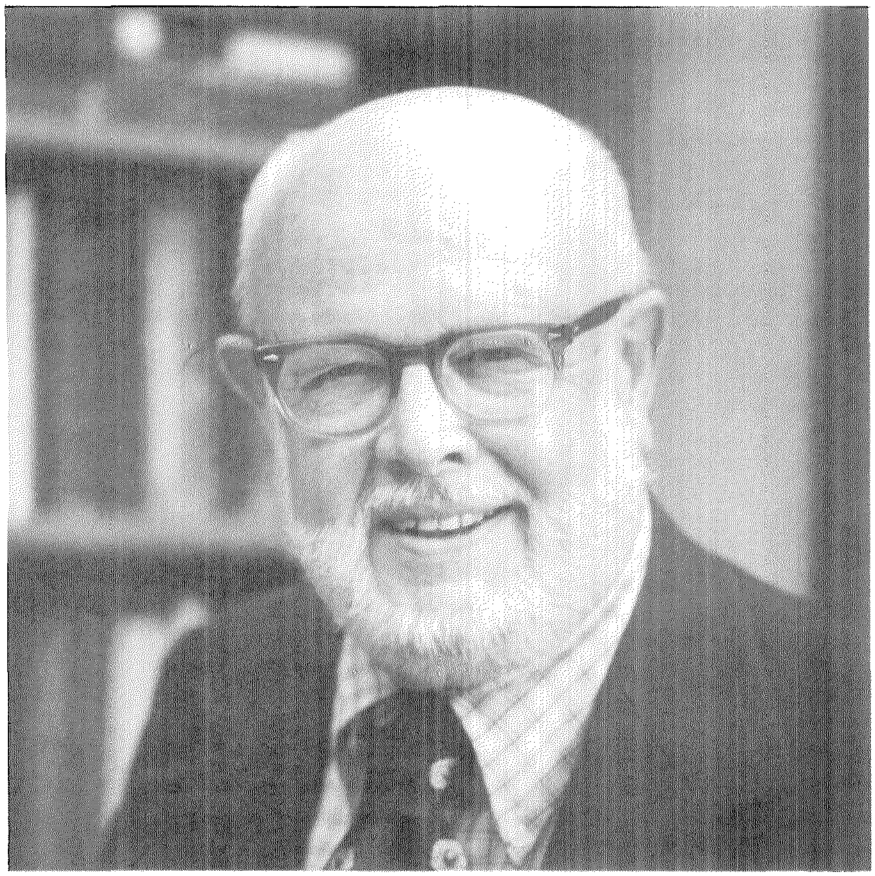
Dilworth returned to the Institute as an assistant professor in 1943 and then spent 1944-45 in Great Britain as an operations research analyst with the 8th Air Force. In 1951, Dilworth became a full professor, and in addition to continuing his research in algebra, he contributed to probability theory and statistics. He was also a most successful teacher. Several of his more than a dozen graduate students have gone on to distinguished professional careers.

During his early years on the faculty at Caltech, Dilworth was active on the Freshman Admissions Committee and was involved in the studies that led to the Institute's switch to the standard national entrance examinations. This led to his serving a term as the national chairman of the College Board's Committee of Examiners in Mathematics. Later, he also served a term as national chairman of the mathematics committee for the Graduate Record Examinations. In this capacity he was instrumental in the establishment of the Graduate Record Examination Board, which now sets policy for the Graduate Record program. He has supervised graduate students in mathematics at Caltech for many years and has served on the faculty committee for graduate study during that time.

These were by no means his only services to the Institute community. As an undergraduate, he was active in both music and athletics, playing the double bass in the orchestra and participating in the campus decathlon — and winning the Doc Haynes Trophy one year. As a faculty member, he continued his interest in athletics, and served for many years as chairman of the Athletic Facilities Committee. He was also chairman of the faculty for the two years 1973-75, initiating the steering committee system for handling the business to come before the Faculty Board. □

William A. Fowler

Institute Professor of Physics, Emeritus



WILLIAM FOWLER became Institute Professor of Physics, Emeritus, in July, capping a 49-year-long career at Caltech's Kellogg Laboratory. Fowler received his BS at Ohio State in 1933 and his Caltech PhD three years later. He stayed on at the Institute and by 1946 was a full professor. In 1970 he was appointed Institute Professor of Physics in recognition of his distinguished contributions to science and to Caltech.

During World War II, he worked on proximity fuses, rocket and torpedo ordnance, and atomic weapons. In 1951-52 he was scientific director of Project Vista, which is still classified because of its important implications for the defense of Europe. Among his awards in recognition of public service, Fowler received the Naval Ordnance Development Award in 1945, the President's Medal for Merit in 1948, NASA's Apollo Achievement Award in 1969, and the National Medal of Science in 1974.

Fowler's research has been in nuclear physics, astrophysics, and relativity. He has made studies of nuclear forces and reaction rates, nuclear spectroscopy, the structure of light nuclei, thermonuclear sources of stellar energy, element synthesis in stars and supernovae, nuclear cosmochronology, the origin of isotopic anomalies in meteorites, and general relativistic effects in quasar and pulsar models. He is a co-author of one of the fundamental papers in nuclear astrophysics, "The synthesis of elements in stars."

Among his awards for scientific achievements are the Ohio State Lammé Medal, the Liège Medal of the Uiversity of Liège, the California Scientist of the Year Award, the Vetlesen Prize from Columbia University, the Tom Bonner Prize of the American Physical Society, the Eddington Medal of the Royal Astronomical Society of London, and the Bruce Gold Medal from the Astronomical Society of the Pacific. He holds several honorary degrees and has been an active citizen in the scientific community, serving on the council and a number of committees for the National Academy of Sciences, of which he has been a member since 1956. He was president of the American Physical Society in 1976, and a member of the National Science Board from 1968 to 1974.

It is not generally known that he is a steam engine buff and that among the personal honors he particularly treasures are his memberships in the Los Angeles Live Steamers, the Cambridge [England] and District Model Engineeering Society, and the National Association of Railroad Passengers. One of the trips he most enjoyed was riding across Asia on the trans-Siberian railroad. He is also greatly pleased to be an honorary member of the Mark Twain Society. □

Norman H. Horowitz
Professor of Biology, Emeritus

NORMAN HOROWITZ arrived at Caltech in 1936 as a graduate student, bringing with him a BS from the University of Pittsburgh and reprints of the first two of what were by 1981 more than 120 professional papers. Those two papers were about his undergraduate research in muscle transplantation, and division chairman Thomas Hunt Morgan decided he should work with embryologist Albert Tyler. Two years later Horowitz had collaborated with Tyler on seven more papers — about research on sea urchin eggs. He received his PhD in 1939 and used the National Research Council fellowship he was awarded for a year of study at Stanford. The next two years were spent back at Caltech as a research fellow in the laboratory of biochemist Henry Borsook, working in a field that led to publication of a paper in the *Journal of Dental Research*. Its title was "Histochemical study of phosphatase and glycogen in fetal heads."

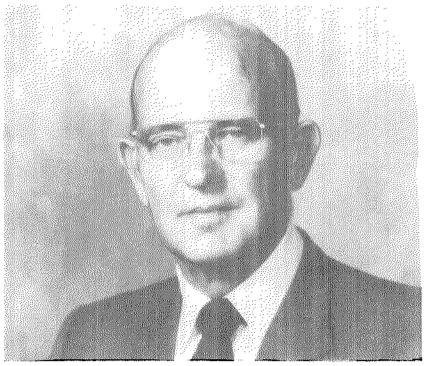
In 1943 Horowitz shuttled back to Stanford again, where as a research associate he worked with biologist George Beadle for four years. The research medium this time was the red bread mold *Neurospora crassa*, and a classic series of genetics papers resulted. When Beadle came to Caltech in 1946 as chairman of the biology division, he brought Horowitz with him as associate professor. He became a full professor in 1953, and from 1970 to 1975 was executive officer for the division, was its acting chairman in 1973, and was chairman from 1977 to 1980.

His career-long interest in the biochemical aspects of evolution led Horowitz to an early and increasing interest in space biology, and in 1965 he went to JPL as chief of its bioscience section, a position he held for five years. He has been deeply involved with the scientific aspects of all the missions to Mars, and he designed and tested some of the basic hardware for the life-seeking experiments of the Viking missions. Because of his interest in the evolution and abilities of organisms to survive in dry environments — on earth or off — in recent years he has done research on the water requirements of Neurospora and its relation to the transport of iron.

Horowitz is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. He is also a member of several professional societies and has been awarded the NASA Public Service Medal. □

Random Walk

New Director



ON OCTOBER 1, Lew Allen Jr. will take office as a Caltech vice president and director of the Jet Propulsion Laboratory. He replaces Bruce Murray, who resigned as director as of June 30. Murray is professor of planetary science at the Institute.

Until his retirement on June 30, Allen held the rank of general and was chief of staff of the U.S. Air Force and a member of the Joint Chiefs of Staff.

His formal training includes graduation from the U.S. Military Academy at West Point in 1946 and graduate work in physics at the University of Illinois, where he received an MS in 1952 and a PhD in 1956. He was then assigned as a research physicist to the Los Alamos Scientific Laboratory and in 1957 became science adviser to the physics division of the Air Force Special Weapons Center.

Allen has had extensive experience in space technology programs, having served in the Space Technology Office of the Office of the Secretary of Defense and from 1965 to 1973 in the Office of the Secretary of the Air Force, first as deputy director of space systems and then as director of special projects. In 1971 he became director, with additional duty as deputy commander for satellite programs, in the Space and Missile Systems Organization. For four years he served in various capacities in the security services of the United States, and in 1977 he was named commander of the Air Force Systems Command. He was promoted to general in 1977 and has been Air Force chief of staff since 1978.

He is a member of the National Academy of Engineering, American Geophysical Union, American Physical Society, and the Council on Foreign Relations. He is also the recipient of numerous military decorations and awards.

Humming Along

THE Division of the Humanities and Social Sciences is offering two new groups of courses this year: Humanities, and Performance and Activities. The three Humanities courses — Hum/Lit 11, Hum/H 12, and Hum/Pl 13 — are titled "Introduction to Humanities" and then further broken down into a term each that stresses literature, history, or philosophy. Each will be taught by Jerome McGann, Dreyfuss Professor of Humanities, as "practical courses in the basic disciplines of the humanities, with emphasis on reading, thinking, and writing."

McGann sees the courses as chiefly for freshmen, and lots of reading in the classics will be required, plus lots of writing. Each of the three major writing assignments each term must be done in the style of whatever author the class has been reading. If it has been *Walden Pond*, for example, students must compose their manuscripts in the style of Henry Thoreau; if they're working on the *Republic*, their essays are supposed to resemble Plato's.

The eight Performance and Activities courses are for what have previously been considered extracurricular activities. Now, for the first time ever at Caltech, units will be given for participation in the instructional aspects of such subjects as choral music, various instrumental music activities, and theater arts. Also included in this category will be the journalism course offered in connection with student publications and the restoration of course work in forensics.

Oppenheimer Revisited

THE American Playhouse production of *Oppenheimer* was shown on many Public Broadcasting System stations for seven Tuesday nights last May and June. And that fact kept a lot of Caltech people tethered to their TV sets for the appropriate seven hours. It also led to a lot of informal reviews of the previous night's episode on Wednesdays. All of which was understandable. J. Robert Oppenheimer was a part-time member of the Caltech faculty from 1928 to 1947. More importantly, he was a distinguished, charismatic, and controversial man and scientist. How well did television portray him, his achievements, his problems, and the events of that piece of history in which he played so large a part — the development of the atomic bomb?

There aren't any official TV critics at the Institute, but there are five professors who were at Los Alamos with Oppenheimer — physicists Robert Bacher, Robert Christy, Richard Feynman, and Robert Walker, and materials scientist David Wood. We asked some of them for comments, which are summarized below.

Most of them felt that on the whole the show was quite well done. Particularly remarkable was the "excellent job of capturing the atmosphere and the general feelings. . . . The thrust of what was happening during those days was very well portrayed." One felt, however, that there was too little said about how Los Alamos worked as a lab.

The characterization of Robert Oppenheimer was much praised — "startlingly true to life . . . he looks, speaks, and moves the way I remember . . . the actor had a remarkable ability to capture Oppy's mannerisms." On the rather harsh portrayal of Oppenheimer's wife, Kitty, most agreed that she could be "pretty rough on people," but they also claimed that she was always nice to them personally.

Some other characterizations came in for more criticism, in particular those of Hans Bethe and of General Leslie Groves, who was "a lot sharper and more capable than the TV made him seem."

The security hearings in 1954 that resulted in Oppenheimer's loss of clearance are still troubling. "The real tragedy was that essentially nothing new was presented in the hearings. It had all been known and cleared before. But that was the McCarthy era, and things were different in the country then."

Robert Oppenheimer on a visit to Caltech in 1955. With him is Robert Bacher.

ALUMNI FLIGHTS ABROAD

This program of tours, originally planned for alumni of Harvard, Yale, Princeton, and M.I.T., is now open to alumni of California Institute of Technology as well as certain other distinguished colleges and universities. Begun in 1965 and now in its sixteenth year, it is designed for educated and intelligent travelers and planned for persons who might normally prefer to travel independently, visiting distant lands and regions where it is advantageous to travel as a group.

The program offers a wide choice of journeys to some of the most interesting and unusual parts of the world, including Japan and the Far East; Central Asia, from the Khyber Pass to the Taj Mahal and the Himalayas of Nepal; the surprising world of South India; the islands of the East, from Java and Sumatra to Borneo and Ceylon; the treasures of ancient Egypt, the world of antiquity in Greece and Asia Minor; East Africa and Islands of the Seychelles; New Guinea; the South Pacific; the Galapagos and South America; and more.

REALMS OF ANTIQUITY: A newly- expanded program of itineraries, ranging from 15 to 35 days, offers an even wider range of the archaeological treasures of classical antiquity in Greece, Asia Minor and the Aegean, as well as the ancient Greek cities on the island of Sicily, the ruins of Carthage and Roman cities of North Africa, and a comprehensive and authoritative survey of the civilization of ancient Egypt, along the Nile Valley from Cairo and Meidum as far as Abu Simbel near the border of the Sudan. This is one of the most complete and far-ranging programs ever offered to the civilizations and cities of the ancient world, including sites such as Aphrodisias, Didyma, Aspendos, Miletus and the Hittite citadel of Hattusas, as well as Athens, Troy, Mycenae, Pergamum, Crete and a host of other cities and islands of classical antiquity. The programs in Egypt offer an unusually comprehensive and perceptive view of the civilization of ancient Egypt and the antiquities of the Nile Valley, and include as well a visit to the collection of Egyptian antiquities in the British Museum in London, with the Rosetta Stone.

SOUTH AMERICA and THE GALAPAGOS: A choice of itineraries of from 12 to 29 days,. including a cruise among the islands of the Galapagos, the jungle of the Amazon, the Nazca Lines and the desert of southern Peru, the ancient civilizations of the Andes from Machu Picchu to Tiahuanaco near Lake Titicaca, the great colonial cities of the conquistadores, the futuristic city of Brasilia, Iguassu Falls, the snow-capped peaks of the Andes and other sights of unusual interest.

EAST AFRICA—KENYA, TANZANIA AND THE SEYCHELLES: A distinctive program of 5 outstanding safaris, ranging in length from 16 to 32 days, to the great wilderness areas of Kenya and Tanzania and to the beautiful islands of the Seychelles. The safari programs are carefully planned and comprehensive and are led by experts on East African wildlife, offering an exceptional opportunity to see and photograph the wildlife of Africa.

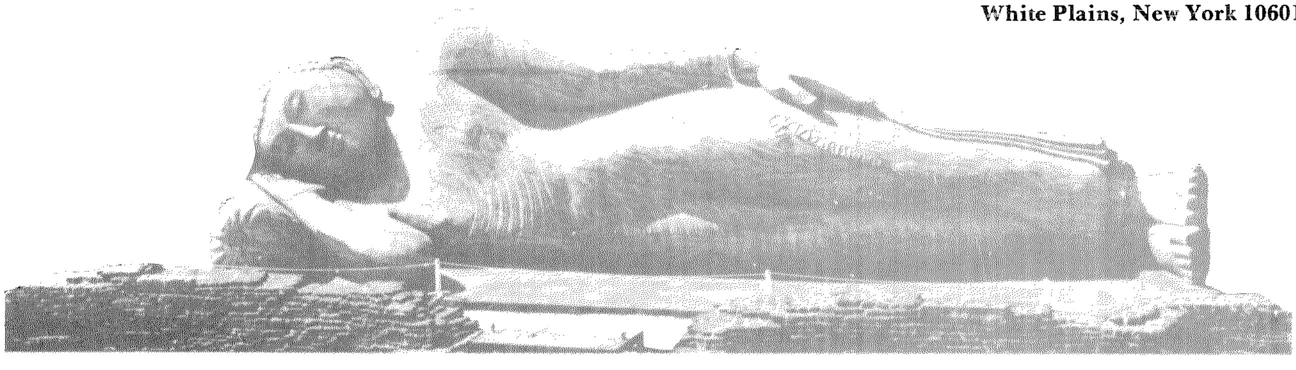
THE SOUTH PACIFIC and NEW GUINEA: A primitive and beautiful land unfolds in the 22-day EXPEDITION TO NEW GUINEA, a rare glimpse into a vanishing world of Stone Age tribes and customs. Includes the famous Highlands of New Guinea, with Sing Sings and tribal cultures and customs, and an exploration of the remote tribal villages of the Sepik and Karawari Rivers and the vast Sepik Plain, as well as the North Coast at Madang and Wewak and the beautiful volcanic island of New Britain with the Baining Fire Dancers. To the south, the island continent of Australia and the islands of New Zealand are covered by the SOUTH PACIFIC, 28 days, unfolding a world of Maori villages, boiling geysers, fiords and snow-capped mountains, ski plane flights over glacier snows, jet boat rides, sheep ranches, penguins, the Australian "outback," historic convict settlements from the days of Charles Dickens, and the Great Barrier Reef. Optional visits can also be made to other islands of the southern Pacific, such as Fiji and Tahiti.

CENTRAL ASIA and THE HIMALAYAS: An expanded program of three itineraries, from 24 to 29 days, explores north and central India and the romantic world of the Moghul Empire, the interesting and surprising world of south India, the remote mountain kingdom of Nepal, and the untamed Northwest Frontier at Peshawar and the Punjab in Pakistan. Includes the Khyber Pass, towering Moghul forts, intricately sculptured temples, lavish palaces, historic gardens, the teeming banks of the Ganges, holy cities and picturesque villages, and the splendor of the Taj Mahal, as well as tropical lagoons and canals, ancient Portuguese churches, the snow-capped peaks of the Himalayas along the roof of the world, and hotels which once were palaces of maharajas.

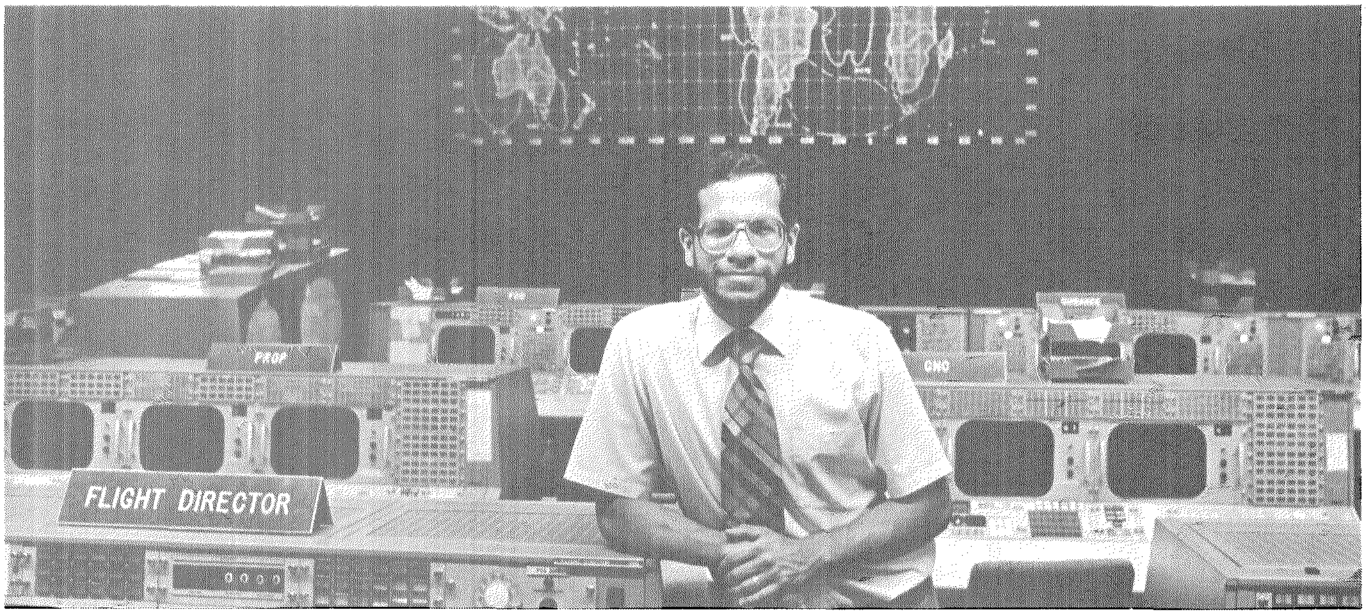
THE FAR EAST: Itineraries which offer a penetrating insight into the lands and islands of the East. THE ORIENT, 30 days, surveys the treasures of ancient and modern Japan, with Kyoto, Nara, Ise-Shima, Kamakura, Nikko, the Fuji-Hakone National Park, and Tokyo. Also included are the important cities of Southeast Asia, from Singapore and Hong Kong to the temples of Bangkok and the island of Bali. A different and unusual perspective is offered in BEYOND THE JAVA SEA, 34 days, a journey through the tropics of the Far East from Manila and the island fortress of Corregidor to headhunter villages in the jungle of Borneo, the ancient civilizations of Ceylon, Batak tribal villages in Sumatra, the tropical island of Penang, and ancient temples in Java and Bali.

Prices range from $2,350 to $4,500 from U.S. points of departure. Air travel is on regularly scheduled flights of major airlines, utilizing reduced fares which save up to $600.00 and more over normal fares. Fully descriptive brochures are available, giving itineraries in detail and listing departure dates, hotels, individual tour rates and other information. For full details contact:

ALUMNI FLIGHTS ABROAD
Dept. CT-1
White Plains Plaza
One North Broadway
White Plains, New York 10601



"I was a member of the team responsible for the verification of the software that lit the space shuttle's main engines and put her into orbit."



—Ben Flores. BS. Aeronautical Engineering. California Polytech State University; MS. Mechanical Engineering. University of California. Berkeley; IBM. Houston. Texas.

"I was in flight software support in Mission Control watching how the software would work and it did work—Columbia tracked like a bat. It was an awesome experience. knowing that I'd had an important role in this flight.

"That's the thing about IBM—they give you responsibility right from the start. all you can handle. And then they recognize performance with awards and raises and promotions. I've had my share of all three in my three years with IBM.

"When I first came to IBM I didn't know anything about managing people. You learn by watching. and you see how the managers honestly care about each person. about helping people shape their careers and use their abilities. If you want to go to a company that cares about its people and rewards your performance and encourages you to be original. IBM's the company you're looking for."

If you'd like to know more about IBM, write to J.J. Halsey, Corporate College Relations Manager, IBM Corporation, 3424 Wilshire Boulevard, Los Angeles, CA 90010.

IBM®

An Equal Opportunity Employer