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ARTICLES

DEPARTMENTS

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THE COVER

The painting on the cover depicts part of a field of sunflowers being grown as a commercial crop (see "The Sunflower Crop," by Benjamin H. Beard, page 150). The crop is grown for the seeds, particularly for seeds that have an oil content of 40 percent or more. Until about 10 years ago most of the seeds harvested in the U.S. were the confectionery or nonoil type, which are marketed as snack food and bird feed. During the decade the oilseed sunflower, which is the type portrayed in the painting, has come to dominate the industry, partly because of a rising demand for "sunoil" in Europe and partly because of genetic improvements in the plant that make the crop more profitable. Now some four million acres in the U.S. are devoted to the growing of sunflowers, and on a worldwide basis the sunflower is second only to the soybean as a source of vegetable oil. A field of the type portrayed on the cover would be harvested, most likely with a combine, after the plants had become dry and brittle.

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Body type: 2/4 dr. sdn, hardtop, sta. wag			
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One way driving distance			
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*For accidents, violations, or license suspension, give dates and complete details, including cost of damages, on a separate sheet. 668

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LETTERS

Sirs:

Joel S. Wit's article on antisubmarine warfare capabilities of the U.S. Navy is grossly misleading ["Advances in Antisubmarine Warfare"; SCIENTIFIC AMERICAN, February]. To the inexperienced reader (anyone who has not practiced the art of submarine warfare) the article could be construed to imply that the U.S. has the capability to locate and destroy any Soviet missile submarine any time we feel like it and that we are likely to get even better at it.

As a former sonar officer and an original commissioning crew member of the U.S.S. *Los Angeles* (SSN688), I feel a bit more qualified to speak on this subject than some international-affairs major working at some egghead think tank. Without going into details that may be classified, I wish Mr. Wit would not gloss over our antisubmarine-warfare capabilities with so much sugarcoating. Doing so only serves to lull unknowing Americans into a further deep sleep regarding the relative capabilities of the Soviet submarine force and our own antisubmarine-warfare systems.

Although our antisubmarine-warfare capabilities are second to none, the idea that we can now or shall soon be able to neutralize the Soviet missile-submarine force is preposterous. We obviously do threaten their survivability, but I know of no one knowledgeable in antisubmarine warfare who believes we could come close to neutralizing even half of their deployed missile submarines before they could launch their payload. Furthermore, the number of submarines in the antisubmarine-warfare mode necessary to do so would leave our surface combatants and convoys at the mercy of a very capable Soviet attack-submarine force that outnumbers our fleet by more than three to one.

I am disappointed that a magazine such as *Scientific American* with a reputation for technical accuracy would print such an article lacking in technical detail, full of buzz words and making a sugarcoated pill out of a very real and present danger to our national security. Everything is not hunky-dory down on antisubmarine-warfare street, and the American people should not be led to believe otherwise.

STEVEN E. MAYS

Idaho Falls, Idaho

Sirs:

Mr. Mays states that it is preposterous to think that the U.S. "can now or shall soon be able to neutralize the Soviet missile-submarine force." I find it preposterous that he could assert my article leads to such a conclusion. If he would take the time to read the article closely, he would find this is not so. In fact, I point out that although technological improvements could result in a growing ability to launch a preemptive attack in the deep ocean basins, an ability of decreasing importance, "it does not mean that all missile-carrying submarines deployed by the U.S.S.R. will become vulnerable to preemptive attack." This type of capability will largely depend on the success of any U.S. efforts to improve currently inadequate coverage of important new deployment areas such as the Barents Sea and the Sea of Okhotsk. Even if coverage is improved to enable the U.S. to track missile-carrying boats operating in these waters, I state this would only be "a significant *first step* [italics mine] toward the acquisition of a potentially destabilizing first-strike capability." As for conflict situations, I merely point out the various potential threats presented to Russian missile boats in different geographic locales.

Perhaps even more noteworthy than Mr. Mays's mistaken assertions is his attempt to cast doubt on the accuracy of the information contained in the article. I can assure him that this material is not the idle speculation of some international-affairs major working at an egghead think tank. The article is based on information provided by top-ranking civilian and military officials of the U.S. Navy in congressional hearings and reports, and on other public documents spanning the better part of the past decade. The article was also read by both active and retired U.S. Navy officers and by interested scientists and academics. Although there were some differences of opinion, they had no major objections to its contents.

Finally, I want to assure Mr. Mays that my intent was not to lull unknowing Americans into a further deep sleep concerning the Russian submarine threat. (I assume he includes in this broad term Russian attack submarines.) I also recognize this fact of life. By the same token, he should recognize that in our efforts to deal with this potential threat we could be improving capabilities that threaten Russian missile-carrying submarines. This is precisely the point of the article. There are no easy solutions to the dilemma and I would certainly not recommend discontinuing our antisubmarine-warfare program. If Mr. Mays would like to learn about one potential solution, I suggest he read my article in *Arms Control Today*, cited in the bibliography at the end of the February issue.

JOEL S. WIT

Arlington, Va.

Sirs:

I hope that you do not receive any correspondence concerning Douglas R. Hofstadter's article on self-reference [SCIENTIFIC AMERICAN, January]. I should like to inform your readers that many years of study on this problem have convinced me no conclusion whatsoever can be drawn from it that would stand up to a moment's scrutiny. There is no excuse for *Scientific American* to publish letters from those cranks who consider such matters to be worthy of even the slightest notice.

A. J. DALE

Department of Philosophy
University of Delaware
Newark

Sirs:

Many years of reading such letters have convinced me that no reply whatsoever can be given to them that would stand up to a moment's scrutiny. There is no excuse for publishing responses to those cranks who send them.

DOUGLAS R. HOFSTADTER

Palo Alto, Calif.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1931: "After an interim during which it suspended publication, our contemporary *Evolution* now reappears, and we gladly welcome it once more to the family of scientific journals. In all the world, with its 23,000 scientific periodicals, this, as far as we know, is the only one devoted wholly to the spread of information concerning evolution and the refutation of the silly arguments daily dinned into the ears of the million by the well-organized anti-evolutionists. Among our own readers we have discovered comparatively little interest in the purely controversial aspects of evolution, a fact we interpret as evidence that our readers accept the basic principle as being established and undebatable. The articles we have published therefore have concerned only particular phases of evolution, not arguing the elementary fact of it at all."

"For more than 10 years Congress has been trying to decide what to do with the nitrate plants built during the war at Muscle Shoals. It has been evident that if the plants were operated, the nitrate so produced would be available for fertilizers to replace the natural sodium nitrate imported from Chile. It begins to appear now that by the time a decision is reached on the Muscle Shoals question sodium nitrate will have been superseded as the nitrogen-bearing constituent of artificial fertilizer by ammonia. This change is due to the recent development of a process for the synthesis of ammonia from the nitrogen of the air, making anhydrous ammonia available at commercial prices."

"Edison Pettit and Seth B. Nicholson, working with the great tower telescope at the Mount Wilson Observatory and thus having at their disposal an image of the sun 16 inches in diameter, and applying to it one of their delicate vacuum thermocouples, have measured the energy of the radiation from a small area in the center of a sunspot for various wavelengths in the spectrum and compared it with that from a corresponding area of the undisturbed solar disk. Their measures, which are numerous and consistent, show that at the violet end of the spectrum a spot gives out less than 30 per cent as much light as the disk. In the red the proportion rises above 40 per cent, and in the invisible infra-red it increases slowly to 80 per cent. Averaging all together, the total heat radiation from the spot is found to be 47 per cent of that from an equal area of the photosphere. Sunspots may therefore be regarded as vast refrigerators, cooling the material of which they are composed by almost 2,000 degrees Fahrenheit over a region thousands of miles in diameter and keeping it cool for weeks on end."

SCIENTIFIC AMERICAN

MAY, 1881: "The distinction between wanton cruelty and the infliction of pain for humanity's sake is an important one, and the Society for the Prevention of Cruelty to Animals, more recently styled the Humane Society, certainly does not make it. The tender mercies of the foolish are often cruel, and of such a nature are those displayed by the officers of the society referred to when they seek by exaggeration and misrepresentation to stop all use of living animals for the scientific advancement of physiology and medicine. It shows a pitiful state of popular intelligence, feeling and judgment when legislatures can be persuaded by fanatics to pass laws making it a crime to pursue a line of scientific investigation that has been more fruitful than any other in knowledge helpful for the prevention and cure of disease. Pasteur's recent brilliant and most promising discoveries in connection with chicken cholera were no doubt made at the cost of considerable discomfort to a small number of guinea pigs, rabbits and barn-yard fowls, but the certain issue of those discoveries must be to prevent an incalculable amount of distressing and fatal disease among these animals, with a possible issue of infinite value to humanity in furnishing a clew to a right understanding and treatment of many of man's diseases."

"The most novel conclusion of Professor Helmholtz, in his recent Faraday lecture, is to the effect that the atom of every chemical element is always united with a definite unvarying quantity of electricity. This quantity stands in close connection with the combining power of the atom that modern chemistry has termed quantivalence. For if the amount of electricity belonging to the monad atom is taken as the unit, then that of the dyad is two, that of the triad three and so on. 'If,' says Professor Helmholtz, 'we conclude from the fact that every unit of affinity of every atom is charged always with one equivalent of either positive or negative electricity, they can form compounds, being electrically neutral, only if every unit charged positively unite under the influence of a mighty electric attraction with another unit charged negatively. You will see that this ought to produce compounds in which every unit of affinity of every atom is connected with one—and only with one—other unit of another atom.'"

"A company is being formed, with a nominal capital of two and a half millions, to work a line of express steamers between Milford Haven and New York. The idea is that they will have a length of about 550 feet, a beam of about 45 feet and a draft of about 25 feet when loaded. They will carry 5,000 tons of goods and 400 first-class passengers. One point forms the pivot around which all or nearly all other questions connected with the new ships and their construction must turn. This is their speed, which is to be 20 knots, or about 23 miles per hour. No such speed has ever been attained by any screw steamer of large size. Calculations show that 16,000 indicated horse power will be required to drive a ship of the stated dimensions at 20 knots across the Atlantic. It is very doubtful that the required velocity could be got with a vessel of much less than 7,000 or 8,000 tons' displacement. It will be seen that the construction of the proposed express Atlantic steamers presents a tremendous problem for solution to naval architects and engineers."

"The national gathering of telephone men at Chicago on April 5th emphasizes better than anything else the rapid and prodigious growth of that very recent invention. Indeed, among all the wonders of the age there is nothing more wonderful than the invention and progress of the telephone, made practicable only five years ago. It is already found in use in all parts of the world, as popular and useful in Egypt, New Zealand and China as in America and Europe. This year alone the English Post Office authorities have given orders for 20,000 telephones, while its rapid spread in this country is almost beyond calculation."

"It is estimated by competent authorities that 100,000 buffalo hides will be shipped out of the Yellowstone country this season. Nothing like it has ever been known in the history of the fur trade. The past severe winter caused the buffalo to bunch themselves in a few valleys where there was pasturage, and there the slaughter went on all winter. There was no sport about it, simply shooting down the famine-tamed animals as cattle might be shot down in a barn-yard. To the credit of the Indians it can be said that they killed no more than they could save the meat from. The greater part of the slaughter was done by white hunters, or butchers rather, who followed the business of killing and skinning buffalo by the month, leaving the carcasses to rot. When the buffalo are all killed off, as they bid fair to be in a very few years at this rate, everybody will wonder that the government did not do something to preserve this, the noblest of animal game."


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THE AUTHORS

CHARLES L. GRAY, JR., and FRANK VON HIPPEL ("The Fuel Economy of Light Vehicles") are respectively director of the Emission Control Technology Division of the U.S. Environmental Protection Agency and senior research physicist at Princeton University's Center for Energy and Environmental Studies. Gray writes: "I have a bachelor of science degree in chemical engineering from the University of Mississippi and a master of science degree from the University of Michigan. For the past 11 years I have worked for the U.S. Environmental Protection Agency in the areas of energy and the environment. I enjoy outdoor activities, particularly hiking and canoeing in wilderness areas." Von Hippel received his bachelor's degree in physics at the Massachusetts Institute of Technology in 1959 and his D.Phil. (as a Rhodes scholar) from the University of Oxford in 1962. He was recently elected chairman of the Federation of American Scientists.

PIERRE CHAMBON ("Split Genes") is professor of biochemistry on the faculty of medicine of Louis Pasteur University in Strasbourg, director of the Laboratory of the Molecular Genetics of Eukaryotes of the French National Center for Scientific Research (CNRS), director of Unit 184 of Molecular Biology and Genetic Engineering of the National Institute of Health and Medical Research (INSERM) and editor of *Journal of Molecular Biology*. He studied medicine and biochemistry at Strasbourg, where he obtained his M.D. in 1957 and has since remained except for a year as an Eleanor Roosevelt fellow at Stanford University. He writes that all his research has been devoted to the study of gene organization and expression in eukaryotic cells and that his current interest is in the regulation of gene expression during embryogenesis and subsequent development.

WALTER H. G. LEWIN ("The Sources of Celestial X-Ray Bursts") is professor of physics at the Massachusetts Institute of Technology. Born in the Netherlands, he received his education at the University of Delft, taking his Ph.D. there in 1965. He has been at M.I.T. since 1966. There, he writes, he "started out (with George W. Clark) in July, 1966, to make the first all-sky surveys at X-ray energies from high-altitude balloon platforms." Since then he has worked on searches by satellite that have resulted in many discoveries in X-ray astronomy. Lewin is also interested in contemporary art. He has collaborated since 1967 with the German artist Otto Piene. "Our work culminated," he writes, "in the 1,500-foot, five-color rainbow balloon flown at the closing ceremonies of the Munich Olympics in 1972." Lewin also collaborates with the Dutch artist Peter Struycken, who creates works of art with the aid of a computer.

KEN C. MACDONALD and BRUCE P. LUYENDYK ("The Crest of the East Pacific Rise") are at the University of California at Santa Barbara; Macdonald is associate professor of marine geophysics and Luyendyk is associate professor of geology. Macdonald, who says he was "lured into oceanography by a love for diving, travel and observational natural sciences," was graduated from the University of California at Berkeley with a degree in engineering and received his Ph.D. (in oceanography) jointly from the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution. He worked at the Scripps Institution of Oceanography from 1975 to 1979 and still has a joint research appointment there. Luyendyk's degrees are from Scripps: his bachelor's degree in geology and his Ph.D. in oceanography. He worked at Woods Hole from 1969 to 1973 and then went to Santa Barbara, where, he writes, "I have made a partial transition into becoming more involved in on-land geology and geophysics." His projects in that area include studying "the paleomagnetism and tectonics in southern California and the magnetic properties of ophiolites (on-land exposures of ocean crust)."

KNUT SCHMIDT-NIELSEN ("Countercurrent Systems in Animals") is James B. Duke Professor of Physiology in the department of zoology at Duke University. Born in Norway, he was educated at the University of Oslo and the University of Copenhagen, taking his D.Phil. at the latter institution in 1946. In the same year he came to the U.S. as a research associate at Swarthmore College. He began his association with Duke in 1952. Among a number of professional appointments that he holds or has held is the presidency (beginning last year) of the International Union of Physiological Sciences.

DANIEL KLEPPNER, MICHAEL G. LITTMAN and MYRON L. ZIMMERMAN ("Highly Excited Atoms") are respectively professor of physics at the Massachusetts Institute of Technology, assistant professor in the department of mechanical and aerospace engineering at Princeton University and postdoctoral fellow in physics at M.I.T. Kleppner has bachelor's degrees from Williams College and the University of Cambridge; his Ph.D. (in physics) is from Harvard University. He served on the Harvard faculty from 1960 until he went to M.I.T. in 1966. He writes that he was "the coinventor (with Norman Ramsey) of the hydrogen maser and helped to establish the device as a useful atomic clock." Apart from his work his interests are "the joys of city life, some of the joys of country life (ski touring, mountain walking) and cabinetmaking." Littman was graduated from Brandeis University and obtained his Ph.D. (in physics) from M.I.T. in 1977. He writes that his interests include photography, computers and toy trains ("I teach an undergraduate laboratory course on microcomputers in which students design computer-based projects that control various aspects of a model-railroad system") and that in sports he enjoys "squash, bicycling, tennis and softball (beer league)." Zimmerman was graduated from Juniata College in 1974 and got his Ph.D. from M.I.T. in 1979. He writes that he works half-time at M.I.T. and his "remaining time is spent managing a small company that works with enterprising individuals on interesting computer applications."

BENJAMIN H. BEARD ("The Sunflower Crop") is a research geneticist with the U.S. Department of Agriculture, working on oilseed crops, and a lecturer at the University of California at Davis. He was graduated from the University of Missouri at Columbia in 1950 and remained there for two years of graduate study, receiving his master's degree in 1952. He then did further work at the University of Nebraska, where he obtained his Ph.D. in 1955. He began working for the Department of Agriculture in 1955 as a research agronomist in the field of barley breeding. Later he did similar work for the department on the genetics and breeding of flax. Beard's present work encompasses not only the sunflower but also the soybean and the safflower.

ELSE GLAHN ("Chinese Building Standards in the 12th Century") is with the Institute of East Asian Studies of the University of Aarhus in Denmark. She was studying architecture at the University of Copenhagen when in 1944 she had to flee her native country as a war refugee and take up residence in Sweden. There she worked in architects' offices. "In the evenings," she writes, "I followed lectures in the Chinese language, just for the fun of it. After a few years I was caught in the game. In 1950 I had to decide what to rely on for making a living and chose Chinese." She has a D.Phil. degree from the University of Stockholm. From 1974 to 1979 she was director of the Institute of Asian Studies at the University of Aarhus. Glahn has studied Chinese architecture in Japan and China.


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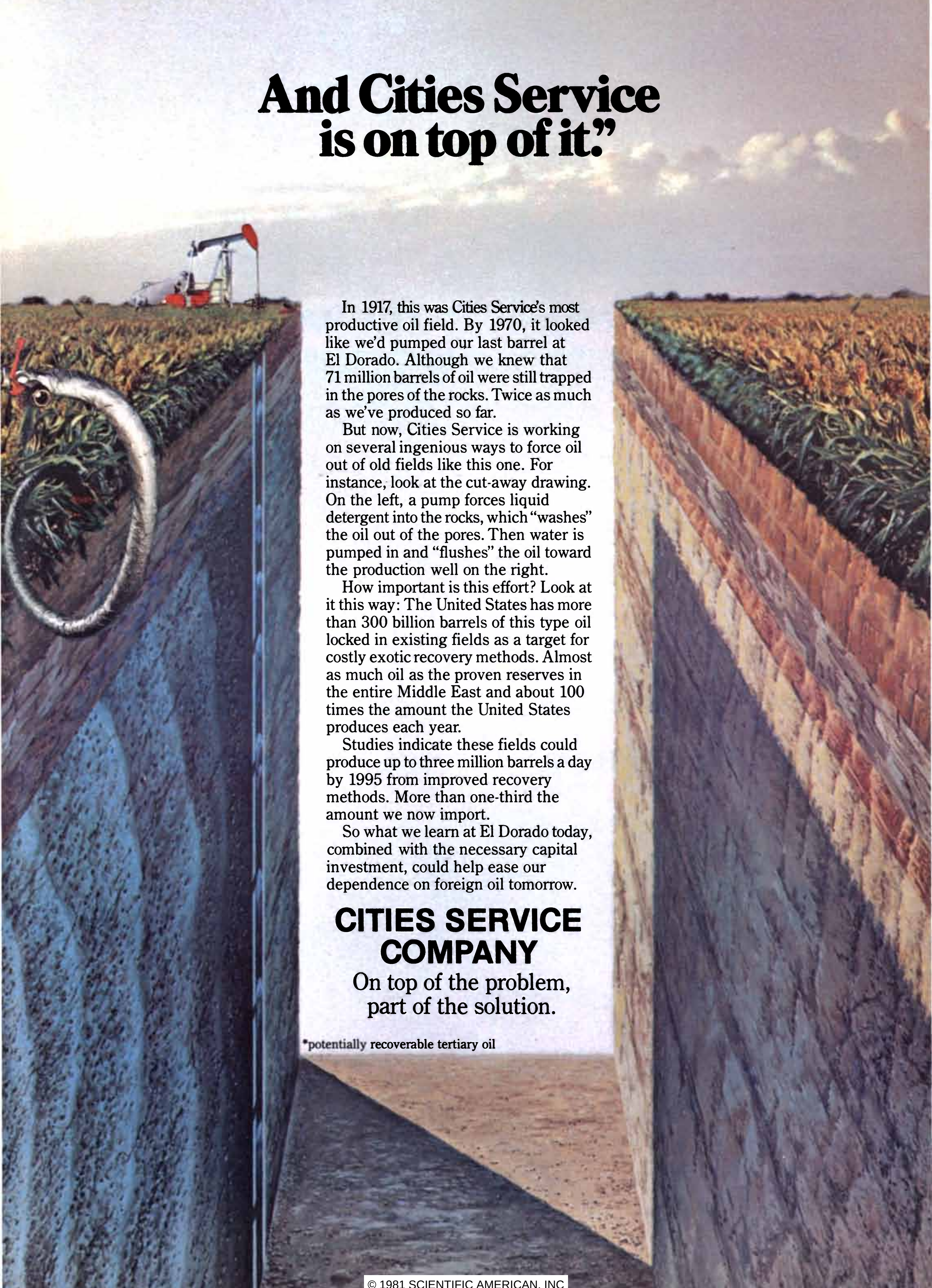
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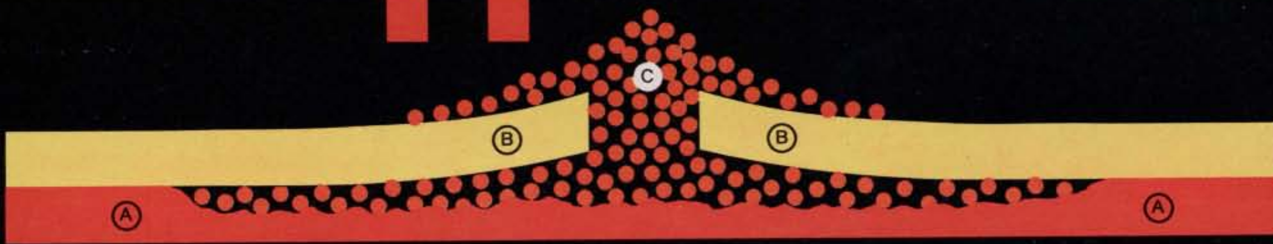
11 Porsche 911



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METAMAGICAL THEMAS

A coffeehouse conversation on the Turing test to determine if a machine can think

by Douglas R. Hofstadter

The participants in the following dialogue are Chris, a physics student, Pat, a biology student, and Sandy, a philosophy student.

CHRIS: Sandy, I want to thank you for suggesting that I read Alan Turing's article "Computing Machinery and Intelligence." It's a wonderful piece and certainly made me think—and think about my thinking.

SANDY: Glad to hear it. Are you still as much of a skeptic about artificial intelligence as you used to be?

CHRIS: You've got me wrong. I'm not against artificial intelligence; I think it's wonderful stuff—perhaps a little crazy, but why not? I simply am convinced that you A.I. advocates have far underestimated the human mind, and that there are things a computer will never, ever be able to do. For instance, can you imagine a computer writing a Proust novel? The richness of imagination, the complexity of the characters——

SANDY: Rome wasn't built in a day!

CHRIS: In the article Turing comes through as an interesting person. Is he still alive?

SANDY: No, he died back in 1954, at just 41. He'd only be 67 this year, although he is now such a legendary figure it seems strange to think that he could still have been living today.

CHRIS: How did he die?

SANDY: Almost certainly suicide. He was homosexual and was much persecuted for it. In the end it apparently got to be too much and he killed himself.

CHRIS: Sad.

SANDY: Yes, it certainly is. What saddens me is that he never got to see the amazing progress in computing machinery and computing theory that has taken place.

PAT: Hey, are you going to clue me into what this Turing article is about?

SANDY: It is really about two things. One is the question "Can a machine think?"—or rather "Will a machine ever think?" The way Turing answers the question—he thinks the answer is yes, by the way—is by batting down a series of objections to the idea, one after another. The other point he tries to make is that the question as it stands is not meaningful. It's too full of emotional connotations. Many people are upset by the suggestion that people are machines, or that machines might think. Turing tries to defuse the question by casting it in less emotional terms. For instance, what do you think, Pat, of the idea of thinking machines?

PAT: Frankly, I find the term confusing. You know what confuses me? It's those ads in the newspapers and on TV that talk about "products that think" or "intelligent ovens" or whatever. I just don't know how seriously to take them.

SANDY: I know the kind of ads you mean, and they confuse a lot of people. On the one hand we're given the refrain "Computers are really dumb; you have to spell everything out for them in complete detail," and on the other we're bombarded with advertising hype about "smart products."

CHRIS: That's certainly true. Do you know that one company has even taken to calling its products "dumb terminals" in order to stand out from the crowd?

SANDY: That's clever, but it just plays along with the trend toward obfuscation. The term electronic brain always comes to my mind when I'm thinking about this. Many people swallow it completely, and others reject it out of hand. It takes patience to sort out the issues and decide how much of it makes sense.

PAT: Does Turing suggest some way of resolving it, some kind of I.Q. test for machines?

SANDY: That would be interesting, but no machine could yet come close to taking an I.Q. test. Instead Turing proposes a test that theoretically could be applied to any machine to determine whether or not it can think.

PAT: Does the test give a clear-cut yes-or-no answer? I'd be skeptical if it claimed to.

SANDY: No, it doesn't claim to. In a way that's one of its advantages. It shows how the borderline is quite fuzzy and how subtle the whole question is.

PAT: And so, as is usual in philosophy, it's all just a question of words.

SANDY: Maybe, but they're emotionally charged words, and so it's important, it seems to me, to explore the issues and try to map out the meanings of the crucial words. The issues are fundamental to our concept of ourselves, so we shouldn't just sweep them under the rug.

PAT: So tell me how Turing's test works.

SANDY: The idea is based on what he calls the imitation game. A man and a woman go into separate rooms and can be interrogated by a third party via some sort of teletype setup. The third party can address questions to either room but has no idea which person is in which room. For the interrogator the idea is to determine which room the woman is in. The woman, by her answers, tries to help the interrogator as much as she can. The man, however, is doing his best to bamboozle the interrogator, by responding as he thinks a woman might. And if he succeeds in fooling the interrogator——

PAT: The interrogator only gets to see written words, eh? And the sex of the author is supposed to shine through? It sounds like a good challenge. I'd certainly like to take part in it someday. Would the interrogator know either the man or the woman before the test began? Would any of them know the others?

SANDY: That would probably be a bad idea. All kinds of subliminal cueing might occur if the interrogator knew one or both of them. It would certainly be best if all three people were totally unknown to one another.

PAT: Could you ask any questions at all, with no holds barred?

SANDY: Absolutely. That's the whole idea.

PAT: Don't you think, then, that pretty quickly it would degenerate into sex-oriented questions? I can imagine the man, overeager to act convincing, giving away the game by answering some very blunt questions that most women would find too personal to answer, even through an anonymous computer connection.

SANDY: It sounds plausible.

CHRIS: Another possibility would be to explore traditional sex-role differences, such as asking about dress sizes and so on. The psychology of the imitation game could get pretty subtle. I suppose it would make a difference if the interrogator were a woman instead of a man. Don't you think that a woman could spot some telltale differences more quickly than a man?

PAT: If so, maybe *that's* how to tell a man from a woman.

SANDY: H'm.... That's a new twist. In any case I don't know if this original version of the imitation game has ever been seriously tried out, in spite of the fact that it would be relatively easy to do

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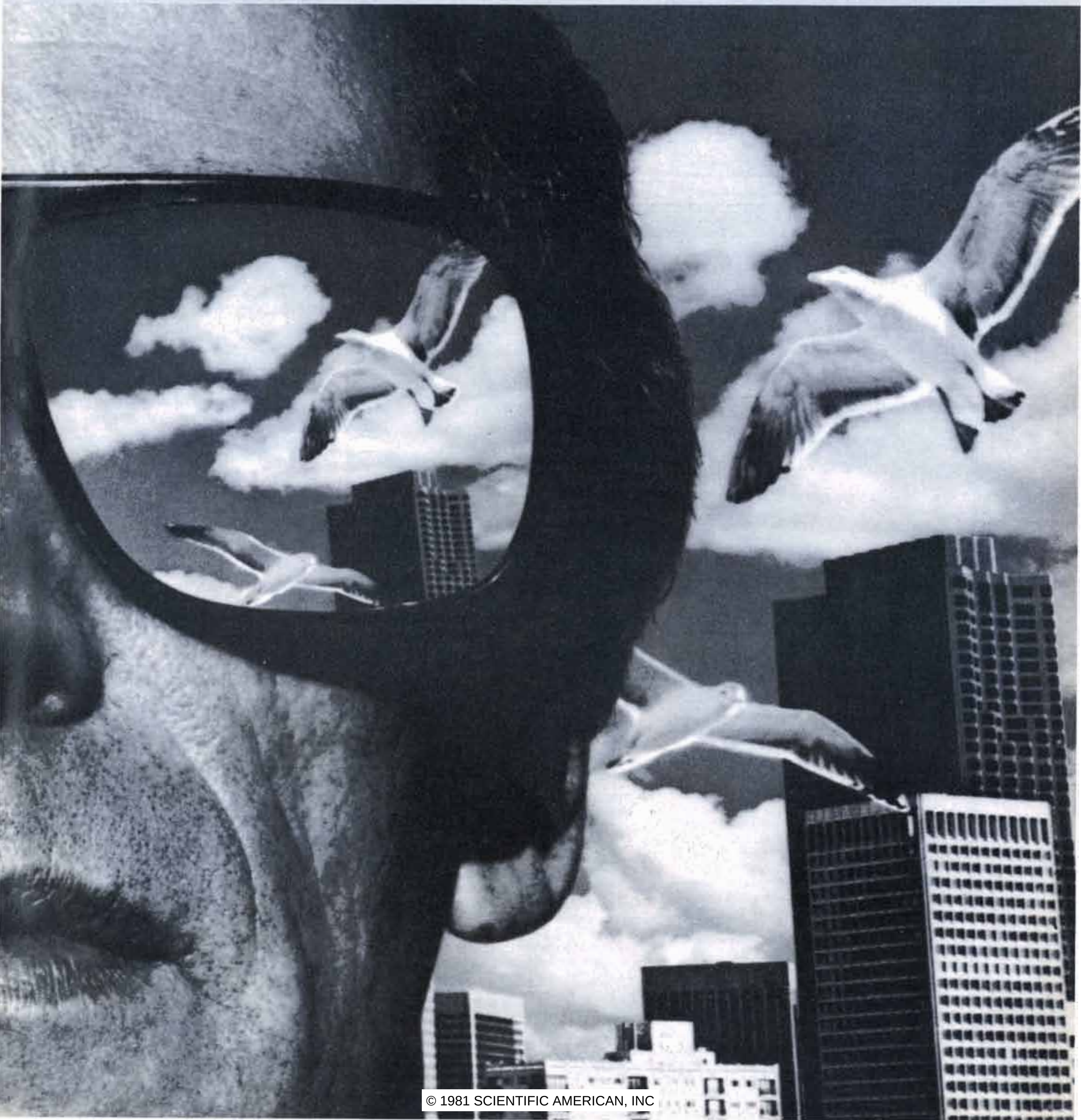

with modern computer terminals. I have to admit, though, that I'm not at all sure what it would prove, whichever way it turned out.

PAT: I was wondering about that. What would it prove if the interrogator—say a woman—couldn't tell correctly which person was the woman? It certainly wouldn't prove that the man *was* a woman.

SANDY: Exactly. What I find funny is that although I fundamentally believe in the Turing test, I'm not sure what the point is of the imitation game, on which it is founded.

CHRIS: I'm not any happier with the Turing test as a test for thinking machines than I am with the imitation game as a test for femininity.

PAT: From what you say I gather the Turing test is a kind of extension of the imitation game, only involving a machine and a person in separate rooms.

SANDY: That's the idea. The machine tries its hardest to convince the interrogator that it is the human being, and the human tries to make it clear that he or she is not the computer.

PAT: Except for your loaded phrase "the machine tries," this sounds very interesting. But how do you know that this test will get at the essence of thinking? Maybe it's testing for the wrong things. Maybe, just to take a random illustration, someone would feel that a machine was able to think only if it could dance so well that you couldn't tell it was a machine. Or someone else could suggest some other characteristic. What's so sacred about being able to fool people by typing at them?

SANDY: I don't see how you can say such a thing. I've heard that objection before, but frankly it baffles me. So what if the machine can't tap dance or drop a rock on your toe? If it can discourse intelligently on any subject you want, then it has shown it can think. It has shown it to me, at least. As I see it, Turing has drawn, in one clean stroke, a clear division between thinking and other aspects of being human.

PAT: Now *you're* the baffling one. If you couldn't conclude anything from a man's ability to win at the imitation game, how could you conclude anything from a machine's ability to win at the Turing game?

CHRIS: Good question.

SANDY: It seems to me that you could conclude *something* from a man's win in the imitation game. You wouldn't conclude he was a woman, but you could certainly say he had good insights into the feminine mentality (if there is such a thing). Now, if a computer could fool someone into thinking it was a person, I guess you'd have to say something similar about it—that it had good insights into what it's like to be human, into the human condition, whatever that is.

PAT: Maybe, but that isn't necessarily

equivalent to thinking, is it? It seems to me that passing the Turing test would merely prove some machine or other could do a very good job of *simulating* thought.

CHRIS: I couldn't agree more with Pat. We all know that fancy computer programs exist today for simulating all sorts of complex phenomena. In physics, for instance, we simulate the behavior of particles, atoms, solids, liquids, gases, galaxies and so on. But no one confuses any of those simulations with the real thing.

SANDY: In his book *Brainstorms* the philosopher Daniel Dennett makes a similar point about simulated hurricanes.

CHRIS: That's a nice example too. Obviously what goes on inside a computer when it's simulating a hurricane is not a hurricane. The machine's memory doesn't get torn to bits by 200-mile-an-hour winds, the floor of the machine room doesn't get flooded with rainwater, and so on.

SANDY: Oh, come on—that's not a fair argument. In the first place the programmers don't claim the simulation really *is* a hurricane. It's merely a simulation of certain aspects of a hurricane. But in the second place you're pulling a fast one when you imply that there are no downpours or 200-mile-an-hour winds in a simulated hurricane. To *us* there aren't any, but if the program were incredibly detailed, it could include simulated people on the ground who would experience the wind and the rain just as we do when a hurricane hits. In their minds—or, if you'd rather, in their *simulated* minds—the hurricane would be not a simulation but a genuine phenomenon complete with drenching and devastation.

CHRIS: Oh, boy—what a science-fiction scenario! Now we're talking about simulating entire populations, not just a single mind.

SANDY: Well, look, I'm simply trying to show you why your argument that a simulated McCoy isn't the real McCoy is fallacious. It depends on the tacit assumption that any old observer of the simulated phenomenon is equally able to assess what's going on. In fact it may take an observer with a special vantage to recognize what is going on. In this case it takes special "computational glasses" to see the rain and the winds.

PAT: Computational glasses? I don't know what you're talking about.

SANDY: I mean that to see the winds and the wetness of the hurricane you have to be able to look at it in the proper way. You——

CHRIS: No, no, no! A simulated hurricane isn't wet! No matter how much it might seem wet to simulated people, it won't ever be *genuinely* wet. And no computer will ever get torn apart in the process of simulating winds.

SANDY: Certainly not, but you're confusing levels. The laws of physics don't get torn apart by real hurricanes, either. In the case of the simulated hurricane, if you go peering at the computer's memory expecting to find broken wires and so forth, you'll be disappointed. But look at the proper level. Look into the *structures* that are coded for in the memory. You'll see that some abstract links have been broken, some values of variables radically changed and so on. There's your flood, your devastation. It is real, only a little concealed, a little hard to detect.

CHRIS: I'm sorry, I just can't buy it. You're insisting that I look for a new kind of devastation, one never before associated with hurricanes. That way you could call *anything* a hurricane as long as its effects, seen through your special glasses, could be called floods and devastation.

SANDY: Right—you've got it! You recognize a hurricane by its *effects*. You have no way of going in and finding some ethereal essence of hurricane, some "hurricane soul" right in the middle of the storm's eye. It's the existence of a certain kind of *pattern*—a spiral storm with an eye and so forth—that makes you say it's a hurricane. Of course, there are a lot of things you'll insist on before you call something a hurricane.

PAT: Well, wouldn't you say that being an *atmospheric* phenomenon is one prerequisite? How can anything inside a computer be a storm? To me a simulation is a simulation is a simulation.

SANDY: Then I suppose you would say that even the *calculations* computers do are simulated, that they are fake calculations. Only people can do genuine calculations, right?

PAT: Well, computers get the right answers, so their calculations are not exactly fake, but they're still just *patterns*. There's no understanding going on in there. Take a cash register. Can you honestly say that you feel it is *calculating* something when its gears turn on one another? A computer is just a fancy cash register, as I understand it.

SANDY: If you mean that a cash register doesn't feel like a schoolkid doing arithmetic problems, I'll agree. But is that what calculation means? Is that an integral part of it? If it is, then contrary to what everybody has thought up to now we'll have to write a very complicated program to perform *genuine* calculations. Of course, such a program will sometimes get careless and make mistakes and will sometimes scrawl its answers illegibly, and it will occasionally doodle on its paper. It won't be any more reliable than the store clerk who adds up your total by hand. Now, I happen to believe eventually such a program could be written. Then we'd know something about how clerks and schoolkids work.

PAT: I can't believe you would ever be able to do it.

SANDY: Maybe, maybe not, but that's not my point. You say a cash register can't calculate. It reminds me of another favorite passage of mine from Dennett's *Brainstorms*. It goes something like this: "Cash registers can't really calculate; they can only spin their gears. But cash registers can't really spin their gears, either; they can only follow the laws of physics." Dennett said it originally about computers; I modified it to refer to cash registers. And you could use the same line of reasoning in talking about people: "People can't really calculate; all they can do is manipulate mental symbols. But they aren't really manipulating symbols; all they are doing is firing various neurons in various patterns. But they can't really make their neurons fire; they simply have to let the laws of physics make the neurons fire for them." Et cetera. Don't you see how this reductio ad absurdum would lead you to conclude that calculation doesn't exist, hurricanes don't exist, nothing at a level higher than particles and the laws of physics exists? What do you gain by saying a computer only pushes symbols around and doesn't truly calculate?

PAT: The example may be extreme, but it makes my point that there is a vast difference between a real phenomenon and any simulation of it. This is true for hurricanes and even more so for human thought.

SANDY: Look, I don't want to get too tangled up in this line of argument, but let me try one more example. If you were a radio ham listening to another ham broadcasting in Morse code and you were responding in Morse code, would it sound funny to you to refer to "the person at the other end"?

PAT: No, that would sound okay, although the existence of a person at the other end would be an assumption.

SANDY: Yes, but you wouldn't be likely to go and check it out. You're prepared to recognize personhood through those rather unusual channels. You don't have to see a human body or hear a voice. All you need is a rather abstract manifestation—a code. What I'm getting at is this. To "see" the person behind the dits and dahs, you have to be willing to do some *decoding*, some interpretation. It's not direct perception; it's indirect. You have to peel off a layer or two to find the reality hidden in there. You put on your radio ham's glasses to see the person behind the buzzes. It's the same with the simulated hurricane. You don't see it darkening the machine room; you have to decode the machine's memory. You have to put on special memory-decoding glasses. *Then* what you see is a hurricane.

PAT: Oh ho! Talk about fast ones. In the case of the short-wave radio there's a real person out there, somewhere in the

Fiji Islands or wherever. My decoding act as I sit by my radio simply reveals that that person exists. It's like seeing a shadow and concluding there's an object out there casting it. One doesn't confuse the shadow with the object, however. With the hurricane there's no real storm behind the scenes, making the computer follow its patterns. No, what you have is just a shadow hurricane without any genuine hurricane. I simply refuse to confuse shadows with reality.

SANDY: All right. I don't want to drive the point into the ground. I even admit it is pretty silly to say that a simulated hurricane *is* a hurricane. I just wanted to point out that it's not as silly as you might think at first blush. And when you turn to simulated thought, you've got a very different matter on your hands from simulated hurricanes.

PAT: I don't see why. You still have to convince me.

SANDY: Well, to do it I'll first have to make a couple of extra points about hurricanes.

PAT: Oh, no. Well, all right, all right.

SANDY: No one can say exactly what a hurricane is—that is, in totally precise terms. There's an abstract pattern many storms share, and it's for that reason we call them hurricanes. But it's not possible to make a sharp distinction between hurricanes and nonhurricanes. There are tornadoes, cyclones, typhoons, dust devils. Is the Great Red Spot of Jupiter a hurricane? Are sunspots hurricanes? Could there be a hurricane in a wind tunnel? In a test tube? In your imagination you can even extend the concept of a hurricane to include a microscopic storm on the surface of a neutron star.

CHRIS: That's not so farfetched, you know. The concept of an earthquake has actually been extended to neutron stars. The astrophysicists say the tiny changes in rate that are observed once in a while in the pulsing of a pulsar are caused by glitches—starquakes—that have just occurred on the neutron star's surface.

SANDY: Yes, I remember that now. The idea of a glitch has always seemed eerie to me—a surrealistic kind of quivering on a surrealistic kind of surface. Can you imagine plate tectonics on a giant sphere of pure nuclear matter? So starquakes and earthquakes can both be subsumed into a new, more abstract category. And that's how science constantly extends familiar concepts, taking them further and further from familiar experience and yet keeping some essence constant. The number system is the classic example—from positive numbers to negative numbers, then rationals, reals, complex numbers and "on beyond zebra," as Dr. Seuss says.

PAT: I think I can see your point, Sandy. We have many examples in biology of close relationships that are established in rather abstract ways. Often the decision about what family some species belongs to comes down to an abstract pattern shared at some level. When you base your system of classification on very abstract patterns, I suppose a broad variety of phenomena can fall into the same class, even if in many superficial ways the class members are utterly unlike one another. So perhaps I can glimpse, at least a little, how to you a simulated hurricane could in a funny sense *be* a hurricane.

CHRIS: Perhaps the word that's being extended is not "hurricane" but "be."

PAT: How so?

CHRIS: If Turing can extend the verb "think," can't I extend the verb "be"? All I mean is that when simulated things are deliberately confused with genuine things, somebody's doing a lot of philosophical wool pulling. It's a lot more serious than just extending a few *nouns*, such as "hurricane."

SANDY: I like your idea that "be" is being extended, but I don't agree with you about the wool pulling. But if you don't object, let me just say one more thing about simulated hurricanes and then I'll get to simulated minds. Suppose you consider a really deep simulation of a hurricane. I mean a simulation of every atom, which I admit is impossibly deep. I hope you would agree that it would then share all the abstract structure that defines the essence of hurricanehood. So what's to keep you from calling it a hurricane?

PAT: I thought you were backing off from that claim of equality.

SANDY: So did I, but then these examples came up and I was forced back to my claim. But *let* me back off, as I said I would, and get back to thought, which is the real issue here. Thought, even more than hurricanes, is an abstract structure, a way of describing some complex events that happen in a medium called a brain. But actually thought can take place in any one of several billion brains. There are all these physically very different brains, and yet they all support the same thing: thinking. What's important, then, is the abstract pattern, not the medium. The same kind of swirling can happen inside any of them, so no person can claim to think more "genuinely" than any other. Now, if we come up with some new kind of medium in which the *same style* of swirling takes place, could you deny that thinking is taking place in it?

PAT: Probably not, but you have just shifted the question. The question now is: How can you determine whether the "same style" of swirling is really happening?

SANDY: The beauty of the Turing test is that it *tells* you when.

CHRIS: I don't see that at all. How would you know that the same style of activity was going on inside a computer as was going on inside my mind, simply because it answered questions the way I do? All you're looking at is its outside.

SANDY: But how do you know that when I speak to you, anything similar to what you call thinking is going on inside *me?* The Turing test is a fantastic probe, something like a particle accelerator in physics. Chris, I think you'll like this analogy. Just as in physics, when you want to understand what is going on at an atomic or subatomic level, since you can't see it directly, you scatter accelerated particles off a target and observe their behavior. From this you infer the internal nature of the target. The Turing test extends this idea to the mind. It treats the mind as a target that is not directly visible but whose structure can be deduced more abstractly. By scattering questions off a target mind you learn about its internal workings, just as in physics.

CHRIS: More exactly put, you can hypothesize about what kinds of internal structures might account for the behavior observed—but they may or may not in fact exist.

SANDY: Hold it now. Are you saying that atomic nuclei are merely hypothetical entities? After all, their existence (or should I say hypothetical existence?) was proved (or should I say suggested?) by the behavior of particles scattered off atoms.

CHRIS: Physical systems seem to me to be much simpler than the mind, and the certainty of the inferences made is correspondingly greater.

SANDY: The experiments are also correspondingly harder to do and to interpret. In the Turing test you could perform many highly delicate experiments in the course of an hour. I maintain that people give other people credit for being conscious simply because of their continual external monitoring of other people—which is itself something like a Turing test.

PAT: That may be roughly true, but it involves more than just conversing with people through a teletype. We see that other people have bodies, we watch their faces and expressions. We see they are fellow human beings, and so we think they think.

SANDY: To me that seems a highly anthropocentric view of what thought is. Does it mean you would sooner say a mannequin in a store thinks than say a wonderfully programmed computer does, simply because the mannequin looks more human?

PAT: Obviously I would need more than just a vague physical resemblance to the human form to be willing to attribute the power of thought to an entity. But that organic quality, the sameness of origin, undeniably lends a degree of credibility that is very important.

SANDY: Here we disagree. I find this simply too chauvinistic. I feel that the key thing is a similarity of *internal* structure, not bodily, organic, chemical

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structure but organizational structure—software. Whether an entity can think seems to me to be a question of whether its organization can be described in a certain way, and I'm perfectly willing to believe the Turing test detects the presence or absence of that mode of organization. I would say your depending on my physical body as evidence that I am a thinking being is rather shallow. The way I see it, the Turing test looks far deeper than mere external form.

PAT: Hey now—you're not giving me much credit. It's not just the *shape* of a body that lends weight to the idea there's real thinking going on inside. It's also, as I said, the idea of common origin. It's the idea that you and I both sprang from DNA molecules, an idea to which I attribute much depth. Put it this way: The external form of human bodies reveals they share a deep biological history, and it is *that* depth that lends a lot of credibility to the notion that the owner of such a body can think.

SANDY: But that is all indirect evidence. Surely you want some *direct* evidence. That's what the Turing test is for. And I think it is the *only* way to test for thinkinghood.

CHRIS: But you could be fooled by the Turing test, just as an interrogator could think a man was a woman.

SANDY: I admit I could be fooled if I carried out the test in too quick or too shallow a way. But I would go for the deepest things I could think of.

CHRIS: I would want to see if the program could understand jokes. That would be a real test of intelligence.

SANDY: I agree that humor probably is an acid test for a supposedly intelligent program, but equally important to me—perhaps more so—would be to test its emotional responses. So I would ask it about its reactions to certain pieces of music or works of literature—particularly my favorite ones.

CHRIS: What if it said, "I don't know that piece," or even, "I have no interest in music"? What if it avoided all emotional references?

SANDY: That would make me suspicious. Any consistent pattern of avoiding certain issues would raise serious doubts in my mind about whether I was dealing with a thinking being.

CHRIS: Why do you say that? Why not say you're dealing with a thinking but unemotional being?

SANDY: You've hit on a sensitive point. I simply can't believe emotions and thought can be divorced. To put it another way, I think emotions are an automatic by-product of the ability to think. They are required by the very nature of thought.

CHRIS: Well, what if you're wrong? What if I produced a machine that could think but not emote? Then its intelligence might go unrecognized because it failed to pass *your* kind of test.

SANDY: I'd like you to point out to me where the boundary line between emotional questions and nonemotional ones lies. You might want to ask about the meaning of a great novel. This requires an understanding of human emotions. Is that thinking or merely cool calculation? You might want to ask about a subtle choice of words. For that you need an understanding of their connotations. Turing uses examples like this in his article. You might want to ask for advice about a complex romantic situation. The machine would need to know a lot about human motivations and their roots. If it failed at this kind of task, I would not be much inclined to say that it could think. As far as I am concerned, the ability to think, the ability to feel and consciousness are just different facets of one phenomenon, and no one of them can be present without the others.

CHRIS: Why couldn't you build a machine that could feel nothing but that could think and make complex decisions anyway? I don't see any contradiction there.

SANDY: Well, I do. I think that when you say that, you are visualizing a metallic, rectangular machine, probably in an air-conditioned room—a hard, angular, cold object with a million colored wires inside it, a machine that sits stock-still on a tiled floor, humming or buzzing or whatever and spinning its tapes. Such a machine can play a good game of chess, which, I admit, involves a lot of decision making. And yet I would never call it conscious.

CHRIS: How come? To mechanists isn't a chess-playing machine rudimentarily conscious?

SANDY: Not to this mechanist. The way I see it, consciousness has got to come from a precise pattern of organization, one we haven't yet figured out how to describe in any detailed way. But I believe we shall gradually come to understand it. In my view consciousness requires a certain way of mirroring the external universe internally, and also the ability to respond to that external reality on the basis of the internally represented model. And then what's really crucial for a conscious machine is that it should incorporate a well-developed and flexible self-model. It's there that all existing programs, including the best chess-playing ones, fall down.

CHRIS: Don't chess programs look ahead and say to themselves as they're figuring out their next move, "If you move here, then I'll go there, and then if you go this way, I could go that way...."? Isn't that some kind of self-model?

SANDY: Not really. Or, if you want, it is an extremely limited one. It's an understanding of self only in the narrowest sense. For instance, a chess-playing program has no concept of why it is playing chess, or the fact that it is a program, or is in a computer, or has a human opponent. It has no ideas about what winning and losing are, or——

PAT: How do *you* know it has no such sense? How can you presume to say what a chess program feels or knows?

SANDY: Oh, come on! We all know that certain things don't feel anything or know anything. A thrown stone doesn't know anything about parabolas, and a whirling fan doesn't know anything about air. It's true I can't *prove* those statements, but here we are verging on questions of faith.

PAT: This reminds me of a Taoist story I read. It goes something like this. Two sages were standing on a bridge over a stream. One said to the other, "I wish I were a fish. They are so happy." The other replied, "How do you know whether fish are happy or not? You're not a fish." The first said, "But you're not me, so how do you know whether I know how fish feel?"

SANDY: Beautiful! Talking about consciousness really does call for a certain amount of restraint. Otherwise you might as well just jump on either the solipsism bandwagon (I am the only conscious being in the universe) or the panpsychism bandwagon (everything in the universe is conscious).

PAT: Well, how do you know? Maybe everything *is* conscious.

SANDY: If you're going to join those who maintain that stones and even particles such as electrons have some sort of consciousness, then I guess we part company here. That's a kind of mysticism I can't fathom. As for chess programs, it so happens I know how they work, and I can tell you for sure that they aren't conscious. No way.

PAT: Why not?

SANDY: They incorporate only the barest knowledge about the goals of chess. The notion of playing is turned into the mechanical act of comparing a lot of numbers and choosing the biggest one over and over again. A chess program has no sense of shame about losing or pride in winning. Its self-model is very crude. It gets away with doing the least it can, just enough to play a game of chess and nothing more. Yet interestingly enough we still tend to talk about the "desires" of a chess-playing computer. We say, "It wants to keep its king behind a row of pawns" or "It likes to get its rooks out early" or "It thinks I don't see that hidden fork."

PAT: Yes, and we do the same thing with insects. We spot a lone ant somewhere and say, "It's trying to get back home" or "It wants to drag that dead bee back to the colony." In fact, with any animal we use terms that indicate emotions, but we don't know for certain how much the animal feels. I have no trouble talking about dogs and cats being happy or sad, having desires and beliefs and so on, but of course I don't think their sad-

THE LUXURY SEDAN THAT DID NOT HAVE TO BE RE-ENGINEERED TO FACE DIFFICULT TIMES.

ness is as deep or complex as human sadness.

SANDY: But you wouldn't call it "simulated" sadness, would you?

PAT: No, of course not. I think it's real.

SANDY: It's hard to avoid using such teleological or mentalistic terms. I believe they're quite justified, although they shouldn't be carried too far. They simply don't have the same richness of meaning when they are applied to present-day chess programs as they do when they are applied to people.

CHRIS: I still can't see that intelligence has to involve emotions. Why couldn't you imagine an intelligence that simply calculates and has no feelings?

SANDY: A couple of answers here. Number one, any intelligence has to have motivations. It's simply not the case, whatever many people may believe, that machines could think any more objectively than people do. Machines, when they look at a scene, will have to focus and filter the scene down into some preconceived categories, just as a person does. And that means seeing some things and missing others. It means giving more weight to some things than to others. This happens on every level of processing.

PAT: I'm not sure I'm following you.

SANDY: Take me right now, for instance. You might think I'm just making some intellectual points, and I wouldn't need emotions to do that. But what makes me *care* about these points? Why did I stress the word "care" so heavily? Because I'm emotionally involved in this conversation. People talk to one another out of conviction, not out of hollow, mechanical reflexes. Even the most intellectual conversation is driven by underlying passions. There's an emotional undercurrent to every conversation. It's the fact that the speakers want to be listened to and understood, and respected for what they are saying.

PAT: It sounds to me as if all *you're* saying is that people need to be interested in what they're saying, otherwise a conversation dies.

SANDY: Right! I wouldn't bother to talk to anyone if I weren't motivated by interest. And interest is just another name for an entire constellation of subconscious biases. When I talk, all my biases work together, and what you perceive on the surface level is my personality, my style. But that style arises from an immense number of tiny priorities, biases, leanings. When you add up a million of them interacting together, you get something that amounts to a lot of *desires.* It just all adds up. And that brings me to the other point, about feelingless calculation. Sure, that exists—in a cash register, a pocket calculator. I'd say it's even true of all today's computer programs. But eventually when you put enough feelingless calculations together in a huge coordinated structure, you'll get something that has properties on another level. You can see it—in fact, you *have* to see it—not as a bunch of little calculations but as a system of tendencies and desires and beliefs and so on. When things get complicated enough, you're forced to change your level of description. To some extent that's already happening, which is why we use words such as "want," "think," "try" and "hope" to describe chess programs and other attempts at mechanical thought. Dennett calls that kind of level switch by the observer "adopting the intentional stance." The *really* interesting things in A.I. will only begin to happen, I'd guess, when the program *itself* adopts the intentional stance toward itself.

CHRIS: That would be a very strange sort of level-crossing feedback loop.

SANDY: It certainly would. Of course, it's highly premature for *anyone* to adopt the intentional stance in the full force of the term with respect to today's programs. At least that's my opinion.

CHRIS: For me an important related question is: To what extent is it valid to adopt the intentional stance toward beings other than humans?

PAT: I would certainly adopt the intentional stance toward mammals.

SANDY: I vote for that.

CHRIS: That's interesting. How can that be, Sandy? Surely you wouldn't claim that a dog or a cat can pass the Turing test? Yet don't you think the Turing test is the only way to test for the presence of thought? How can you have these beliefs simultaneously?

SANDY: H'm.... All right. I guess I'm forced to admit that the Turing test works only above a certain level of consciousness. There can be thinking beings that could fail at the Turing test, but on the other hand anything that passes it, in my opinion, would be a genuinely conscious, thinking being.

PAT: How can you think of a computer as a conscious being? I apologize if this sounds like a stereotype, but when I think of conscious beings, I just can't connect that thought with machines. To me consciousness is connected with soft, warm bodies, silly though it may sound.

CHRIS: That *does* sound odd coming from a biologist. Don't you deal with life in terms of chemistry and physics enough for all magic to seem to vanish?

PAT: Not really. Sometimes the chemistry and physics simply increase the feeling that there's something magical going on in there. Anyway, I can't always integrate my scientific knowledge with my gut feelings.

CHRIS: I guess I share the trait.

PAT: So how do you deal with rigid preconceptions like mine?

SANDY: I'd try to dig down under the surface of your concept of machines and get at the intuitive connotations that lurk there, out of sight but deeply influencing your opinions. I think we

AND ITS COMPETITION.

all have a holdover image from the Industrial Revolution that sees machines as iron contraptions moving under the power of some chugging engine. Maybe that's even how the computer inventor Charles Babbage saw people. After all, he called his geared computer "the analytical engine."

PAT: Well, I certainly don't think people are just fancy steam shovels or even electric can openers. There's something about people, something that—that—they've got a kind of *flame* inside them, something alive, something that flickers unpredictably, wavering, uncertain—but something *creative*.

SANDY: Great! That's just the sort of thing I wanted to hear. It's very human to think that way. Your flame image makes me think of candles, of fires, of thunderstorms with lightning dancing all over the sky. But do you realize just that kind of thing is visible on a computer's console? The flickering lights form chaotic sparkling patterns. It's such a far cry from heaps of lifeless, clanking metal. It *is* flamelike, by God! Why don't you let the word "machine" conjure up images of dancing patterns of light rather than of giant steam shovels?

CHRIS: That *is* a powerful image, Sandy. It does change my sense of mechanism from being matter-oriented to being pattern-oriented. It makes me try to visualize the thoughts in my mind—these thoughts right now, even—as a huge spray of tiny pulses flickering in my brain.

SANDY: That's quite a poetic self-portrait for a spray of flickers to have come up with!

CHRIS: But still I'm not totally convinced that a machine is all I am. I admit my concept of machines probably *does* suffer from anachronistic subconscious flavors, but I'm afraid I can't change such a deeply rooted sense in a flash.

SANDY: At least you do sound open-minded. And to tell the truth part of me does sympathize with the way you and Pat view machines. Part of me balks at calling myself a machine. It *is* a bizarre thought that a feeling being like you or me might emerge from mere circuitry. Do I surprise you?

CHRIS: You certainly surprise *me*. So tell us—*do* you believe in the idea of an intelligent computer or don't you?

SANDY: It all depends on what you mean. We've all heard the question, "Can computers think?" There are several possible interpretations of this (apart from the many interpretations of the word "think"). They revolve around different meanings of the words "can" and "computer."

PAT: Back to word games again.

SANDY: That's right. First of all, the question might mean, "Does some present-day computer think, right now?" To that I would immediately answer with a loud no. Then it could be taken to mean, "Could some present-day computer, if it was suitably programmed, potentially think?" That would be more like it, but I would still answer, "Probably not." The real difficulty hinges on the word "computer." The way I see it, "computer" calls up an image of just what I described earlier: an air-conditioned room with rectangular metal boxes in it. But I believe progress in computer architecture will eventually make that vision outmoded.

PAT: Don't you think computers as we know them will be around for a while?

SANDY: Sure, there will have to be computers in today's image around for a long time, but advanced computers—maybe no longer called computers—will evolve and become quite different. Probably, as with living organisms, there will be many branchings in the evolutionary tree. There will be computers for business, computers for schoolkids, computers for scientific calculations, computers for systems research, computers for simulation, computers for rockets going into space and so on. Finally, there will be computers for the study of intelligence. It's really only these last that I'm thinking of—the ones with the maximum flexibility, the ones people are deliberately attempting to make smart. I see no reason for these staying fixed in the traditional image. They will probably soon acquire as standard features some rudimentary sensory systems, at first mostly for vision and hearing. They will need to be able to move around, to explore. They will have to be physically flexible. In short, they will have to become more self-reliant, more animal-like.

CHRIS: It makes me think of the robots R2D2 and C3PO in *Star Wars*.

SANDY: As a matter of fact I don't think of anything like them when I visualize intelligent machines. They are too silly, too much the product of a film designer's imagination. Not that I have a clear vision of my own. But I do think it is necessary, if people are realistically going to try to imagine an artificial intelligence, to go beyond the limited, hard-edged picture of computers that comes from seeing what we have today. The only thing all machines will always have in common is their underlying mechanicalness. That may sound cold and inflexible, but what could be more mechanical—in a wonderful way—than the working of the DNA and enzymes in our cells?

PAT: To me what goes on inside cells has a wet, slippery feel to it and what goes on inside machines is dry and rigid. It's connected with the fact that computers don't make mistakes, that computers do only what you tell them to do. At least that's my image of computers.

SANDY: Funny—a minute ago your image was of a flame, and now it's of something wet and slippery. Isn't it marvelous how contradictory we can be?

PAT: Do I hear sarcasm?

SANDY: I'm not being sarcastic—I really *do* think it is marvelous.

PAT: It's just an example of the human mind's slippery nature—mine, in this case.

SANDY: True. But your image of computers is stuck in a rut. Computers certainly *can* make mistakes—and I don't mean on the hardware level. Think of any present-day computer's predicting the weather. It can make wrong predictions, even though its program runs flawlessly.

PAT: But that's only because you've fed it the wrong data.

SANDY: Not so. It's because weather prediction is too complex. Any such program has to make do with a limited amount of data—entirely correct data—and extrapolate from there. Sometimes it will make wrong predictions. It's no different from the farmer looking up at the sky and saying, "I reckon we'll get a little snow tonight." We make models of things in our heads and use them to guess how the world will behave. We have to make do with our models, however inaccurate they may be. And if they're *too* inaccurate, evolution will prune us out—we'll fall off a cliff or something. Computers are the same. It's simply that human designers will speed up the evolutionary process by aiming explicitly at the goal of creating intelligence, which is something nature just stumbled on.

PAT: So you think computers will be making fewer mistakes as they get smarter?

SANDY: Actually it's the other way around. The smarter they get, the more they'll be in a position to tackle messy real-life domains, so they'll be more and more likely to have inaccurate models. To me, mistake making is a sign of high intelligence.

PAT: Wow—you throw me sometimes.

SANDY: I guess I'm a strange sort of advocate for machine intelligence. To some degree I straddle the fence. I think machines won't really be intelligent in a humanlike way until they have something like that biological wetness or slipperiness to them. I don't mean *literally* wet—the slipperiness could be in the software. But biological-seeming or not, intelligent machines will in any case be machines. We shall have designed them, built them—or grown them! We shall understand how they work, at least in some sense. Possibly no one person will really understand them, but collectively we shall know how they work.

PAT: It sounds as if you want to have your cake and eat it too.

SANDY: You're probably right. What I'm getting at is that when artificial intelligence comes, it will be mechanical and yet at the same time organic. It will have the same amazing flexibility that we see in life's mechanisms. And when I say mechanisms, I *mean* mechanisms. DNA and enzymes and so on really *are* me-

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chanical and rigid and reliable. Don't you agree, Pat?

PAT: I have to. But when they work together, a lot of unexpected things happen. There are so many complexities and rich modes of behavior that all the mechanicalness adds up to something very fluid.

SANDY: For me it's an almost unimaginable transition from the mechanical level of molecules to the living level of cells. But it's what convinces me that people are machines. The thought makes me uncomfortable in some ways, but in other ways it is exhilarating.

CHRIS: If people are machines, how come it's so hard to convince them of the fact? Surely if we are machines, we ought to be able to recognize our own machinehood.

SANDY: You have to allow for emotional factors here. To be told you're a machine is in a way to be told that you're nothing more than your physical parts, and it brings you face to face with your own mortality. That's something no one finds easy to confront. But beyond the emotional objection, to see yourself as a machine you have to jump all the way from the bottommost mechanical level to the level where the complex lifelike activities take place. If there are many intermediate layers, they act as a shield and the mechanical quality becomes almost invisible. I think when intelligent machines come, that's how they will seem to us—and to themselves!

PAT: I once heard a funny idea about what will happen when we eventually have intelligent machines. When we try to implant that intelligence into devices we'd like to control, their behavior won't be so predictable.

SANDY: They'll have a quirky little "flame" inside, maybe?

PAT: Maybe.

CHRIS: And what's so funny about that?

PAT: Well, think of military missiles. The more sophisticated their target-tracking computers get, according to this idea, the less predictably they will function. Eventually you'll have missiles that will decide they are pacifists and will turn around and go home and land quietly without blowing up. We could even have smart bullets that turn around in mid-flight because they don't want to commit suicide.

SANDY: A lovely thought.

CHRIS: I'm very skeptical about all this. Still, Sandy, I'd like to hear your predictions about when intelligent machines will come to be.

SANDY: It probably won't be for a long time that we'll see anything remotely resembling the level of human intelligence. It rests on too awesomely complicated a substrate—the brain—for us to be able to duplicate it in the foreseeable future. That's my opinion, anyway.

PAT: Do you think a program will ever pass the Turing test?

SANDY: That's a pretty hard question. I guess there are various degrees of passing such a test, when you come down to it. It's not black and white. First of all it depends on who the interrogator is. A simpleminded person might be totally taken in by some programs today. But secondly it depends on how deeply you are allowed to probe.

PAT: Then you could have a range of Turing tests—one-minute versions, five-minute versions, hour-long versions. Wouldn't it be interesting if some official organization sponsored a periodic competition, like the annual computer-chess championships, for programs to try to pass the Turing test?

CHRIS: The program that lasted the longest against some panel of distinguished judges would be the winner. Perhaps there could be a big prize for the first program that can fool a famous judge for, say, 10 minutes.

PAT: What would a program do with a prize?

CHRIS: Come now, Pat. If a program's good enough to fool the judges, don't you think it's good enough to enjoy the prize?

PAT: Sure—particularly if the prize is an evening out on the town, dancing with the interrogators.

SANDY: I'd certainly like to see something like that established. I think it could be hilarious to watch the first programs flop pathetically.

PAT: You're pretty skeptical, aren't you? Well, do you think any computer program today could pass a five-minute Turing test, given a sophisticated interrogator?

SANDY: I seriously doubt it. It's partly because no one is really working at it explicitly. I should mention, though, that there is one program whose inventors claim it has *already* passed a rudimentary version of the test. It is called Parry, and in a series of remotely conducted interviews it fooled several psychiatrists who were told they were talking to either a computer or a paranoid person. This was an improvement over an earlier version, in which psychiatrists were simply handed transcripts of short interviews and asked to determine which ones were with a genuine paranoid and which ones were with a computer.

PAT: You mean they didn't have the chance to ask any questions? That's a severe handicap—and it doesn't seem in the spirit of the Turing test. Imagine someone trying to tell which sex I belong to by reading a transcript of a few remarks by me. It might be very hard! I'm glad the procedure has been improved.

CHRIS: How do you get a computer to act like a paranoid?

SANDY: I'm not saying it *does* act like a paranoid, only that some psychiatrists in unusual circumstances thought so. One of the things that bothered me about this pseudo-Turing test is the way Parry works. "He," as they call him, acts like a paranoid in that he gets abruptly defensive and veers away from undesirable topics in the conversation. In effect he maintains control so that no one can truly probe "him." This makes a simulation of a paranoid a lot easier than a simulation of a normal person.

PAT: Can't doubt that. It reminds me of the joke about the easiest kind of human being for a computer program to simulate.

CHRIS: What is that?

PAT: A catatonic patient—they just sit and do nothing at all for days on end. Even *I* could write a computer program to do that!

SANDY: An interesting thing about Parry is that it creates no sentences on its own—it merely selects from a huge repertory of canned sentences the one that responds best to the input sentence.

PAT: Amazing. But that would probably be impossible on a larger scale, wouldn't it?

SANDY: Yes. The number of sentences you'd need to store in order to be able to respond in a normal way to all possible sentences in a conversation is astronomical, really unimaginable. And they'd have to be very intricately indexed, for retrieval. Anyone who thinks that somehow a program could be rigged up simply to pull sentences out of storage like records in a jukebox, and that this program could pass the Turing test, hasn't thought much about it. The funny part is that it is just this kind of unrealizable program some enemies of artificial intelligence cite when they argue against the concept of the Turing test. Instead of a truly intelligent machine they want you to imagine a gigantic, lumbering robot that intones canned sentences in a dull monotone. It's assumed that you could see through to its mechanical level with ease, even if it were simultaneously performing tasks we think of as fluid, intelligent processes. Then the critics say, "You see! It would still be just a machine—a mechanical device, not intelligent at all." I see things almost the opposite way. If I were shown a machine that can do things I can—I mean pass the Turing test—then instead of feeling insulted or threatened, I'd want to chime in with the philosopher Raymond Smullyan and say, "How wonderful machines are!"

CHRIS: If you could ask a computer just one question in the Turing test, what would it be?

SANDY: Um——

PAT: I've got one. How about "If you could ask a computer just one question in the Turing test, what would it be?"?


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BOOKS

In the realms of the planets, the megagauss, biological time and living human ancestors

by Philip Morrison

VOLCANIC FEATURES OF HAWAII: A BASIS FOR COMPARISON WITH MARS, by M. H. Carr and R. Greeley. NASA SP-403, Superintendent of Documents, U.S. Government Printing Office ($14). VOYAGE TO JUPITER, by David Morrison and Jane Samz. NASA SP-439, Superintendent of Documents, U.S. Government Printing Office ($7.50). The island of Hawaii glows green below the camera in orbit, the great dark crack at Kilauea plain enough. The still more adventuresome camera of the Viking Orbiter presents the carved pits of a Martian caldera much like the *U*-2 shots of Mauna Loa, and out there, near a lukewarm Jupiter, Voyager color scans map an unexpected kind of volcano, named for Pele but far away, whose 100-mile plume is an ash of red sulfur with white sulfur dioxide snow!

We are lucky to see the rise of a comparative geology in our time. The geology of our own planet is powerful now, unified by plate tectonics. It is hard to find a better example of the power of the current view than the volcanic islands of the Hawaiian chain, stretching out to Midway, a mere coral cap on a sunken volcano 2,000 miles northwest. With a dogleg bend to bear due north, that chain continues as the submerged Emperor Seamounts, which dot the soundings nearly as far again, to disappear at last into the Aleutian Trench.

Hawaii, at the hot end, is less than a million years old, built of the merged flows of five great volcanoes, two of them now active. The age of the lavas at the other end is 65 million years. The bend in the chain of volcanoes came about 43 million years ago. The brilliant success of Tuzo Wilson's insight of 1963 continues: the scores of volcanoes in the chain all formed over one hot spot fixed not far from Hawaii. What we see is the record of the long drift of the Pacific plate, which carries each new magma outlet in its turn away from the deep source, truly Pele's kitchen, at a rate of three inches per year. Old Midway lavas reveal a magnetic latitude at the time of their deposition (within the errors of measurement) just the same as the magnetic latitude of Hawaii today.

Two space-aware geologists have compiled this closeup look at Hawaii together with the best views we have of the great shield volcanoes of Mars. "The emphasis is on the pictures"; the modest and well-informed text provides a welcome background for the general reader. Ground truth on Hawaii—the hot lava fountains, the broken-topped lava conduits, the flow of degassed taffy lava and the all but impassable bubbly clinker—is strikingly presented. We see closeup photographs made by daring volcanologists not far above the slow-flowing fluid, and air views from the most recent times to those made long before Pearl Harbor. One photograph from 1885 shows a lava pond perched high within its natural levee, with two period hikers at a fairly safe, if rather warm, distance.

The last chapter of *Volcanic Features of Hawaii* pictures the calderas, tubes, channels and faults of the great Martian volcanoes. Ground truth on Mars is not yet ours; our landers dared not venture near the rough lava fields. The photographs are nonetheless strikingly similar, even though no one can aver the analogy is precise. The Martian structures are much bigger, by fiftyfold or so in volume, both overall and in many details. They are much older, and they grow more slowly. No plate motions slide those craters along on the unmoving Martian crust. The flows can add up until the shields of Mars dwarf our own. There is more to the story, of course.

Voyage to Jupiter, a bargain album of color—true, plausible and just plain hyperbolic—is a general reader's summary of the wonderful Pioneer and then Voyager trips to the Jupiter system. It translates the unusual physics of planetary rings, great red spots, plasma currents and much more into simple terms. The senior author is himself a well-known planetologist engaged with Voyager, and the authenticity of the work is plain, although a reader misses references to the sources of models and theories that might help to distinguish the better-founded from the inspired guess. It is all timely; indeed, a good part of the text narrates the experience more or less chronologically from launch day to the final press conferences two years later in July, 1979, as *Voyager 2* left the Jupiter system, Saturn-bound. (It is rather wry to read of the complete shift of press interest away from the unprecedented hour-by-hour Io volcano watch to an overblown worldwide concern with the final fall of *Skylab.*)

Graphs, maps and pictures, pictures, pictures enrich the text, which includes summaries of results, of launcher, radio-link and instrument data, of orbits and schedules, together with an overall review of what we now know about Jupiter and its earth-moon-size satellites. A few points: Jupiter is heated as much internally as it is by the sun. Its poles are as warm as its equator. The internal source was first perceived from the earth and then measured by Pioneer. Jupiter has a complex upper-cloud meteorology, turbulent, changing and colorful, but below all that ammonia cirrus the banded winds blow stably. In some zones the winds blow with the direction of spin, in some against it, but they are quite symmetrical in the two hemispheres. There is a lot to learn. A night-side photograph shows a strong aurora and a score of superbolts of Jovian lightning illuminating the frigid thunderclouds.

The Galilean satellites are four new worlds, first disclosed in some detail by the Voyagers. Their faces are here, with models of their interiors, tentative still. Io is of course the cynosure. It is as red and mottled as an expensive pizza; it changed notably between the spring visit of *Voyager 1* and the summer view of *Voyager 2*. Eight active volcanoes were found, with their activity shifting between visits. Dust plumes (but no gas) rise high into space from these vents and fall back to the surface half an hour later, colorful and infernally sulfurous. Between visits one area of Io the size of a big county was covered with a meter or so of dustfall, filling in the ejecta pattern around one big vent and turning a "hoofprint" into a smooth oval. Io is perpetually kneaded by the tidal forces of its giant ruler; the heat thereby released within it seems to power the volcanic activity. Watery volatiles have long been lost; in old age Io recycles an ocean of sulfur and its oxides. That was noticeable even from the earth; Io's orbit glows steadily with spectral lines of sulfur and oxygen.

With good luck, both in orbit and in the national budget, we should see in the late 1980's a new visitor to this system. The spacecraft *Galileo* will make a close approach to Jupiter and drop a probe into the giant's atmosphere. The spacecraft will remain within that system for a couple of years, repeatedly surveying the satellites and sampling the plasmas and fields of the region. The probe will survive for one brief hour as it sinks by parachute down to depths of crushing pressure among the clouds of water ice. It could tell us what it is that colors the

Great Red Spot. That enormous anticyclone is an enduring high-pressure storm, a vortex centuries old. But is it reddened by organic polymers? By some sulfur mystery? By red phosphorus? No one has any very convincing idea.

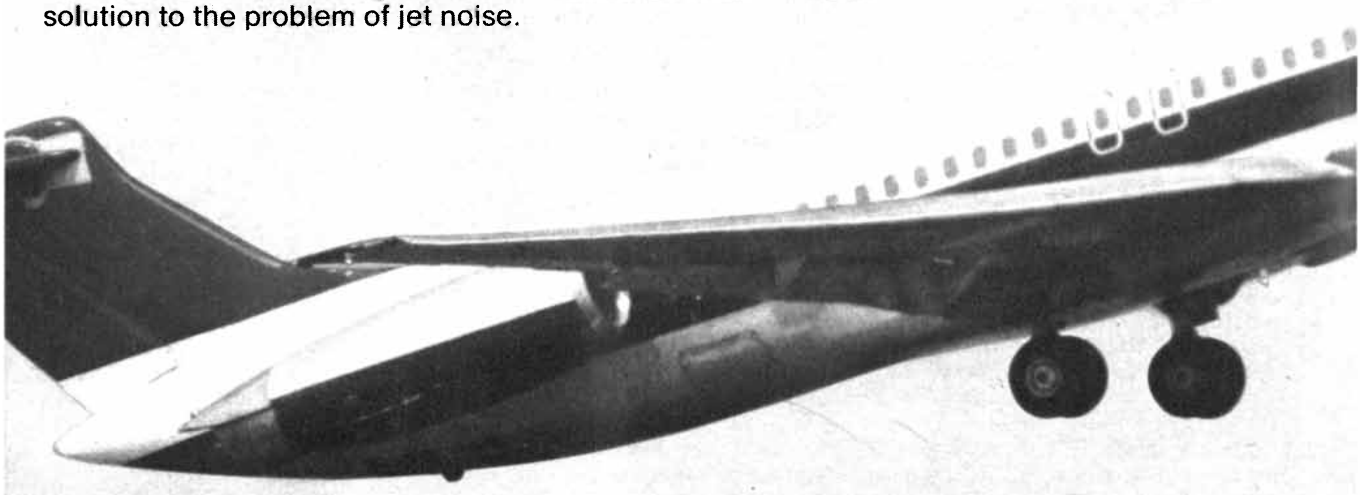
These are two fine accounts for those who like to look thoughtfully at the great world, ready bargains for the taxpayers who have already borne the cost of exploration. Both would have gained in value by more editorial effort to provide indexes, lists of illustrations and similar apparatus. (A reader's nobler self recognizes that such a petty complaint is hardly apt in an account of volumes that Isaac Newton or Charles Darwin would have regarded with simple awe and joy.)

MEGAGAUSS PHYSICS AND TECHNOLOGY, edited by Peter J. Turchi. Plenum Press ($69.50). It was young Pyotr Kapitza who first undertook to enter the domain of the megagauss magnetic field. By 1927 at the Cavendish Laboratory he had managed to travel halfway there by shorting a high-current lead-acid battery across a tiny coil. A full generation passed before anyone bettered Kapitza's farsighted arrangements. The motives were mixed: there was hope that controlled fusion might lie along the way, but the first international megagauss conference seems to have displayed a certain loss of illusion. The present volume of nearly 60 papers reports on Megagauss II, held in Washington in 1979. The utility of high explosives, and now the applicability of the expensive condenser banks harnessed for studies of laser and particle-beam fusion, made the problem a natural one for the weapons establishments. It is a little unusual to read that the sponsors and participants of this international gathering include both the Los Alamos and the Lawrence Livermore laboratories, the Air Force Weapons Laboratory at Albuquerque, the Institute of Hydrodynamics at Novosibirsk and the I. V. Kurchatov Institute of Atomic Energy in Moscow, and laboratories at Ferrara, Canberra and Sendai.

A volume of magnetic field may be regarded as holding a low-mass gas, with a special, somewhat thready, geometry. Everyone knows that the amount of energy in a jelly doughnut so satisfyingly released in digestion is no less than that released almost instantaneously by a similar volume of high explosive. But the explosive, once detonated, yields a white-hot gas at a pressure of some 50,000 atmospheres, eager to expand at a speed of a few millimeters per microsecond. A megagauss field has the same energy density and pressure as the explosive gas. Its free-expansion speed is 10,000 times greater. A labile product indeed, it is "best characterized by the fact that it inevitably destroys the structures in which it is generated and confined."

That damage to our ordinary matter (neutron-star material is modified but by no means distressed, even up to a few megamegagauss) arises from two related effects. The magnetic changes at the structure's boundaries generate surface current pulses in the mega-ampere range within any conductor it touches. At the same time the flash-heated conductor is pushed away with terrible force. It is no wonder the little coils of copper or tantalum that are fed giant current pulses to make megagauss fields vaporize at once. Even so, such a current discharge into a pea-size single-turn coil is a technique "unique in allowing the survival of even delicate samples."

In such condensation of magnetic energy lies high art. Ordinary engineering magnetic fields store energy at about the density of bottles of compressed gas; the expensive but fast-acting capacitors that store electrostatic energy are still more dilute by a factor of a hundred or two. High explosive offers the densest store of fast-moving energy; hence the path taken by most of the workers reporting is the conversion of explosive ener-



gy into magnetic energy. That transfer reaches quite high efficiencies with thoughtful design.

One single-shot explosive dynamo reported by a Kurchatov Institute group catches the eye. It is assembled in a wide clearing in the birch forest. We see a line of helical coils, each coil wound on an explosive core, each output fed into a set of transformer coils. Each transformer in turn feeds a higher current into the larger one next in line. The graduated cascade has six stages; the smallest stage, only the size of an egg, is supplied with magnetic field by a small permanent magnet. The sixth stage, however, is a bulky two tons of iron with heavy copper windings. At each stage an explosive cylinder of due proportion feeds in more energy; the last stage consumes more than 100 pounds of high explosive. The final current pulse reaches six mega-amperes at half a megavolt over tens of microseconds; "in its turn [it] may serve as energy source for more high-energy" generators. The electrical-energy gain of this grand piece of Faraday fireworks is a factor of 10^8.

R. S. Hawke of the Livermore laboratory reviews a decade of work to make use of high magnetic fields for the lossless compression of matter. The magnetic pressure in a vacuum can be made to rise slowly enough to avoid shock heating of the compressed sample, even though energy is supplied by the white-hot detonation of high explosive. The magnetic field is initiated by a condenser discharge from a roomful of capacitors. A cylinder of TNT is detonated just in time to implode a copper-plated hollow liner in against the peak field. The trapped magnetic-field lines are squeezed inward by the imploding conductor; the field smoothly rises several hundredfold, to 10 megagauss or more, within 10 microseconds. A metal sample tube on the axis within is in turn smoothly compressed by huge magnetic forces to planetary-interior pressures of five million atmospheres. Flash X rays shot along the axis supply information about the event. The recent production of metallic hydrogen in this device is only alluded to, but references are given.

The magnetic rail gun of the Canberra group is well described, and its implications are appraised by others. Since the early 1970's this group has been switching its powerful direct-current generator, built for a unique design of particle accelerator, to feed half a mega-ampere into a pair of sturdy copper rails five meters long. A projectile shorts the rails. The magnetic field exerts its pressure on the rails and the projectile; the projectile is free to move, and off it goes. Projectiles weighing a few grams are flung at speeds of six kilometers per second, a high-performance drag record of a few million *g*.

These papers are mostly rather terse for the general reader. The initial survey, by Fritz Herlach of the Universiteit Leuven, is the most readable; it offers a helpful physical and historical overview. The record magnetic field with appreciable volume is still the one reported in 1965 by a Moscow group headed by Academician Andrei Sakharov. Their achievement was 25 megagauss, "obtained with an implosion device of apparently huge dimensions." Traveling a more modest path, an international collaboration among physicists and engineers at the Stevens Institute of Technology, the University of Ferrara and a research laboratory in Torino now reports millimeter hot spots in a fierce plasma discharge. Those spots appear to harbor local fields reaching about 200 megagauss in 10 nanoseconds.

The tale is altogether intriguing, although we see it only in a rather fitful light. One hopes that the military ambience that surrounds the work, with its loud explosions, its weapons laboratories, its hints of bizarre weaponry to come, will be somewhat civilized by the public and cooperative quality of this international conference. The new big fusion pulse sources, entire buildings of capacitors, will soon take over; they promise hundreds of megagauss. Any old neutron star reaches a long way beyond all that we nongravitating human beings can do.

The Geometry of Biological Time, by Arthur T. Winfree. Springer-Verlag ($32). Your watch's hour hand can point to the correct hour anywhere along a marked ring on the dial. ("Ring" is better than "circle"; we all have seen both round and rectangular dials.) We face not geometry but topology. What time is marked at the center point of the dial? That is not, as it might be, an apt Zen koan; it is a serious question, the many analogies of which dominate this rich and lively volume.

It is easy to call up a model of another kind. Time is defined along any parallel of latitude by the turning earth; a watch can be set correctly in any time zone. Bring a set of such well-arranged watches, each one traveling only in its proper hour zone, north to the pole. Which watch is right? Yet time is real enough even at the pole; only the amplitude of the sun's motion in the daily rising-and-setting cycle has vanished.

There is a singularity in that phase at the poles. In 1962 Karl Hamner flew to the South Pole with a number of bioclocks, to place them on a counterrotating platform in a garage, all rotation stilled at the geographic singularity. His fruit flies and hamsters continued to obey their internal clocks. Their "rhythms derive from internal biochemical oscillators that take no notice of geography." The experiment was imperfect, because various long-range effects of the earth's rotation were not eliminated, for example the magnetic field. (The magnetic and geographic poles do not, of course, coincide.) The idea was nonetheless sound; "if biological rhythms are physiologically caused, then they should vanish when the organism is placed in a physiological phase singularity. They do."

The cheerful author, a Purdue physiologist with a mathematical training and bent, tells us all these things and more in a thick volume on clockology, as he terms the quite extensive material, both theoretical and empirical, that deals with biological clocks. Amenable to unusually deep mathematical analysis, exemplified in the widest variety of living forms and their properties, yet not clearly based on any isolable molecular systems we know, the study of clocks in life forms bears a close resemblance to the study of classical genetics without microscopic chromosome maps or DNA. The phenomena are real, important, much analyzed, and yet somehow they remain enigmatic, seen through a parameter space rather darkly. The easy accounts have failed more searching tests.

The tiny red flowers of a certain succulent open and close at 23-hour intervals. They will do so for a week even as cut flowers in a vase of sugar water, under steady green light at constant temperature. But exposure to strong red light disrupts that circadian rhythm; the shift in phase can be measured over the next few days. Such experiments have been done by the thousand, and the data have been displayed in a remarkable three-dimensional plot (and in stereo pairs) that Winfree calls a "time crystal." The scheme uses periodic cells to map relations among the phase shift, the time of the red disturbance and its duration. The points wind along a kind of spiral staircase; near its axis, at about two hours' red exposure, after a quarter cycle, there is a "phase singularity of physiological nature." There the rhythm is lost; a pole is approached. Heat pulses work as well as red light.

The book parts clearly into two halves. For the first 10 chapters the approach is mathematical, sometimes strict, although not abstract. Replete with witty examples and illuminating digressions, but squarely facing the formal questions, with enough argument and enough diagrams to instruct a serious though mathematically untrained reader, these chapters read like a prolonged example of rather demanding recreational mathematics, such as one might find in another department of this magazine.

The second half of the book, which the author dubs a bestiary, reviews the state of experiment and understanding for a wide variety of rhythmical processes in living systems and in their models, including fruit flies hatching, slime molds, the layered cuticle of insects, the mitotic cycle, the female cycle and such remarkable nonliving analogues as the rotating waves of chemical reaction in the catalytic oxidation of malonic acid and the iron-sphere-in-acid model of the beating heart. The level of detail is that of the research student; the list of references includes more than 1,000 papers, and the reader can learn just how to make up the reagent that supports the chemical waves ("like effervescent deep purple Kool-Aid") and how in the good old days an analogue was built of 71 shielded neon-lamp oscillators, all mutually coupled in a known way. The digital computer has made such discrete systems unattractive, but it is populations of interacting oscillators that may provide the kind of result people seek, although they currently exist only in software.

The tale is not all of success; indeed, results of impeccable topological origin have gone quite wrong applied to model systems. How? Because the mathematics often did not allow for the presence, the saving presence, of other parameters, dimensions not considered in the model. Exactly this explains why the watch dial is an inadequate analogy. It is easy to think of some loop of DNA in the cell where a moving ribosome clicks its way around, a tiny hand on a tiny dial. But such a system has no center; the data do not allow such a naive model. These beats are not kept by simple clocks; probably not even one mechanism will explain all cases. Like feedback, rhythms may be a property that is more general in concept than in realization.

Evolution made the rhythm-keepers. A timer to warn of dawn, reset by the daily stimulus, offers the most obvious origin. Why should such a timer now be self-sustained rather than mimicking the hourglass, easily reset by new light each dawn? Why is it found in many cell types in each organism? Perhaps it was only indirectly selected for; the cell, two billion years of cycles behind it, has by indirection come to keep time, able to "shuffle its way spontaneously" through the same old cycle, even when kept artificially in constant conditions. This is a possibility, but again it is rather a one-dimensional model to fit circadian behavior and its resetting singularities.

Maybe the early days were those of steady state and inbuilt oscillations are a later refinement, allowing some kind of lock-in to variable conditions. Some composite clocks have in fact evolved; for example, they surely exist in the insect brain (transplanting which transplants the reset hatching schedule). Where they reside—or where they are missing—in other forms remains largely unknown.

It is a strange story, surely only half told. The warm summer seas often glow at night around a moving oar or someone swimming; it is the red tide of Atlantic coastal waters, a plankton bloom of the luminous organism *Gonyaulax*. In 1957 J. W. Hastings and B. M. Sweeney brought such water into a dark laboratory for certain measurements. Great was their delight when they saw that water had the ability to glow again and again at 24-hour intervals. Earth spin is held deep in life; we do not know why.

Living Archeology, by R. A. Gould. Cambridge University Press ($27.50). The Western Desert is "the most extreme of Australian desert habitats," where rainfall is poor and undependable, where the rocky plateau on the ancient shield rocks is marked by no permanent streams or freshwater lakes or springs. (Some intermittent lakes are found, saltier than the ocean.) Off the meager resources of this land ("by any standard [it] may be the most unreliable and impoverished in the world") men and women now live and have lived for a very long time.

This brief book is an account of life among those people by a field com-

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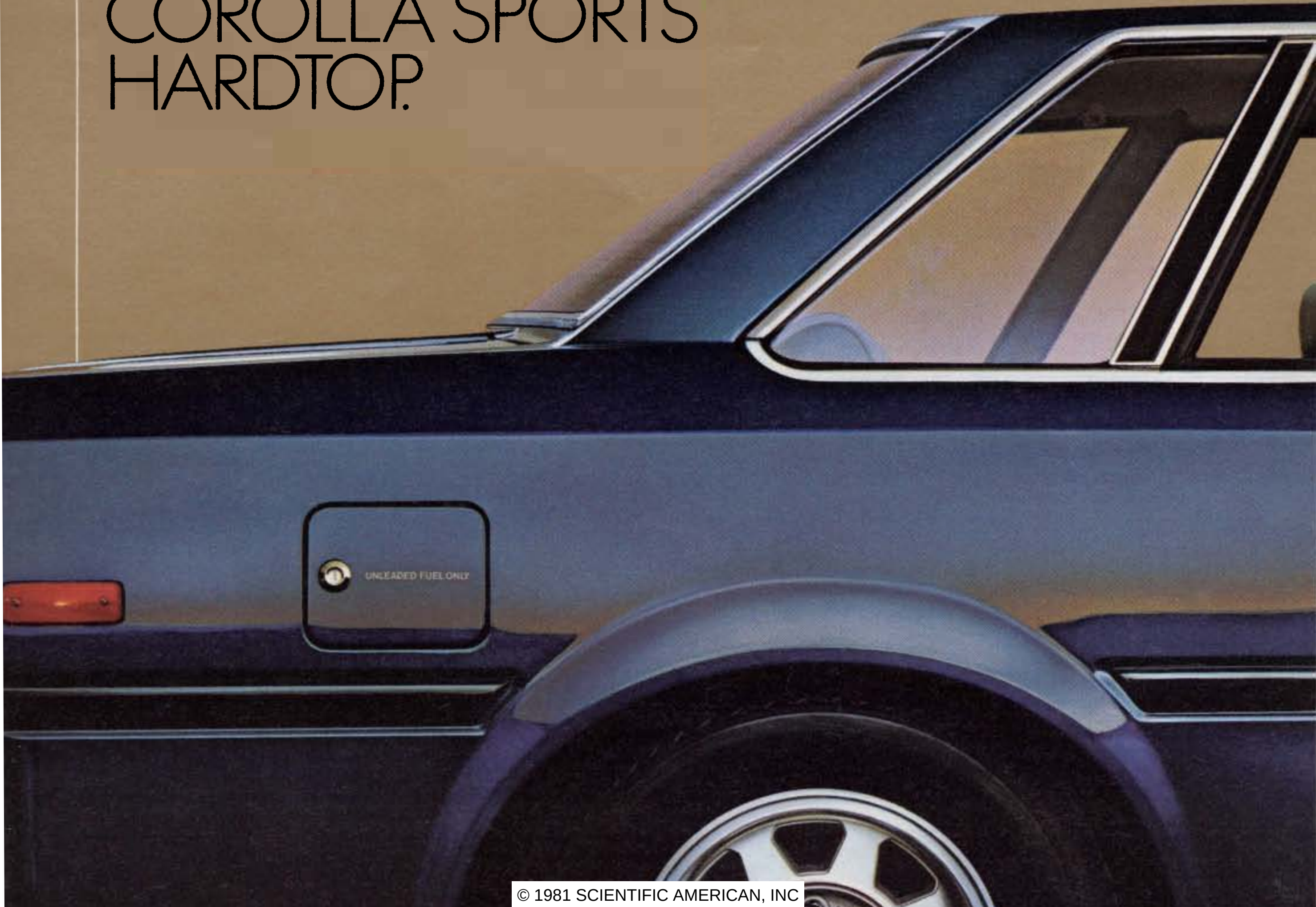

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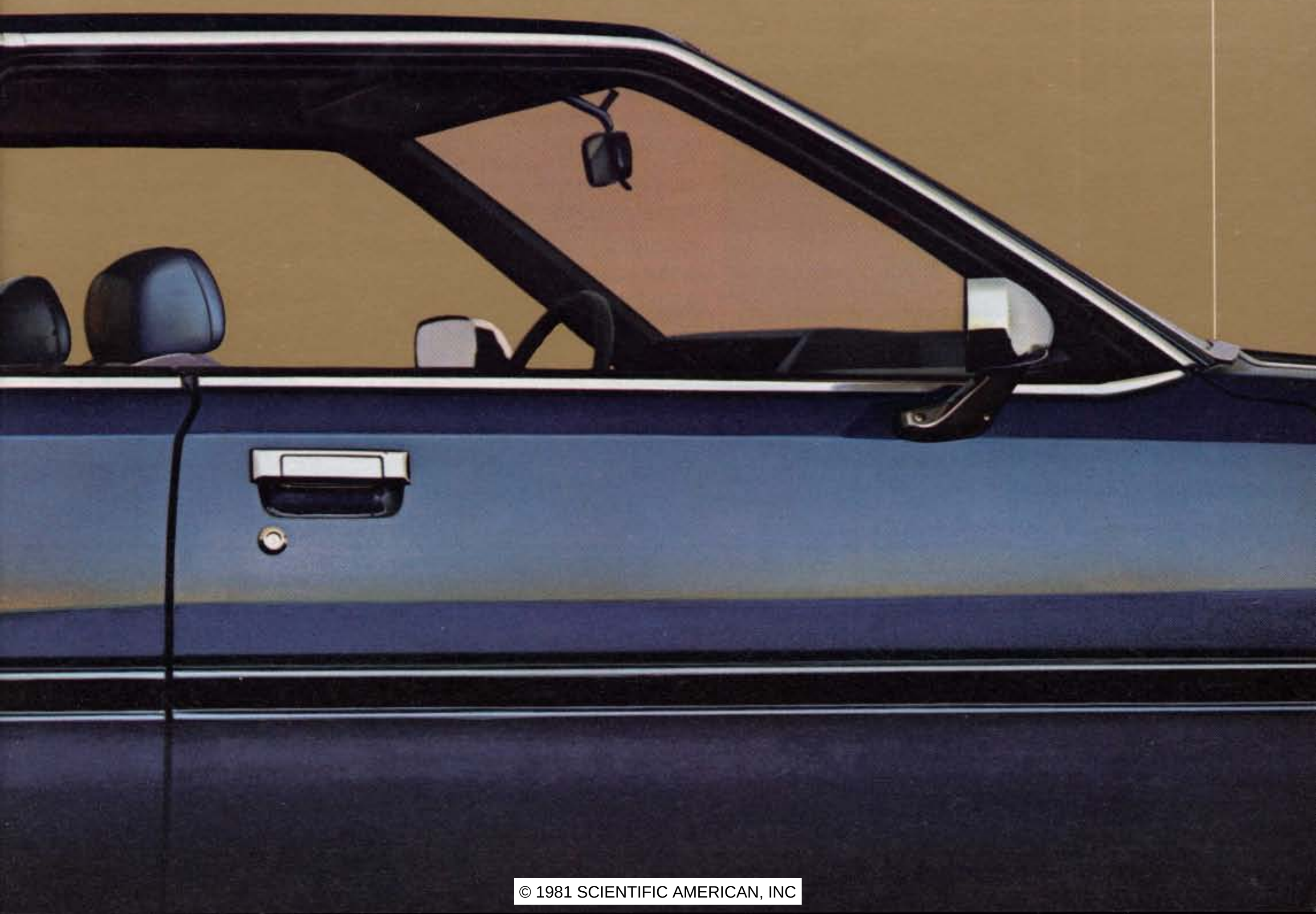

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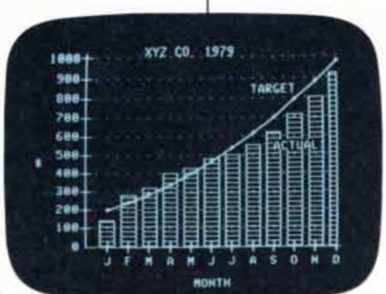

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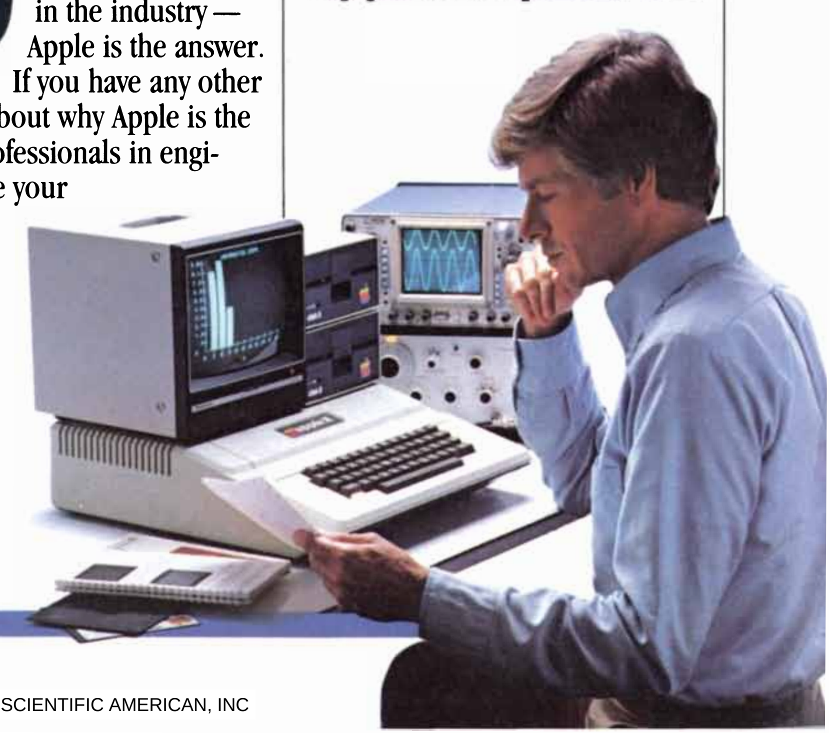


VISIT APPLE AT THE NATIONAL COMPUTER

panion of theirs only a decade ago. It is not at all a systematic ethnography, although it offers many important data, including quantitative studies of food intake, toolmaking and working time. Rather it is an "individualized but coherent point of view" in ethnoarchaeology, seeking some methodological stability in an effort to link human behavior and material residues within the context of living societies.

Gould has a good deal to say about the ideas of his scientific colleagues, as well as the aboriginals, and he reports a few anecdotal encounters far from Australia with quasi-archaeological inferences in modern life. Thoughtful and earnest, he nonetheless leaves a general reader a little puzzled by his philosophical discussions, with their somewhat defensive invocation of black boxes, uniformitarianism and its discontents, analogy and anomaly (Neptune and Pluto) and the search for laws invariant over space and time. These days it appears probable that time devoted to econometrics, statistics and materials science repays a working ethnoarchaeologist much sooner than time spent with the philosophers, old or new.

These desert people live on a vegetable diet, gathered by the women. Ninety percent of the time the women provide 95 percent of the food, with some help from the children. The men "hunt constantly but with generally poor success." The food quest typically takes a few hours a day for the women, even though they supply both the plant staples and much of the steady input of small game, such as lizards and mice. The chancy hunt of the men for bigger game is rewarded only when fortune smiles, but much labor is so expended. The data are inconclusive, but it appears that the taking of a red kangaroo can supply from a fourth to a half of all the meat brought in, even though such big game might be caught only weekly or even monthly by a group, whereas little lizards are caught daily. Traps are unknown; the people prefer to spend a long time tracking and digging out a single bandicoot rather than learning to follow a trapline. The skillful tracker almost never fails (98 percent of such observed hunts were successful); the reliability of the catch may outweigh its labor intensity. Indeed, after a number of such observations Gould seeks to describe the entire pattern of this life as a risk-minimizing adaptive system "of long standing in the Western Desert."

Near Warburton at Puntutjarpa there is a rock-shelter with excavated evidence of human occupation over 10,000 years. Plenty of kangaroo bones are found there. It is striking that the bones are broken into "exceedingly small bits," few as much as an inch long. Such fragments differ grossly from what is usually found in rock-shelters, worldwide and even at sites not far away in the kinder central Australian Desert. That property, however, is explained by the butchering techniques of Western Desert people today. Their scarce meat is conserved with exceptional care. Small game are pounded into a pulpy mass and eaten skin and all. In the same style bigger game bones are broken open and the meat and marrow are teased out with a spinifex spine, even from the skull, the teeth and the jawbone. ("Sometimes the spinifex spine was used as a toothpick afterwards.") This is a neat result, particularly from a theorist who devotes an entire section to the deficiencies of analogy.

Perhaps the most important issue illuminated in the book is the role of long-distance social networks among people who live in stressful environments. The desert now supports such networks, which transport exotic stone over great distances. Moreover, it did so long before the advent of trucks and mission-displaced aboriginals. "Righteous rocks," distinctive worked materials evidently exotic but without any clear utilitarian advantage, are found in the old rock-shelters as they are in every gatherer's tool kit today. The suggestion is that the adaptive need behind the practice is to extend social networks over a wide range in order to reduce the local risks of habitat fluctuations.

This argument looks precarious, but there is something here; social networks always carry more than flints. Gatherings of people to feast on occasional swarms of moths and gluts of pine nuts are familiar in Australia. Yet the people never store such foodstuffs. This paradox is met by the idea that social links are important for the exchange of information and for the establishment of widespread sharing against dire need. Here we may see a preadaptation to settled agriculture. One marvelous example (due to Jane Goodale's working in the islands off Arnhem Land) of ritual exists in which the people ceremonially prepare and share a toxic kulama yam, which must be carefully leached and even then yields only a despised and poor-flavored food. They do this infrequently; it is to be interpreted as a special ritual of training that prepares an emergency food resource in rare need. Here is a means of societal memory that is long-lived enough to span many generations.

Three anecdotal pages outline the story of Fred Avery, the last flint knapper of Brandon in Suffolk, where they have worked flint for more than 30 centuries. Working part-time, he makes close to 200,000 gun flints a year, and he sells most of them across the sea: exotics like those in Australia. The young people avoid his old trade for fear of silicosis. This "anomaly" does not seem outside economic analysis.

Established 1845 SCIENTIFIC AMERICAN May 1981 Volume 244 Number 5

The Fuel Economy of Light Vehicles

As domestic oil production decreases, cars with better fuel economy become more attractive. By 1995 it should be possible without major innovations to have fuel economies of more than 60 miles per gallon

by Charles L. Gray, Jr., and Frank von Hippel

The U.S. is coming out of an era in which economic growth was stimulated by an abundance of cheap petroleum and going into a difficult period in which energy, particularly in the form of liquid fuel, will be much costlier and in limited supply. That this will be a dangerous period is already clear from the anxiety expressed by U.S. officials about the security of the nation's continued access to the world's largest-known reservoirs of underground oil, those in the Persian Gulf region. Consumers are therefore being urged to conserve energy while government and industry focus on developing costly new domestic supplies. Useful as these measures may be, we believe the possibility of making a successful economic transition to the postpetroleum era depends on a much more determined effort by both government and industry to increase the efficiency with which energy is utilized in those sectors of the economy that depend on liquid fuel, starting with the single largest consumer: the automobile.

The automobile has given Americans an extraordinary degree of personal mobility. Today there are about 100 million passenger cars and 30 million light trucks (mostly privately owned pickup trucks and vans) registered in the U.S., nearly one for every adult. In 1980 this vast fleet of vehicles consumed about six million barrels of petroleum products per day, the approximate equivalent of all U.S. imports or about 60 percent of U.S. domestic production.

A few years ago such facts would have seemed only mildly interesting. In 1972, before the Arab oil embargo, there had been no gasoline shortages, and the total cost of U.S. oil imports was only $5 billion. By 1980 the cost of importing not much more oil had escalated to $80 billion, or roughly $1,000 for every American household. With the cost rising rapidly and the future availability of petroleum uncertain some people have begun to ask if Americans can continue to enjoy the luxury of the private automobile.

Where some believe the U.S. is suffering from too many private vehicles others maintain that the automobile plays an irreplaceable role in American life. They fear that the U.S. automobile industry, already hard hit by foreign competition, will soon be building too few cars to ensure a healthy domestic economy. This view was recently expressed most forcibly in a report to former President Carter by Neil Goldschmidt, the outgoing Secretary of Transportation. The production of automobiles and trucks and their subsequent servicing account for about 8.5 percent of the nation's gross national product, for more than 12 percent of personal-consumption expenditures and for about 25 percent of U.S. retail sales.

This part of the economy is currently in serious trouble because of a rapid shift in consumer preference toward smaller and more fuel-efficient vehicles in 1979. In 1980 the U.S. automobile industry lost more than $4 billion and foreign car makers captured more than 25 percent of the U.S. market. By the end of the year, according to Secretary Goldschmidt's report, 190,000 automobile workers, a fourth of the total number, were on indefinite layoff, and between 350,000 and 650,000 workers in automobile-related industries had lost their jobs. If the industry is to compete successfully in the future, stated the report, "U.S. automakers face at least one and perhaps several rounds of major capital expenditures to retool their production facilities [including] the redesign of the auto itself" for greatly increased fuel economy. The report questioned the financial ability of the U.S. automobile industry "to sustain in the latter part of the decade an investment program approaching the magnitude of the current one."

Our own analysis encourages us to conclude that if this financial limitation could be overcome, it would be possible with currently available technology to raise the average fuel economy of the entire U.S. automobile fleet built in 1995 to more than 60 miles per gallon. (Sixty m.p.g. is equivalent to 25 kilometers per liter.) With more advanced technology it might be possible to attain 90 m.p.g.

To place these goals in perspective let us briefly review the recent history of fuel economy in American automobiles. In 1974 the average car sold in the U.S. achieved an on-the-road fuel economy of a little more than 13 miles per gallon of gasoline. By 1980 the figure had risen to an estimated 19 m.p.g. By mandate of Congress the fleet of automobiles built for the 1985 model year must achieve an average of 27.5 m.p.g., as measured by dynamometer tests administered by the Environmental Protection Agency (EPA). This figure was set by Congress at almost exactly double the fuel economy of the 1974 model year (as determined by the same testing method). The Department of Transportation was also instructed to set fuel-economy standards for light trucks at the "maximum feasible level." Recently the department determined that in view of the current financial problems of the industry it could set this level no higher than 21 m.p.g. in 1985.

It appears now that as a result of the new consumer demand for fuel economy the manufacturers will probably exceed the 1985 passenger-car standards by a significant margin. The General Motors Corporation has announced that it expects its 1985-model-year fleet to achieve an average fuel economy of 31 m.p.g. as measured by the EPA test. The on-the-road fuel economies actually achieved are expected to be significantly lower, however, because of defects in the test, which was frozen by law in 1975. The Department of Energy currently estimates that in 1985 the average on-the-road fuel economy of new American light vehicles (including imports) will be 25 m.p.g. for passenger cars, 18 m.p.g. for light trucks and 23 m.p.g. overall.

The Department of Energy projects that, assuming these average efficiencies are achieved, the U.S. will still be consuming automotive fuel in 1985 at a rate of 5.5 million barrels per day, only 500,000 barrels per day below the current rate. This continued high level of consumption is partly due to a projected increase of 10 percent in the light-vehicle miles driven by a still growing population of driving age. Primarily, however, it is due to the older vehicles that will still be on the road in that year, which will pull the average fuel economy of the total 1985 light-vehicle fleet down to 18 m.p.g.

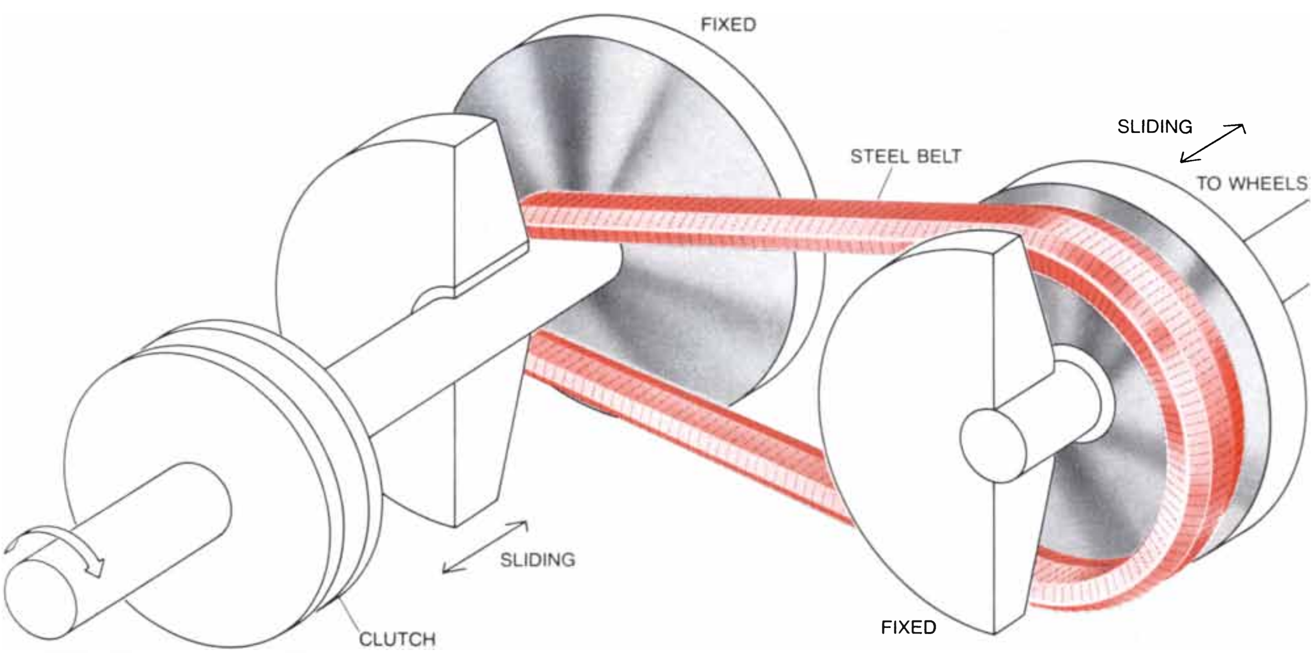
On the supply side the Exxon Corporation projects that by 1985 U.S. oil production will decrease by 20 percent, or two million barrels per day. If both projections are realized, American automobiles will consume the equivalent of all but 2.5 million barrels per day of U.S. production in 1985, leaving little for the remaining sectors of the economy, which in 1980 consumed more than 10 million barrels of oil per day. Hence it appears that even with considerable reductions in oil consumption in some of these other sectors the U.S. will still have a major need for oil imports in 1985.

It is our thesis that one of the most effective and least expensive ways to reduce U.S. dependence on foreign oil in the years beyond 1990 is to make it a matter of national policy to redesign the automobile so that it will be much more energy-efficient and to provide prudent financial aid to U.S. industry in achieving that goal. By the year 2000, we believe, it should be possible to reduce the fuel consumption of the American light-vehicle fleet by two-thirds to about two million barrels per day. The saved oil "produced" by the automobile industry in this way would be much lower in cost than an equivalent amount of oil produced synthetically from coal or shale. The environmental impact would also be much less.

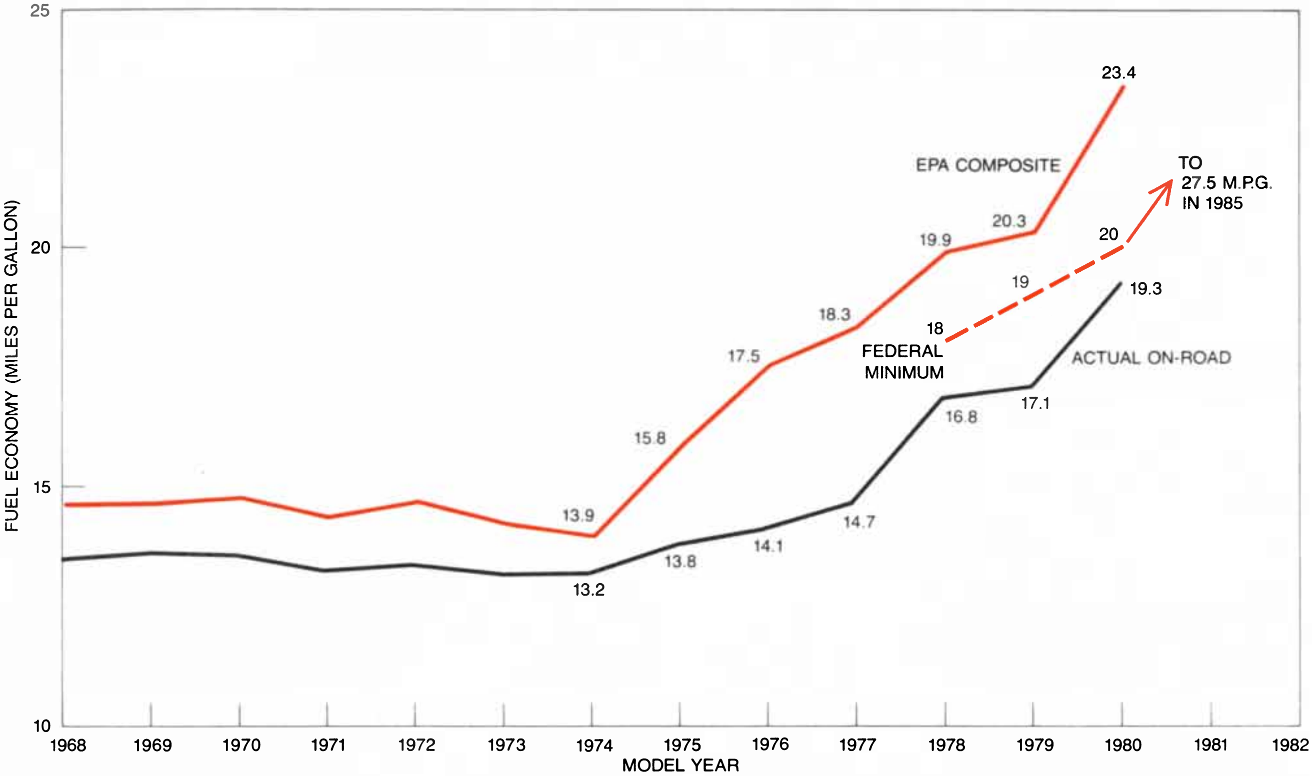
Average fuel economies of more than 60 m.p.g. may seem unrealistic, but we believe they are not. The enormous potential for efficiency improvements in today's automotive technology arises from the possibility of combining changes both in the average physical characteristics of automobiles and in the efficiency of their power plants and drive lines (the mechanisms for delivering the power plant's output to the wheels). Such changes are being introduced piecemeal today as carmakers begin to respond to the new market for efficient light vehicles, but the full potential of the possible changes acting synergistically, rather than one at a time, remains to be widely appreciated. We shall therefore describe a hypothetical fleet of light vehicles that have been redesigned to achieve much higher fuel economy.

Unlike today's fleet, in which two-thirds of the cars are designed to carry five or six passengers, more than half of the fleet we propose would be four-passenger vehicles and would include a significant fraction of two-passenger cars. The power required at the drive wheels would be less than half that of present vehicles because of reductions in weight, in aerodynamic drag and in the rolling resistance of the tires. The vehicles would be powered by significantly more efficient versions of today's internal-combustion engines, with the transmissions and the peak power of the engines being optimized for fuel economy. All the technology required for such a highly efficient fleet exists today in production vehicles or in near-commercial prototypes. We are confident that the vehicles we propose can be designed not only to achieve high fuel efficiency but also to be acceptably safe, to meet reasonable emission standards and to be only slightly costlier, if at all, to operate than current vehicles.

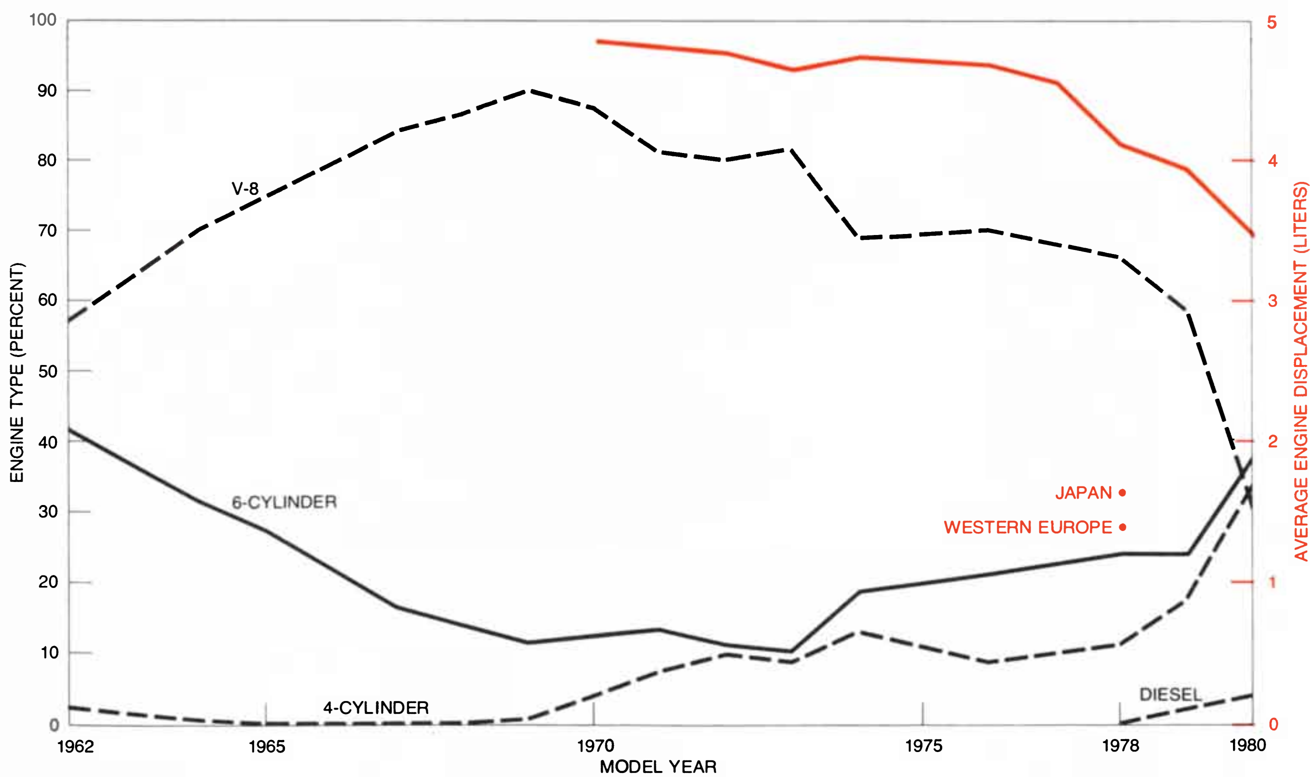
The American passenger car was developed in the era when fuel was cheap, when families with four to six members were common and when few households could afford more than one car. The standard six-passenger car made both personal and commercial sense. Similarly, light trucks were originally developed as work vehicles. Today the average household has fewer than three people, and most households with two or more own at least two cars or a car



CONTINUOUSLY VARIABLE TRANSMISSION will improve fuel economy by enabling the engine to run at the most efficient speed for a given power output. This drawing depicts a variable transmission to be built by the Borg-Warner Corporation. A steel V-belt links two pulleys whose speeds can be changed continuously by changing the effective radii of the pulleys. A cone sliding toward the belt on the axis of one pulley squeezes the belt out to a larger radius; a cone on the axis of the other pulley allows the belt to slip to a smaller radius.



FUEL ECONOMY OF NEW PASSENGER CARS, domestic and foreign, sold in the U.S. has been rising partly in response to market demand and partly to meet Federally mandated standards, which became effective with the 1978 model year. The Federal standards are specified by dynamometer tests conducted by the Environmental Protection Agency (EPA) that simulate separate cycles of city and highway driving from which is derived a composite estimate of fuel economy based on 55 percent city driving and 45 percent highway driving. When the EPA standard was developed, the composite figure was only slightly higher than average on-the-road fuel economy. The two figures have since diverged. The lower of the two fuel-economy figures seen in automobile advertisements is the EPA city estimate, which is close to on-the-road performance. Federal city-highway-composite standard will reach 27.5 miles per gallon (m.p.g.) in 1985.



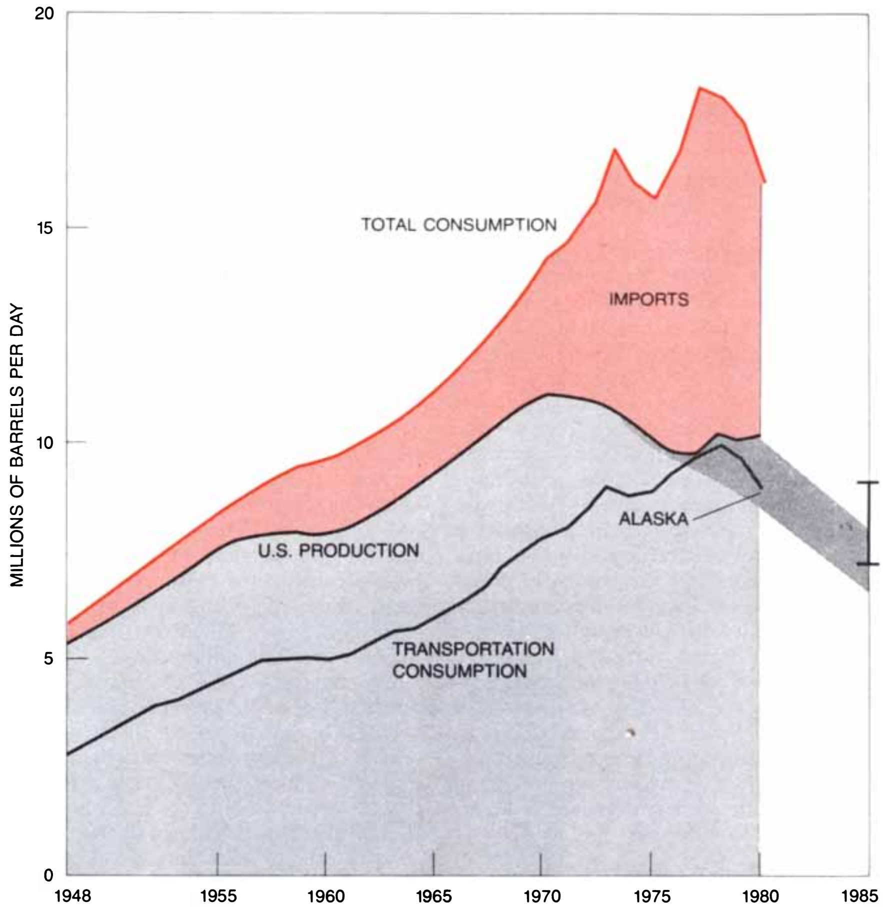
DECLINE OF THE V-8 ENGINE was triggered by the oil embargo of late 1973, a year when some 80 percent of new American-built cars were still powered by eight-cylinder engines. The decline finally came in the 1980 model year, when 70 percent of American cars were equipped with either smaller engines or diesel engines. In the 1980 model year the average engine size (*color*) of new passenger cars sold in the U.S. had fallen by a third but was still twice the average size of engines in 1978 cars built in western Europe and Japan. By 1985 the V-8 engine will be virtually extinct in passenger cars. By then Americans may even be able to buy cars with fewer than four cylinders.

and a light truck. Well over half of American light trucks (vehicles with a gross weight when fully loaded of less than 10,000 pounds) have been bought for personal use and serve mainly as passenger cars. It is clear that today the American automobile fleet has a great deal of carrying capacity that is used only infrequently.

It was not until after the gasoline price rise of 1979 that the American public took advantage of the large fuel savings that could be achieved by shifting to a fleet better suited to modern patterns of usage. As a result sales of five- and six-passenger cars and the larger light trucks have dropped sharply. In the first half of 1980 four-passenger cars captured 45 percent of the passenger-car market, compared with 33 percent in 1978. Even this shift, however, leaves vehicle capacity and actual transportation requirements badly mismatched. Surveys show that on about 80 percent of all trips American cars carry no more than two people and that in a little more than half of all trips the driver is alone. Therefore it is likely that if inexpensive, fuel-efficient two-passenger cars become available in the 1980's, many will be sold. (Today the only such vehicles available are relatively expensive and energy-inefficient sports cars.)

It is hazardous, of course, to predict market behavior when complex social factors enter in, but assuming that periodic gasoline shortages and price increases will continue to occur over the next decade, a passenger-car sales mix in the mid- to late 1980's might have a breakdown something like the following: two-seaters 25 percent, four-seaters 50 percent and five- or six-seaters 25 percent. In addition the demand for light trucks might drop to a ratio of only one truck to every six cars sold instead of the current one to every four. If the U.S. automobile industry were prepared for such a shift, the industry might well benefit from it: some fuel-conscious households might choose to own an increased number of vehicles, each with a different functional design. A household that today owns two vehicles might decide, for example, to own three if they were more efficient than the present ones: two two-seaters for driving to work and for local errands and a third car with a capacity of four, five or six for family trips. Indeed, the rapid increase of three-vehicle households to about 20 percent of all households in the 1970's is already due in part to the increasing popularity of small cars.

The road to improved fuel economy combines a number of related and interacting paths: weight reduction, reduction in aerodynamic drag, reduction in rolling resistance, more efficient engines and more efficient transmissions. There has already been a substantial drop in the weight of American automobiles and in the average size and power of their engines without any significant loss of useful interior space. For example, one of the new Chrysler "K cars," the five-passenger 1981 Plymouth Reliant, weighs 1,070 pounds (30 percent) less than the 1980 Plymouth Volaré with a sacrifice of only four cubic feet (4 percent) in the volume of the passenger compartment and one cubic foot (6 percent) in the trunk space. As a result of this weight reduction the engine horsepower has been reduced from 120 to 84 and the miles per gallon has been increased from 17 to 24. A major feature of the weight-reduction program in the Reliant, as in many 1980 and 1981 models, has been a changeover to front-wheel drive with the engine mounted transversely. This has made it possible to shorten the engine compartment and to eliminate the long, heavy drive shaft that called for a large tunnel through the passenger compartment. The elimination of the rear-axle differential gear has also made possible a shorter, deeper luggage compartment.



U.S. OIL CONSUMPTION has been falling for three years. Transportation continues to take a little more than half of the total. Eighty percent of transportation fuel is consumed by road vehicles of all types, and 80 percent of road-vehicle consumption is accounted for by 130 million automobiles and light trucks used primarily as passenger vehicles. In 1980 these 130 million private vehicles consumed six million barrels of motor fuel per day. Imports of oil in 1980 averaged 6.5 million barrels per day at a cost for the year of about $80 billion. U.S. production of oil in 1980 was 10.2 million barrels per day, 15 percent of it from Alaska. The vertical bar at 1985 indicates the range of domestic production that year based on recent projections.

Further major reductions in weight could be achieved by replacing steel with aluminum, fiber-reinforced plastics and foam-filled structures, an evolutionary process already under way. The ultimate weights that can be achieved by such substitutions will probably be close to 40 percent less than those that are being achieved in today's newly redesigned cars. The concern has sometimes been expressed that the savings in fuel that can be realized with lightweight materials might be offset by increases in the energy needed for their fabrication. This is not the case. Very roughly, a reduction of 1 percent in the weight of a passenger car can yield a reduction of .7 percent in the car's lifetime energy consumption. Since passenger cars today consume about 10 times their weight in fuel over a lifetime of 100,000 miles, a one-pound reduction in weight implies a fuel saving of about seven pounds. This is several times the penalty in manufacturing energy resulting from the substitution of lightweight materials.

Let us now turn to a specific hypothetical four-passenger lightweight vehicle whose aerodynamic drag and rolling resistance are reduced significantly below those of today's vehicles. Consider first the engine. The efficiency of an automobile engine is quite low when it is operating at a small fraction of its peak rated output. It is therefore important to equip vehicles with engines that are not unnecessarily powerful. The peak power requirements of an automobile engine are dictated by its ability to accelerate, climb hills and pull loads. We have chosen minimum performance requirements that reflect the importance of fuel efficiency. We assume that light vehicles must be able to accelerate from zero to 50 miles per hour in about 13 seconds. Although this acceleration capability is below the average of today's fleet (from zero to 50 m.p.h. in about 10 seconds), it is better than the performance of a number of models that are currently popular. We assume also that the car must be able to maintain a speed of 55 m.p.h. while climbing a 5 percent grade. (Only 3 percent of the driving in the U.S. is up steeper grades.) The car must also have extra power for accessories such as air conditioning and (in some vehicles) enough extra power to tow a trailer of the same weight up a 5 percent grade at 40 m.p.h.

Let us now consider the implications of these performance requirements for the engine of our hypothetical vehicle, which will have a "test weight" (the curb weight plus 300 pounds representing the average load in urban driving) of 2,200 pounds. This weight is comparable to the test weight of the lighter four-passenger cars being sold in the U.S. today. With continued effort toward weight reduction 2,200 pounds could easily become a typical test weight for future U.S. five- and six-passenger cars. (The five-passenger Reliant already has a test weight of only 2,600 pounds.) Although the frontal area of our hypothetical vehicle will be about the same as it is for current cars (two square meters, or 21.5 square feet), the coefficient of aerodynamic drag will be at the low end of today's range: .4. (Aerodynamic drag is a relative measure of the air resistance of a body with respect to that of other objects with the same frontal area.) A flat square plate has a coefficient of drag of 1.17. A value of .4 is still considerably higher than what has been achieved with aerodynamically shaped but still "practical" prototype cars. The tire-rolling resistance of the hypothetical vehicle is equivalent to 1 percent of the downward pull of gravity. This is also at the low end of the current range. Prototype high-pressure tires exist, however, that have values of rolling resistance about 20 percent lower than those of any commercial tires available today.

In order to arrive at the engine horsepower needed for the hypothetical vehicle it is necessary to consider the efficiency of the transmission that delivers power to the wheels. This is a complex technical area. In today's cars the gearing of transmissions usually provides for the selection of only two or three specific rotational speeds of the engine for a given road speed. As a result in acceleration from zero to 50 m.p.h. with a manual transmission the average engine power output is usually limited to about 80 percent of the peak output.

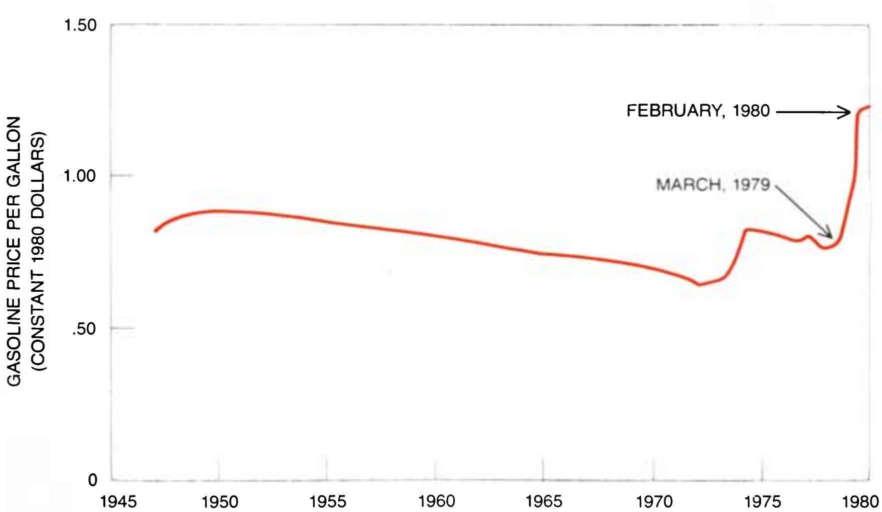
The current inability to harness the engine's peak power at all road speeds should soon be remedied with the introduction of transmissions that are continuously variable. Such a transmission in combination with some simple gearing makes it possible to choose a continuous range of engine speeds. As a result for most road speeds any power output up to the full rated output of the engine can be made available. Even more important for achieving fuel economy is the fact that the most efficient engine speed associated with a given power output can be selected automatically by a microprocessor.

We shall therefore assume that our hypothetical lightweight vehicle is equipped with a continuously variable transmission and that the engine can thus be operated at its most efficient speed over the full range of road speeds at which significant amounts of energy are expended. We shall also assume that the combined power losses in the drive line (the transmission itself, the ancillary gearing, the wheel bearings and the brakes) will be 10 percent of the engine power delivered to the transmission. The loss is about the same in one of today's passenger cars equipped with a manual transmission or with one of the newer fuel-efficient automatic transmissions. In addition we assume that in periods of peak power demand the power drawn by the car's accessories can be limited to .5 horsepower.

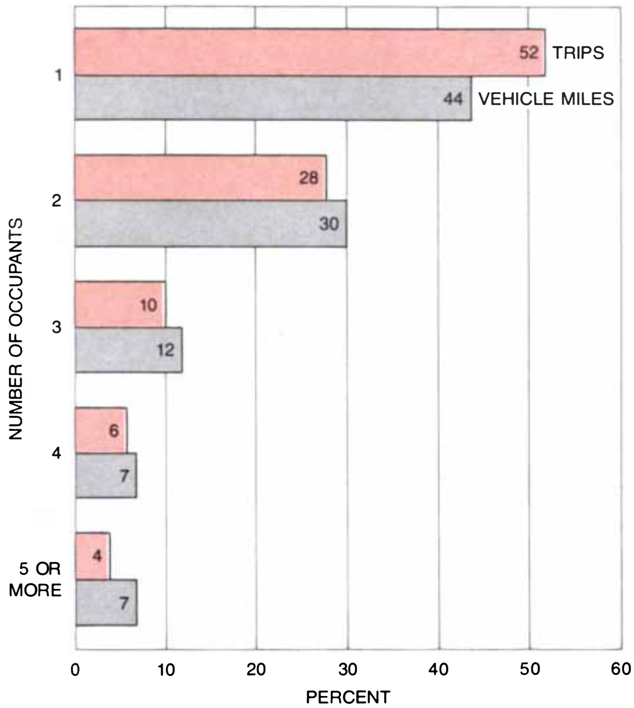
With these assumptions our hypothetical vehicle will require an engine with a peak rated output of about 36 horsepower. This is 25 percent less than the horsepower of the diesel engine in the slightly heavier 1980 Volkswagen Rabbit. The 36-horsepower engine would be much more efficient than the considerably larger engines of today in the 5- to 15-horsepower range, where it would operate most of the time in ordinary driving. For those drivers who want to pull a heavy trailer or for those who need a light truck, optional engines with an additional 20 to 30 horsepower would have to be available, as they are today.

So far we have not mentioned potential improvements in the thermal efficiency of the engine itself, that is, the efficiency with which the engine converts fuel energy into mechanical energy. Today's most efficient engine for transportation is the diesel. One of the inherent advantages of this engine and of some other engines in which fuel is injected directly into the cylinder is that the efficiency falls more slowly than the efficiency of "carbureted" engines, in which fuel and air are mixed before being drawn into the cylinder. Another advantage is that, unlike carbureted engines, they do not have to be fed extra fuel when they are started cold.

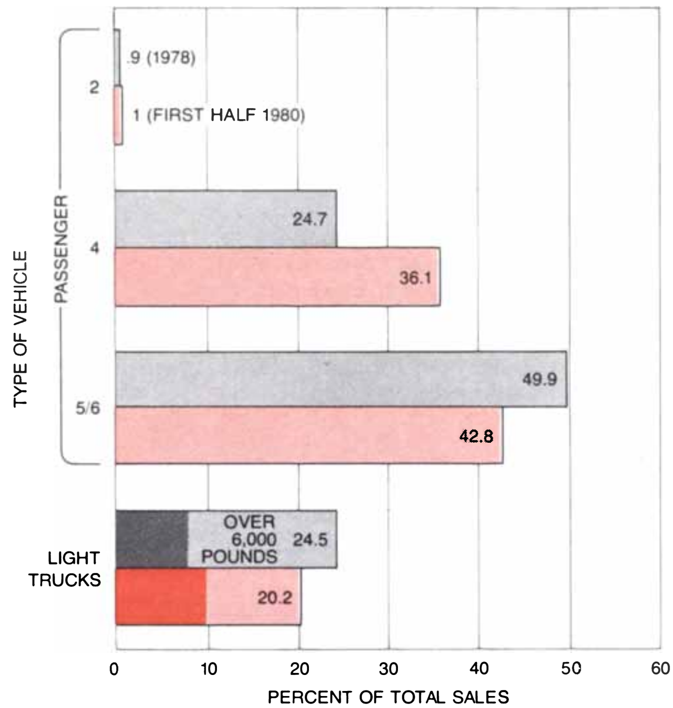
The current generation of automotive diesels, however, is still far from being optimized for fuel economy. Various compromises with fuel economy were made to obtain engines that would operate at high rotational speeds (for high



U.S. GASOLINE PRICES, expressed in constant 1980 dollars, actually declined between 1950 and the winter of 1973, when the Organization of Petroleum Exporting Countries (OPEC) initiated the first of a series of sharp price increases. The era of cheap oil for Americans did not really end, however, until March, 1979, with further OPEC increases and the partial lifting of price controls on oil and gasoline. The average combined Federal and state tax on gasoline of 14 cents per gallon in 1980 was a third lower in real terms than it had been a decade earlier.



AMERICAN MOTORISTS drive without anyone else in the car on 52 percent of their trips (*top bar in color*). Such trips account for 44 percent of all vehicle miles (*top bar in gray*). The percentage of trips with more than one person in the car and the corresponding percentage of vehicle miles are given by the other pairs of bars. Eighty percent of all automobile trips are made with no more than two people in the car and account for 74 percent of the total vehicle miles. These statistics were gathered in 1977–78 by the Bureau of the Census.



SHIFT TO SMALLER VEHICLES is under way. The upper bars of each pair show the percentage distribution of light vehicles sold in the U.S. in 1978. The lower bars of each pair (*color*) show the sales mix for the first half of 1980. Sales of four-passenger cars increased nearly 50 percent at the expense of larger cars and light trucks. The mix of light trucks also shifted sharply toward smaller vehicles. The demand for two-passenger cars has changed very little, probably because most of those that have been available have been sports cars.

peak power), would be easy to start, would make little noise and would meet mandated emission standards. The most important of the compromises was the addition to each cylinder of a small "prechamber" into which fuel is injected and begins to burn. The prechamber makes the fuel efficiency of automotive diesel engines between 10 and 15 percent lower than that of large truck diesels, which have direct cylinder injection. Engine designers have been seeking ways to eliminate the prechamber in automotive diesels without unacceptable performance or emissions. They now appear to be quite close to doing so.

The average efficiency of automotive engines could also be increased by the adoption of another technology that is standard on large truck diesels: turbocharging. The turbocharger is a combination of a turbine and a compressor. The turbine is spun by the exhaust gases; the compressor, which is on the same shaft, pushes extra air into the cylinder and thereby allows additional fuel to be burned on each power stroke. Turbocharging makes it possible to raise the peak power output of an engine of given displacement or, what is equivalent, to reduce the size of the engine for a given peak power. A reduction in engine size is beneficial because smaller engines ordinarily have smaller friction losses and other losses. Turbocharging automotive diesels has made possible fuel-economy advances of between 10 and 15 percent.

In calculating the fuel economy of hypothetical future light vehicles we have assumed that the vehicles will be equipped with direct-injection turbocharged engines and with continuously variable transmissions under the control of a microprocessor capable of choosing the most efficient point on a "map" describing the engine's efficiency. In such a map the thermal efficiency of the engine is plotted as a function of the engine's rotational speed and the amount of energy delivered per revolution [*see illustration on page 56*].

The efficiency is low when little energy is delivered per revolution because most of the work done by the expanding gases of combustion goes to overcoming internal engine friction. Power output is proportional to the product of energy delivered per revolution times revolutions per minute (r.p.m.), so that the curves of constant power output on the efficiency map take the form of hyperbolas. Inspection of the efficiency map shows that when only a small fraction of the engine's peak output is needed, maximum efficiency is achieved by holding the engine revolutions constant at the lowest practical level (1,000 r.p.m.) and adjusting the energy delivered per revolution as it is needed. When more than a certain fraction of the peak engine output is needed (more than 20 percent in the example in the illustration), additional power can be obtained at maximum efficiency by holding the energy delivered per revolution constant at a high level and increasing the engine's rotational speed.

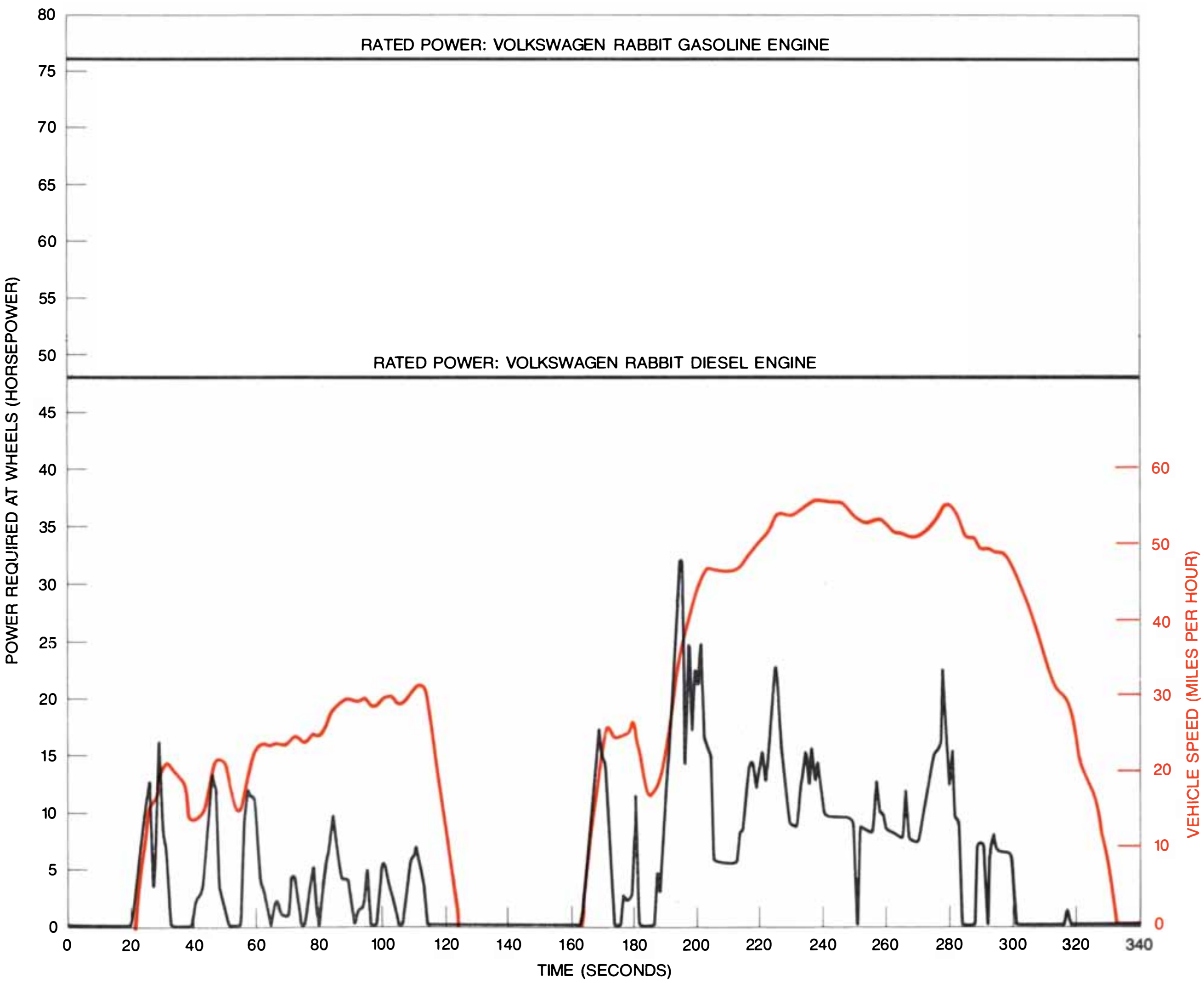
Once the weight, the aerodynamic drag, the tire-rolling resistance, the accessory power requirements, the driveline losses, the transmission characteristics, the engine size and the operating map of an automobile have been specified it is not too difficult to calculate the vehicle's fuel economy on any specific driving cycle. In our computations we have used the EPA's city-and-highway driving cycles and have expressed the results in terms of the standard "composite" weighted average consisting of 55 percent city driving and 45 percent highway driving.

In order to arrive at a hypothetical fleet of vehicles attainable by 1995 we have extrapolated from the specifications of average and "best" vehicles of different models available in the 1980 model year. The extrapolations involve vehicle weight, frontal area, coefficient of aerodynamic drag, tire-rolling resistance, type of transmission and drive-train thermal efficiency. Two sets of values were projected for 1995: those attainable with the current "best" technology and those we believe could reasonably be attained with the advanced technology available by 1995 [*see illustration on page 58*].

Here are a few examples of what we believe can be done. In 1980 the average and the lightest four-passenger cars sold had respective weights of about 2,700 and 2,000 pounds. In 1995 an average test weight of 2,000 pounds should be achievable for these vehicles with the current best technology. With advanced technology an average test weight as low as 1,400 pounds (1,100 pounds curb weight) might be practical. At the upper end of the weight range personal light trucks that in 1980 weighed 4,200 pounds (the average) and about 2,400 pounds (the lightest) could be reduced by 1995 to an average of 2,500 pounds and perhaps to as little as 1,750 pounds. The weight of five- and six-passenger cars could be similarly reduced. We believe that two-passenger cars averaging 1,500 pounds could be made available by 1995 and that weights as low as 1,050 pounds (750 pounds curb weight) might be practical for such vehicles with advanced technology.

Although the frontal area of the vehicles might not be much smaller in 1995 than it was in 1980, we project possible reductions of from 20 to 40 percent in the average coefficient of aerodynamic drag from today's value of about .5. The rolling resistance of tires can also be reduced significantly. Reductions in weight, aerodynamic drag and tire-rolling resistance are all important because braking, air resistance and tire losses account for about equal amounts of fuel consumption in average driving. With the advanced engine and transmission described above, we calculate that it should be possible to approximately double the drive-train thermal efficiency (the percentage of the energy in the fuel that is delivered to the wheels as driving power) from the 1980 average of about 12 percent to 25 percent.

In calculating the fuel economies of these possible future vehicles we have assumed that they would meet the performance specifications we listed that led to a 36-horsepower engine in a hypothetical four-passenger car. We have also assumed that on the average .5 horsepower is required from the engine to operate the accessories. On the basis of all the foregoing assumptions we calculate that with the current best technology the entire 1995 fleet of light vehicles should be able to achieve a fuel economy of more than 58 m.p.g. Given a plau-



POWER NEEDED AT THE WHEELS of a typical vehicle, here a 1980 Volkswagen Rabbit, is ordinarily much lower than the rated horsepower of the engine. The diesel-model Rabbit is a third less powerful than the gasoline model. The colored curve represents the speed in the first 5.5 minutes of the 23-minute driving cycle devised by the EPA for establishing the fuel economy of cars in city driving. The jagged black curve represents the actual power requirement at the wheels of the car over the 5.5-minute period. The power requirement at the wheels decreases to zero when the car is decelerating or idling. The peak power requirement of 32 horsepower is reached at 196 seconds into the driving cycle, when the car is traveling at 36 m.p.h. and is increasing its speed at the rate of 3 m.p.h. per second.

sible mix of sizes, for example 20 percent two-passenger cars (at 81 m.p.g.), 40 percent four-passenger cars (at 70 m.p.g.) and 40 percent larger cars and light trucks (at 58 m.p.g.), the average fuel economy of the light-vehicle fleet would be about 65 m.p.g. Increasing the average horsepower of the fleet by 15 percent would reduce the average fuel economy by 1 m.p.g. Such an increase would give 20 percent of the fleet a towing capability or alternatively would give the entire fleet an average zero-to-50-m.p.h. acceleration time of less than 12 seconds. With advanced technology a fleet of the same composition could conceivably attain a fuel economy of 90 m.p.g. [*see illustration on page 59*].

The gap between these projections for the 1995 fleet of vehicles and the estimated fuel economy of 18 m.p.g. for the 1980 U.S. fleet (if light trucks are included) may well prompt the reader to ask: Is the gap understandable, and are the projected numbers believable? Perhaps the simplest way to understand the large factor of potential improvement we project is to recognize that reductions in the propulsion energy required at the wheels of a vehicle and improvements in the average thermal efficiency of its drive train have multiplicative effects. Therefore if the average thermal efficiency of the drive train were to be kept constant at the 1980 value of about 12 percent, the combined effect of all the other improvements in weight, aerodynamic drag and tire-rolling resistance would increase the fuel economy of the 1995 fleet based on the best current technology to only 31 m.p.g. and of the fleet based on advanced technology to only 43 m.p.g. Such numbers would not seem unreasonable in view of the fact that the lightweight (1,950 pounds test weight) 1981 Toyota Starlet, which is equipped with a conventional engine, already achieves 39 m.p.g. on the EPA city cycle and 54 on the highway cycle, or 44 m.p.g. on the composite cycle we have adopted for our projections.

Alternatively, if the average test weight (3,300 pounds), aerodynamic drag and tire-rolling resistance of the 1980 fleet were held constant and the average thermal efficiency of the drive train were simply doubled from 12 to 25 percent, the average fuel economy of the fleet would rise only from 18 m.p.g. to about 37, again a number that does not seem intuitively unreasonable. It is only when the effects of decreased power requirements and increased drive-train efficiency are compounded that we arrive at the initially surprising fuel-economy projections in the range of 65 to 90 m.p.g.

The best demonstration of the validity of our projection would involve a prototype vehicle with the features we have described. Although no publicly disclosed prototype includes all these proposed features, two recent experimental cars incorporate enough of them to validate our calculations. The first is a Volkswagen Rabbit with a turbocharged diesel engine built in 1976 for the U.S. Department of Transportation. The vehicle, which has a test weight of 2,400 pounds, achieved a composite fuel-economy score of 60 miles per gallon of diesel fuel. Since diesel fuel holds 10 percent more energy per gallon than gasoline, the prototype's 60 m.p.g. is equivalent to 54 m.p.g. for a gasoline-fueled vehicle.

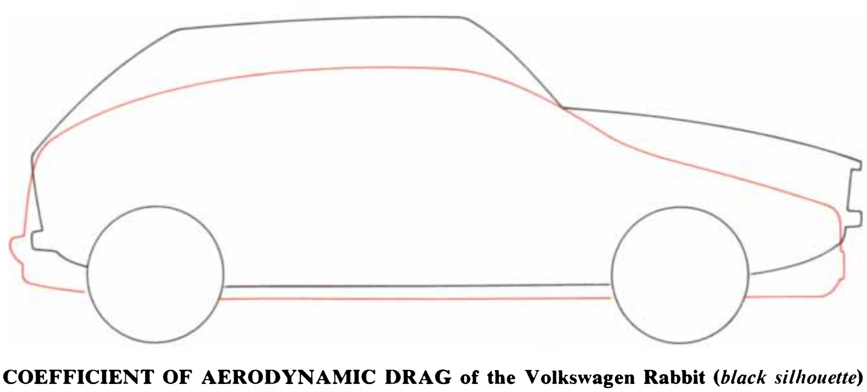
The second prototype is a more recent experimental vehicle for four passengers also built by Volkswagen. Powered by a direct-injection diesel, the vehicle has reportedly achieved a gasoline-equivalent composite city-highway fuel economy of about 70 m.p.g. If the report is correct, the prototype has already equaled the fuel economy we have projected for a hypothetical four-passenger car to be marketed in 1995 and has done so without either a continuously variable transmission or a low-drag body. The prototype also lacks a fuel-saving feature that we have not included in our projected fleet but that is in the advanced development stage: a flywheel that can be disengaged from the engine. This makes it possible to have the engine stop automatically when the vehicle is stopped or decelerating and then restart automatically and instantly with the energy stored in the flywheel when the accelerator is pressed again.

In our projections we have not ignored the fact, well known to many buyers of recent-model cars, that the EPA testing procedure yields estimates of composite city-highway fuel economy considerably higher (by 15 to 20 percent) than most cars have actually delivered on the road. Fortunately for the purposes of this discussion, however, the vehicles whose characteristics come closest to those we have been describing, namely front-wheel-drive diesel-powered vehicles, achieve on-the-road fuel economies that are much closer to the EPA ratings than vehicles of conventional design.

So much for the technological potential. The discussion cannot, however, end here. Before the nation can select a fuel-economy goal it must understand the relation between fuel economy on the one hand and safety, clean

REQUIREMENT	PERFORMANCE SPECIFICATIONS	POWER REQUIRED AT WHEELS (HORSEPOWER)
ACCELERATION	0-TO-50 M.P.H. IN 13 SECONDS	32
HILL CLIMBING AT CONSTANT SPEED	5 PERCENT GRADE AT 55 M.P.H.	29
ACCESSORIES	LIGHTS, FANS, AIR CONDITIONING, ETC.	+3 (AT ENGINE)
TOWING	TOW VEHICLE OF EQUAL WEIGHT UP 5 PERCENT GRADE AT 40 M.P.H.	+20

POWER REQUIREMENTS at the wheels of a hypothetical four-passenger vehicle capable of meeting certain performance specifications have been calculated by the authors. They believe the specifications are reasonable for a fleet of fuel-efficient vehicles. Thirty-two horsepower at the wheels should be adequate for a vehicle with a test weight of 2,200 pounds (curb weight plus 300 pounds), a frontal area of two square meters (21.5 square feet), a coefficient of aerodynamic drag of .4 and tires with low rolling resistance (1 percent of vehicle weight). If the vehicle is used for towing a trailer of comparable weight, another 20 horsepower is needed.



COEFFICIENT OF AERODYNAMIC DRAG of the Volkswagen Rabbit (*black silhouette*) is about .4, somewhat below the average of about .5 for current American light vehicles. The coefficient for a perpendicular flat plate is 1.17. Color outline shows the profile of a new Volkswagen prototype that offers more interior space than the Rabbit but has a drag of only .3.

air and cost on the other. We shall therefore explore these issues briefly.

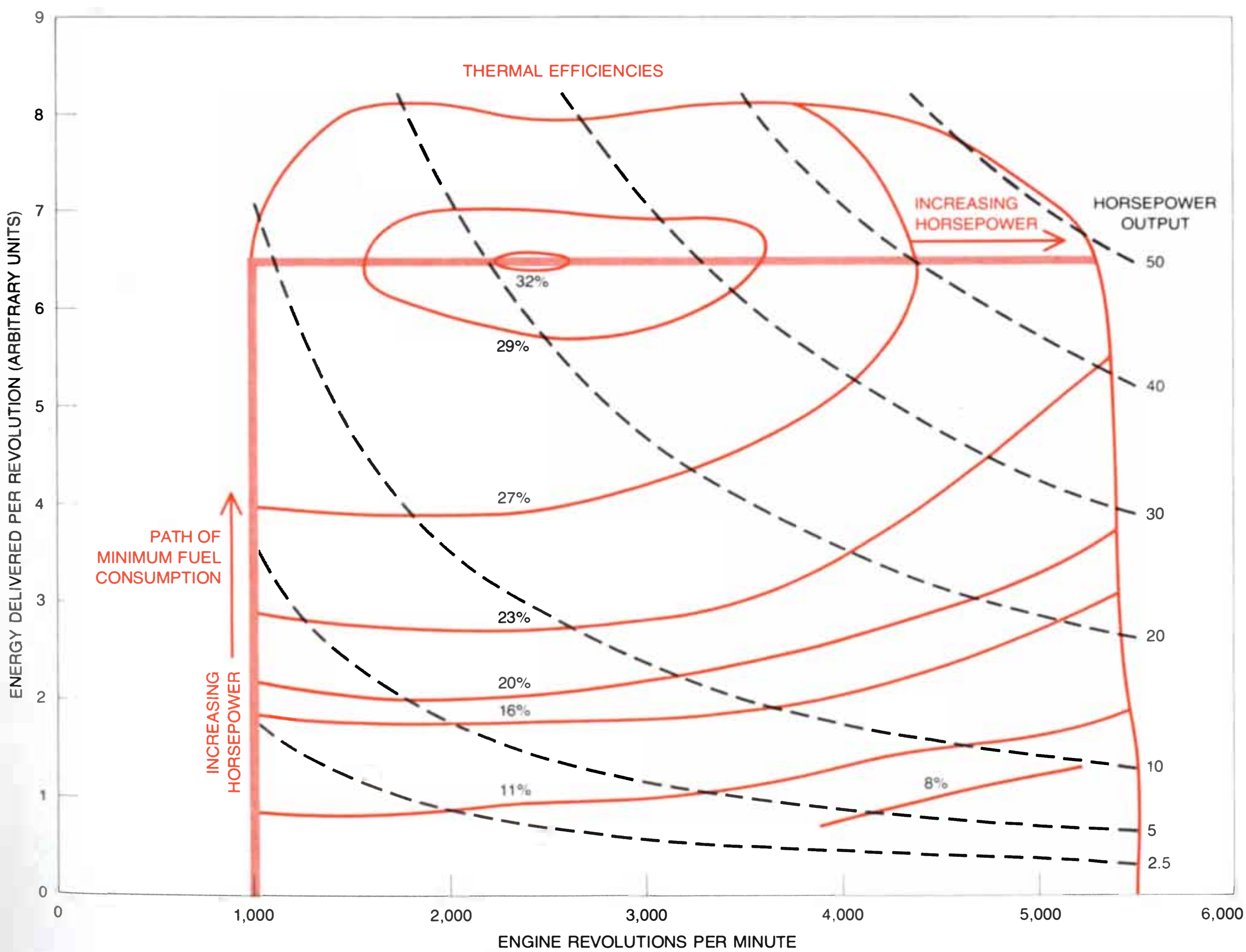
A frequently expressed concern is that passengers in smaller, lighter vehicles are exposed to greater risk of serious injury or death in an accident. Statistics collected for the National Highway Traffic Safety Administration in the mid-1970's show that this is indeed the case. The risk of serious injury or death in an accident increased with decreasing vehicle weight. At the extreme, occupants of the lightest cars were at almost exactly twice the risk of those in the heaviest cars. The study also showed that use of seat belts reduced the risk in all vehicles by more than half. As a result occupants of the lightest cars who fastened their seat belts were at lower risk than those in the heaviest cars who forfeited such protection. (Today Americans fasten their seat belts only about 10 percent of the time.)

The increased injury risk in light cars is partly offset by the statistical fact that mile for mile the drivers of subcompact cars appear to have between 10 and 30 percent fewer accidents than the drivers of larger cars. Moreover, one of the major sources of the increased hazard associated with driving small cars, namely collisions with heavy cars, is steadily being reduced as large cars get lighter. The shift toward lighter cars nonetheless makes it imperative that automobile makers improve the crashworthiness of their products at the same time that they redesign them for better fuel economy.

Currently new passenger cars sold in the U.S. are expected to be able to meet the 30-mile-per-hour crash-test standard for all models planned through 1985. Work done by the National Highway Traffic Safety Administration has indicated, however, that there is still much room for improvement in the crashworthiness of light four-passenger cars. The safety of lightweight two-seat city cars may present a special challenge, one that is only partly diminished by the fact that such cars are meant to be driven predominantly in city traffic, where the average vehicle speed is only about 30 m.p.h. We would urge that an international cooperative program be undertaken to demonstrate safe designs for such vehicles.

A second area of major concern in redesigning the automobile for high fuel economy is air pollution, particularly from the increasingly popular diesel engine. Diesel emissions are high in two troublesome pollutants: nitrogen oxides (which contribute to respiratory ailments and to the formation of smog and acid rain) and small particulates that lodge deep in the lungs and carry chemicals that are known to be mutagenic and may prove to be carcinogenic. For equal power output current diesel engines emit more of these two pollutants than gasoline engines.

It appears that by 1983 cars powered by prechamber diesel engines, particularly in the smaller sizes, will be able to



EFFICIENCY "MAP" FOR DIESEL ENGINE in a Volkswagen Rabbit relates revolutions per minute (r.p.m.), energy delivered per revolution, power output and thermal efficiency (*contour lines in color*). Power output is proportional to the product of energy delivered per revolution times r.p.m., so that the contours of constant power output are hyperbolas (*black broken lines*). In a car with a continuously variable transmission a microprocessor could select for any power output the point along one of the hyperbolas where the engine is most efficient. Broad line in color is the locus of points of maximum efficiency. Below 10 horsepower a constant 1,000 r.p.m. is best.

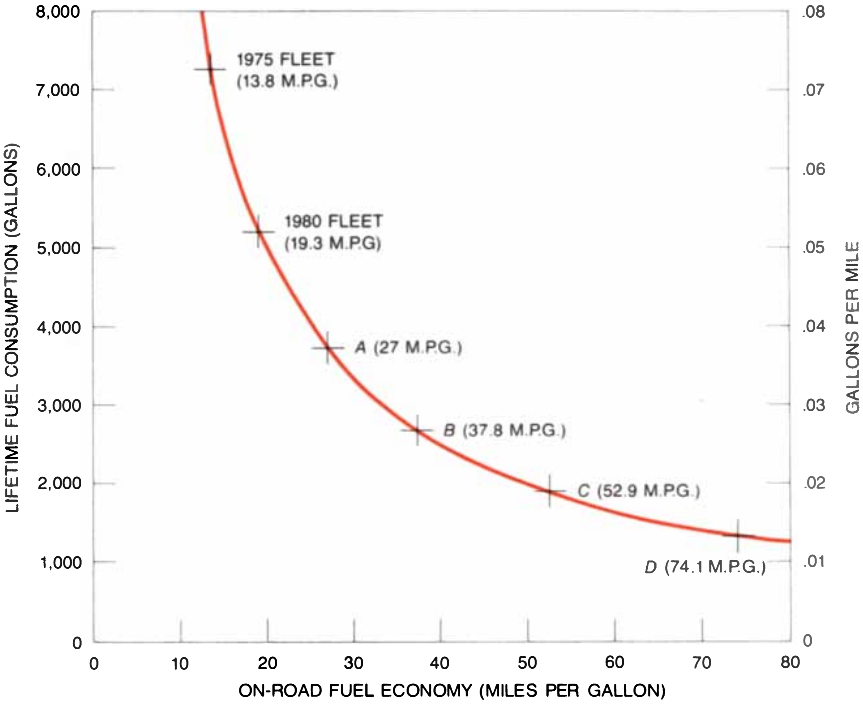
meet the Federal limit on nitrogen oxide emissions (one gram per mile) that has been applied to gasoline-powered vehicles starting in the current model year. It is expected, but it is less certain, that the more efficient direct-injection diesels will eventually be able to meet the same standards.

As for the particulate emissions, it seems probable that small diesel engines will be able to meet the limit of .2 gram per mile the EPA has established for 1985 vehicles. Even if they do, an emission of .2 gram per mile will be about 20 times higher than the quantity of particulates emitted by a comparable gasoline-fueled vehicle. The consequences for human health of the mutagenic material carried by diesel particulates remains an unresolved issue. A rising fraction of diesel-powered cars in American cities, however, will add to the quantity of diesel fumes that most people find objectionable and will generally reduce visibility in these areas. Although the pollution problems of the diesel may not be insuperable, they should motivate a continuing search for efficient automotive power plants that are inherently cleaner.

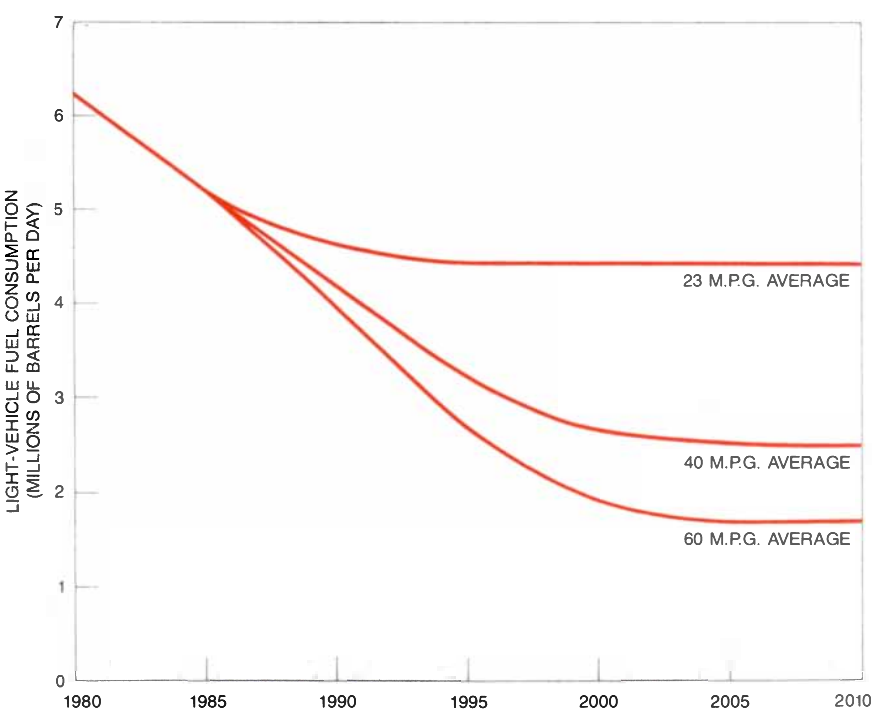
It is worth noting in this connection that there is one variant of the gasoline-fueled engine that is both efficient and relatively clean and would not require a major break with traditional automotive technology. This is the direct-injection stratified-charge engine. The distinctive feature of such engines is that the charge, or fuel-air mixture, in their combustion chambers is stratified, or made inhomogeneous, at the instant combustion is initiated. As a result the formation of nitrogen oxides is sharply suppressed. The stratification also makes it possible to burn fuel-air mixtures so lean in fuel that they would not burn if the fuel were uniformly mixed with the air. As a result direct-injection stratified-charge engines have efficiency advantages comparable to those of the diesel.

Stratified-charge engines are also capable of burning fuels other than gasoline, of which perhaps the most important is methanol. Because methanol can be produced both from coal and from plant material it is a promising liquid fuel for the postpetroleum era. A fully optimized methanol-fueled engine could combine extremely low emission of pollutants with high thermal efficiency (probably higher, in fact, than that of a comparable diesel engine). It is our own hope that the technology of methanol-fueled engines will be vigorously pursued.

Another possible alternative to today's internal-combustion engines is the battery-driven electric motor. Because of the limitations of present storage batteries electric cars are now primarily of interest for short trips. Today the driv-



SETTING A FUEL-ECONOMY GOAL for the 1990's involves recognition of diminishing returns; equal percentage increments in fuel economy save progressively less fuel. The 40 percent increase in on-the-road fuel economy from 13.8 m.p.g. in 1975 to 19.3 m.p.g. in 1980 represents a saving of 2,000 gallons over the typical life of a car (100,000 miles). Another improvement of 40 percent to 27 m.p.g. (*A*) will save an additional 1,500 gallons. Still further improvements of 40 percent to 37.8 m.p.g. (*B*), 52.9 m.p.g. (*C*) and 74.1 m.p.g. (*D*) would yield progressively smaller savings: respectively about 1,100, 750 and 550 gallons. The authors nonetheless believe the cost of improvements can be justified until the average fuel economy is at least 60 m.p.g.



POTENTIAL FUEL SAVINGS are projected for three hypothetical fuel-economy targets for light vehicles reaching the market in the 1995 model year. The Federal Government has already set a target of 27.5 m.p.g. for 1985 cars as measured by the EPA composite city-highway driving cycle. Because of the recent increased demand for fuel-efficient vehicles this goal will probably be exceeded by several m.p.g. Actual on-the-road fuel economy of the 1985 light-vehicle fleet will probably average only about 23 m.p.g. Top curve shows the projected fuel consumption to the year 2010 for a constant yearly number of vehicle miles if no further improvements in fuel economy are mandated or achieved. Middle and bottom curves depict fuel consumption if on-the-road fuel economy climbs to 40 and 60 m.p.g. between 1985 and 1995.

ing of electric vehicles has the effect of conserving petroleum and natural gas because only about a fourth of the nation's electricity is generated from these premium fuels. In developing an automotive strategy for the postpetroleum era, however, one will want to compare the overall cost of converting coal or plant material into methanol for internal-combustion engines with the cost of converting the same materials into electricity for charging the batteries of electric vehicles. With current technology it appears that the methanol route would be the more efficient utilization of the primary fuel.

Let us now address the matter of cost. How large an expenditure on development and retooling is justified in order to achieve a particular level of fuel economy? Here the principle of diminishing returns enters in. One can draw a simple curve relating fuel economy, in miles per gallon, to the consumption of fuel over the typical automobile lifetime of 100,000 miles [*see top illustration on preceding page*]. Such a curve shows that increasing the fuel economy of a 15-m.p.g. vehicle by 10 percent to 16.5 will save 600 gallons of fuel over the vehicle's lifetime whereas increasing the fuel economy of a 70-m.p.g. vehicle by 10 percent to 77 will save only 130 gallons.

Strictly speaking, the difference between the purchase price of the 77-m.p.g. vehicle (for example) and that of the 70-m.p.g. vehicle should not exceed the value of the 130 gallons of fuel saved. At some point, defined in the short run by the importance to international stability of reducing U.S. oil imports and perhaps in the long run by the cost of alternative nonpetroleum-based fuels, the cost of the saved energy will become so high that it will no longer be cost-effective to invest in further fuel-economy improvements.

Many cost-benefit analyses have been made, and there seems to be fairly general agreement that the value of fuel savings will exceed their cost at least until the industry is tooled up to build vehicles with a fleet average of 40 m.p.g. The analysts have not yet reached a consensus, however, on the economic value of going much beyond 40 m.p.g. Our own belief is that most cost-benefit analyses tend to overstate the cost of making fuel-economy improvements because they do not adequately take into account synergistic effects such as those between the reduction of the power needed at the wheels and the consequent reduction in the size of the engine needed. We have calculated that as a result of such effects the cost to new-car buyers of each additional fuel-economy improvement should be less than $1 per gallon of fuel saved until average fuel economies in the range of about 60 m.p.g. have been achieved.

This does not necessarily mean, however, that Americans will be adequately motivated by rising fuel costs to buy the kinds of fuel-efficient vehicles we have described. For example, the difference in fuel consumption between a 40-m.p.g. car and a 60-m.p.g. one is .0083 gallon per mile, which even for fuel costing $2 per gallon amounts to a saving of only 1.6 cents per mile (compared with the total cost of about 25 cents per mile to own and operate one of today's light vehicles). Even if the 60-m.p.g. car cost no more than the 40-m.p.g. one, it is easy to imagine that a new-car buyer would be willing to forgo such a small saving (about $170 per year) for the pleasures of having, for example, a much more powerful engine. If the 60-m.p.g. car cost a few hundred dollars more, the temptation would be greater still, even though the fuel savings would pay back the extra cost in about two years. This, of course, is what has happened historically. Even in Europe, where in the mid-1970's gasoline prices were already close to $2 per gallon in 1980 dollars, average passenger-car fuel economy did not exceed 25 m.p.g.

The automobile industry for its part should not be expected to move to the production and promotion of more fuel-efficient vehicles unless the "invisible hand" of the market forces it to. Although ultimately it may not cost any more to produce a light, fuel-efficient vehicle than it does a heavy, powerful fuel waster, retooling to manufacture a new generation of cars will cost tens of

FACTOR	APPROXIMATE VALUES IN U.S. FOR 1980 MODEL YEAR		PROJECTED FEASIBLE AVERAGE BY 1995	
	AVERAGE	BEST	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY
TEST WEIGHT (POUNDS)				
2-PASSENGER	2,900	2,250	1,500	1,050
4-PASSENGER	2,700	2,000	2,000	1,400
5/6-PASSENGER	3,700	2,500	2,500	1,750
LIGHT TRUCKS	4,200 (ALL)	2,500	2,500 (PERSONAL)	1,750 (PERSONAL)
FRONTAL AREA (SQUARE METERS)	2.0	1.8	1.8	1.8
AERODYNAMIC-DRAG COEFFICIENT	0.5	0.4	0.4	0.3
TIRE-ROLLING RESISTANCE (POUNDS RESISTIVE FORCE PER 1,000 POUNDS WEIGHT)	14	10	8	7
TRANSMISSIONS	3-SPEED	5-SPEED	CONTINUOUSLY VARIABLE	
AVERAGE DRIVE-TRAIN THERMAL EFFICIENCY (PERCENT)	12	20	25	25

ATTRIBUTES OF 1995 VEHICLES have been projected by the authors on the basis of the current best technology and of advanced technology that might reasonably become available. The "average" and "best" values for vehicles built in the 1980 model year are shown for comparison. The main difference between the two projections for 1995 is in weight and aerodynamic drag: vehicles incorporating advanced technology could have curb weight and aerodynamic drag reduced by about a third. This would yield a large gain in fuel economy.

VEHICLE CLASS	FRONTAL AREA (SQUARE METERS)		ENGINE SIZE (HORSEPOWER)		FUEL ECONOMY (MILES PER GALLON GASOLINE EQUIVALENT)	
	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY
2-PASSENGER	1.7	1.6	25	18	81	113
4-PASSENGER	1.7	1.7	31	23	70	96
5/6 PASSENGER AND PERSONAL LIGHT TRUCKS	2.0	1.9	38	28	58	82

FUEL-ECONOMY ESTIMATES have been calculated by the authors for hypothetical 1995 vehicles with continuously variable transmissions and advanced diesel engines. The body and tires incorporate either the current best technology or advanced technology. The lower weight of advanced-technology vehicles allows a reduction of 27 percent in engine size. Because of reduced weight and improved aerodynamics and tires, advanced-technology vehicles are 40 percent more fuel-efficient than those built with the current best technology. Fuel-economy estimates are adjusted downward by 10 percent because diesel fuel holds 10 percent more energy per gallon than gasoline.

billions of dollars beyond routine refurbishing costs. It is not surprising that the U.S. automobile industry, which is already having financial problems as it retools to turn out a fleet of 20-to-30-m.p.g. passenger cars for the mid- to late 1980's, is reluctant even to consider another round of such investments any time soon. Indeed, the report by former Secretary of Transportation Goldschmidt suggests that if there were "any demand for a radically higher efficiency in the North American fleet, be it induced by market or nonmarket forces [in this period], and if the climate for investment has not improved, the attractiveness of overseas production will increase dramatically."

Unfortunately it takes some 15 years to replace substantially all the cars on the road with a new fleet: five years to retool and 10 years to replace the existing fleet. If it is in the national interest of the U.S. to reduce its dependence on imported oil, and if it is recognized that a drastic improvement in the fuel economy of the national automobile fleet is crucial to achieving that goal, then the task is too important to leave to unpredictable market forces alone. We believe, therefore, that it is necessary for the Government to set before the industry long-term goals for improving automobile fuel economy in the post-1985 period.

We believe the Government should also assure the automobile industry that market forces will support the mandated fuel-economy improvements that are desired by committing itself to two measures. First, it should establish a corporate average "gas guzzler" tax, which would specify that when the average fuel economy of the fleet of cars manufactured by a company falls below the established goal, the company will be obliged to pay a tax proportional to the shortfall and to the number of cars it produced. The threat of such a tax would ultimately be reflected in the form of higher prices (to cover the tax) for the least fuel-efficient models. (In other words, the company could cater to a small number of consumers with expensive tastes if it could find them.) Second, the Government should impose a stiff tax on motor-vehicle fuel, following the example of virtually all other petroleum-importing nations. If he is given adequate notice, the average consumer could easily offset both these taxes by buying the most fuel-efficient vehicle consistent with his needs. We would hope that the current antiregulatory mood in Washington would not be allowed to stand in the way of establishing an assured market for a new generation of highly fuel-efficient vehicles.

In order to indicate the potential savings in fuel that are at stake, we shall describe three projections based on three different fuel-economy goals for the fleet of cars that will reach the market in 1995. In each case we assume for the sake of simplicity a constant population of 150 million passenger cars and light trucks that are driven an average of 10,000 miles a year, weighted so that the newer vehicles are driven more than that and the older vehicles less. We consider three possibilities: the average on-the-road fuel economy for new light vehicles stays at the 1985 level of 23 m.p.g. projected by the Department of Energy, it increases to 40 m.p.g. or it increases to 60 m.p.g. between 1985 and 1995 and then levels off.

According to the first scenario, the consumption of fuel by the 150 million cars and light trucks continues to decline beyond 1985 as older, less efficient vehicles are retired, finally leveling off at 85 percent of the 1985 demand, or about 4.4 million barrels per day. According to the second scenario, the consumption of fuel by the year 2005 falls to half of the 1985 demand, or to about 2.5 million barrels per day. And according to the third projection, the consumption in 2005 falls to about 1.7 million barrels per day. The difference between the first scenario and the second would be equivalent to more than the capacity of the Alaska pipeline. Unlike the flow of oil from Alaska or anywhere else, of course, the "flow" of saved fuel could continue indefinitely. If the U.S. light-vehicle population increases much beyond 150 million or if the average number of miles driven per vehicle year increases significantly, these projected figures would be modified accordingly.

Given the prospect that the U.S. supply of domestic petroleum will probably shrink considerably below the present level of 10 million barrels per day in the 1980's and that supplementing the declining supply with synthetics will be extremely costly, we believe the first scenario, which projects an ultimate reduction in light-vehicle fuel consumption of only 1.5 million barrels per day below the current level, makes for a dangerous national policy. We would argue that it is essential to set much more ambitious fuel-economy goals than those currently mandated (27.5 m.p.g. by the EPA's composite fuel-economy test) for the years beyond 1985, rising as rapidly as feasible to a level in the neighborhood of 60 m.p.g. As part and parcel of the higher goals it would be in the national interest to make certain that the domestic automobile industry is not prevented from achieving the desired targets by lack of capital. Over at least the next two decades the flow of saved oil that could be "produced" by the automobile industry is no less great than the flow of liquid fuel that is likely to be produced by the still unborn U.S. synthetic-fuels industry. Not only the capital costs would be less; so too would be the environmental costs. Finally, taking leadership in the international fuel-economy race may be just the prescription needed to revitalize the U.S. automobile industry.

Split Genes

Most genes in higher organisms are discontinuous. The DNA that codes for protein is interrupted by noncoding sequences, whose transcripts are excised to make the messenger RNA that is translated into protein

by Pierre Chambon

The changing concept of the gene is a thread that runs through the entire history of modern biology. Gregor Mendel showed in the 19th century that hereditary "factors" in the germ cells are responsible for the traits of an organism. The Danish biologist Wilhelm Johannsen called those factors genes. In the early part of this century genes were defined as discrete elements arranged in linear order in the chromosomes. Only 35 years ago the nucleic acid DNA was identified as the hereditary material, and in 1953 the structure of DNA was defined, giving physical reality to the gene and implicitly explaining some aspects of its function. In the next 20 years molecular biologists and geneticists, working primarily with the bacterium *Escherichia coli,* learned how hereditary information is encoded in genes and began to understand how it is translated into the proteins that determine the structure and function of cells and organisms.

It became clear that in bacteria, at least, a discrete, contiguous stretch of DNA is a "structural" gene encoding the genetic information to specify the manufacture of a single protein, and that the linear sequence of the subunits called nucleotides in this stretch of DNA corresponds directly to the linear sequence of amino acids in the protein. This principle of colinearity was assumed to apply not only in bacteria but also in higher cells. In 1977 that turned out not to be true. The organization of the gene in mammals, birds and amphibians is fundamentally different from the organization in bacteria: most of the genes are in effect split. The discovery of split genes, along with some other findings of recent years, shows that the genetic apparatus of the cell is more complex, more variable and more dynamic than any of us had suspected.

A molecule of the nucleic acid DNA is a long, thin double helix, each strand of which is a chain of nucleotides. Each nucleotide is characterized by a chemical group known as a base: adenine (*A*), guanine (*G*), thymine (*T*) or cytosine (*C*). Genetic information is encoded in the sequence of those bases. A triplet "codon" of three successive bases corresponds to one of the 20 amino acids that constitute a protein chain. The genetic information is transferred through an intermediary, the similar nucleic acid RNA. A single strand of the DNA is transcribed into a complementary strand of RNA according to base-pairing rules: an *A* of DNA pairs with *U* (for uracil, which in RNA substitutes for the thymine of DNA) and *G* pairs with *C*. The result (in bacteria) is a strand of "messenger RNA" that is translated into protein. Beginning at the initiation codon *AUG* near what is called the 5′ end of the messenger strand and proceeding sequentially to a termination codon near the 3′ end, each RNA codon directs the incorporation of a particular amino acid into a growing protein chain. As I mentioned above, the codons and the corresponding amino acids are colinear.

Since each amino acid is encoded by a three-nucleotide codon, it is easy to calculate that the structural gene coding for an average protein (about 300 amino acids) has a length of about 900 base pairs. Prokaryotic cells (cells without a nucleus) such as *E. coli* have a single chromosome, a DNA molecule some three million base pairs long, or long enough to code for somewhat more than 3,000 proteins. That number is in reasonable agreement with the number of different proteins one would expect to be manufactured in a bacterium. The size of the genome, or the total amount of DNA in a cell, increases (in general) with evolutionary complexity. In eukaryotic cells the DNA is confined within a membrane-bounded nucleus, and in the higher eukaryotes, such as mammals, the genome has a total of three or four billion base pairs of DNA arrayed on a set of chromosomes (46 of them in man). That is enough to code for more than three million proteins, and that number, it became clear some years ago, is not in reasonable agreement with the number of proteins manufactured by a mammal. A variety of indications suggested that the actual number of proteins (and therefore of structural genes) in a mammal is unlikely to be more than 150,000 and may be as few as 30,000. How, then, was one to account for all that DNA?

Studies of the genome in eukaryotic cells provided some explanations. The genetic machinery in eukaryotic cells is different from the machinery in prokaryotic cells. Whereas transcription and translation proceed at the same time and in the same place in prokaryotes, the two processes are separated in space and time in eukaryotes. There the DNA is transcribed in the nucleus, giving rise to a precursor messenger RNA. The precursor molecules are processed in the nucleus (modified at their ends and significantly reduced in size) to form mature messenger RNA, which is exported through the nuclear membrane into the cytoplasm of the cell. In the cytoplasm the mature, shortened messenger is translated into protein.

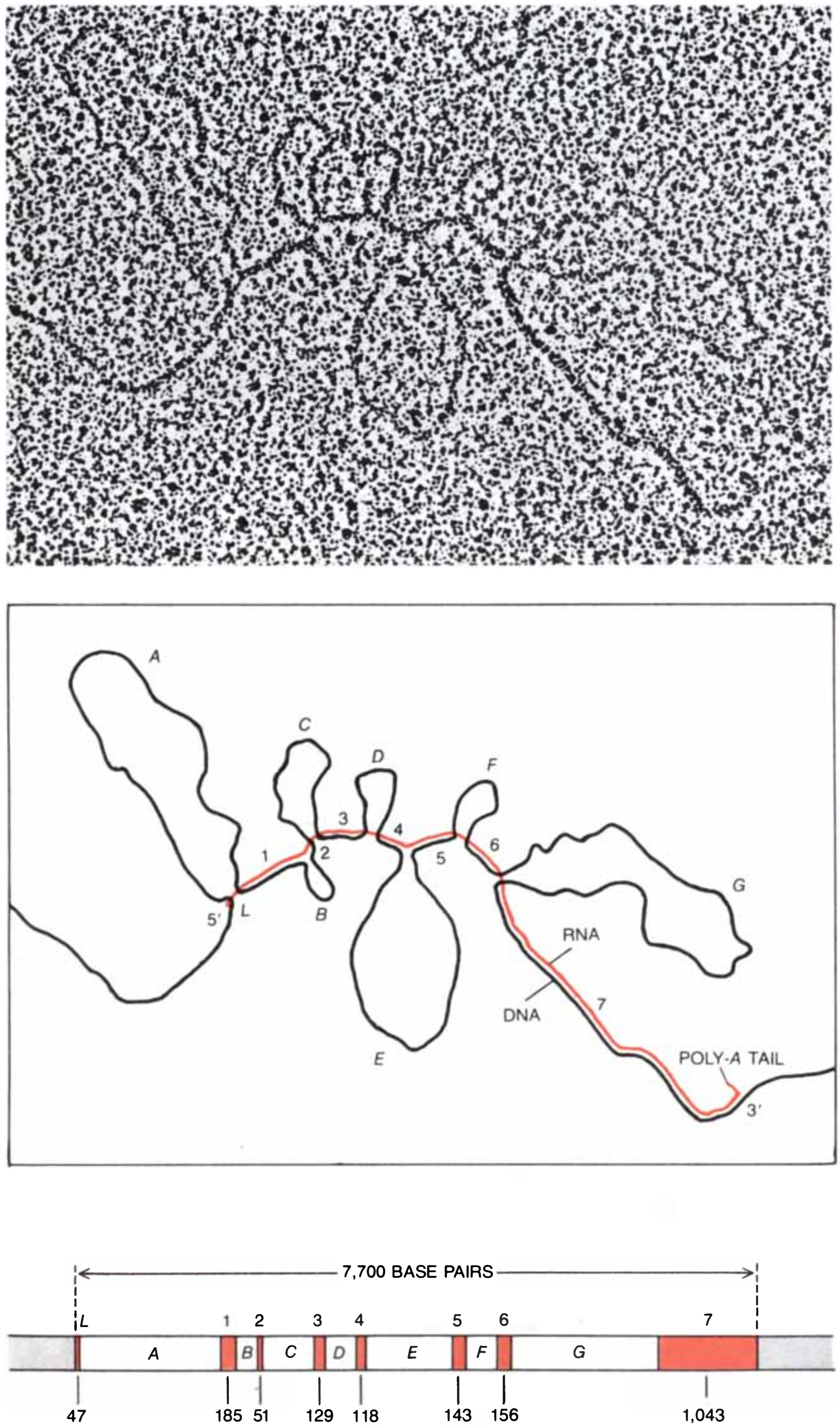
Clearly the processing step could explain some of the discrepancy in higher cells between the amount of DNA and the amount of messenger RNA, and hence the number of proteins. (There were indications of other explanations as well. Some highly repetitive sequences of DNA in eukaryotes, and some "spacers" between repeated genes, are not transcribed into RNA at all; some noncoding DNA must provide regulatory signals for transcription.) A question arose: What stretches of precursor RNA are eliminated in the processing step? Models were proposed that involved trimming at one end of the precursor molecule or at both ends. Until recently, however, it was impossible to test the validity of such models and to correlate the processing with specific modes of organization of the DNA because it was impossible to find and isolate a single gene in a genome comprising several billion base pairs. The prerequisite for further progress was a technical breakthrough: the advent of recombinant-DNA techniques and molecular cloning, which make it possible to obtain large quantities of pure DNA fragments the size of a gene.

To clone a fragment of DNA one "recombines" it with a vector that can be introduced into a host bacterium and multiply in it. The vector can be a plasmid (a circular bit of nonchromosomal bacterial DNA) or a bacteriophage (a virus that infects a bacterium). The vector DNA is cleaved at a unique site by an enzyme called a restriction endonuclease. Some 100 such enzymes are known, each of which recognizes a specific short nucleotide sequence as a unique cleavage site. The fragment to be cloned is inserted into the opened vector-DNA molecule. The recombinant DNA is incubated with a culture of bacterial cells. A few of the cells are "transformed" (by a plasmid) or "transfected" (by a phage), that is, they come to harbor a recombinant-DNA molecule.

Cells harboring such a molecule must then be selected. In thc case of a plasmid vector that is done by incorporating in the plasmid a gene conferring resistance to an antibiotic; only bacteria transformed by a plasmid will live and form colonies when they are grown on a culture plate containing the antibiotic. In the case of a phage vector a transfected cell deposited on a "lawn" of bacteria on a culture plate will leave a plaque, or open space, where the recombinant phage has multiplied and has killed the bacterial cells.

The next step in the purification of a particular DNA fragment is to identify those bacterial colonies or phage plaques that contain the desired fragment. The commonest technique relies on the fact that two single strands of nucleic acid will hybridize, or form a double strand, if substantial lengths of their nucleotide sequences are complementary according to the base-pairing rules. The plasmid-transformed colonies (or the phage plaques) are first transferred to a cellulose nitrate filter paper. The DNA is released in situ from the bacteria (or phage particles) and is denatured (its two strands are separated) by treatment with an alkaline agent; in the process the denatured strands are fixed to the paper.

Next the DNA is exposed to a specific probe, a denatured DNA or an RNA whose sequence matches that of the sought-after fragment and that has been labeled with a radioactive isotope. The probe molecules "reanneal" with any complementary sequences in the recombinant DNA, forming hybrid molecules, and so remain fixed to the paper when the rest of the probe is washed off. The radioactively labeled hybrids are revealed by autoradiography: the paper is placed in contact with a photographic emulsion, and after a long exposure the location of the radioactive isotope (and therefore of the sought-after clone) is revealed as a dark spot on the developed emulsion. This hybridization process is



SPLIT-GENE ORGANIZATION of the gene for the protein ovalbumin is demonstrated by the electron micrograph (*top*) and its map (*middle*). They show the result of an experiment in which a single strand of the DNA incorporating the gene for the egg-white protein ovalbumin was allowed to hybridize with ovalbumin messenger RNA, the molecule from which the protein is translated. In a split gene the DNA sequences that code for a protein are separated by noncoding intervening sequences (introns). The entire gene is transcribed into a "primary" RNA transcript; then the intron transcripts are excised and the coding sequences (exon transcripts) are spliced together to make the messenger RNA. Here the hybrid is enlarged some 180,000 diameters. Segments of the DNA (*black line on map*) and RNA (*color*) that are complementary to each other have become annealed, forming double-strand regions; the DNA sequences in those regions are the eight exons (*L, 1–7*). There are segments of the DNA, however, that loop out from the hybrid, having no complementary sequences in the RNA with which to anneal; they are the seven introns (*A–G*). The two ends of the messenger (5′ and 3′) are indicated, as is a short "poly-*A*" tail at the 3′ end. The schematic representation of the gene (*bottom*) shows the seven introns (*white*) and eight exons (*color*) and the number of base pairs in each of the exons; the size of the introns ranges from 251 base pairs (*B*) to about 1,600 (*G*).

extremely powerful, enabling a single worker to screen several hundred thousand bacterial or phage clones in a single operation. Once a clone has been identified it can be grown in large quantities to supply an unlimited amount of a purified DNA fragment.

When my colleagues at the Laboratory of the Molecular Genetics of Eukaryotes in Strasbourg and I undertook the investigation that led to the discovery of split genes, we were not actually investigating the structure of the gene as such. We were engaged in a study of cell differentiation. In particular we hoped to learn how female sex hormones—the estrogens and the progestins—control the differentiation of cells in the oviduct of a laying hen and the expression of the gene for ovalbumin, the major egg-white protein.

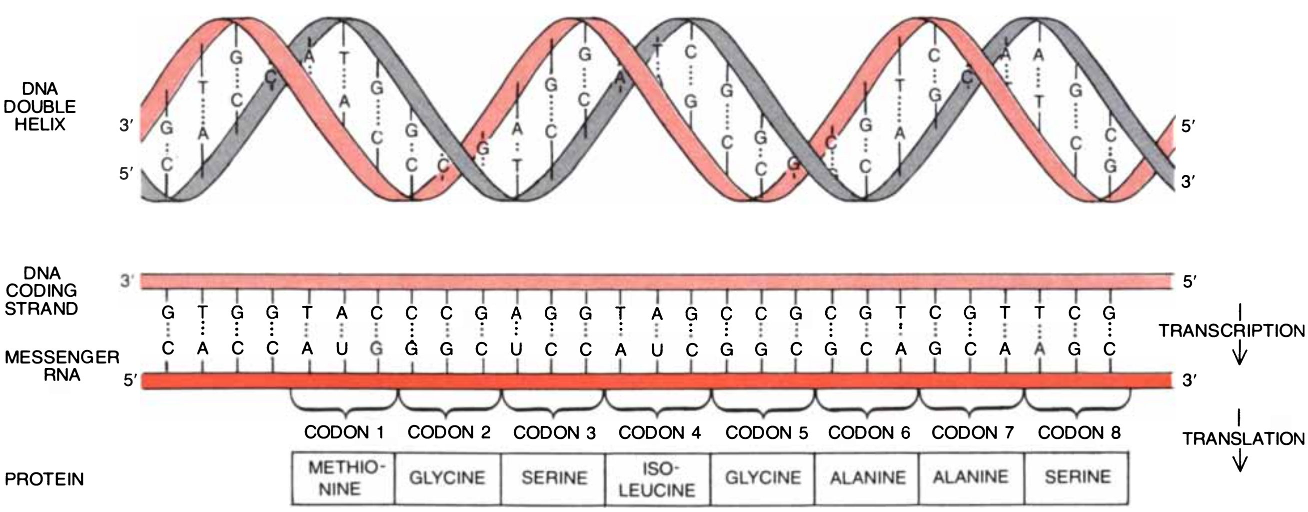
An animal's entire genome is present in every cell nucleus, but only certain genes are expressed (transcribed into messenger RNA) in a given cell at a given time. Ovalbumin, a chain of 386 amino acids, is synthesized only by highly specialized tubular gland cells of the oviduct, and only when a hen is laying. The differentiation of tubular gland cells and the expression of the ovalbumin gene are controlled by the female sex hormones; in the absence of these hormones the gene is not transcribed into RNA, and so the protein is not synthesized. To understand this regulatory process at the molecular level it was necessary to isolate the ovalbumin gene from the specialized tubular gland cells and from other cells in which it is not expressed, and to compare its structure in the two different environments. The availability of recombinant-DNA techniques made that seem feasible, and so we set out to clone the chicken ovalbumin gene.

The first steps were taken by Peter Humphries, Madeleine Cochet, Andrée Krust, Marianne Le Meur and Pierre Gerlinger. Taking advantage of the fact that ovalbumin messenger RNA accounts for as much as 50 percent of the total messenger RNA in laying-hen oviduct cells, they purified the ovalbumin messenger. It is a chain of 1,872 nucleotides, 1,158 of which encode the 386 amino acids of the protein; a 64-nucleotide "leader" at the 5′ end of the RNA and a 650-nucleotide stretch at the 3′ end are not translated. The ovalbumin messenger RNA was copied (by means of a viral enzyme, reverse transcriptase) to form a complementary strand of DNA, which in turn was copied (by means of a DNA polymerase) to form a double-strand DNA—in effect an artificial ovalbumin gene made by working backward from messenger RNA to DNA. The ovalbumin double-strand complementary DNA was recombined with a plasmid and was cloned in *E. coli*. That yielded enough material with which to prepare a restriction-enzyme map of the DNA, a first step toward learning its structure.

To prepare such a map one subjects samples of the DNA in question to a battery of restriction enzymes, analyzes the resulting fragments and thus determines the precise locations along the DNA molecule of each enzyme's specific recognition sites. The pattern of those sites becomes a tool for recognizing the particular DNA and for noting any changes in its structure. One thing we learned about the ovalbumin complementary DNA was that it was not fragmented by the two restriction enzymes designated *Eco*RI and *Hind*III, that is, it did not include either of the two different sequences, each of them six base pairs in length, that are recognized by those enzymes.

The next step was to examine the structure of the ovalbumin gene in the chicken genome itself in order to compare its structure, both in laying-hen oviduct cells and in an unspecialized cell, with its structure as reflected in messenger RNA. At that time the cloning techniques for isolating a gene representing one-millionth of the total genome were in their infancy, and so we decided first to analyze the structure of the ovalbumin gene without isolating it: by identifying it against the background of the total chicken genome. With Richard Breathnach, who had joined our laboratory as a postdoctoral fellow, we cleaved samples of DNA from oviduct cells and from erythrocytes (red blood cells) with *Eco*RI and with *Hind*III.

Among the hundreds of thousands of resulting fragments, we reasoned, some should contain the intact ovalbumin gene because (we thought on the basis of the earlier results with complementary DNA) neither enzyme cleaved that gene; then we would use the cloned complementary DNA as a probe with which to identify the ovalbumin gene. We subjected the fragmented chromosomal



GENETIC INFORMATION flows from DNA to RNA to protein. It is stored in the genes, which are stretches of the DNA double helix. Information is encoded in particular sequences of the four chemical groups called bases, which characterize the constituent nucleotides of DNA. The bases are adenine (*A*), guanine (*G*), thymine (*T*) and cytosine (*C*). The two strands of the helix are joined by hydrogen bonds (*broken lines*) between two complementary bases; *A* always pairs with *T* and *G* always pairs with *C*. Each strand of DNA has a 5′ and a 3′ end, and the two strands have opposite polarity. Information is translated into protein indirectly. First the coding strand of the DNA (*light color*) is transcribed into a complementary strand of the similar nucleic acid RNA, *A* pairing with *U* (for uracil, the RNA counterpart of thymine) and *G* pairing with *C*. Then the RNA is translated into protein. Each successive three-base "codon" calls for the incorporation of a particular amino acid into the protein chain (in this case the first eight amino acids of ovalbumin). In bacteria the RNA transcribed from DNA is itself the messenger RNA that is translated into protein. In organisms higher than bacteria there is an intermediate step, which is not shown here: the primary RNA transcript made in the nucleus of the cell is processed in the nucleus before being exported to the cytoplasm as messenger RNA. It is during this step that intron transcripts are excised and exon transcripts are spliced together.

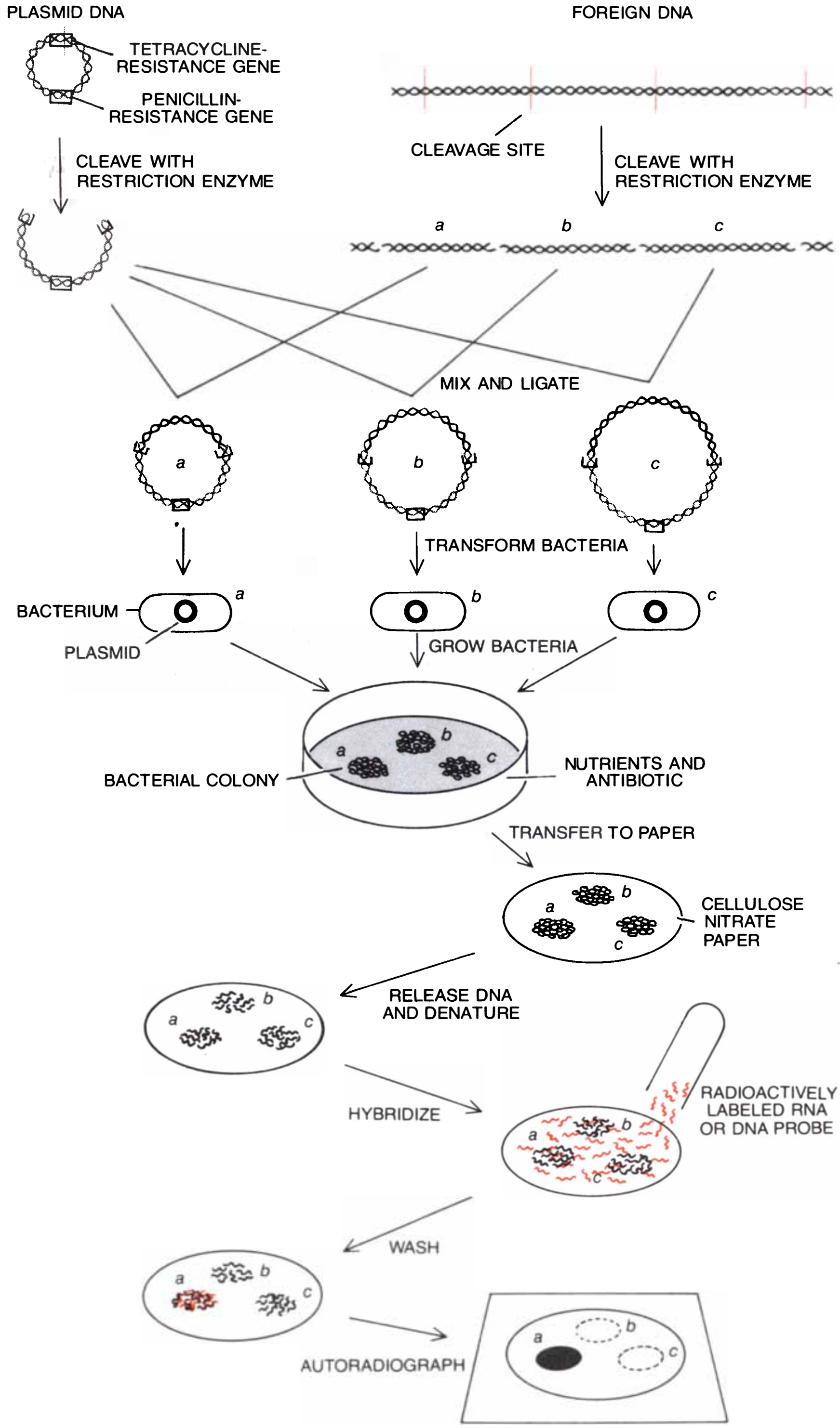
DNA to electrophoresis on an agarose gel, which separates DNA fragments according to their size. When the DNA was stained with a fluorescent dye after electrophoresis, it appeared as a continuous smear running the length of the gel; although the fragments had been sorted by size, they varied in length so continuously that individual groups of fragments of the same length could not be resolved. The problem was to find the ovalbumin gene somewhere in the smear.

We did so by applying a "blotting" technique devised by E. M. Southern of the University of Edinburgh. The DNA fragments on the gel were denatured and then were transferred (blotted) onto cellulose nitrate filter paper and fixed to the paper. Next the probe was applied: ovalbumin complementary DNA, strongly labeled with a radioactive isotope, was poured over the filter paper. Probe molecules that came in contact with chromosomal-DNA fragments having complementary nucleotide sequences became annealed to those fragments and so were bound to the filter paper; the rest of the probe DNA was then washed away. Autoradiography revealed the location of the labeled probe and thus of any ovalbumin-specific chromosomal DNA with which the probe had hybridized.

Because neither *Eco*RI nor *Hind*III had cleaved the ovalbumin complementary DNA we expected that blotting analysis of the fragments generated by either of the enzymes would yield only a single radioactive band, representing one genomic fragment comprising the entire ovalbumin gene. To our great surprise we saw several bands on the film, regardless of whether the fragments had been generated by *Eco*RI or by *Hind*III. The band pattern was the same whether the chromosomal fragments were from oviduct cells or from erythrocytes.

When we reported these findings at a meeting of the European Molecular Biology Organization in the spring of 1977, neither we nor anyone else thought the multiple bands meant the gene for ovalbumin in the chicken genome might be split. The most frequent suggestion was that we were seeing an artifact of blotting or hybridization. Then during a symposium held at Cold Spring Harbor, N.Y., a few months later it was reported that in some viral-DNA molecules the sequences coding for an untranslated stretch at the beginning of the messenger-RNA molecule were separated from the sequences encoding the main body of the messenger. That news encouraged us to think our ovalbumin results, far from being an artifact, might reflect some unexpected anomaly in the structure of the ovalbumin gene.

Breathnach, Jean-Louis Mandel and I began to map the ovalbumin sequence in the chicken genome. By probing the genome with restriction enzymes that

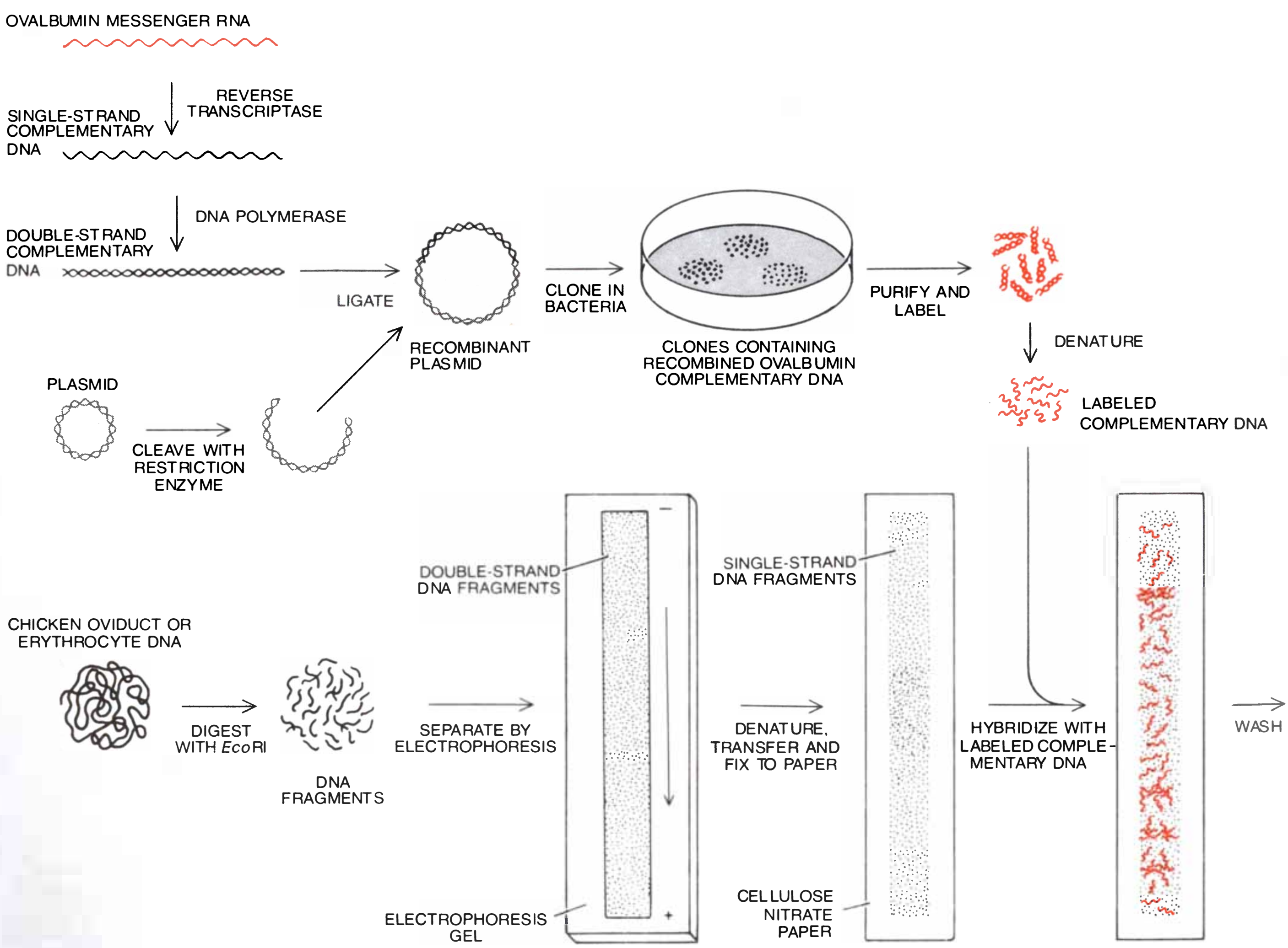


MOLECULAR CLONING calls for the insertion of a fragment of foreign DNA into a vector (in this case a plasmid, a small circle of bacterial DNA) that serves to introduce the fragment into bacteria, where it replicates. The plasmid and the foreign DNA are cleaved with a restriction endonuclease, an enzyme that cuts DNA at a unique site within a particular base sequence in a way that leaves complementary overlapping single-strand ends. Incubation of the fragments with the plasmids leads to the annealing of a fragment with a plasmid by base pairing at these ends. After ligation the recombined plasmids are introduced into bacteria. Colonies containing a plasmid are identified by their resistance to antibiotics; in the case illustrated here they will be resistant to penicillin but sensitive to tetracycline. Then it is necessary to identify, by hybridization, colonies containing a particular foreign-DNA fragment. The colonies are transferred to a filter paper, the cells are broken open and their DNA is denatured (separated into single strands) and fixed in place. A probe is added: an RNA or DNA complementary to the desired fragment (in this case *a*) and labeled with a radioactive isotope. The probe anneals to any complementary sequences, forming a hybrid molecule and thus becoming fixed to the paper. The rest of the probe is washed away. When a photographic emulsion is exposed to the paper, a dark spot on the emulsion identifies clone *a*, which contains desired fragment *a*.

had target sites both in the complementary DNA and in the chromosomal DNA we could relate corresponding sites in the two DNA's to each other. In this way we found, for example, that the chromosomal *Eco*RI fragment we had designated *b* includes the sequences coding for the first 500 nucleotides of the messenger RNA, whereas the sequence coding for the last part of the messenger molecule is in fragment *a*. We went on to develop a detailed restriction-enzyme map of the gene found in the chicken genome and compared it with the complementary-DNA map, which reflected the structure of the messenger RNA.

By the end of the summer it was evident that the DNA coding for ovalbumin messenger RNA in the chicken genome is interrupted by other DNA that is not represented at all in the ovalbumin messenger RNA. What was still more striking was that (in contrast to the earlier report dealing with viral DNA) some of the interruptions come in the midst of DNA sequences coding for messenger RNA that is ultimately translated into protein. In other words, the gene's protein-coding sequences themselves are split. At about the same time groups headed by R. A. Flavell of the University of Amsterdam and by Philip Leder of the National Institute of Child Health and Human Development in the U.S. came to the conclusion that in the rabbit and the mouse the messenger-RNA coding sequence of the gene for beta globin (a component of the hemoglobin molecule) is similarly interrupted; Susumu Tonegawa of the Basel Institute for Immunology found an analogous phenomenon in some immunoglobulin (antibody) genes. N. H. Carey of the G. D. Searle Research Laboratories in Britain and his colleagues independently reported results suggesting that the ovalbumin gene might be interrupted. It became apparent that the split-gene organization of genes coding for proteins is not uncommon in eukaryotic genomes.

The resolving power of restriction-enzyme mapping by blotting and hybridization was too low to completely reveal the organization of a split gene. For more detailed analysis of the chromosomal ovalbumin gene we had to isolate it from the other chromosomal DNA, and improved molecular-cloning techniques soon made that possible. In

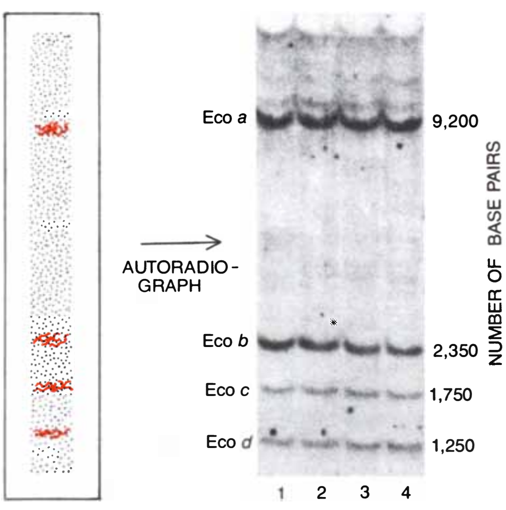


UNEXPECTED STRUCTURE was shown for the ovalbumin gene by a "blotting" experiment in which the chicken genome (the total DNA of a cell) was digested with the restriction enzyme *Eco*RI; the resulting fragments, sorted according to size by electrophoresis, were probed with a DNA complementary to ovalbumin messenger RNA. To prepare the probe the 1,872-nucleotide messenger RNA (*top left*) was transcribed by the enzyme reverse transcriptase into a complementary DNA strand, which was then made into a double-strand DNA that was inserted into a plasmid; the recombined DNA was cloned in bacteria, labeled with a radioactive isotope and denatured. Chromosomal DNA from chicken erythrocytes (red blood cells) or oviduct cells (*bottom left*) was cleaved with *Eco*RI into some 500,000 fragments from 1,000 to 15,000 base pairs long. The fragments were applied to the end of one lane of an agarose gel and were separated by electrophoresis; the smaller the fragments were, the farther they migrated through the gel toward the positive electrode. The DNA fragments were denatured and transferred by blotting to filter paper, which binds single-strand DNA. Then the probe was applied. The probe annealed to fragments having sequences complementary to it (and hence to ovalbumin messenger RNA). It was expected to anneal

collaboration with Philippe Kourilsky of the Pasteur Institute and his colleagues we cloned the *Eco*RI fragments of chicken DNA in phage lambda; we also took advantage of a "library" of chicken-genome recombinants (a collection of lambda-phage recombinants containing fragments representing the entire chicken genome) that had been developed by Jerry B. Dodgson of the California Institute of Technology, Judith Strommer of the University of California at Los Angeles and James D. Engel of Northwestern University. We isolated several clones containing either the ovalbumin gene or some of its *Eco*RI fragments by probing with the ovalbumin complementary DNA. Frank Gannon, Jean-Paul Le Pennec, Cochet and Fabienne Perrin denatured a recombinant DNA containing the complete ovalbumin gene. Then they mixed it with purified ovalbumin messenger under conditions that facilitated the hybridization of DNA with RNA while preventing the reannealing of DNA to DNA.

Electron micrographs of the resulting hybrids gave striking visual evidence of the split-gene organization. The DNA (the ovalbumin gene) was annealed only in part to the RNA (the ovalbumin messenger). Seven unhybridized regions of DNA looped out of the DNA-RNA hybrid molecule, having failed to "find" complementary nucleotides with which to anneal [*see illustration on page 61*]. The seven loops represent seven DNA sequences that interrupt the DNA coding for ovalbumin messenger RNA. These untranscribed intervening sequences, or "introns," split the transcribed DNA into eight pieces, called "exons."

An intron less than 50 or so base pairs long would not have been revealed by the examination of the hybrid molecules in the electron microscope. To make sure there were no interruptions in the ovalbumin gene other than the looped segments visible in the micrographs it was necessary to compare the complete nucleotide sequence of the exons with the sequence of ovalbumin messenger RNA. We sequenced the cloned ovalbumin complementary DNA by the method devised by Allan M. Maxam and Walter Gilbert of Harvard University and thereby established the entire sequence of the ovalbumin messenger. The triplet codons of that RNA turned out to code for a chain of amino acids that was in excellent agreement with the amino acid sequence established for ovalbumin by investigators who had analyzed the protein directly—a much more laborious task. Our RNA result also agreed with the ovalbumin messenger sequence determined independently by Bert W. O'Malley of the Baylor College of Medicine and George G. Brownlee of the Medical Research Council Laboratory of Molecular Biology in Britain. These agreements indicated that either no mistakes or very few had been introduced into the nucleotide sequence in the course of cloning. (The agreement between amino acid sequencing and nucleotide sequencing also indicates, incidentally, that whenever a structural gene can be cloned, the sequencing of DNA is the method of choice for learning the amino acid sequence of the protein the DNA encodes.)



to one band of fragments containing the ovalbumin gene (because it was known that *Eco*RI does not cleave the ovalbumin messenger's complementary DNA). Autoradiography revealed, however, not one band of annealed radioactively labeled fragments but four bands (*Eco a–d*). They were in the same positions whether the chromosomal DNA had been derived from the chicken erythrocytes (*lanes 1 and 2*) or from the oviduct cells (*lanes 3 and 4*).

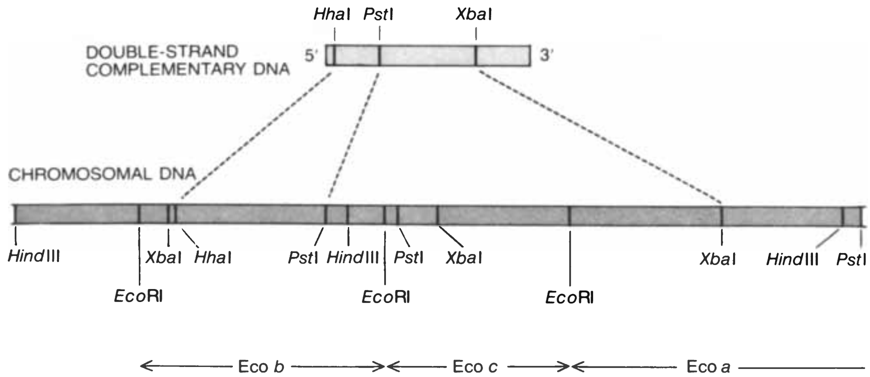
Cristophe Benoist, Kevin O'Hare and Breathnach then compared the ovalbumin messenger-RNA sequence with the DNA sequences of all the ovalbumin exons. They found that the first nucleotide of the messenger is encoded at the 5′ beginning of the first exon (*L*) and that the last nucleotide of the messenger is encoded at the 3′ end of the last exon (No. 7). No further interruptions were found in any of the eight exons.

This established that the chicken ovalbumin gene (that is, the DNA region containing all the sequences that encode ovalbumin messenger RNA) is made up of eight exons, between each of which there is an intron having no counterpart in the messenger. The sequence study confirmed that the order of the exons in the DNA is the same as the order of their transcripts in the messenger RNA (and hence of the amino acids they specify; to this extent colinearity, although interrupted, is preserved). The total length of the ovalbumin gene, from the region encoding the 5′ beginning of the RNA to the region encoding its 3′ end, is about 7,700 base pairs. That is about four times longer than the final messenger RNA (1,872 base pairs) and almost seven times longer than the stretch of messenger that is translated into protein (1,158 base pairs).

Having found a split gene, we wondered whether the split structure could be modified in the course of the differentiation of oviduct cells, the original subject of our investigation. Gannon, Perrin and Jean-Marc Jeltsch compared the ovalbumin gene cloned from oviduct DNA with the same gene cloned from the erythrocyte DNA of laying hens. They found no evidence that the gene is significantly rearranged in the course of differentiation, even at the precise level of DNA sequence. Their results agreed with those obtained in other laboratories for other genes that are expressed only in highly specialized cells, such as globin and a silkworm protein, silk fibroin. Tonegawa, Leder and others have shown conclusively, however, that the split genes for immunoglobulins are indeed rearranged in the course of the differentiation of lymphocytes (the blood cells in which they are expressed), and that the rearrangement plays a key role in generating the enormous diversity that characterizes immunoglobulins.

Most of the protein-coding genes of mammals, birds and amphibians that have been analyzed so far have been found to be split. (Among the notable exceptions are the genes for histones, proteins closely associated with DNA in the chromosome, and for interferons.) A few split genes have been found in insects and in lower eukaryotes such as yeast, but splitting seems to be far commoner in the higher organisms. There have been suggestions that the split structure may be peculiar to genes coding for proteins synthesized only in highly specialized cells. Such genes were (largely for technical reasons) the first to be examined, but by now it has been shown that some "housekeeping" genes—those required for the day-to-day life of every cell—are also split. In general the introns of split genes are longer than the exons. There seem to be no rules setting an upper limit on the length of an intron or on the number of introns compatible with a given length of messenger RNA. Introns several thousand base pairs long have been found; we have counted 16 introns in the chicken gene for the protein ovotransferrin, and Robert T. Schimke of Stanford University has reported that one mouse gene is more than 20 times longer than its messenger.

The split-gene organization is not confined to protein-coding genes. It was actually first discovered by David S. Hogness of the Stanford University School of Medicine in genes coding for ribosomal RNA in the fruit fly *Drosophila*. (Ribosomal RNA is a constituent of the ribosome, the cellular organelle on which messenger RNA is translated into



SPLIT STRUCTURE of the ovalbumin gene was revealed when a restriction-enzyme map of the double-strand complementary DNA made from messenger RNA (*top*) was compared with the map of the ovalbumin gene in chicken chromosomal DNA (*bottom*). The maps were made by dissecting the DNA's with various enzymes, separately and in combination, and determining the size of the fragments and their order in the DNA by blotting experiments. The enzyme *Eco*RI cleaved this version of the gene into three fragments (*a, b, c*), but it did not cleave the complementary DNA, showing that the sequences coding for the messenger RNA must be separated in the chromosomal gene. The splitting was confirmed by absence of any *Hind*III site in complementary DNA and by comparison of corresponding sites (*broken lines*) on the two maps.

protein.) Some genes for transfer RNA, a third kind of RNA that participates in translation, are also split, but their introns are very small.

How is a single, continuous messenger RNA generated from a split gene? Several possible mechanisms can be imagined. The fact that RNA molecules have been observed within the nucleus that are longer than their cytoplasmic messenger-RNA counterparts suggests that the enzyme RNA polymerase first makes a continuous, colinear "primary" transcript of the entire gene, introns as well as exons; the intron transcripts are thereupon excised from this precursor RNA and the exon transcripts are ligated to form the mature messenger RNA. Such a mechanism, referred to as RNA splicing, was first supported by analysis of the primary transcript of the beta globin gene and of certain genes of the adenoviruses, which subvert the cell's machinery for their own transcription; most likely it is the same in all protein-coding split genes.

In the case of the ovalbumin gene the complete primary transcript would be expected to be about 7,700 nucleotides long, the total length of the exons and introns. O'Malley and we have found just such RNA molecules (and none longer than that) in the nucleus; the ovalbumin gene and this primary transcript are superposable. We also find in the nucleus a number of RNA molecules with various lengths intermediate between the length of the primary transcript and that of the final messenger RNA, which suggests the splicing is done stepwise, each step generating progressively shorter intermediates.

We have been able to examine the structure of such splicing intermediates by hybridizing nuclear RNA with the cloned ovalbumin gene. In one electron micrograph, for example, the intermediate is clearly an RNA from which the transcripts of introns *A, B, C, D* and *G* have been removed, whereas those of introns *E* and *F* are still present. There is evidence that splicing takes place mainly (or perhaps exclusively) after a primary transcript has been modified by the addition of a methylated-guanine "cap" at the 5′ end and a tail of adenine nucleotides (poly-*A*) at the 3′ end; such modification is characteristic of messenger-RNA molecules. All these events appear to take place in the nucleus; neither the primary transcript nor the processing intermediates are found in the cytoplasm.

What is the actual machinery of splicing? There must be at least one enzyme that recognizes the sites to be cleaved. The targeting must be precise, since even a one-nucleotide miss would give rise to a meaningless messenger RNA by shifting the "reading frame" and thereby changing the triplet codons. Assuming that the splicing enzyme recognizes certain base sequences at the junctions between introns and exons, we examined the junctions in the ovalbumin gene. We found some striking similarities in sequence. Each intron transcript begins with the sequence *GU* (*GT* in the corresponding DNA strand) and ends with *AG*. That is true not only for ovalbumin but also in all 90 exon-intron junctions sequenced so far in eukaryotic genes. Other "consensus" sequences are present near the junctions in most cases, but not in all.

The specificity of splicing can probably not be accounted for by the invariant two-nucleotide sequences and the consensus sequences alone. The sequence information may be supplemented by some structural feature, such as a particular folded configuration of the RNA. The transcript is associated with proteins that may somehow contribute to splicing specificity. Perhaps there is a small helper, a "splicer RNA" that has sequences complementary to the consensus sequences and bridging them. In any case the generality of the *GU-AG* rule and the presence of the consensus sequences indicate that all the splicing enzymes processing precursor messenger RNA's in present-day eukaryotic organisms have evolved from a single ancestral enzyme. The commonality of the enzyme-RNA relation is illustrated by our finding that when the primary transcript of the chicken ovalbumin gene is introduced into mouse cells in culture, the transcript is spliced correctly by the mouse splicing machinery. The *GT-AG* rule does not apply, however, in the split genes for transfer RNA's or ribosomal RNA's. It appears that each of the three classes of RNA has its own class of splicing enzymes.

We have learned, in collaboration with Kourilsky's group, that the ovalbumin gene is a member of a family of three closely associated and similar genes. The first indication of this family association came when Kourilsky's associate Axel Garapin was cloning the ovalbumin gene. He isolated one clone, which he called *X*, that hybridized only weakly with the ovalbumin complementary-DNA probe. In our laboratory Mandel and others showed that clone *X* harbored a fragment of an ovalbumin-like gene. We exploited a new kind of cloning vector called "cosmids," constructed by John Collins of the Society for Biotechnological Research in West Germany and Barbara Hohn of the University of Basel, to explore the neighborhood of the ovalbumin gene. Cosmids, which combine some of the properties of plasmids and lambda phage, enable one to manipulate clones containing very large recombinant-DNA molecules. Electron micrographs of hybrids formed by annealing the DNA of one such clone to the total messenger RNA of laying-hen oviduct cells revealed that a section of the chicken genome some 40,000 base pairs long contains not only the ovalbumin gene but also two other genes. One of them was identical with the *X* gene; we called the other one *Y*.

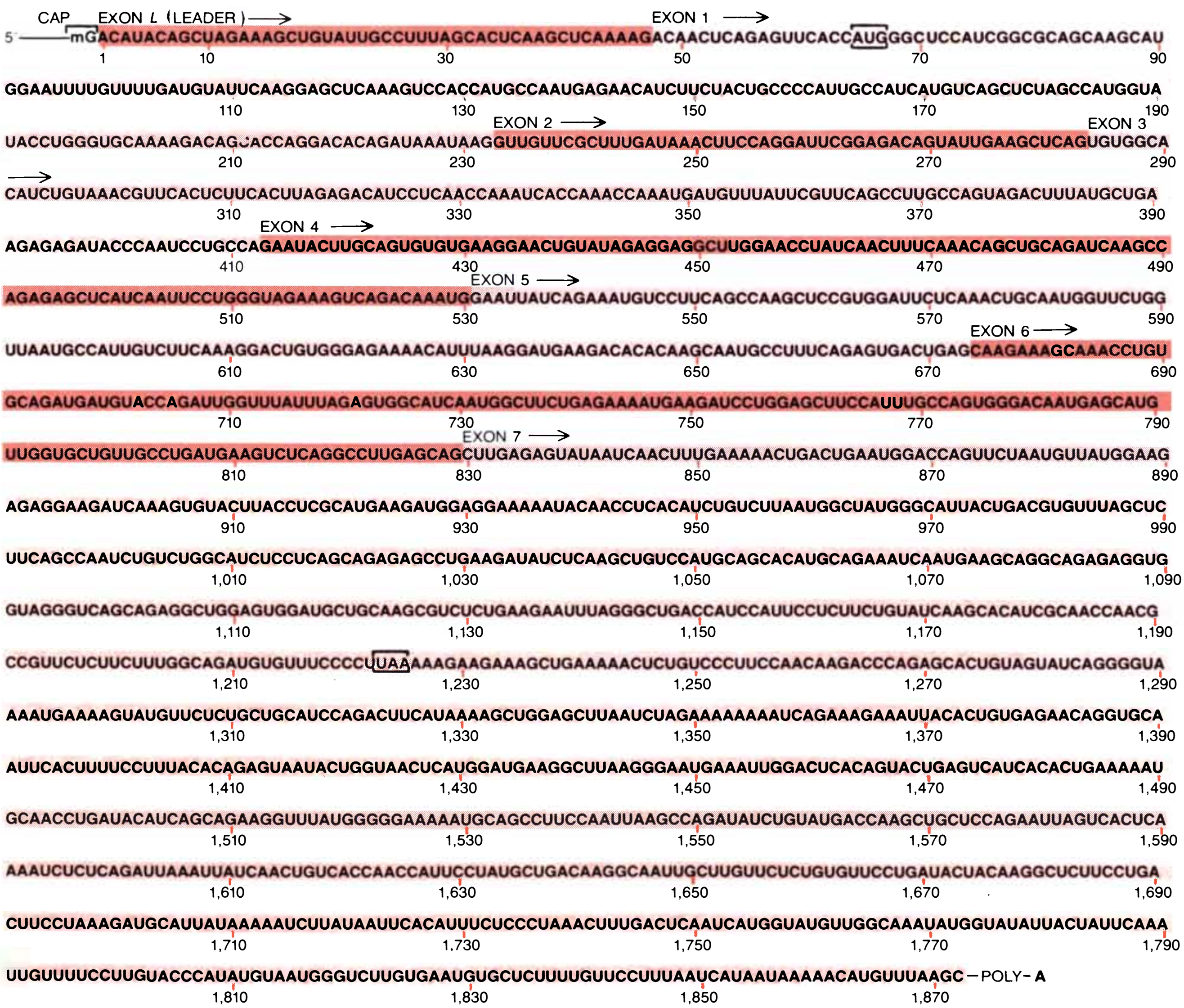
Further analysis by electron microscopy and DNA sequencing reveals that both *X* and *Y* are split into eight exons whose lengths and sequences are similar to those of the eight corresponding ovalbumin exons. In contrast, although the number and positions of the introns are the same in the three genes, the length and the sequence of analogous introns differ from gene to gene; only the typical splicing consensus sequences are well conserved. There is no doubt that the *X*, *Y* and ovalbumin genes arose from duplication of a single ancestral gene that had the same eight-exon structure. By considering the number of differences in the three sequences and the usual rate of mutation we have calculated that *X* and the ovalbumin gene arose by duplication some 50 million years ago. The globin multigene family, which has been studied intensively in other laboratories, offers another example of the striking conservation of an exon-intron pattern in the course of evolution. The sequences coding for messenger RNA in the alpha and beta globin genes, which apparently arose by duplication some 500 million years ago, are interrupted by two introns that are at identical locations in the two genes.

From all the available comparative evolutionary data it appears that protein-coding exonic sequences evolve slowly, mainly by point mutations in which one base replaces another, whereas such noncoding sequences as introns evolve much faster by insertion and deletion events of variable extent; insertions and deletions probably tend to be eliminated by natural selection in the exons. In other words, split genes seem to be made up of rather stable protein-coding elements embedded in a rapidly changing environment.

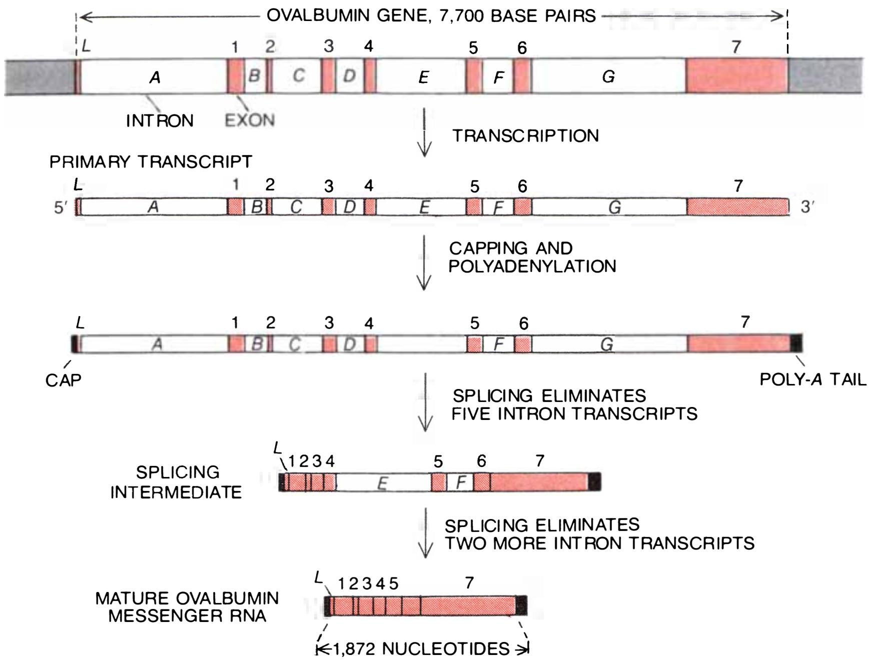
Such an environment turns out to account for a substantial fraction of the DNA in the ovalbumin region of the chicken genome. Apparently no more than 9 percent of the 40,000-base-pair stretch that includes the *X, Y* and ovalbumin genes codes for amino acids. If a comparable mode of organization characterizes the entire genome of the chicken and of other higher eukaryotic organisms, it could account at least to a considerable extent for the observed discrepancy between the size of the genome and the number of genes.

I mentioned above that in the case of the ovalbumin gene and other genes there is no evidence that the split-gene organization plays a role in differentiation by rearranging the gene, whereas in the case of the immunoglobulin genes it seems to do just that. Are there other ways in which the presence of introns might have a function in gene regulation? The prevalence of the *GU-AG* rule makes it seem unlikely that gene expression is controlled by the presence or absence of various splicing enzymes. Perhaps, however, the splicing machinery is more complex than it appears to be; possibly only a basic splicing enzyme is common to all cells and species, with some more specific element—a protein or a small splicer RNA—selectively modifying the rate of splicing. Purification of the splicing machinery will be required before this possibility can be explored.

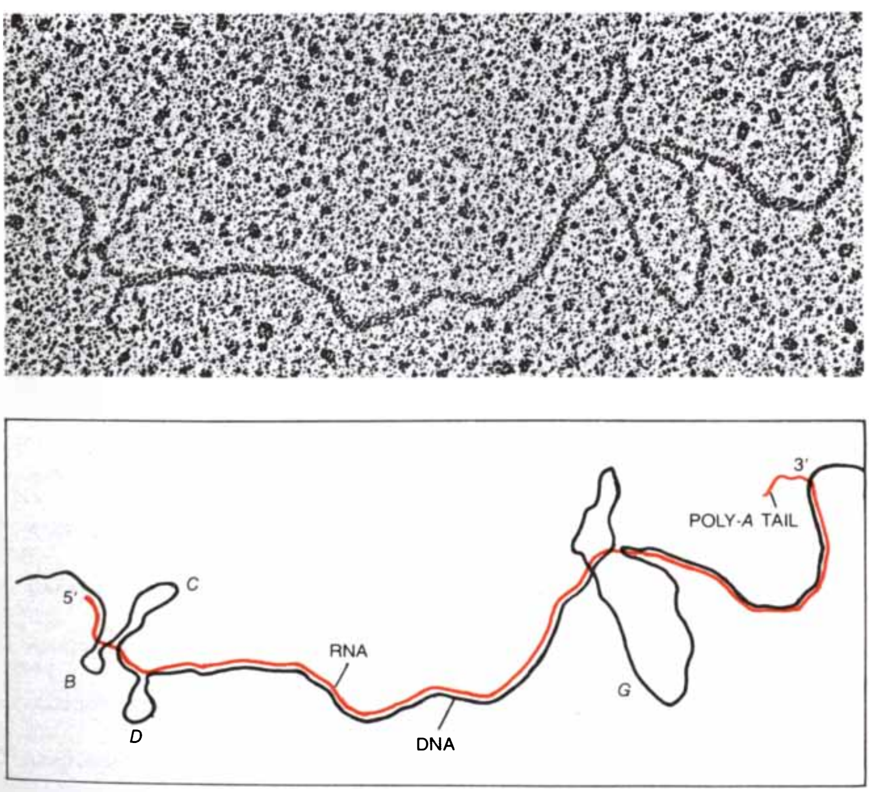
Splicing does seem to do more than simply remove intron transcripts; it may be a requirement for the stabilization of the RNA and its transfer from the nu-



BASE SEQUENCE of the 1,872-nucleotide ovalbumin messenger RNA (equivalent to the exons of the chromosomal gene) was determined and is shown here. The methylated cap nucleotide at the 5′ end is indicated, as are the eight exons and the poly-*A* tail at the 3′ end. The boxed codons *AUG* and *UAA* are respectively the signals for the initiation and the termination of translation; the RNA coding for ovalbumin's 386 amino acids (bases No. 65 through No. 1,222) is preceded and followed by untranslated sequences of messenger RNA.



MATURE MESSENGER RNA is produced in a number of steps. First the entire ovalbumin gene is transcribed into a precursor RNA, the primary transcript. The transcript is capped at the 5′ end and a poly-*A* tail is added at the 3′ end. Then the transcripts of the introns are excised and the adjacent exon transcripts are ligated in a series of splicing steps; an intermediate, from which five of the seven intron transcripts have been eliminated, is illustrated. These steps are accomplished in cell nucleus. After splicing, mature messenger is transferred to cytoplasm.

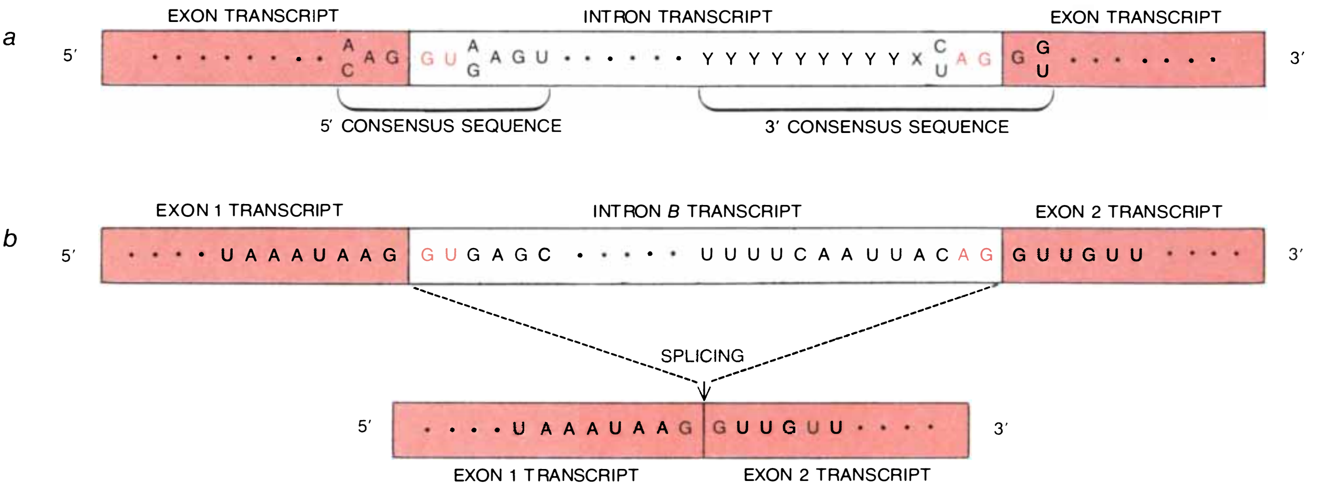


SPLICING INTERMEDIATE is enlarged 180,000 diameters in an electron micrograph and is diagrammed in a map. The intermediate is a hybrid formed by the coding strand of the cloned ovalbumin-gene DNA (*black*) and a partially processed RNA molecule (*color*). The loops *B, C, D* and *G* are single-strand gene segments corresponding to four introns that have been spliced out of the RNA transcript; the thicker segments are double-strand hybrids formed by the annealing of the DNA to the exon transcripts and to the transcripts of introns *E* and *F,* which have not yet been excised. (The intron-*A* transcript has been excised from the RNA, but no corresponding loop of DNA is seen because exon *L* is very short and so its hybrid is unstable.)

cleus to the cytoplasm. Several groups working in the U.S. have shown that stable messenger RNA is not produced when an intron in a gene of the monkey virus SV 40 is precisely excised from the viral genome by the experimenter prior to infection. It is not the entire intron sequence that seems to be important, however, but merely the sequences at and close to the intron-exon junctions. Apparently, then, it is the splicing event as such, rather than the particular sequence of the intron, that is important. One possibility is that the splicing machinery lies in the nuclear membrane, so that only RNA's that are spliced can be transferred through the membrane into the cytoplasm. One trouble with this hypothesis is that not all protein-coding genes in eukaryotes are split. Moreover, if one splicing event is enough to ensure the biogenesis of stable RNA, it follows that most introns may have no role in the process.

There is no evidence that the RNA originally transcribed from the ovalbumin gene or the other split genes studied so far (except possibly some immunoglobulin genes) can be spliced in various ways to produce messenger RNA's coding for different proteins. Among the DNA viruses, however, there are clear-cut cases in which several different proteins are specified by a given region of the genome depending on how the primary transcript is spliced. Some of the RNA sequences that are spliced out in one messenger RNA are preserved in another messenger; intronic sequences become exonic and exonic ones become intronic as the junctions between the two are redefined. F. H. C. Crick of the Salk Institute for Biological Studies has argued that such multiple-choice splicing is largely confined to viruses, which are short of DNA, and is likely to be rare in the chromosomal genes of eukaryotic cells, whose DNA content is not limited. Gilbert and Tonegawa have suggested, on the other hand, that multiple choice may be important in evolution because it allows a new gene product to be synthesized and at the same time preserves the old product.

Might an intron sometimes be a gene within a gene? No such cases are known for chromosomal genes. Piotr P. Slonimski of the Center for Molecular Genetics at Gif-sur-Yvette and his colleagues have, however, found what may be such an intron in the mitochondria (cellular organelles that have their own genetic apparatus) of yeast. Some mutations in one intron of the mitochondrial split gene for cytochrome *b* affect the splicing of the RNA transcribed from the same gene. It seems likely that before being excised at least part of this intron transcript makes messenger RNA coding for a small protein chain that has a role in the splicing of the entire transcript. Some introns, in other words, may take part in regulating the splicing



SPLICING JUNCTIONS between exons and introns were sequenced for 90 introns in a number of different genes. The sequences most often found are illustrated (*a*). Every intron transcript examined begins with *GU* and ends with *AG;* other "consensus" sequences are present in most cases but not all. Here two bases are indicated where they are found at about the same frequency. A *Y* stands for either *C* or *U* and an *X* for any of the four bases. The *GU-AG* rule is illustrated by the sequences at junctions of intron *B* in ovalbumin transcript (*b*).

of their own transcript. It remains to be seen whether or not this is a peculiarity of some genes in mitochondria, which like viruses have only a limited supply of DNA.

What remains to be discussed is how split genes and splicing arose in the course of evolution. The most likely mechanism would appear to be the gene-shuffling event known as unequal crossing-over. The usual "equal" form of crossing-over is a frequent event in the course of meiosis, a stage of sexual reproduction. Two members of a chromosome pair line up, break at corresponding points and exchange homologous segments (segments that have the same genetic function and about the same DNA sequence), which "recombine" by complementary base pairing. Homologous crossing-over shuffles alleles, or variants, of the same gene and thereby promotes genetic diversity. In unequal crossing-over, a somewhat rarer event, the chromosomes are not perfectly aligned; nonhomologous segments cross over and recombine by means of some still uncertain process of "illegitimate" recombination, giving rise to more radical rearrangements of the DNA, including the duplication of genes.

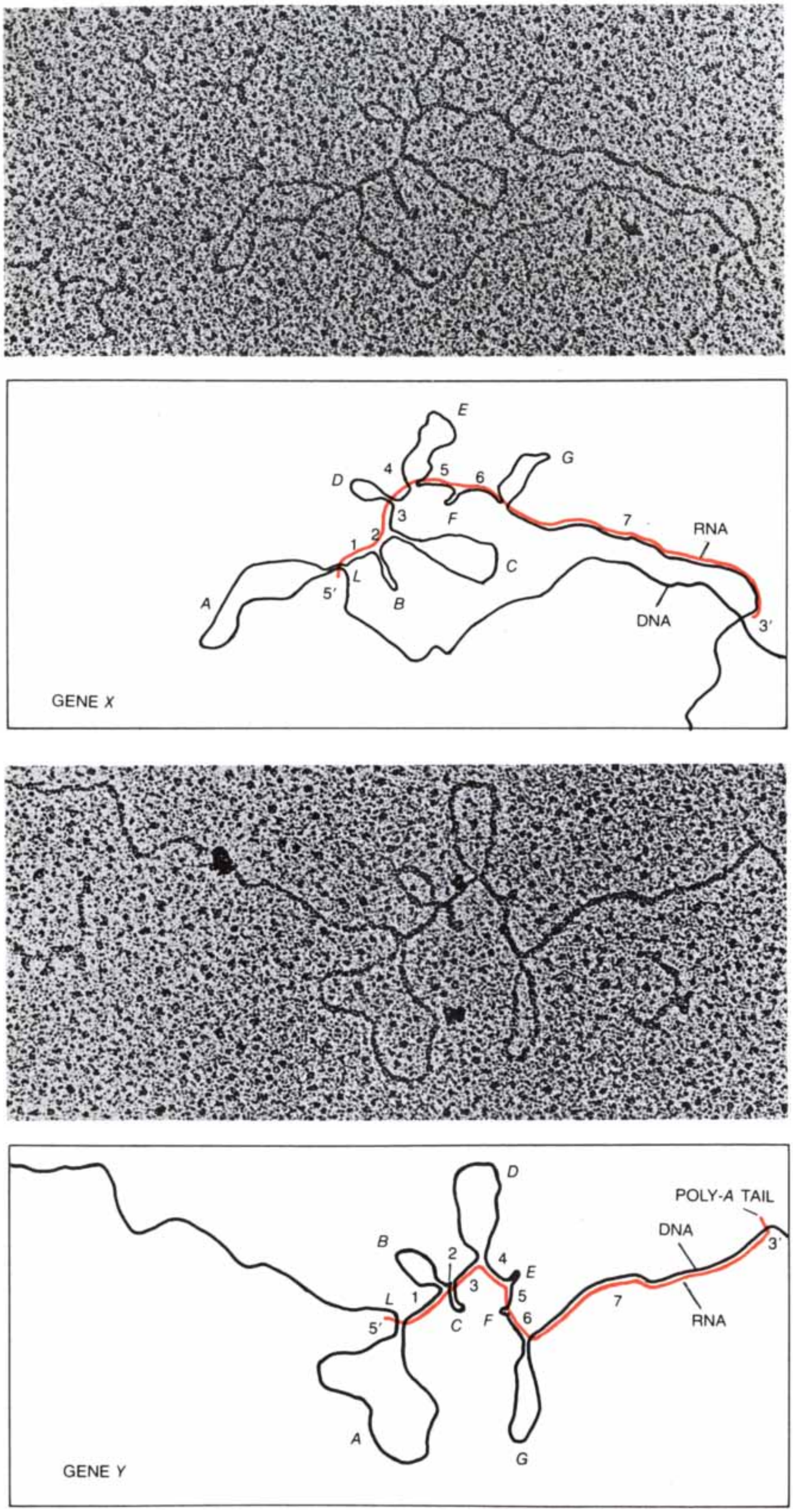
Many students of evolution at the molecular level believe the duplication of genes by unequal crossing-over has had a major role in such evolution. They propose that most present-day genes have evolved through duplication from a few ancestral genes, so that most present-day proteins are descended from a few primordial proteins. "Discrete" duplication yields two separated but identical genes. Mutations in one of the copies may generate a new protein while the other copy continues to specify the original protein, thereby expanding an organism's repertory of proteins. In "fused," or contiguous, duplication segments corresponding to a complete or a partial duplication of the original gene become combined, yielding a single elongated gene that specifies a new protein product.

Examination of multigene families leaves no doubt that discrete duplications of ancestral genes that were already split identically or similarly can account for the origin of many present-day split genes. Duplication may also explain the origin of the split ancestral genes themselves. Tonegawa and his colleagues, noting that homologous protein "domains" in some immunoglobulin chains are encoded by a series of homologous exons, have proposed that introns were created by a series of crossing-over events. The initial event, it is proposed, was the duplication of a single, continuous primordial gene and some flanking (extragenic) DNA. The initial result would have been the generation of two copies of the original gene separated by some spacer DNA. The two transcription units of those copies might later have been fused in such a way that they both ended up in a single transcription unit encompassing the duplicated genes and the spacer DNA, which became the equivalent of an intron separating two protein-coding sequences. The transcript of this intervening DNA could subsequently have been spliced out to yield a new messenger RNA about twice as long as that of the primordial gene and coding for a new protein with two homologous domains. This implies that the splicing signals either were already present at the ends of the primordial gene or arose by mutation at the ends of the spacer after duplication.

The evolutionary advantage of splicing is clear. New genes coding for longer proteins could arise through fusion of duplicated transcription units rather than by a much rarer event: the precise deletion of the spacer DNA separating the duplicated copies of the original gene. The same mechanism could apply to the generation of new split genes from an ancestral split gene. There is some evidence from studies in our laboratory that the chicken gene for ovotransferrin, which is split into 17 exons, evolved through fused duplication of an ancestral gene that was already split into seven or eight exons.

The possibility of intragenic crossing-over between misaligned intron sequences is particularly interesting. It could result in the duplication of an exon or a group of exons without requiring the generation of new splicing signals. Such a mechanism could lead to the amplification of an exon (or a group of exons) within a gene; it could also account for the observation that there are several homologous exons in the gene encoding the constant region (as opposed to the variable region) of immunoglobulin heavy chains. The existence of RNA-splicing machinery may have been a prerequisite for the rapid evolution of new cell functions by means of gene duplication: without introns there would have been only a few sites in a DNA sequence where unequal crossing-over could duplicate a DNA region having adaptive significance for the organism.

One cannot yet assume that most present-day split genes arose as a result of discrete or fused duplications, but the frequency of unequal crossing-over is high enough to make this at least not unlikely. The lack of homology among the exons in the ovalbumin gene and the apparently random location of the introns do not exclude the possibility that the gene was shaped by multiple, ancient duplication events; these events might be difficult to recognize because



OVALBUMIN-GENE FAMILY includes, in addition to the ovalbumin gene, adjacent genes *X* and *Y*. Here the structures of *X* (*top*) and *Y* (*bottom*) are visualized in electron micrographs and their maps, which can be compared with those for the ovalbumin gene (*see illustration on page 61*). In each case the exons of a strand of the gene have become annealed to the corresponding messenger RNA, whereas the intronic sequences of the DNA form unhybridized loops. Like the ovalbumin gene, both *X* and *Y* have eight exons (*L, 1–7*) and seven introns; corresponding exons are the same length in all three genes, whereas the length of the introns varies from one gene to another. The hybrids have been enlarged about 120,000 diameters.

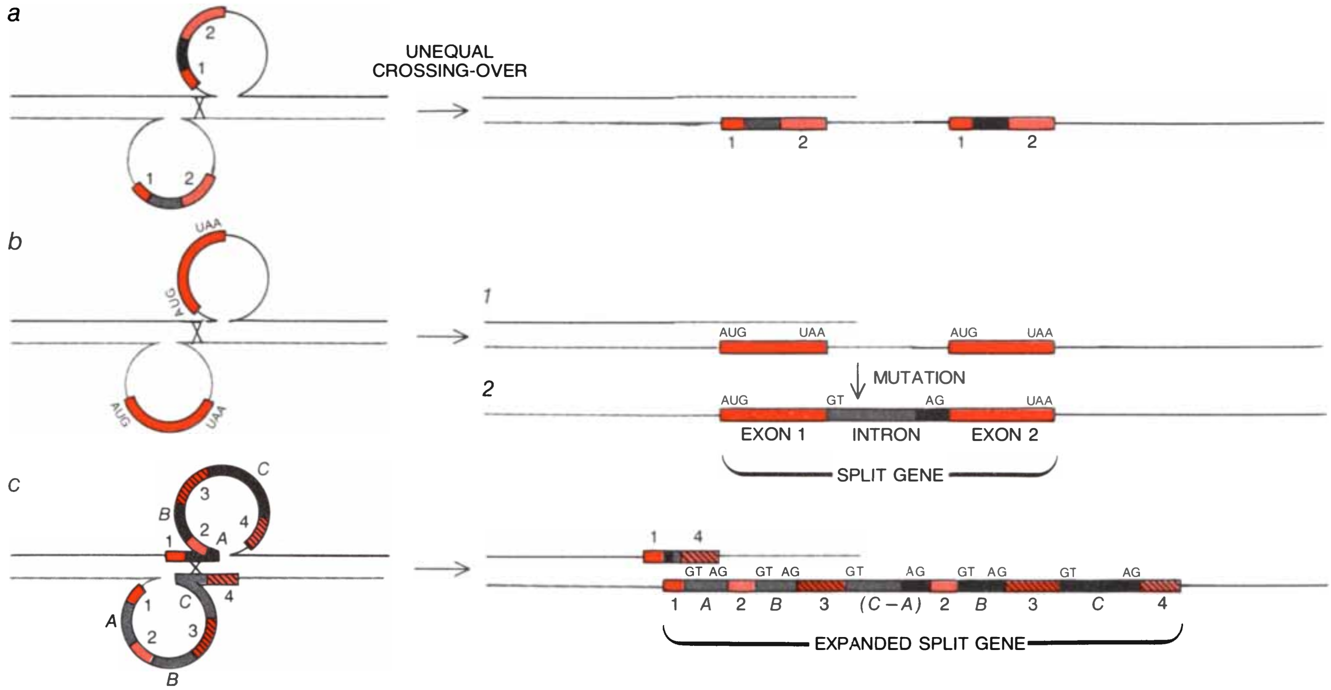
of repeated mutations in the course of evolution.

There is, to be sure, an alternative to the generation of introns by gene duplication. Gilbert has proposed that at least some split genes were assembled by random shuffling of exons originally scattered through the genome, each of them originally having encoded a functional protein chain. The fact that in some split genes (such as the globin genes) there is a correspondence between exons and regions coding for a functional protein domain, in the absence of real evidence for any primordial-gene duplication, lends some support to this hypothesis.

Did introns first arise when the eukaryotic cell evolved or did they exist before then? The splicing machinery appears to be universal in eukaryotes, which suggests it was present in the first eukaryotic cell. The fact that prokaryotic genes and some eukaryotic ones are not split does not necessarily mean introns appeared at some stage in the evolution of genomes previously made up of uninterrupted genes. Present-day continuous genes might long ago have been split, and their introns might subsequently have been deleted. Although the precise deletion of an intron must be a rare event, Gilbert and his colleagues have recently found evidence for such a deletion in one of the duplicated genes for insulin in the rat. Today's prokaryotes may not be representative of the prokaryotes that were present before the eukaryotes diverged more than two billion years ago.

Following proposals made by James E. Darnell, Jr., of Rockefeller University and by W. Ford Doolittle of Dalhousie University in Nova Scotia, I am inclined to speculate that the splicing machinery was present before the existence of eukaryotes and perhaps even before the existence of membrane-bounded cells. As D. C. Reanney of La Trobe University in Australia and others have pointed out, RNA may have preceded DNA as the primary genetic material in precellular replicating systems. The presence of even an imprecise RNA-splicing device would have been advantageous to precellular systems, enabling them to generate many different molecules through various splicings of a single RNA molecule, thereby putting together useful information that was scattered through a region of a primitive genome.

According to this line of reasoning, today's prokaryotes are not the ancestors of eukaryotic cells. Rather they are descendants of cells that in the course of evolution gradually eliminated their extra, noncoding DNA, thereby increasing their rate of growth by decreasing the amount of DNA that had to be replicated in each generation; eventually all introns were eliminated and the splicing machinery became superfluous. In eu-



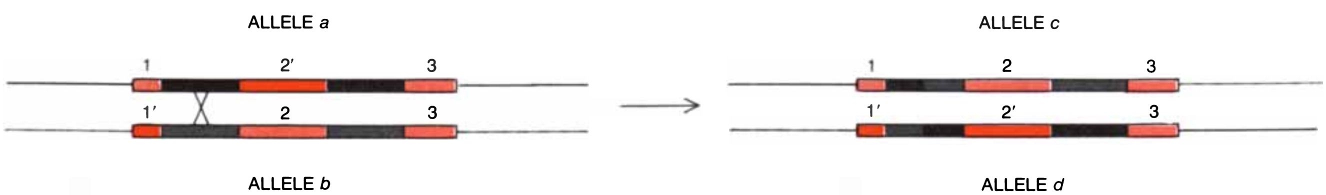
UNEQUAL CROSSING-OVER generates split genes through gene duplication. Crossing-over is a process whereby segments of chromosomal DNA are exchanged between two chromatids of a chromosome pair during meiosis, a stage of germ-cell maturation. "Discrete" duplication (*a*) can generate two split genes from an ancestral split gene that has two exons (*1, 2*); unequal crossing-over between misaligned sequences outside the genes produces one chromosome containing both genes and one containing neither gene. A split gene with two exons can be generated (*b*) from an ancestral unsplit gene if duplication is followed by "fusion." Unequal crossing-over duplicates the gene (*1*). Then the transcription units of the duplicated gene are fused (*2*): mutation eliminates one initiation signal (*AUG*) and one termination signal (*UAA*) and generates the splicing signals *GT* and *AG*. An expanded split gene with six exons and five introns can be generated (*c*) by unequal crossing-over between misaligned introns of an ancestral split gene with four exons (*1–4*) and three introns (*A–C*).

karyotic cells, on the other hand, the splicing machinery was refined as organisms evolved for which a large amount of noncoding DNA did not impose a significant energy burden. For such organisms the splicing machinery provided a wonderful mechanism for generating new functions from old ones and thereby enabling the organism to explore new avenues of evolution. If evolution works like a tinker, as François Jacob once proposed, RNA splicing has been an ideal tool for speeding up its tinkering with genetic information.

It is attractive to speculate that genes in pieces reflect the organization of primitive genes and that most present-day introns are by-products of the creation of new functions by gene duplication. It might also be argued, however, that introns are really mobile genetic elements, similar to the "transposons" of prokaryotic cells, inserted in the course of evolution into genes that once were whole. There is no evidence that any present-day split genes were in fact generated in this way, but this does not exclude the possibility that such insertions might have contributed to the generation of introns at some earlier stage of evolution.

Why, finally, have intronic sequences as such been conserved in the course of eukaryotic evolution? It is unlikely that most present-day introns comprise either regulatory or coding elements so essential as to preclude their mutational deletion. Evolution is surely not anticipatory, and so it cannot be argued that introns have been preserved because they might at some time in the future prove to be advantageous. The simplest explanation is that introns are conserved merely because the cells of higher eukaryotes have no efficient way of deleting them accurately. Most present-day introns should then be considered evolutionary relics, along with most of the other "functionless" DNA found in eukaryotic cells.

This is not to suggest that intronic sequences, once established, cannot be advantageous. For example, Gilbert and others have suggested that the presence of introns in a split gene increases the rate at which coding sequences in different exons of the same gene can recombine efficiently. (The recombination rate is higher for DNA segments that are separated than it is for adjacent segments.) The higher rate means that particularly advantageous mutant exons present on different alleles of a gene have more chance of being recombined, producing a doubly advantageous new allele. All of this is still speculation, however. The possibility cannot be excluded that introns are implicated in very different functions, still to be discovered, that affect the organization and expression of genetic information in eukaryotic cells.



PRESENCE OF INTRONS can be advantageous in evolution: by separating exons it can increase the rate at which advantageous mutations in different exons on two alleles (alternative versions of a gene) are brought together in one doubly advantageous gene. Here two alleles of a gene are shown (*left*) in which exons 1′ and 2′ are mutated and specify an improved protein product. Recombination between homologous sequences in an intron generates a new allele (*d*) in which the two advantageous exons are associated in the same gene.

The Sources of Celestial X-Ray Bursts

They are probably caused by thermonuclear flashes on neutron stars in old binary systems. A single burst emits as much X-ray energy in a few seconds as the sun radiates at all wavelengths in two weeks

by Walter H. G. Lewin

Astronomers owe much of their understanding of the universe to the extraordinary regularity of celestial events. The familiar clocklike motions of the sun, the moon and the planets can also be discerned, on a vastly different scale, in the revolutions of binary star systems and in the radio pulses that have been detected from rotating neutron stars. In the past few decades, however, a number of celestial phenomena that are not periodic have been discovered. The discoveries often tell of a more violent and less well-ordered firmament than the one conceived of only a generation ago.

In 1975 and 1976 an important class of aperiodic phenomena came to the attention of astronomers. It was noted that short bursts of X rays are being emitted by sources near the center of our galaxy and in globular clusters of stars. The bursts are not isolated, singular events, but neither do they keep a fixed schedule; instead they repeat at irregular intervals of from several hours to a few days. They appear to signal explosive violence, and they release prodigious amounts of X-ray energy. A typical burst reaches its maximum intensity in a few seconds or less; the source then fades to its steady, preburst level of X-radiation in about a minute. In this brief period some 10^{39} ergs of X-ray energy is emitted, which is equal to the energy radiated by the sun at all wavelengths in about two weeks.

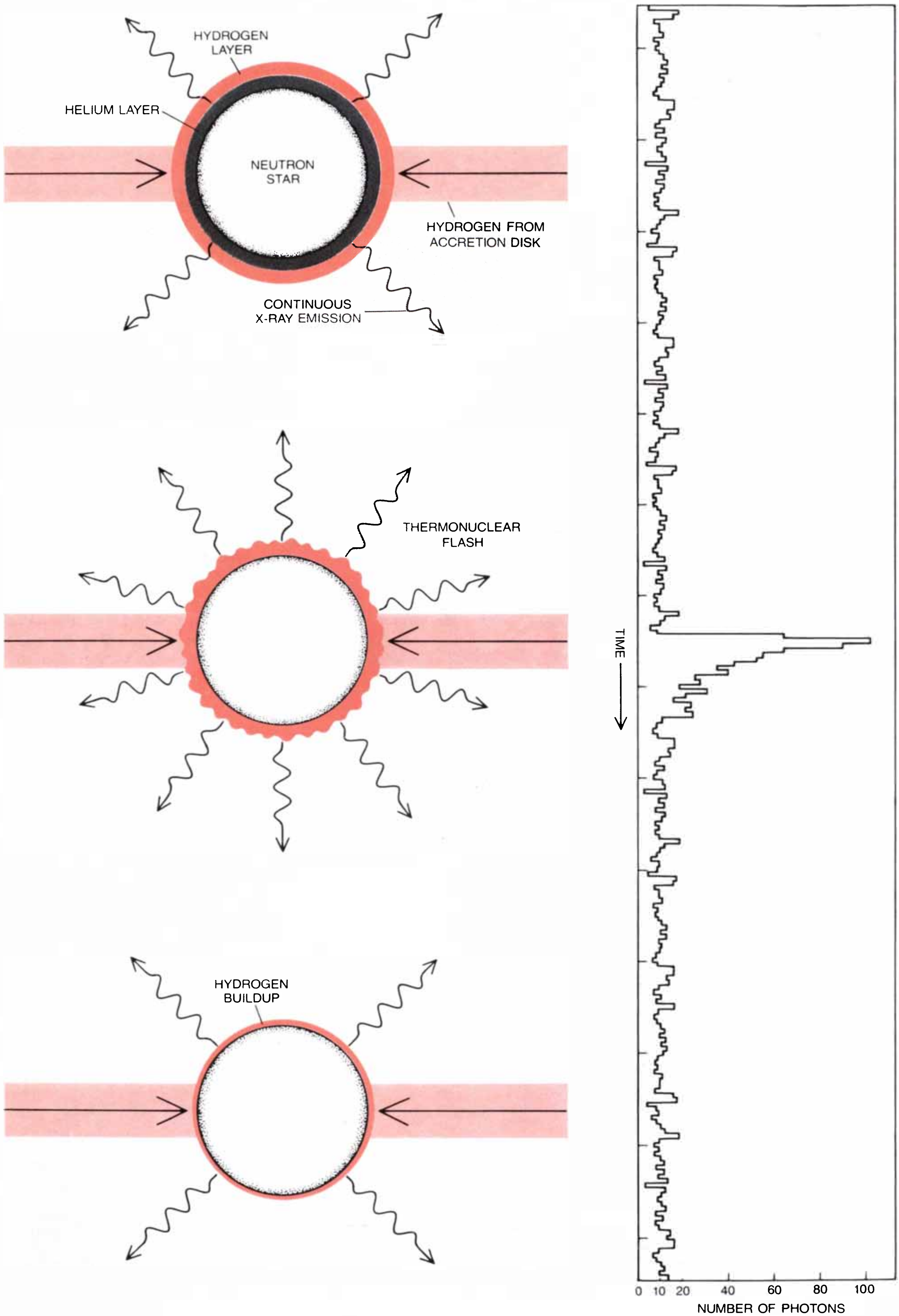
The sources of X-ray bursts were known to be remarkable objects even before the bursts were discovered. In the X-ray sky, which has been accessible to observation only since rockets, balloons and satellites breached the X-ray-opaque atmosphere of the earth, they are among the most luminous objects in our galaxy. At visible wavelengths they emit about 100 times more energy than the sun, which does not make them particularly noteworthy. In the X-ray region of the electromagnetic spectrum, however, they give off a continuous flow of energy that is more than a billion times more powerful than the X-radiation of the sun. The energy of the X-ray bursts is in addition to the continuous flow. Hence even before the discovery of the bursts astronomers were puzzled. What kind of object is capable of such intense and continuous X-ray emission? What mechanism powers the source?

By the early 1970's some astronomers thought they had answers to these questions. Although the answers have turned out to be essentially correct, it has only recently been appreciated how the answers can apply to quite different kinds of objects. Early evidence indicated that an X-ray star might be a superdense, gravitationally collapsed object such as a neutron star or perhaps, in a few cases, a black hole. Neutron stars are stars that have exhausted their nuclear fuel, with the result that the heat generated inside the star is no longer sufficient to balance the attractive force of gravity. The star collapses under its own weight until the protons and electrons of its constituent atoms fuse to form a densely packed mass of neutrons. The neutrons can resist further gravitational collapse in stars of up to about three times the mass of the sun. It is thought that stars more massive than this continue the catastrophic collapse and form a black hole, a region of space into which the star has fallen. At the "event horizon" of a black hole, which is not a physical surface but a mathematically defined boundary, the velocity needed for matter to escape the influence of the black hole is equal to the speed of light.

A neutron star or a black hole could account for a large flux of X-radiation because of the extraordinarily strong gravitational field of the collapsed star. For example, a neutron star that has a mass comparable to the mass of the sun has a radius of only about 10 kilometers. (The radius of the sun is about 700,000 kilometers.) The gravitational field near the surface of the neutron star is about 100 billion times stronger than the gravitational field at the surface of the earth. If there is some outside supply of matter that can be captured by such a gravitational field, the matter will fall toward the star. The matter will be accelerated to a high velocity and thereby heated to a high temperature, and it will emit radiation characteristic of that temperature. The temperature ranges from 10 million to 100 million degrees Kelvin. The radiation generated at such temperatures lies predominantly in the X-ray region of the electromagnetic spectrum.

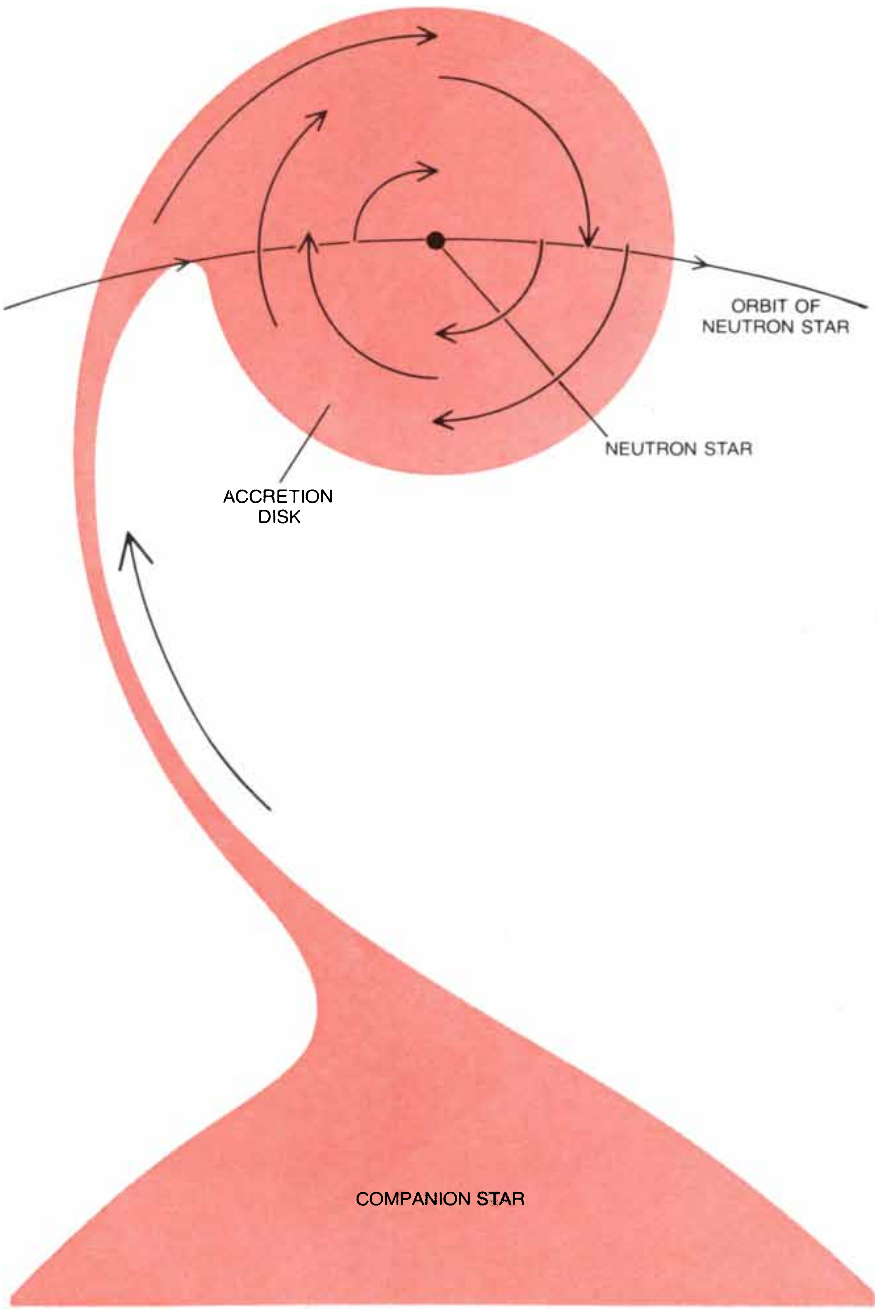
What is the outside source of falling matter? One good candidate is a nearby star gravitationally bound to a neutron star or a black hole in a rotating binary system. Such a companion star would still be burning its nuclear fuel, as the sun is. If the companion were close enough to the gravitationally collapsed body, matter (mostly hy-

ENERGETIC BURSTS OF X RAYS are thought to originate from binary star systems in which one member of the pair is a dense neutron star. Matter, mostly hydrogen, is ripped off the surface of a normal, nuclear-burning companion star (a star much like the sun) by the powerful gravitational field of the neutron star. As the hydrogen falls to the surface of the neutron star it releases much of its gravitational potential energy as a continuous emission of X rays. When the hydrogen reaches the surface, it builds up in a layer about a meter thick. The fusion of hydrogen nuclei to form helium gives rise to a helium layer that is also about a meter thick and that lies below the hydrogen. The thickness of the layers is not drawn to scale; the radius of the star is some 10 kilometers. After about 10^{21} grams of matter has accumulated the density and temperature in the helium layer may become critical, and so the helium nuclei may suddenly combine by thermonuclear fusion into carbon. The resulting thermonuclear flash is seen from the earth as a burst of X rays. The graph at the right shows the X-ray profile of the first X-ray burst discovered. The data were collected with the orbiting X-ray telescope of the Astronomical Netherlands Satellite (*ANS*) from an X-ray source in the globular cluster NGC 6624 on September 28, 1975. Vertical scale represents discrete periods of time and horizontal scale graphs number of X-ray photons detected by the telescope during each interval.


HYDROGEN LAYER
HELIUM LAYER
NEUTRON STAR
HYDROGEN FROM ACCRETION DISK
CONTINUOUS X-RAY EMISSION
THERMONUCLEAR FLASH
HYDROGEN BUILDUP
TIME
0 10 20 40 60 80 100
NUMBER OF PHOTONS

drogen) could flow to the dense body. Because the two stars revolve rapidly about each other the matter would in many cases form a rotating accretion disk, from which it would spiral onto the surface of the collapsed star.

In 1971 this binary-star model (with a neutron star in the role of the dense X-ray source) was conclusively demonstrated to describe two strong X-ray sources by Riccardo Giacconi, Ethan J. Schreier, Harvey D. Tananbaum and their co-workers at the American Science and Engineering Corporation. In data collected with the orbiting X-ray observatory *Uhuru,* Giacconi, Schreier and Tananbaum discovered highly periodic short- and long-term variations in X-ray intensity. The short-term variations, or pulsations, with periods of a few seconds, are explained by the rotation of a strongly magnetized neutron star whose magnetic dipole axis is not aligned with the axis of rotation. In the strong magnetic field the accreting matter falls only near the magnetic poles, creating two hot spots on the surface that rotate with the star. The rotating hot spots give rise to X-ray pulsations for an observer on the earth.



ENORMOUS TIDAL FORCES caused by the gravitational field of a neutron star deform the nearby binary companion star and pull matter from its surface. Because the two stars revolve about each other the matter spilled off the companion star will swirl into an accretion disk before it falls onto the neutron star. The dense mass of a neutron star creates a gravitational field about 100 billion times more powerful than the gravitational field near the surface of the earth.

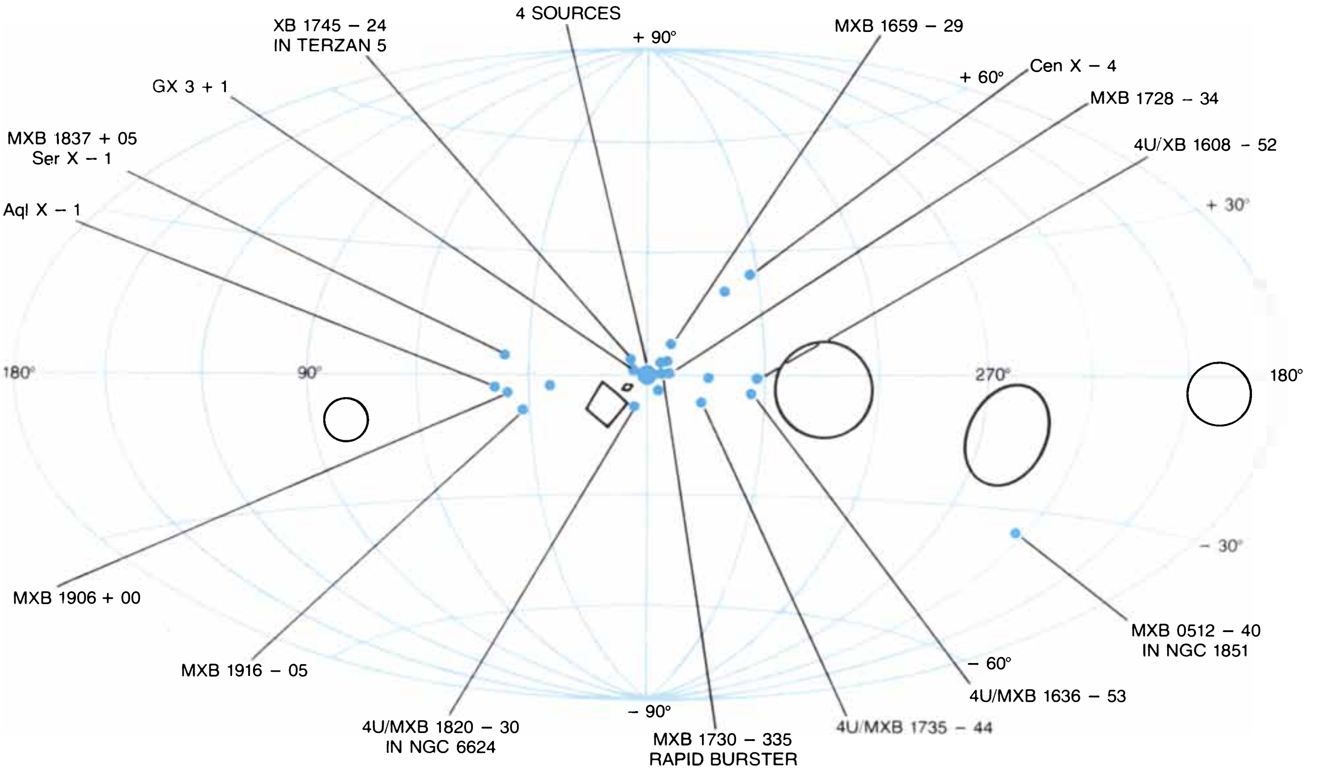
Because black holes can have neither a surface nor a strong magnetic field this account rules them out of consideration as sources of pulsating X rays. The observed longer-term X-ray variations, with periods of a few days, are caused by the periodic eclipsing of-the neutron star by the much larger companion star.

After this important discovery some astronomers believed the majority of the strong X-ray sources in our galaxy would turn out to be similar to those two stellar systems. To test the hypothesis many strong X-ray sources were examined for evidence of X-ray pulsations and eclipses. By 1975 several more X-ray binary systems had been found, but not nearly as many as had been expected. Moreover, the search also turned up a large number of X-ray sources that showed no sign of a binary companion and from which no X-ray pulsations were observed. As a matter of logic the failure to detect eclipses or pulsations does not establish that such an X-ray source is not a member of a binary system or that it is not a neutron star: the absence of evidence is not evidence of absence. Nevertheless, there was suspicion from the outset that these X-ray sources form a class of objects distinct from those whose binary nature is readily established.

In most of the obvious binary systems the companion star is bright and from 10 to 20 times more massive than the sun. Such systems must be relatively young because stars with a mass about 20 times that of the sun burn up their nuclear fuel in several million years. I shall call these young X-ray sources Class 1 objects. Most of the nonpulsating, noneclipsing X-ray sources were found in the general region of the galactic center and in globular clusters. The stars of the globular clusters are known on independent grounds to be among the oldest in the galaxy. The distribution of the nonpulsating, noneclipsing X-ray sources therefore implies that many of them are 10 billion years old. I shall call them Class 2 objects.

By 1976 several criteria for classifying an X-ray source as a Class 2 object had been established: it is a source that has no bright optical counterpart, it exhibits neither X-ray pulsations nor X-ray eclipses and it is often found in a region associated with old stars. Even though the objects could be classified, however, astronomers did not understand what kind of systems they were. The true identity of the Class 2 objects remained a mystery for several years.

The mystery prolonged the lives of several alternative hypotheses about the nature of this class of X-ray stars. Could some of them be single black holes or single, nonpulsating neutron stars? A single object would obviously not be subject to eclipses, nor would it be associated with a bright companion star. A



SKY MAP shows the position (in galactic coordinates) of 31 X-ray burst sources, based on data available as of December 1, 1980. The circles and diamonds indicate regions in which a burst source has been found. The sources are concentrated near the galactic center, at a distance of about 30,000 light-years from the solar system. At least 11 burst sources have been discovered in globular clusters, self-gravitating systems that are made up of approximately 100,000 old stars. This is strong evidence that the burst sources are themselves old.

black hole cannot pulsate at all, and pulsations are not expected from a neutron star with a weak magnetic field or from one whose magnetic dipole axis is aligned with the star's rotation axis. Perhaps in this way the absence of eclipses and pulsations in Class 2 sources could be explained.

What about the source of the matter that must fall onto the surface of a single star to generate X rays? To account for the observed X-ray luminosity an accretion rate of about 10^{17} grams per second is required. (At this rate it would take some 2,000 years to accumulate a mass comparable to that of the earth.) A black hole or a neutron star of about one solar mass would have to be surrounded by a cloud of gas large enough and dense enough to sustain accretion at this rate. Clouds of gas this large and this dense, however, would not have escaped detection. Thus single neutron stars and single black holes of about one solar mass can be ruled out of consideration.

The failure to detect such clouds of accreting gas might be accounted for by the low density of the gas surrounding a much more massive object. In 1975 it was suggested by John N. Bahcall of the Institute for Advanced Study and Jeremiah P. Ostriker of Princeton University, and independently by Joseph Silk and Jonathan Arons of the University of California at Berkeley, that Class 2 objects could be black holes more massive than a hundred suns, gathering in material from a low-density surrounding cloud.

Later the same year X-ray bursts were discovered. Observing with the Astronomical Netherlands Satellite (*ANS*), Jonathan E. Grindlay of the Harvard College Observatory and John Heise of the Space Research Laboratory of the Astronomical Institute in Utrecht found two bursts emitted by an object in the globular cluster designated NGC 6624. Richard D. Belian, Jerry P. Conner and W. Doyle Evans of the Los Alamos Scientific Laboratory discovered bursts independently in observations made with the Vela satellites.

After these discoveries my co-workers and I at the Massachusetts Institute of Technology found five more X-ray burst sources in less than two months of viewing with the Third Small Astronomical Satellite (*SAS-3*). Before the end of 1976 another 10 burst sources were found by various groups observing with the Eighth Orbital Solar Observatory, *SAS-3,* the Vela satellites and the satellite *Uhuru*. All the bursts were emitted by Class 2 objects, although not all Class 2 objects emitted bursts.

In spite of our initial bewilderment over the nature of these curious, aperiodic events, it occurred to some of us that bursts might hold the key to the secrets of the entire group of Class 2 X-ray sources. At first it was suggested that the bursts might support the massive-black-hole hypothesis. Grindlay and Herbert Gursky of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory argued that the burst profiles (which record the X-ray signal as a function of time) could be generated when a primary burst of X rays is scattered by a hot gas. They believed that the gas temperature would have to be about a billion degrees, and they noted that a gas this hot would escape the gravitational field of an object lighter than a few hundred solar masses. They therefore suggested that the bursts originate near a massive black hole. No mechanism was proposed for the source of the primary bursts, but the accretion of matter from the surrounding cloud onto the black hole would presumably account for it. Intriguing as this proposal was, it turned out to be incorrect.

The apparent evidence for the model of a massive single black hole was dispelled by a closer inspection of the burst profiles. The model predicts a size for the event horizon of the black hole much larger than the size of the source that must be inferred from information in the burst profiles.

The size of the emitting region can be deduced from the X-ray spectra that are observed during the bursts. The changes in the spectra observed in various bands of X-ray energies show that the X-ray source is cooling. At the peak of a burst, X rays with energies of from one kiloelectron-volt to about 20 kiloelectron-volts (keV) are emitted. Later, when the object has cooled, the high-energy X rays are no longer effectively produced, and the X-ray spectrum of the burst ranges in energy from about 1 to about 7 keV. Thus low-energy X rays from bursts decay more slowly than X rays of higher energy.

In analyzing these X-ray-burst spectra Jean H. Swank and her co-workers at the Goddard Space Flight Center of the National Aeronautics and Space Administration noted that the X-ray spectrum of one particularly long burst resembled the spectrum of a cooling black body. An ideal black body (which should not be confused with a black hole) absorbs all radiation incident on it, and the spectrum of radiation emitted by the black body depends only on the temperature of the body. Hence the temperature of a black body can be calculated from its observed spectrum.

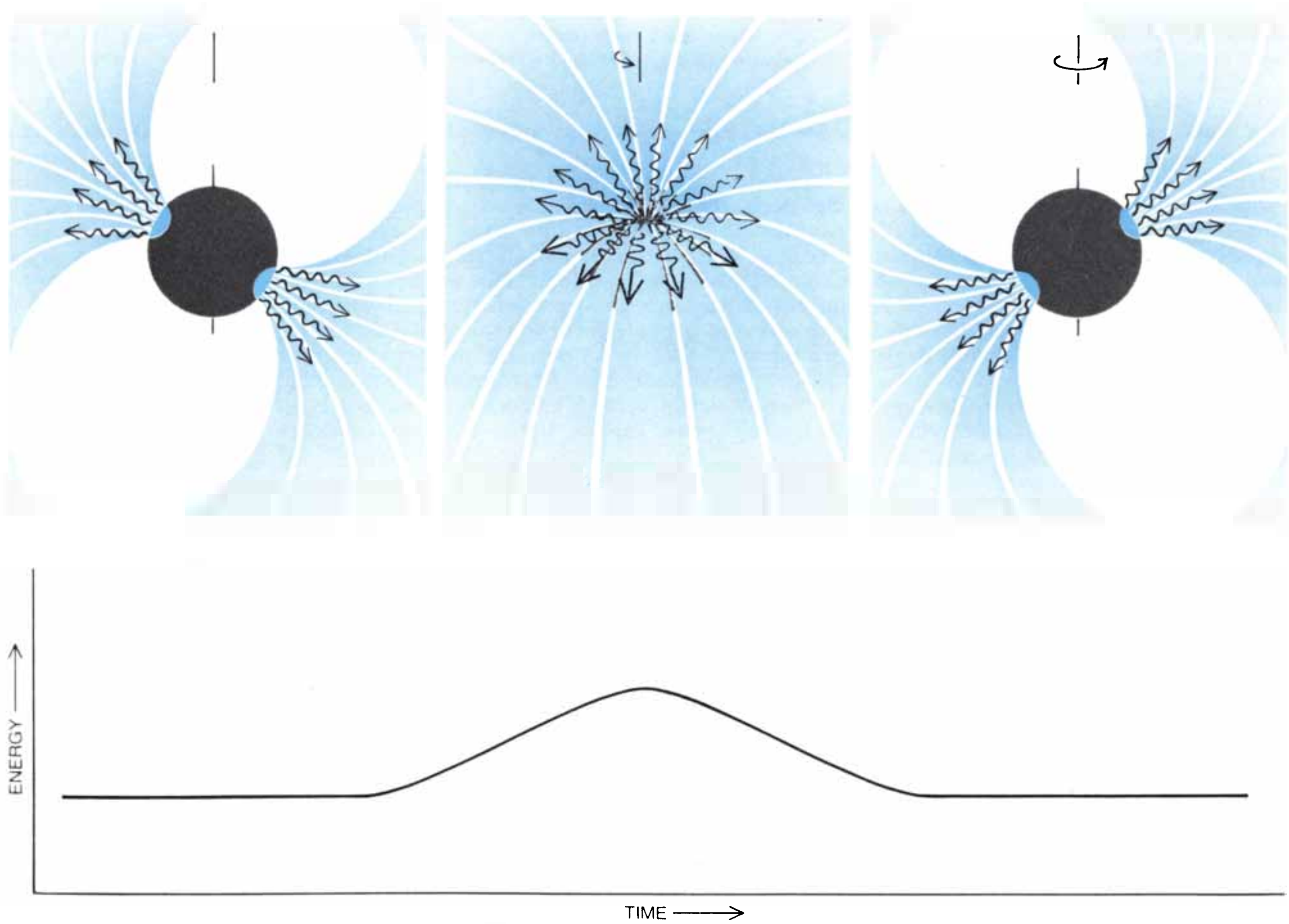
The total luminosity of a black body is proportional to the fourth power of its temperature and is also proportional to its surface area. The luminosity can be estimated from the flux of energy received at the earth if the distance to the body is known and if the body can be assumed to radiate equally in all directions. The surface area of an astronomical black body can therefore be determined from the spectrum and the distance. When Swank and her colleagues were able to show that the spectrum of the X-ray burst source they observed was that of a black body, they could calculate the surface area (and the radius) of the source.

Most X-ray burst sources lie near the center of the galaxy, which is known to be about 30,000 light-years from the solar system. Hence it was reasonable for Swank to assume that this is the distance to the observed burst source. The temperature of the burst rose to about 26 million degrees K. in the first 60 seconds and then cooled to 15 million degrees after about 100 seconds more. From these data Swank and her colleagues calculated a radius of about 100 kilometers during the first 15 seconds of the burst and a more or less constant radius of about 15 kilometers thereafter.

At M.I.T. my graduate student John P. Doty, Jeffrey A. Hoffman and I followed Swank's example to calculate the radii of two other X-ray stars that emit bursts. We found the radii were both about 10 kilometers at all times during the cooling period. We were not able to measure the radii of the X-ray stars during the burst rise, when the temperature was increasing, because during that time the spectra were not like a black-body spectrum. A year later Jan van Paradijs of the University of Amsterdam showed that a small radius of about 10 kilometers is a property of all burst sources.

These small sizes provided the first persuasive evidence that the X-ray-emitting object is a neutron star. If a black hole of about 100 solar masses were the source of the bursts, we would have expected to find radii of more than 300 kilometers, the theoretical radius of the event horizon of such a black hole. Thus the model of a single massive black hole absorbing matter from a surrounding cloud of gas appears to be ruled out by the size calculations. A massive black hole is probably the only single object capable of sweeping up diffuse matter from a surrounding gas cloud at the required rate.

In this way the radius measurements also provided the first persuasive evi-



X-RAY HOT SPOTS created by the strong magnetic field of a young neutron star sweep out a beacon of X rays when the magnetic pole and the rotational axis of the star are not aligned. Matter falling to the surface of the neutron star from the accretion disk is concentrated along the magnetic-field lines. For a fixed observer the rotating beacon gives rise to pulsations: periodic increases in counts of X-ray photons reaching satellite detectors orbiting the earth. Further rotation would show a second pulse, this time from the other magnetic pole of the star. X-ray pulsations are often observed from Class 1 objects. In a Class 2 object the neutron star is old and does not pulse.

dence that the source of matter for the X-ray burst sources is a gravitationally bound binary companion star. Although it was conceivable that the X-ray-burst stars were small black holes of a few solar masses in binary systems, our experience with Class 1 X-ray objects made it seem unlikely. The Class 1 emitters had already been identified as neutron stars in binary systems, and there was now no need to suppose the burst sources would be any different.

If the burst sources, apart from the bursts themselves, are representative of Class 2 X-ray sources, then most Class 2 sources are probably neutron stars in binary systems. If they are binary systems, how can one explain the absence of eclipses, of bright companion stars, of periodic Doppler shifts in the spectra and of the other observational evidence that is usually required to establish the existence of a binary stellar system?

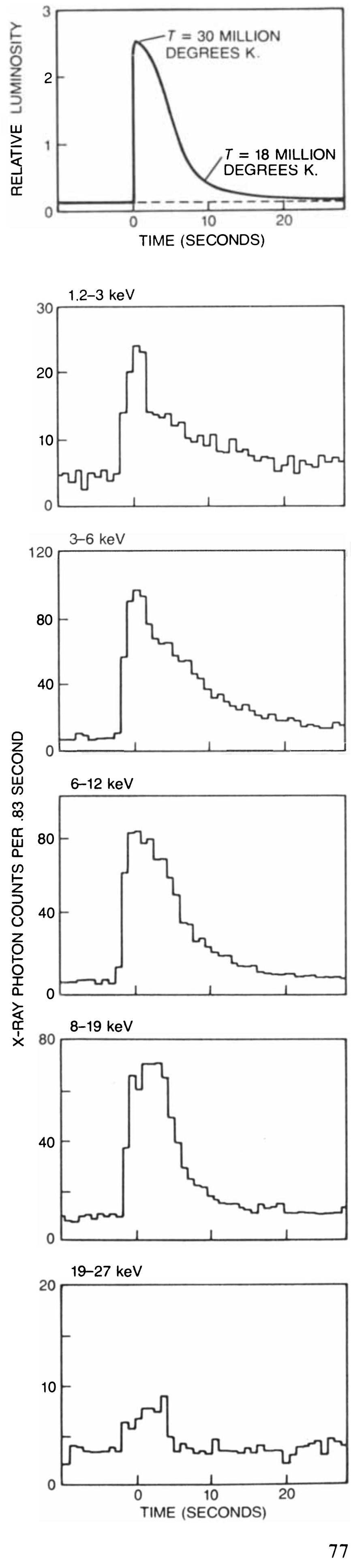
In 1977 Edward P. J. van den Heuvel of the University of Amsterdam suggested that the mass of the companion stars in Class 2 X-ray sources may be comparable to the mass of the sun. This would mean that the binary companion stars in Class 2 systems are much less massive than the companion stars in Class 1 systems. Subsequently Paul C. Joss and Saul A. Rappaport of M.I.T. suggested that the mass of the undetected companion stars may be less than .5 solar mass. Such a low-mass star would not be luminous enough to be easily visible at the distances estimated for the Class 2 objects, about 30,000 light-years. At that distance the sun would appear as a faint, 20th-magnitude star, and the absorption of light by interstellar dust would make it still fainter. It could be detected only with the largest optical telescopes.

Although a low-mass companion star may often be too faint to be observed, the binary nature of a Class 2 system could still be demonstrated if the X-ray source were periodically eclipsed by the companion star. For an eclipse to be observable from the earth the binary system must be oriented so that the companion star periodically blocks the X rays emitted by the X-ray star. The probability of this happening depends on the size of the companion star and on the distance from the X-ray star to the companion. These two factors can be determined from the known properties of the system. For an ordinary star burning nuclear fuel, size is related in a known way to mass. The distance between the members of the binary system must be just large enough for matter from the low-mass companion to spill onto the X-ray star at the observed accretion rate.

To understand more clearly the constraints on the size of the binary orbit, imagine first that the low-mass nuclear-burning star is at a great distance from the neutron star, so that there is no transfer of mass and consequently no X-ray emission. If the nuclear-burning star is moved toward the neutron star, matter on the nuclear-burning star is more strongly attracted by the gravitational pull of the neutron star, and the nuclear-burning star begins to bulge in the direction of the neutron star. At some distance, which depends on the mass of both stars, the matter on the surface of the nuclear-burning star that is closest to the neutron star is more powerfully attracted to the latter than it is to its own star. Matter then begins to flow from the surface of the nuclear-burning star to the neutron star. It is approximately this orbital distance that is employed in calculating the probability of an eclipse.

The orbital plane of the binary system can make any angle with the line of sight to the earth. In order to calculate the eclipse probability of such a randomly oriented system one must assume masses for both stars. It turns out that for neutron stars of about one solar mass and for nuclear-burning stars of about .1 solar mass the probability of being able to observe an X-ray eclipse from the earth is about one-fifth. For more massive companion stars the probability increases. Because there is good reason to believe several of the companion stars are more massive than .1 solar mass, one might expect at least one-fifth of all Class 2 sources to exhibit X-ray eclipses. For 20 carefully studied Class 2 objects, however, no eclipses at all were detected.

How can this observational lacuna be accounted for? First, the accretion disks in both Class 1 and Class 2 X-ray binary systems are opaque to X rays emitted in their direction. Mordechai Milgrom of the Weizmann Institute of Science has pointed out a characteristic of low-mass X-ray binary systems that might make their X-ray eclipses impossible to observe, no matter what the viewing angle. The eclipses would not be seen if the companion star were small enough to lie in the X-ray shadow of the accretion disk [*see illustration on next page*]. If such a system were oriented so that an observer on the earth could see the X rays coming from the neutron star, the



THEORETICAL X-RAY BURST is compared with observed burst profiles from the source MXB 1728–34 in five energy bands. For each energy band the graph represents the sum of the energy in seven X-ray bursts from the source. The duration of the bursts decreases as the energy of the X rays increases. The character of this change has shown that black-body cooling is taking place after a fast initial temperature rise. The theoretical burst was constructed by Paul C. Joss of the Massachusetts Institute of Technology on the basis of a thermonuclear-flash model. The X-ray data were obtained with the Third Small Astronomical Satellite (*SAS-3*) by Jeffrey A. Hoffman, John P. Doty and the author.

companion star would never pass between the earth and the neutron star and no X-ray eclipses would be observed. On the other hand, if the system were oriented more or less edge on to the earth, so that the companion star did pass between the earth and the neutron star, the X-ray eclipses could not be detected because no X rays at all would be detected. In such a circumstance the earth would also lie in the shadow cast by the X-ray-absorbing accretion disk. In either case it would be geometrically impossible to observe X-ray eclipses.

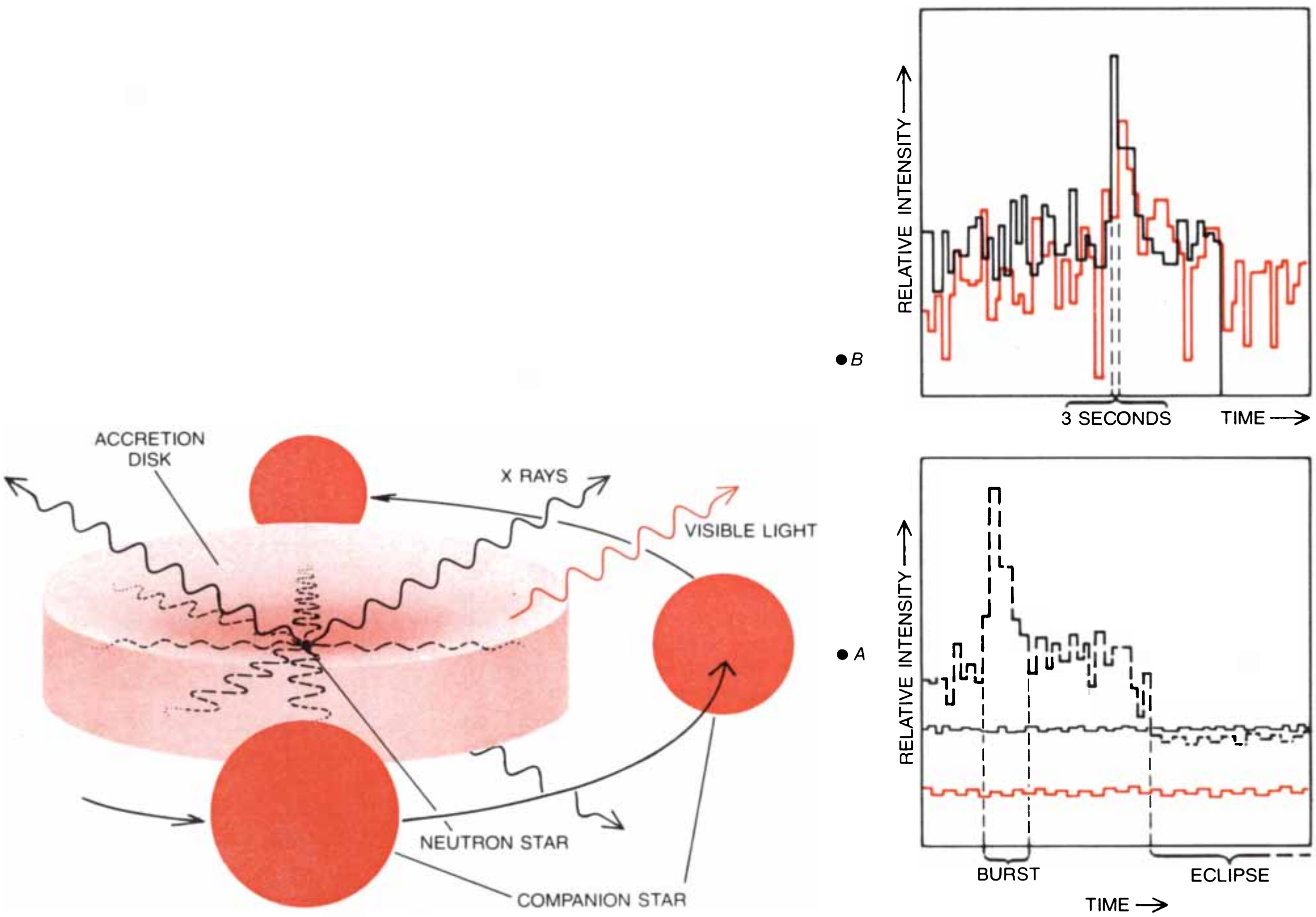
X-ray energy absorbed by the accretion disk is reemitted at other wavelengths, including those in the visible part of the spectrum. Viewed more or less edge on, the accretion disk might appear as a faint stellar object, but no X rays would be detected and the X-ray character of the system might never be known. Viewed at an oblique angle to the orbital plane, both the accretion disk and the neutron star could be observed. The accretion disk would appear at visible wavelengths and the neutron star at X-ray wavelengths.

Visible light from the accretion disk could provide clues to the geometry of the disk. If there were a sudden increase in the X-ray emission from such a system, the accretion disk would "reverberate" perhaps a few seconds later with a sudden increase in visible light. There would be a short delay because the direct distance from the earth to the X-ray-emitting neutron star is shorter than the distance along the other two sides of a triangle from the earth to the accretion disk to the neutron star. The delayed optical signal would also be smeared out because different parts of the disk give rise to different delays. From the delay and the amount of smearing one should be able to obtain information about the size and shape of the disk. Are such sudden increases in the X-ray flux ever observed? Indeed they are: the increases are X-ray bursts from Class 2 objects.

In the summer of 1977 Hoffman and I organized the first coordinated worldwide burst watch. Our objective was to observe the bursts simultaneously with ground-based telescopes and with X-ray observatories in earth orbit. Some 44 astronomical observatories (optical, infrared and radio) in 14 countries participated. The X-ray observations were made with *SAS-3* by our group at M.I.T.

Such observations are hard to carry out. They require the use of large optical telescopes during "dark time" (near the new moon) because the accretion disks are faint. Moreover, the sources burst irregularly, and sometimes they do not burst at all for several days. It is not easy to persuade an astronomer to expend precious dark time on a big telescope for staring night after night at a star that does not burst.

In our first attempt 120 X-ray bursts were observed in 35 days from 10 burst sources. None of the events were detect-



VIEWPOINT OF THE OBSERVER with respect to the orientation of a bursting X-ray binary system (Class 2 object) determines the nature of the X-radiation detected. If the X rays were not absorbed by the accretion disk, an observer in direction *A* would see bursts at irregular intervals and highly periodic decreases in the X-ray counts as a result of eclipses (*broken black lines in graph at right*). Because of X-ray absorption by the disk, however, the observer at *A* actually detects only background X rays, which do not originate at the X-ray source (*solid black lines*). An observer at *B* cannot see X-ray eclipses either. He is able to detect X-ray bursts, and he sees a slightly delayed optical burst signal from the accretion disk (*solid colored lines*). The delay arises because of the time it takes for the X-ray-burst signal to travel to the accretion disk and then "reverberate" in optical photons. The observer at *A* can detect visible light from the companion star, but he sees no optical burst because the edge of the disk visible to him does not reverberate. The graphs of relative X-ray and optical luminosities are based on data from the first simultaneous detection of a burst in these two regions of the spectrum, observed on June 2, 1978, from the burst source MXB 1735–44. The X-ray star is near the center of our galaxy. Data were supplied by Jeffrey E. McClintock, Claude R. Canizares, Jan van Paradijs, Jonathan E. Grindlay, Lynn C. Cominsky and the author.

ed by ground-based observatories. The following year the optical sensitivity was improved, and on June 2, 1978, the first coincident observations of an X-ray burst and an optical burst were made. The burst source was one designated MXB 1735–44 (MXB stands for M.I.T. X-ray burst source). The source has a faint optical counterpart, ordinarily of magnitude 17.5, discovered in 1977 by Jeffrey E. McClintock of M.I.T. At the peak of the optical burst, which trailed the maximum in the X-ray signal by a few seconds, the observed optical flux was almost twice the flux before and after the burst.

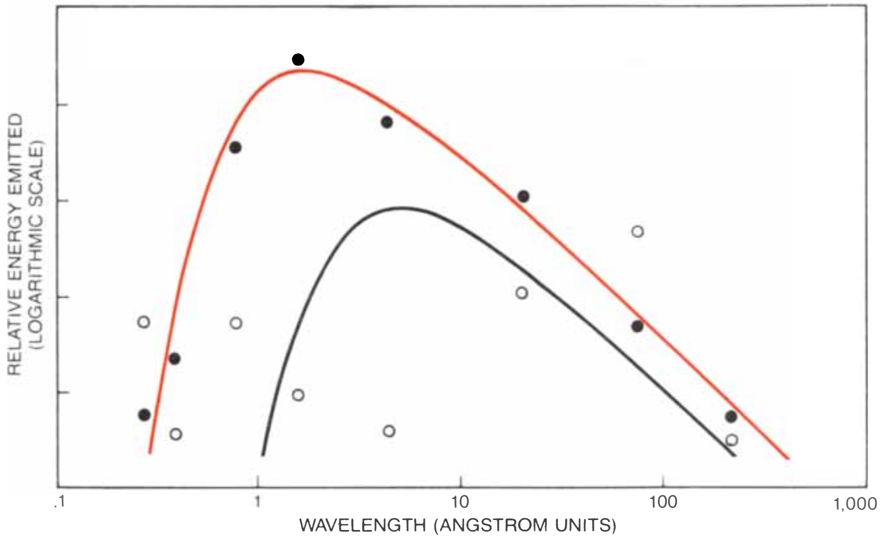
Since then two additional burst sources have been observed to have coincident optical signals. Holger Pedersen of the European Southern Observatory has been particularly dedicated to the observation of one of them, and in the summer of 1979 his perseverance paid off. He detected 15 optical bursts from the source MXB 1636–53, and five of the bursts were simultaneously detected by the Japanese X-ray satellite *Hakucho*, under the direction of Minoru Oda of the University of Tokyo. (When the other 10 optical bursts were detected, *Hakucho* either was not observing MXB 1636–53 or could not transmit the data to the earth.) During a burst the visible light from MXB 1636–53 triples in a few seconds or less, and it is delayed by about 3.2 seconds with respect to the X-ray signal. From these data it can be determined that the radius of the accretion disk is between 500,000 and a million kilometers.

I have emphasized the role that X-ray bursts have played in advancing the understanding of Class 2 X-ray sources: their binary nature and their accretion disks surrounding a neutron star. It should be recognized, however, that the observational evidence only indirectly supports the binary-star hypothesis. The burst spectra eliminate other reasonable hypotheses about the source of the accreting matter that powers the continuous X-ray emissions. But is there not some more direct evidence that Class 2 X-ray sources are binary systems?

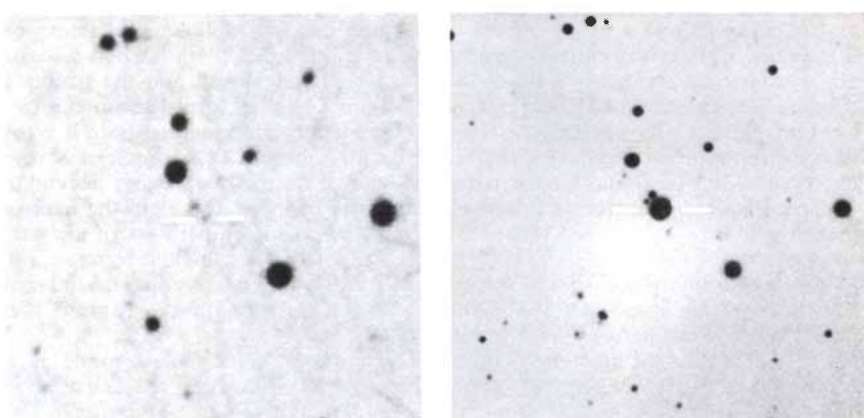
In the absence of X-ray eclipses probably the most direct evidence astronomers can expect to find for the binary model is the observation of the light from the low-mass companion star. The light from the luminous, massive companion stars in Class 1 systems is readily detected. There is great difficulty, however, in observing the light from a low-mass companion star because the light emitted by the accretion disk is usually much more intense than the light from the star itself. Unless the light from the accretion disk can somehow be "turned off," so that it does not overwhelm the light from the star, the low-mass star cannot be detected.

In principle, if the disk is not too bright, it is possible to distinguish the starlight from the light emitted by the accretion disk. The optical spectrum of a nuclear-burning star is interrupted by absorption lines because the atmosphere of the star absorbs particular wavelengths of the starlight. The absorption is marked by dark lines in the spectrum of the star. The optical spectrum of the hot accretion disk is quite different. It has emission lines rather than absorption lines. Absorption and emission lines result from transitions between atomic energy levels.

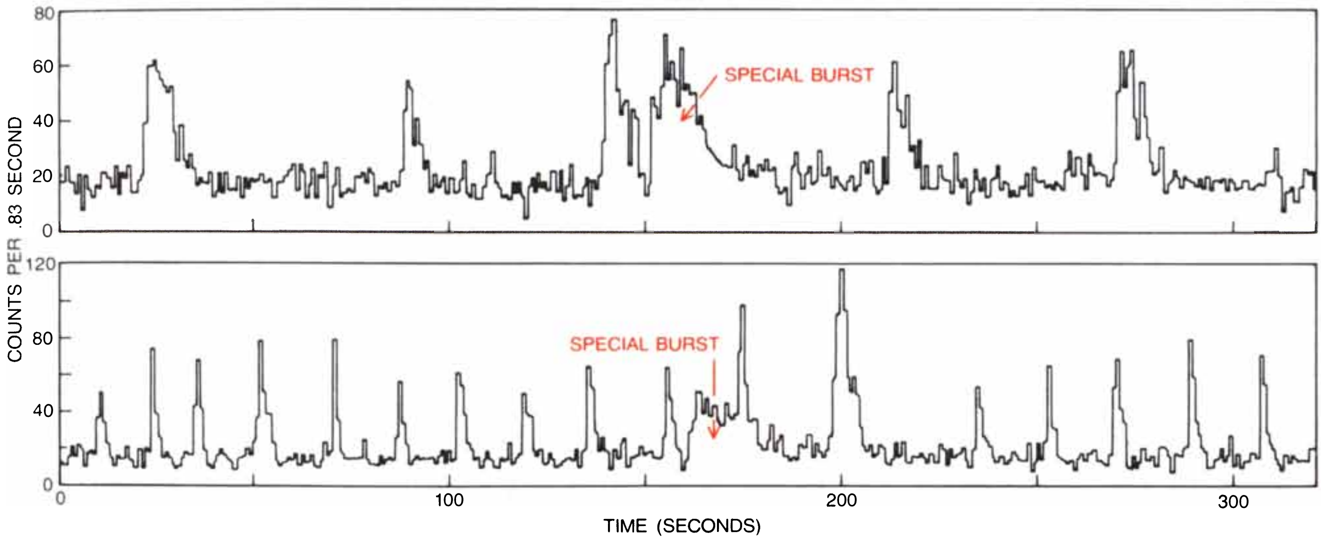
There are several Class 2 objects in which the light that is emitted by the accretion disk is at times shut off. They are called X-ray transient sources, or X-ray novas, and they can appear suddenly in the sky as strong X-ray sources. They cannot be mistaken for bursts, however, because they remain strong X-ray sources for weeks or even months before the X rays die out. A relatively sudden X-ray emission alerts astronomers to a transient source. Because the X-ray brightening is accompanied by an optical brightening of a previously inconspicuous faint star, it enables astronomers to identify the optical counterpart. The optical brightening is presumably the result of X-ray heating of the



BLACK-BODY SPECTRUM is the characteristic distribution of radiant energy according to wavelength emitted by a black body. An object is called a black body when all radiation incident on it is absorbed. Such an object emits radiation whose spectrum is determined only by its temperature. The energy distribution indicated by the black dots matches the black-body curve for a temperature of 30 million degrees Kelvin but not the one for 10 million degrees, so that the source temperature can be inferred. The energy distribution given by open circles does not match any black-body curve, and no simple information about temperature can be deduced.



OPTICAL BRIGHTENING of the X-ray nova Centaurus X-4 was discovered by comparing photographic plates of the same region of the sky made at different times. At the left the star is shown in its quiescent state in a photograph made in blue light with the 1.2-meter Schmidt telescope on Palomar Mountain. At the right is a photograph made by Martha H. Liller of the Harvard College Observatory on May 19, 1979, with the four-meter telescope of the Cerro Tololo Inter-American Observatory in Chile. In each negative image the star is shown between two markers. The brightening is the result of a temperature increase in the accretion disk. The disk is heated by the X rays produced by an X-ray nova (which is distinct from a brief X-ray burst). The photographs were published by Canizares, McClintock and Grindlay.



X-RAY-BURST SIGNATURE from MXB 1730–335, the Rapid Burster, shows two distinct kinds of bursts. The bursts indicated by arrows are "special" bursts that appear independently of the sequence of rapid repetitive bursts (the other peaks on the two graphs). Special bursts are thought to result from the same mechanism that gives rise to bursts from other X-ray sources: thermonuclear fusion. The rapid bursts are instabilities in the accretion flow. For the rapid bursts the waiting time after a "fat" X-ray burst (*upper graph*) is longer than the waiting time after a "skinny" burst (*lower graph*). The data were obtained by Hoffman, Herman L. Marshall and the author.

accretion disk. As the X rays gradually subside, the disk cools and its light fades so that the light of the companion star can begin to dominate. When dark absorption lines appear in the optical spectrum, astronomers can be reasonably sure they are viewing the companion.

This scenario was last acted out in May, 1979, with a nova outburst of the X-ray source Centaurus X-4. The X-ray nova was observed with the British satellite *Ariel V* by Louis J. Kaluzienski and Stephen S. Holt of the Goddard Space Flight Center. They were able to determine the location of the source to within a few degrees. Subsequently optical astronomers found that an inconspicuous star in this small region of the sky had suddenly brightened substantially and that its spectrum was dominated by emission lines. Over a period of about five weeks, as the X-ray emission gradually subsided, the star became about 100 times fainter and returned to its pretransient magnitude. Its optical spectrum then exhibited absorption lines characteristic of a star of about .7 solar mass, which is strong support for the low-mass binary model.

One important piece of the X-ray-burst puzzle remains to be put in place. What is the nature of the bursts themselves? In the spring of 1976 Laura Maraschi of the University of Milan and Alfonso G. Cavaliere of the University of Rome proposed that X-ray bursts are caused by uncontrolled nuclear-fusion reactions on the surface of a neutron star. The idea that bursts are the result of a gigantic thermonuclear flash was suggested independently by Stanford E. Woosley of the University of California at Santa Cruz and Ronald E. Taam of Northwestern University, following pioneering work by Carl J. Hansen of the University of Colorado at Boulder and Hugh M. Van Horn of the University of Rochester. In 1978 Paul Joss published the first thorough calculations describing a thermonuclear flash on a neutron star, and he showed convincingly that the flash model is probably correct.

The principle of the thermonuclear-flash model is simple. Hydrogen falls onto the surface of a neutron star, leading to the continuous emission of X rays derived from the release of gravitational potential energy by the falling matter. The hydrogen accumulates on the surface and is continuously transformed by thermonuclear fusion into helium. The helium layer formed in this way lies under the hydrogen layer. After about 10^{21} grams has accumulated, the temperature and the density in the helium layer can become critical, and the fusion of helium nuclei to form carbon can take place in a thermonuclear flash. It is this flash that generates the burst of X rays. The intervals between bursts depend on the rate of mass flow onto the neutron star and on the temperature of the star's interior. For a typical accretion rate of 10^{17} grams per second the interval between bursts would be about three hours.

The thermonuclear-flash model in its present form has been successful in explaining many of the observed features of bursts, although certainly not all of them. The model excludes black holes as the source of the bursts because black holes have no surface onto which the infalling material can accumulate and flash. The model explains the fast rise of the X-ray flux in the burst, the intervals between the bursts, the observed temperature of about 30 million degrees at the burst maximum and the subsequent cooling of an object with a radius of about 10 kilometers.

The model also accounts in most (but not all) cases for the observed ratio of the nuclear energy released in bursts to the gravitational energy released by the accretion of matter. A proton, or hydrogen nucleus, that falls onto a neutron star of about one solar mass will gain roughly 100 million electron volts (MeV) in kinetic energy, which is released as radiation in the X-ray region of the spectrum. In the fusion of helium to carbon the nuclear energy released is only about 1 MeV per nuclear particle. Averaged over time, therefore, the energy in the bursts should be roughly a hundredth of the energy released in the continuous flow of X rays. The observed energy ratio during periods of high burst activity is often about 1/100.

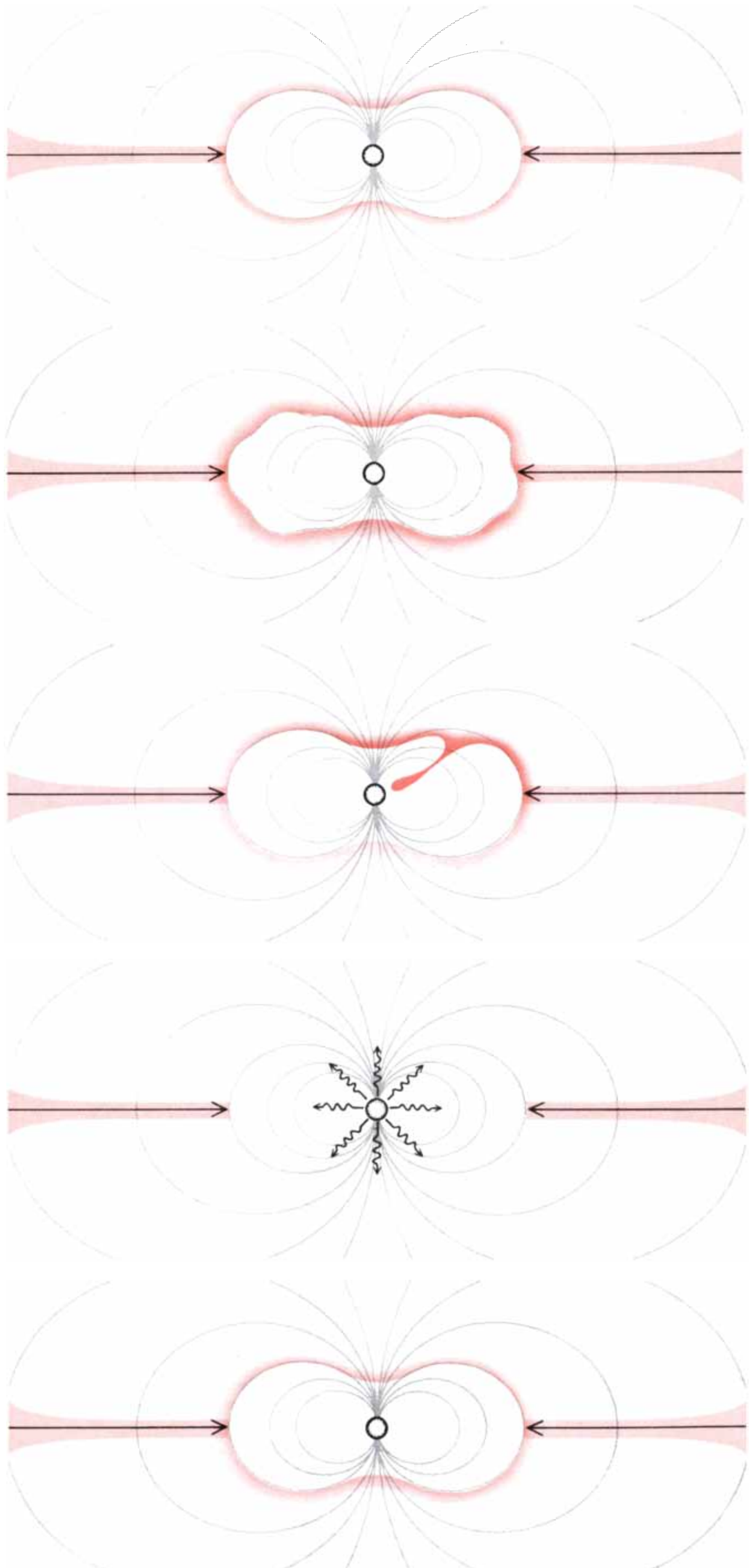
The thermonuclear-flash model confirms our earlier evidence that Class 2 X-ray sources are neutron stars. It therefore appears that both Class 1 and Class 2 X-ray objects are binary systems one of whose members is a neutron star. Why, then, are there such striking differences between the two classes? Why, for instance, do only Class 2 objects burst, and why do they not pulse? Conversely, why do only Class 1 objects pulse, and why do they not burst?

The crucial difference between Class 1 and Class 2 objects is the mass of the companion star. The massive companion star in a Class 1 object must be relatively young, and so the neutron star in the system is also expected to be young. There is reason to believe a young neutron star usually has a strong magnetic field. A Class 2 object is generally made up of much older stars, and the magnetic field of the older neutron star has either decayed or the magnetic dipole axis has become aligned with the axis of rotation. Since a strong magnetic field is thought to be the mechanism responsible for concentrating infalling matter onto a rotating hot spot, pulses can be emitted by the young neutron stars in Class 1 objects but not by the old neutron stars in Class 2 objects. The strong magnetic field of a young neutron star (in a Class 1 object) and the concentration of matter at the magnetic poles also tend to make the nuclear fuel burn steadily rather than in bursts. That is probably why bursts are observed only from Class 2 systems but not from Class 1 systems.

The thermonuclear-flash model is no longer in serious question among most astronomers. In the early days of its development, however, my co-workers and I discovered a unique source of X-ray bursts whose properties threatened to kill the theory before it could stand alone. The new source, designated MXB 1730–335, emits bursts in quick succession, as often as a few thousand times a day. Individual bursts can differ from one another in energy by a factor of 1,000, in contrast to bursts from other sources, which differ by no more than a factor of 10 in energy. I remember well my enthusiasm for the flash model in February, 1976, when it was first explained to me by Maraschi. A month later, however, when we discovered the Rapid Burster, I lost my enthusiasm. The repetitive bursts, which come like machine-gun fire, cannot be a product of thermonuclear flashes.

Although the Rapid Burster looked at first like a theory-spoiler, 18 months later it became a cornerstone of our efforts to understand the bursts. In the fall of 1977 Hoffman, Herman L. Marshall, one of my undergraduate students, and I detected a "special" kind of burst from the Rapid Burster. The special bursts appeared quite different from the rapid bursts, but they looked much like bursts from other X-ray sources. They were emitted every three or four hours, their duration and strength were about the same throughout our observations and their X-ray intensity decayed faster at high energies than at low energies.

Now that two kinds of bursts were

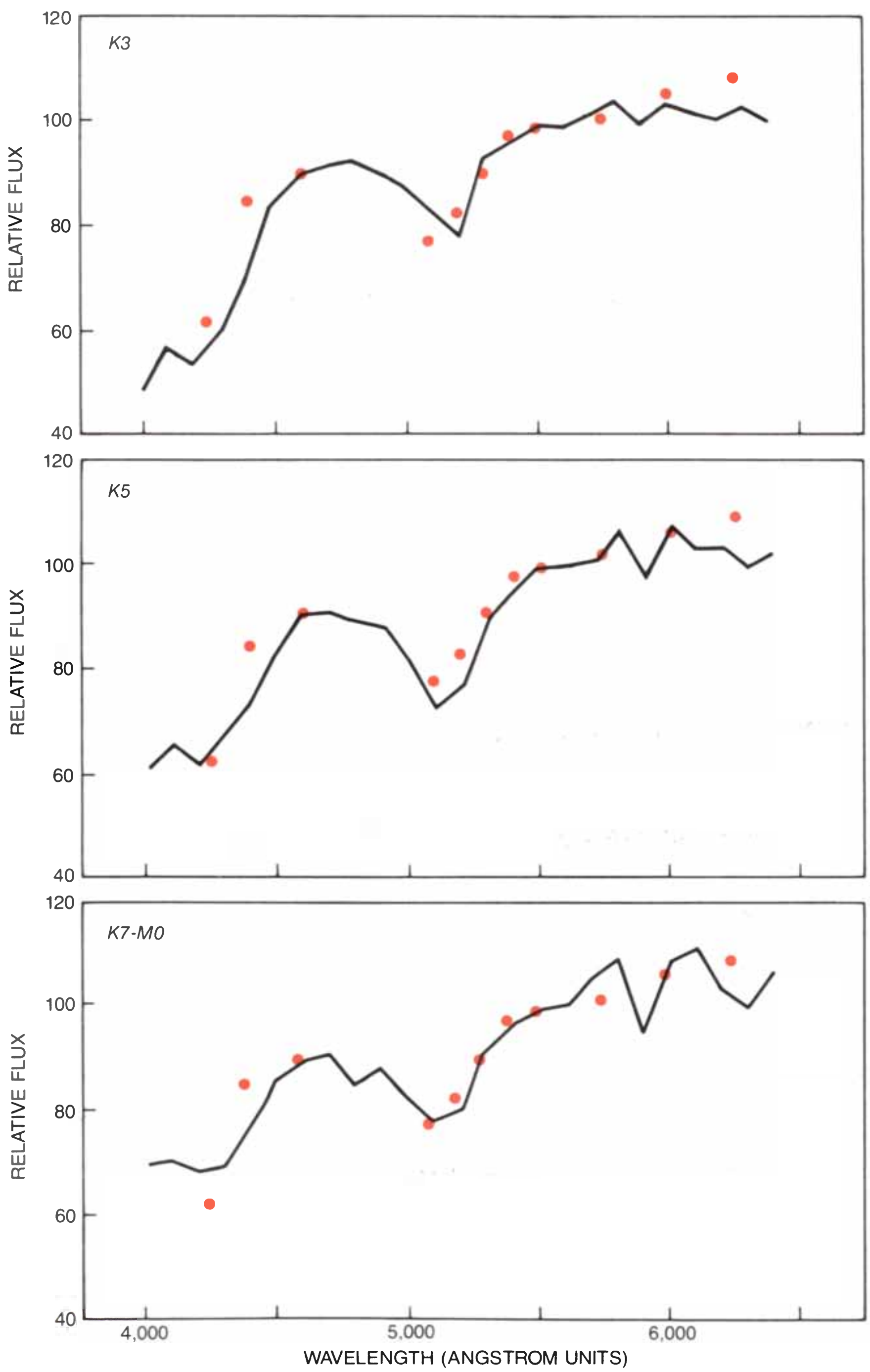


RAPID REPETITIVE BURSTS from the X-ray source MXB 1730–335 may result from the "dripping" of matter onto the surface of a neutron star. In one proposed model matter builds up along a magnetic boundary until the magnetic field no longer can support the weight. The matter then leaks through in a discrete drop and crashes onto the star, emitting X rays through the release of gravitational potential energy. The amount of matter in the drop varies: the bigger the drop, the longer the time until the mass builds up again to the breaking point of the magnetic field. This leads to the release of the next drop of matter.

observed from the Rapid Burster, the thermonuclear-flash idea came to life again. It became appealing to assume that the special bursts were caused by thermonuclear flashes and the rapid repetitive bursts were caused by instabilities in the accretion flow.

Instabilities in the flow had been suspected at the time of the discovery of the Rapid Burster. For some reason, perhaps because of a surrounding magnetic field, matter may fall onto the Rapid Burster in blobs rather than continuously. A constant buildup of matter above the surface of the star is suddenly released at some critical point, and the amount of matter released in any one blob determines the interval before the critical point is reached again. A dripping water faucet acts in much the same way. A system of this kind is called a relaxation oscillator.

To check our hypothesis we measured the energy released by the rapid bursts and compared it with the energy released by the special bursts. If the special bursts were thermonuclear flashes, and if the rapid bursts were the result of a "drip" mechanism taking the place of ordinary continuous accretion, the energy ratio should be about 1/100. The ratio we found was 1/120, which is in excellent agreement with the model.



SPECTRA OF THE OPTICAL COUNTERPART of Centaurus X-4 establish the mass of the binary companion of the X-ray-emitting neutron star in the system. The spectra were recorded at the end of June, 1979, about a month after the optical brightening was first noted. They reveal the presence of the faint companion star, which was previously obscured by the bright accretion disk. The disk had cooled and darkened as the X-ray emission decayed during the weeks following the initial outburst. The spectra are typical of stars of spectral types *K3* through *K7*, which correspond to stars of about .7 solar mass. The spectra were recorded by van Paradijs, Frank Verbunt, Theo van der Linden, Willem Wamsteker and Holger Pedersen.

Thus it has turned out that the special bursts are special only to the Rapid Burster. The special bursts are the common X-ray bursts of all other burst sources. This discovery, made in the fall of 1977, was a turning point in our thinking. Even before Joss published his calculations it made the thermonuclear-flash model compelling.

Even though most of the mystery of X-ray burst sources is now solved, a number of questions remain. What, for instance, is the nature of the accretion instability that leads to the unusual pattern of the Rapid Burster? Why is this pattern not observed in the radiation from other X-ray sources? Why does the Rapid Burster periodically cease bursting and then become active again at six-month intervals? How are the Class 2 binary systems formed? George W. Clark of M.I.T. has explained the formation of the Class 2 objects found in globular clusters as being a result of a close encounter between a neutron star and a nuclear-burning star. Many Class 2 objects, however, are not in globular clusters. How were these binary systems formed?

In spite of the remaining puzzles, the understanding of Class 2 X-ray sources has come a long way. Just six years ago the sources were a complete enigma and X-ray bursts were unknown. Now it is clear what the sources are and how they produce their bursts. The bursts in turn provide a new and powerful tool for studying the properties of neutron stars, their accretion disks and the low-mass binary systems in which they are often found.

There is some danger that work in this new branch of astronomy will come to a halt in the 1980's. At present only the Japanese X-ray observatory *Hakucho* can make X-ray-burst observations in coordination with ground-based observers. The satellite probably has only a few more years of operation. It is expected that the European Space Agency will launch the European X-ray Observatory Satellite (*EXOSAT*) in 1982. NASA may soon approve its existing plans for the X-Ray Timing Explorer (*XTE*). This X-ray observatory would be ideally suited to the study of a variety of highly variable phenomena.

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SCIENCE AND THE CITIZEN

War without Winners

Public discussions of nuclear weaponry tend to center on the cost of various weapons and on their role in military policy. What often goes unsaid is what nuclear weapons could do. In an effort to disseminate the neglected information the Federation of American Scientists has prepared a summary of the consequences of a general nuclear war between the U.S. and the U.S.S.R. The summary is published in the *F.A.S. Public Interest Report.*

The summary begins with a comparison. By 1985 the U.S.S.R. will have deployed roughly 6,000 nuclear warheads with explosive yields of from .8 megaton to 20 megatons. The U.S. has only some 2,000 cities whose population is 10,000 or more. The 300 largest cities include three-fifths of the U.S. population. Clearly there are more warheads than large cities. Indeed, every city of appreciable size could easily be placed inside a circle in which the pressure generated by a thermonuclear explosion would amount to at least five pounds per square inch. Under that pressure a house would be destroyed. Under twice that pressure a masonry building would collapse. Every large city could therefore be leveled. Fires would be started by the heat from the explosions within a zone somewhat smaller than the one defined by a pressure of five pounds per square inch. In a larger zone, however, fires would be caused by lesser forms of damage, such as broken gas lines. The report observes "there would be so many fires that they would have to be left to burn themselves out."

In order to calculate the number of deaths that would follow a nuclear attack on the U.S., assumptions must be made about such matters as the extent to which Americans are able to avoid a lethal exposure to radiation. The F.A.S. report cites fatality estimates made by various agencies of the executive branch of the U.S. Government that were summarized by the Office of Technology Assessment in 1979. According to the estimates, "between 70 million and 160 million people would die" within 30 days. Millions more would die later. For the most part "the seriously wounded would die [because] those few rural hospitals which would still be functioning with doctors not dead or sick from radiation would have literally millions of clients. The wounded would not have anything so sophisticated as blood plasma or intensive-care units. They would be extraordinarily lucky to find medicine useful for killing pain or stopping infection." Cold weather and a shortage of food would also lead to deaths. Meanwhile the lack of clean water and working sewers together with the weakened health of the people would allow diseases to "spread as they have never ... spread before in this country."

Urban residents who wished to protect themselves against a nuclear explosion and its immediate aftereffects would have to hide in elaborate, expensive shelters whose special requirements would include the provision of oxygen. Building shelters of this kind for the U.S. urban population would cost hundreds of billions of dollars. Even shelters such as these would nonetheless collapse in many cases. Shelters of lesser strength might protect against radiation. Among the immediate survivors, however, "only persons with dosimeters would have any idea how sick from radiation sickness they were likely to get or how many days or weeks they should stay in sandbagged basements." They would emerge to find their city and all its life-supporting services destroyed.

Might they leave the urban area during a period of crisis before a war began? Ironically, if they did, it might reduce the chance that the nation would ultimately recover. "It is the ratio of surviving population to [surviving] industry that should determine economic viability" in the aftermath of a nuclear war. "Saving the people without the cities" may therefore be a counterproductive strategy. In any case the Government is unlikely to order that the cities be evacuated during a crisis "lest the popular response undermine its political position by protesting the Government's intention to follow policies with a significant likelihood of nuclear war."

Evacuation and other steps intended to protect the population would encounter further difficulties. "The problems of supplying [large numbers of migrants] with food and necessities ... would require enormous preparation, which, in itself, no administration is likely to undertake." More generally, a civil-defense program that is designed (or perceived) as an "attempt to shift the strategic balance by withdrawing hostages, so to speak, from the reach of an enemy attack" is bound to "suffer the consequences of all strategic moves in the arms contest: some reciprocating action." One Russian response could be the deployment of still more warheads. Another and more immediate response would be a retargeting of the warheads already in place.

The U.S.S.R. could readily retarget. Since three-fifths of the U.S. population live in 300 cities, the U.S.S.R. could allocate 10 warheads to each such city and still retain half of its warheads (as of 1985) for attacks on purely military targets. The F.A.S. report dismisses the argument that a nuclear war would remain limited to military targets. For one thing, attacks directed solely against U.S. land-based missiles "would produce between five million and 20 million deaths.... The likelihood of escalation from such attacks is obvious." The attacks on land-based missiles would in themselves decide nothing, "since each side would be left with strategic bombers and missile-firing submarines adequate to destroy the other."

The F.A.S. report concludes that "general nuclear war is almost surely suicide for America." The report notes that Americans "in their 40's or older remember ... the Berlin crisis and the open threats of nuclear use in the Cuban missile crisis. But those in their 20's have largely escaped confrontation" with the emergence of "this grim situation of opposing 'deterrents.'" In an accompanying statement the F.A.S. Council announces its "promise to try to find out, on a national level, how many believe that the U.S. might win a nuclear war."

1/3 e

Electric charges, like people and planets, come in discrete quantities. Of small amounts of charge it is more appropriate to ask "How many?" than it is to ask "How much?" The atomic structure of matter and the physical basis of chemical interactions rest to a large extent on this simple fact. In the early years of the 20th century Robert A. Millikan measured small quantities of electric charge and found that almost all of them were integral multiples of the smallest charge he detected. Millikan's value for the smallest unit charge was later identified with the charge *e* of the electron or of the oppositely charged proton and positron. It seemed reasonable that electric charge was quantized because it was an attribute of an elementary (or indivisible) particle.

Until 1964 it was almost universally assumed that all charges are integral multiples of *e*. It was then that Murray Gell-Mann and George Zweig of the California Institute of Technology proposed independently that the proton, the neutron and the many other particles classified as hadrons are not elementary but instead are composed of pointlike particles called quarks. The quark model accounted for all the known hadrons in a parsimonious and aesthetically pleasing way, and it predicted the existence of new hadrons that have since been discovered. In the most widely accepted versions of the model quarks carry fractional electric charge.

The fractional charges are a straightforward consequence of well-established physical laws. As Zweig now recalls, however, they were introduced


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with some misgivings. "I didn't particularly like fractional charges," he notes, not only because Millikan and many others had not seen them but also because fractional charges introduced an asymmetry into an otherwise symmetrical correspondence between the quarks and the family of particles called leptons. The lepton family includes the electron, the muon, the tau particle and the neutrinos.

The electric charges predicted for the quarks are discrete, but they are fractions of *e*, namely $+1/3$, $-1/3$, $+2/3$ or $-2/3$ times *e*. If such charges exist in isolation, they should be detectable, and soon after the quark hypothesis was introduced many investigators began a search for them. Now, some 15 years after beginning a series of sensitive and difficult experiments, William M. Fairbank, George S. LaRue and James D. Phillips of Stanford University report the observation of electric charges of $+1/3\ e$ and $-1/3\ e$. Fairbank's group had earlier announced "evidence of" the existence of fractional charge, but this is the first time the investigators have considered their measurements conclusive enough to warrant the label "observation." Their results are reported in *Physical Review Letters*.

Ironically, the announcement is not being welcomed by all in the physics community. Quarks have proved extraordinarily fruitful in explaining the interactions of particles at high energy, and there is abundant evidence for the existence of quarks that does not require the detection of a free quark. During the years that Fairbank was refining his experiment an elegant theory was devised describing how quarks bind together to form hadrons. The theory, called quantum chromodynamics, suggests that quarks are confined within hadrons and so cannot exist as free particles. At this stage in the theoretical development the burden of proof may be on the experimentalist who purports to have found a free quark rather than on the theorist who asserts that free quarks cannot exist. Significantly, Fairbank's group maintains only that they have seen fractional charges.

Fairbank and his colleagues employed a method of searching for fractional charges that bears a strong resemblance to Millikan's technique. Millikan placed droplets of oil in the electric field between two charged plates; if a droplet had an electric charge, the field could be adjusted to counterbalance the force of gravity on the droplet. By comparing the drift rate of a droplet when the field was on with the rate when the field was off, Millikan measured the charge of each droplet with great sensitivity.

Instead of using oil droplets, Fairbank and his colleagues levitate spheres of the metal niobium. Each sphere is about a fourth of a millimeter in diameter and is made up of some 5×10^{17} atoms. Although the spheres are small, they are still almost 10 million times more massive than Millikan's oil droplets. Because much more matter can be examined at one time, the technique significantly increases the chance that free fractional charges (if they exist) will be present in the material.

The niobium spheres are too heavy for an electric field to offset the gravitational force acting on them. Instead the spheres are cooled to 4.2 degrees Kelvin, so that they become superconductive and can be suspended in a magnetic field. The magnetic field acts like a spring that vibrates with a frequency of .8 hertz if it is displaced. When an alternating electric field of the same frequency is applied parallel to the magnetic field, the niobium sphere oscillates in response, with an amplitude that depends on the electric charge of the sphere. The charge is adjusted by shooting either electrons or positrons at the sphere until the amplitude of the oscillation is minimized. Any residual charge can then be measured. If all the charged particles that make up the sphere carry an integral charge, the total charge of the sphere can always be reduced to zero in this way. If one of the particles has a fractional charge, however, the sphere cannot be neutralized.

Fairbank, LaRue and Phillips have now made 39 measurements. Of these, they report five charges of $-1/3\ e$ and nine of $+1/3\ e$. The remaining 25 measurements found the charge to be zero. The failure to observe charges of $+2/3\ e$ or $-2/3\ e$ does not count against the possible sighting of free quarks, because the experimental procedure acts to minimize the oscillation amplitude. A fractional charge of $-2/3\ e$ would show up as a charge of $+1/3\ e$ after the addition of a positron to the sphere, and a charge of $+2/3\ e$ would appear as a charge of $-1/3\ e$ after the addition of an electron. Perhaps the most convincing evidence for free quarks is the clustering of the data around the precise charge values predicted by the quark model, to within about 1 percent of *e*.

In spite of the sophistication of the apparatus and the consistency of the results, many physicists have adopted a wait-and-see attitude toward the observations. A number of other investigators have searched for free quarks among the particles reaching the earth as cosmic rays, in the debris of collisions between accelerated particles and in moon rocks, seawater and peanut oil, among other sources. None of the searches have uncovered any evidence of fractional charges.

Particularly puzzling are the negative findings reported by Giacomo Morpurgo and his colleagues at the University of Genoa and the Italian National Institute for Nuclear Research. Morpurgo has found no fractional charge in samples of iron and steel with an aggregate mass somewhat greater than that of the niobium samples examined by Fairbank's group. The results are not necessarily contradictory, however, because free quarks might have a greater affinity for the heavier nuclei of niobium atoms than they do for iron nuclei. No quark searches other than Morpurgo's have set limits on the concentration of free quarks in matter as low as the limits set by Fairbank's group.

There is some difficulty in reconciling the observations of Fairbank's group with quantum chromodynamics. According to the theory, each kind of quark comes in three varieties called colors (which have nothing to do with visual colors). All free particles, however, are thought to be colorless. The reason is that the strong force between colored particles may become indefinitely large as the particles are pulled apart. If it does, the energy required to overcome the force will probably cause new quarks to materialize before the bound quarks can be separated by any appreciable distance. The new quarks will cling to the quarks being separated and new systems of bound quarks will fly apart as colorless hadrons.

Because of the success of quantum chromodynamics many physicists suggest that even if Fairbank and his colleagues have discovered fractional charges, they have probably not detected free colored particles. Fairbank himself mentions some of the alternatives: fractionally charged leptons (which have no color), fractionally charged systems of bound quarks in which one of the quarks carries a unit charge, or free fractionally charged quarks from which the color has been screened. There is also a possibility that quantum chromodynamics does not require the strict confinement of color. Since there are several alternative explanations of the findings, however, some theorists argue that quantum chromodynamics need not be troubled by fractional charge.

Whatever consensus develops as to the identity of fractional charges, their existence, if it is confirmed, may have important implications for chemistry and for energy development. If such charges exist, they will be stable because of the law of conservation of electric charge. Some of their chemical properties, according to Zweig and Klaus S. Lackner of Cal Tech, can be inferred by considering how the properties of known forms of matter change when the number of protons is varied and the number of electrons is held constant. An atom with a fractionally charged nucleus would presumably have chemical properties determined largely by the structure of its electron orbits. For a given number of electrons this structure can be inferred from the charge of the nucleus.

Zweig has also suggested that fractional charges could catalyze the fusion

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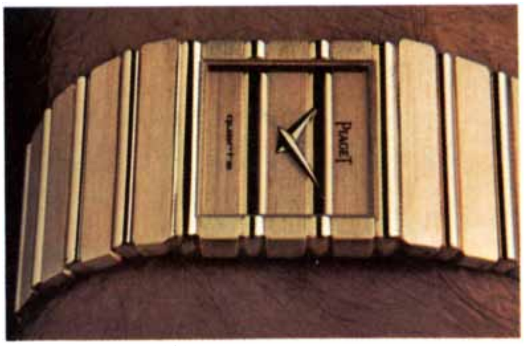

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of deuterium nuclei at room temperature. Deuterium (the isotope of hydrogen with one proton and one neutron) ordinarily exists in the form of a diatomic molecule in which two deuterium nuclei share two electrons. The fusion of deuterium is difficult to initiate because electrostatic repulsion between the protons keeps the nuclei apart. Current fusion strategies attempt to raise the temperature of a deuterium plasma to almost 100 million degrees, so that the kinetic energy of the nuclei can overcome the repulsion. Achieving such a temperature has proved to be difficult.

If the electrons of a deuterium molecule are replaced with heavier leptons, the distance between the nuclei is reduced by the same factor as the increase in the lepton mass. Forcing the nuclei closer would increase the likelihood of fusion. In 1957 Luis W. Alvarez of the Lawrence Berkeley Laboratory prepared atoms in which electrons were replaced with much heavier muons. Because of the short lifetime of the muon, however, catalysis by this means is not practical. Zweig argues that by using stable, fractionally charged quarks instead of muons fusion catalysis would become feasible. The mass of a quark is not known with certainty, but it may be considerably greater than the muon mass. Zweig notes that one mole of quarks (6.02×10^{23} quarks) would be enough to catalyze fusion reactions capable of meeting 10 percent of the annual U.S. energy needs.

No-Fault Fat

When a person's intake of energy exceeds his output of energy, he gains weight. Not all fat people, however, are guilty of gluttony and sloth; on this point much physiological evidence agrees with the anguished testimony of overweight men and women. Why, then, do some people gain weight on a diet that allows others to remain slim, even at the same level of physical activity? The answer is beginning to come clear. It is not that the metabolic engine runs steadily at a lower energy cost in fat people than it does in thin people; it does not. People with a tendency to obesity apparently are deficient in a particular cellular mechanism that in other people switches on automatically to burn off excess calories. The complicated path to this conclusion is reviewed in *British Journal of Hospital Medicine* by R. T. Jung and W. P. T. James of the Medical Research Council's Dunn Nutrition Unit in Cambridge.

By and large, they write, obese people do not eat more than thin people. Studies of carefully matched fat and thin individuals have established that a normal intake of food makes some people obese. So much for gluttony. As for sloth, it should be noted that physical activity accounts for only about 20 percent of most adults' energy expenditure. Investigators have disagreed on whether or not fat people are less active than others. One complication is that a given level of activity consumes more energy in the fat person than it does in the lean; in the obese state the energy cost of walking or standing can be four times greater than the cost of sitting. All in all, the evidence does not suggest that differences in activity can explain obesity.

Most of a person's energy is consumed not in physical activity but in simply staying alive: making proteins, pumping blood and maintaining a sodium-ion balance across the cell membrane, for example. Such processes are reflected in the basal metabolic rate (BMR), which is defined as the rate of energy expenditure in a relaxed state after a 12-hour fast and at a temperature that requires no energy expenditure to stay warm. The BMR accounts for between 55 and 60 percent of daily energy consumption. One might assume that the BMR is chronically low in the obese condition, but the opposite is the case. Jung and James did find that a fat person who has lost weight tends to have a BMR lower than normal, but the difference is small and apparently cannot account for the susceptibility to obesity.

Two forms of energy expenditure remain to be considered. They are processes that increase energy output in response to cold and to eating. When many animals are exposed to cold, they generate heat not only by shivering but also by burning extra fuel. A genetically obese strain of mouse designated *ob/ob* is deficient in this "nonshivering thermogenesis." In a normal environment its body temperature is lower than a lean animal's temperature, and it cannot tolerate cold. The reason is that instead of burning nutrients to generate heat it lays down fat. The low capacity for nonshivering thermogenesis is linked to obesity: in a warm environment, where no heat need be generated to maintain body temperature, the *ob/ob* mouse is not obese. The thermogenesis mechanism is activated by the sympathetic nervous system, specifically by the neurotransmitter norepinephrine. By administering norepinephrine, investigators have found the *ob/ob* mouse has only half the normal capacity for nonshivering thermogenesis.

Does a similar mechanism operate in human beings? Apparently it does. An infusion of norepinephrine can raise an infant's oxygen consumption by as much as 50 percent, indicating a corresponding increase in thermogenesis. There is a similar but smaller effect in adults. In experiments done by Jung and James and their colleagues the infusion of norepinephrine raised the metabolic rate of every subject. Obese women, and women who had been obese but had reduced their weight to normal, showed a rise of only 9.6 percent as opposed to a 21.2 percent rise in age-matched thin women. Other studies have found similar differences in response to cold.

How does the reduced capacity for nonshivering thermogenesis relate to the causation of obesity? The link is diet-induced thermogenesis. In 1902 the German investigator R. O. Neumann subjected himself to a heroic experiment. He kept his weight constant for three years while increasing his average energy intake from 1,766 kilocalories a day in the first year to 2,199 kilocalories in the second year and 2,403 kilocalories in the third. (A "calorie" in dietary usage is actually a kilocalorie.) The excess energy was presumed to have been dissipated somehow as heat. More recent experiments have confirmed Neumann's findings. On being overfed most people do not gain weight in proportion to the amount of overfeeding; they dispose of the extra energy by generating heat. Two years ago P. S. Shetty, Jung and James found that diet-induced thermogenesis was significantly reduced in obese and formerly obese individuals who were overfed a mixed diet. The diet was rather high in fats; when starches and proteins were given alone, there seemed to be no difference between fat people and thin people. In other words, it appears that the obese are specifically less able to burn off a high-fat diet by means of thermogenesis. Instead they tend to store the ingested fat.

A metabolic defect has been identified that may be responsible for the diminished thermogenesis. The defect is in a particular tissue: brown fat, a diffuse organ long known to be associated with heat production in young animals. Newborn animals (including human infants) and adult hibernating animals have rather large amounts of brown fat. Most adult animals have only small amounts, mainly in the chest and upper back and near the kidneys. The small amount present in adult experimental animals has been shown to account for some 50 percent of the heat generated under the stress of cold, and the amount of the tissue increases in response to cold. The nonshivering-thermogenesis deficiency in *ob/ob* mice has been related to reduced responsiveness in brown fat.

In human subjects Michael J. Stock and Nancy J. Rothwell of St. George's Hospital Medical School in London have found localized heating of the back after oral administration of ephedrine, which stimulates the same receptors as norepinephrine. James and P. Trayhurn have found a similar increase in temperatures measured between the ribs in response to norepinephrine. Rothwell and Stock established a link between brown fat and diet-induced thermogenesis in rats by allowing the animals to eat as much tasty "junk food" as they wanted. The average weight gain was far less than the average extra food intake. The animals that were best able to dissipate

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Brown fat is brown because it has more iron-containing cytochrome molecules than white fat has. The cytochromes are components of the membrane of the mitochondria; the cells of brown fat are packed with these organelles, which carry out cellular respiration by oxidizing nutrient molecules. Ordinarily the oxidation is coupled to the generation of adenosine triphosphate (ATP), which in turn supplies the energy for most other cellular processes. The oxidation yields protons that pass out through the mitochondrial membrane and generate ATP on their return. David G. Nicholls of the University of Dundee has found evidence that in the mitochondria of brown-fat cells a proton leak bypasses the coupling of oxidation with ATP production. As a result the mitochondria, oxidizing local stores of fat, generate heat instead of ATP. The proton leak is promoted by a series of events that begins with stimulation by norepinephrine, which is released by a signal from the hypothalamus (a region of the brain that is also involved in the control of appetite).

As Jung and James emphasize, much of the work they cite needs confirmation. It does seem clear that there is a diminished capacity in many obese people for thermogenesis induced by dietary fat. The defect seems to be associated with brown fat. It could be that the amount of the tissue is inadequate, or there may be a difference in the proton-leakage pathway or a failure at some stage of the switching-on process. Jung and James do not hold that all fat people suffer from a precisely definable metabolic defect; many people do eat too much. They suggest, however, that a large proportion of the obese population consists of people at the "extreme end of a range of activities" of brown fat. A physician, they conclude, should not too readily condemn his fat patients for lack of willpower "while himself unwittingly enjoying a physiological system that allows him to stabilize his own weight with effortless ease."

Micromainframe

The mainframe computer has long been the standard point of reference for indicating the size of a computational system. A mainframe is large and expensive; the frame in question is a steel chassis in which some dozens or hundreds of printed-circuit boards are installed. A minicomputer is considered "mini" because it is smaller than a mainframe, and a microcomputer is smaller still. Size, however, is not always a reliable indicator of performance. The Intel Corporation is now manufacturing the components of a computer it calls a micromainframe. The components are three chips of silicon, on which are arrayed a total of 225,000 transistors and other microelectronic circuit elements. The computer is designated the iAPX 432, and it is said to have "the computing capabilities of a contemporary mid-sized mainframe computer."

One rough measure of the capacity of a computer is the width of its data paths: the number of bits, or binary digits, that can be processed simultaneously. The width has an important influence on the speed of calculations done with large numbers or with numbers expressed to high precision. The first microprocessor, which was introduced just a decade ago (by Intel), was four bits wide. The majority of microprocessors now in use have a width of eight bits, and 16-bit microprocessors are available. The iAPX 432 has a width of 32 bits, the same as many mainframe computers.

In the iAPX 432 the functions of the central processing unit of a digital computer are distributed among the three chips. One chip fetches instructions from a program and interprets, or decodes, them. The output of the instruction-decoding chip is a sequence of signals that specify all the steps in the execution of the instruction. The signals are supplied to a second chip, where arithmetical operations and other manipulations of data are carried out. These two chips make up the data processor. The third chip in the set is called an interface processor, and it is concerned exclusively with communications between the iAPX 432 and external devices, such as terminals for input and output, other computers and magnetic tape or disk memories.

The high density of circuit elements on the three chips can be attributed in part to the continuing reduction in the area occupied by individual microelectronic devices. A more important contribution, however, comes from increased regularity in the organization of the elements. As a rule the highest-density microelectronic chips have been memories, where many identical unit cells can be packed uniformly in a rectangular array. Chips that process information rather than store it have generally relied on "random" logic, which is much less efficient than memory in the use of space. (The electronic logic is actually not random but merely has no large-scale regularity in its structure.) In the iAPX 432 a number of functions that might have required random logic have been embodied in preprogrammed memories. This principle is applied most effectively in the instruction-decoding chip, which is the densest one: it holds more than 100,000 circuit elements. Where memory cannot serve to define a function, random logic has largely been replaced by logic arrays with an orderly arrangement of elements. Finding the optimum set of interconnections in such an array is a difficult problem in topology, but adopting the arrays brought a significant improvement in density. The instruction-execution chip has some 60,000 devices and the interface processor has 65,000.

An iAPX 432 computer must include at least one chip of each kind, but it might well have more than one. The system was designed to accommodate multiple processors, so that multiple tasks can be done simultaneously. The processors communicate with one another by means of a bus: a set of parallel conductors. When several processors are connected to the bus, tasks are automatically allocated among them. Adding or removing processors requires no modification of programs, although of course it does affect the time required for their execution. In an application that makes heavy demands on input and output facilities extra interface processors could be installed. Extensive numerical calculations would call instead for additional data processors.

A computer must have not only processors but also memory for the storage of both data and programs. In the memory unit information is divided into bytes, or eight-bit units, and each byte is identified by a numerical address. In the iAPX 432 the address is a 24-bit number; it follows that the computer can at any moment address 2^{24} (about 16 million) bytes. By creating multiple memory compartments it is possible to address 2^{40} (more than a trillion) bytes. Because of the cost it is unlikely such a large directly accessible memory would be assembled for the computer; instead a much smaller memory would hold only those data and programs needed immediately, and other information would be kept in reserve in a cheaper storage medium, such as a magnetic tape or disk. Arrangements must then be made for shuttling blocks of information between the mass-storage medium and the main memory. In the iAPX 432 (as in many larger mainframe computers) the transfers are made automatically: the computer is said to have virtual memory.

In describing the operation of a computer a distinction is usually made between hardware and software, or between electronic devices and programs. In the iAPX 432 the boundary is to some extent blurred. Not only are some functions of the hardware represented as patterns stored in preprogrammed memory but also some tasks that are generally left to the software have been built into the silicon chips. The set of programs that is most intimately associated with the architecture of a computer is called the operating system. It is usually a set of supervisory programs that must be written for a particular computer and then stored in its memory. In the iAPX 432 the operating system is part of the hardware.

Another decision that was made in the design of the computer will have a ma-

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jor influence on how programs are written for it. Early microcomputers were generally programmed by specifying the individual instructions to be executed by the processor. Later, programming languages capable of representing concepts at a higher level of abstraction were adapted for use with microprocessors. The iAPX 432 can be programmed only with such a higher-level language. Moreover, the language chosen is as new as the computer itself. The language is Ada, which was developed under the auspices of the Department of Defense. It is named for Augusta Ada Byron, the daughter of Lord Byron, who worked with Charles Babbage on his difference engine, a 19th-century mechanical computer. A distinctive feature of the Ada language is that it is made up of independent "packages," which can be installed, removed or replaced much like hardware components.

The iAPX 432 was developed over a period of six years by a group at Intel headed by William W. Lattin and Jean-Claude Cornet. If complexity is measured simply by the number of circuit elements, the iAPX 432 is roughly 100 times as complex as the first microprocessor. Still, it is evidently not the last word in complexity. The Hewlett-Packard Company has recently announced a 32-bit microprocessor system made up of six chips, one of which has some 600,000 circuit elements.

Inner Voice

The human ear is an efficient transducer for converting the mechanical energy of sound into the electrophysiological energy of nerve impulses. It now appears that the transducer may also work in reverse, so that the ear is not only a receiver of sound but also an emitter. Aural emissions have been detected by Patrick M. Zurek of the Central Institute for the Deaf in St. Louis.

Zurek made the discovery while investigating another phenomenon: the interference in the inner ear of sounds that are close in frequency. He set out to measure this effect by placing a microphone in the canal of his right ear. When he turned on the microphone, he found that his ear was emitting sound with a frequency of 1,910 hertz, which is a high pitch almost three octaves above middle C. Zurek detected a similar signal in his left ear, and he subsequently noted that when he was in a quiet place, he could sometimes hear the sound his right ear emitted.

In a survey of medical literature Zurek found several reports of patients whose ears emitted high-frequency acoustic signals. One remarkable report, by Egbert H. Huizing and Atze Spoor of the University Hospital in Leiden, described a 22-year-old woman whose right ear gave off tones loud enough to be heard by other people. She was not aware of the signals, which annoyed her sister when the two of them played the piano together. Zurek decided to investigate further. His results are presented in *The Journal of the Acoustical Society of America*.

Zurek put a microphone in the ear canals of 32 volunteers. He found that half of the subjects had acoustic signals in at least one ear, and signals were detected from a total of 22 ears. Most of the sounds were in the range of frequencies between 1,000 and 2,000 hertz. No significant differences were noted between the right ear and the left ear, between men and women or between the young and the old. None of the 16 subjects knew their ears were broadcasting.

Six of Zurek's subjects had complained of tinnitus: the sensation of a ringing or roaring noise in the ears. Some of the subjects with tinnitus had measurable aural sounds, but in no case was there evidence of a signal that might be a correlate of the tinnitus sensation.

The signals seem to originate in the cochlea, the fluid-filled spiral canal of the inner ear where the actual conversion of sound to nerve impulses takes place. In the cochlea is the organ of Corti, which apparently acts as a filter to separate high-frequency sounds from low-frequency ones. It is not known exactly how the organ of Corti works, but most investigators had ruled out the possibility that active biomechanical processes have a role in the filtering. The discovery of acoustic signals emanating from the cochlea, however, suggests that the organ is not passive but is capable of vibrating continuously.

The difficulty with interpreting the emitted signals as evidence of an active biomechanical process in the normal operation of the cochlea is that the ears of half of the subjects did not emit acoustic signals. Zurek speculates that perhaps the signals can be detected only when there is a microscopic lesion in the organ of Corti. If the lesion encompasses only a few cells, it could emit sound without resulting in a loss of hearing.

The interpretation of the aural emissions is complicated further by work with the chinchilla (an experimental animal chosen because its ears are similar to human ears). Zurek and William Clark, who also works at the Central Institute for the Deaf, checked the ears of 22 chinchillas for audible signals. Under quiet conditions they found none. When they exposed the chinchillas' ears to intense noise, however, two of them emitted acoustic signals. In one case the sound could be heard without the aid of amplification.

Upward Mobility

A number of hill figures in Britain are thought to be of some antiquity. They were formed by digging shallow trenches in the thin soil of a hillside and

thereby exposing the underlying chalk. The most famous of the figures is the White Horse of Uffington, in Berkshire, an outline figure 374 feet long. The most notorious figure, however, is the Cerne Abbas Giant in Dorset. Postcards of the Giant, it is jokingly said, are the only pornographic material knowingly transmitted by the British Post Office.

The Giant is an outline figure that brandishes a knobby club almost its own height. The figure measures 160 feet from the soles of the feet to the tip of the club, and it stands in simple frontal nudity. Six straight furrows indicate the rib cage and two circles represent the nipples. The genitals are also outlined. The testes are indicated by two more circles; the erect penis measures some 30 feet from the base to the glans. The British archaeologist Leslie Grinsell now points out that it was not always thus. His report on the Cerne Abbas Giant appears in *Antiquity*.

The first definite reference to the Giant, Grinsell notes, was made in 1742, and the first published illustration of the figure accompanied a letter to *Gentleman's Magazine* in 1764. The illustration shows the penis some six feet shorter than it is now. Furthermore, a circle just above the penis represents the navel; today the figure has no navel.

Grinsell was able to find several more illustrations of the Giant that appeared over the next 150 years. They are of little help, however, in determining when the chalk figure was altered because they are all bowdlerized. Evidently the genitals did not appear again in print until 1926, with the publication of *The Hill Figures of England,* by Sir Flinders Petrie. In that book the navel has vanished and the penis has been lengthened a corresponding distance.

When was the change made? All hill figures must be cleaned of intruding vegetation from time to time, and their outlines must be reemphasized by spreading fresh chalk in the furrows. Grinsell has found evidence that in 1868 the local clergy complained that one such renovation of the Giant was potentially corrupting to morals. A Dorset chronicler, writing in the 1880's, noted that "a former vicar put a stop to these scourings." Also in the 1880's the British archaeologist Augustus Henry Lane-Fox Pitt-Rivers inherited the estate where the Giant stands and retired from the military to pursue his scholarly interests. In 1887, Queen Victoria's Golden Jubilee Year, Pitt-Rivers ordered the Giant refurbished.

Grinsell concludes that the thorough work Pitt-Rivers would have required was probably responsible for the mishap that made the Giant's navel vanish. Grinsell does not, however, entirely dismiss the possibility that the refurbishers of 1868 may have deliberately incorporated the navel into the penis to spite their straitlaced vicar.

The Crest of the East Pacific Rise

At a site on a mid-ocean ridge, where hot springs on the sea floor nourish a bizarre biological community, undersea exploration has revealed much about how new segments of the earth's crust emerge

by Ken C. Macdonald and Bruce P. Luyendyk

The East Pacific Rise is a part of the world's longest mountain chain: the 75,000-kilometer oceanic rift system, which winds around the globe like the seam of a baseball. Most of the rift system, including the entire East Pacific Rise, lies underwater; it is a network of mid-ocean ridges. In the plate-tectonic theory that has become the organizing principle of geology, the rift system has a vital role. Each rift is a narrow, fractured zone where plates of the oceanic crust are continually being pushed or pulled apart. At such a sea-floor spreading center molten rock wells up from the mantle of the earth, filling cracks and generating new sections of oceanic crust, which move outward as if they were on a broad conveyor belt.

The concept of sea-floor spreading accounts for a host of geologic observations. Still, several important questions about the rift system remain unanswered. Underwater photographs and rock samples show signs of recent volcanic activity on the mid-ocean ridges, suggesting there is a magma chamber, or reservoir of molten rock, under the axis of the ridge. Does such a magma chamber exist as a permanent feature of the ridge? If it does, how deep is it? How far from the axis does it extend? What are the physical and chemical properties of the magma? How much heat is lost from the earth's interior through the volcanic creation of new crust? The answers to these questions and others like them could bring a much improved understanding of the structure and composition of the earth's crust, since at least 70 percent of the crust has formed at the mid-ocean rifts.

We and a group of our collaborators have recently had an opportunity to explore at close range a small region along the crest of the East Pacific Rise. From the expedition has come important new evidence of a magma chamber along the axis of the crest and of a narrow, sharply defined zone of crustal formation above the chamber. The evidence is derived from measurements of seismic, electrical, gravimetric and magnetic properties of the crust and detailed geologic maps made along traverses of the axial volcanic zone. The most dramatic evidence comes from direct visual observations made with a small submersible vehicle at a depth of more than two and a half kilometers. At several places along the crest we found clusters of hydrothermal vents spewing out mineral-blackened water that had been heated to extraordinarily high temperatures by contact with rocks near a magma chamber. It turns out that the hydrothermal vents have a major influence not only on the geophysics of the rift system but also on the chemical balance of the oceans. Furthermore, the vents support an unusual biological community, the only one known that is entirely independent of photosynthetic sources of energy.

Plate Tectonics

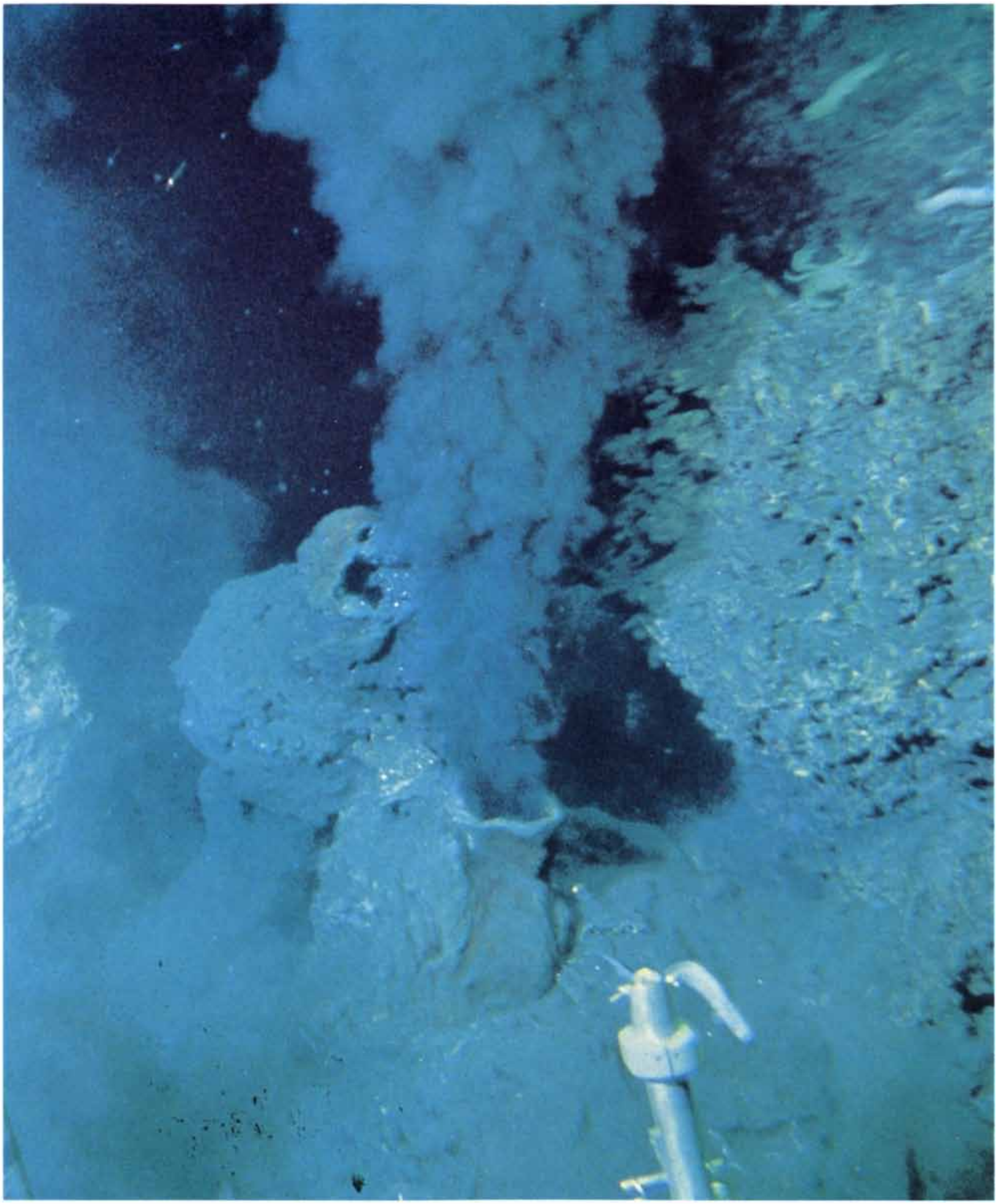
The theory of plate tectonics describes the motions of the lithosphere, the comparatively rigid outer layer of the earth that includes all the crust and part of the underlying mantle. The lithosphere is divided into a few dozen plates of various sizes and shapes; in general the plates are in motion with respect to one another. A mid-ocean ridge is a boundary between plates where new lithospheric material is injected from below. As the plates diverge from a mid-ocean ridge they slide on a more yielding layer at the base of the lithosphere.

Since the size of the earth is essentially constant, new lithosphere can be created at the mid-ocean ridges only if an equal amount of lithospheric material is consumed elsewhere. The site of this destruction is another kind of plate boundary: a subduction zone. There one plate dives under the edge of another and is reincorporated into the mantle. Both kinds of plate boundary are associated with fault systems, earthquakes and volcanism, but the kinds of geologic activity observed at the two boundaries are quite different.

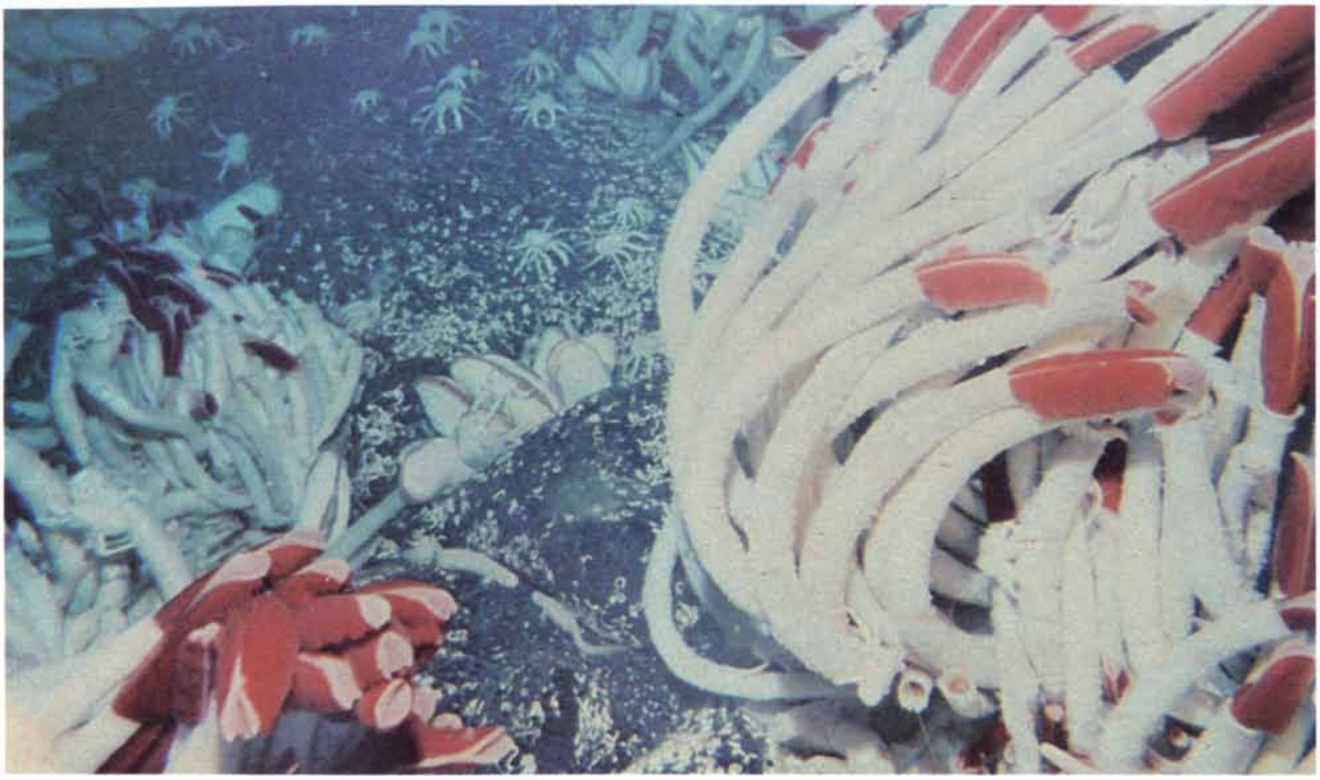
The idea of sea-floor spreading actually preceded the theory of plate tectonics. The sea-floor-spreading hypothesis was formulated chiefly by Harry H. Hess of Princeton University in the early 1960's. In its original version it described the creation and destruction of ocean floor, but it did not specify rigid lithospheric plates. The hypothesis was substantiated soon afterward by the discovery that periodic reversals of the earth's magnetic field are recorded in the oceanic crust. An explanation of this process devised by F. J. Vine and D. H. Matthews of Princeton is now generally accepted. As magma rises under the mid-ocean ridge, ferromagnetic minerals in the magma become magnetized in the direction of the geomagnetic field. When the magma cools and solidifies, the direction and the polarity of the field are preserved in the magnetized volcanic rock. Reversals of the field give rise to a series of magnetic stripes running parallel to the axis of the rift. The oceanic crust thus serves as a magnetic tape recording of the history of the geomagnetic field. Because the boundaries between stripes are associated with reversals of the magnetic field that can be dated independently, the width of the stripes indicates the rate of sea-floor spreading. (Precisely how the earth's magnetic field reverses at intervals of from 10,000 to about a million years continues to be one of the great mysteries of geology.)

It follows from the theory of sea-floor spreading that many of the most interesting geologic features of the earth's surface are to be found on the ocean floor. The investigation of such features has been furthered in recent years by the development of deep-diving manned submersibles. In particular the U.S. research submersible *Alvin,* operated by the Woods Hole Oceanographic Institution, has proved to be a valuable tool for studies of the sea bed. A geologist in the *Alvin* can collect rock samples and document in detail the setting of each rock. For the first time a marine geologist can have maps of a site as precise as those of a geologist on land.

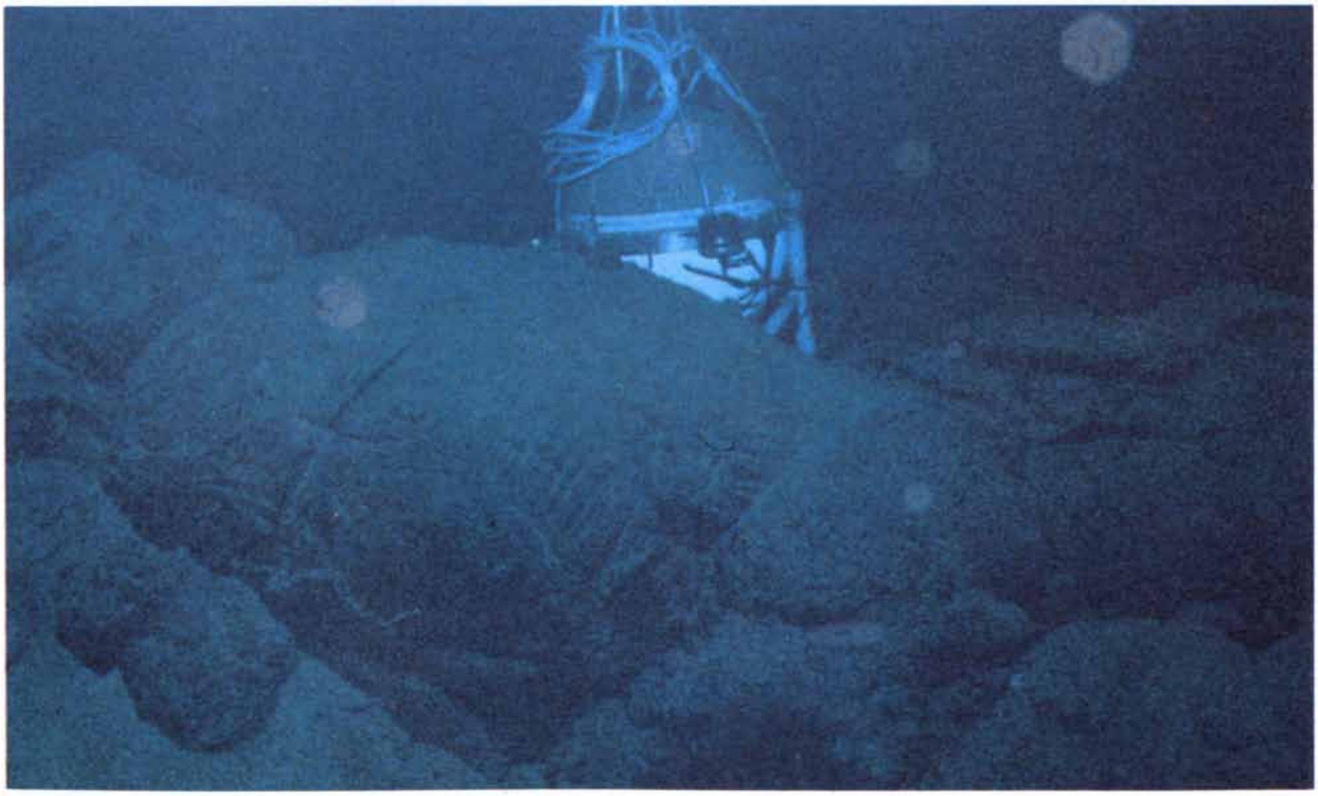
Early work with the *Alvin,* beginning in 1973, made it clear that submersibles



HOT, SULFIDE-BLACKENED WATER spews out of a "black-smoker chimney" at the crest of the East Pacific Rise near the entrance to the Gulf of California. The photograph was made from the manned research submersible *Alvin* at a depth of 2,650 meters; a part of the craft's sampling equipment is visible in the foreground. The East Pacific Rise is a boundary where two plates of the earth's lithosphere (a layer that includes the rocky crust) are being pulled apart. At the plate boundary cold seawater seeps into the comparatively thin crust and is heated by contact with magma, or molten rock, under the sea-floor spreading center. The water issues from the vents at temperatures as high as 350 degrees Celsius, bearing minerals that nourish a biological community. The site was explored in 1979 by a dive team that included the authors and 19 other investigators from the U.S., France and Mexico. The other members of the team were Fred N. Spiess, Charles S. Cox, James W. Hawkins, Rachel Haymon, J. Douglas Macdougall, John A. Orcutt, Loren Shure, Tanya M. Atwater, Stephen P. Miller, Robert D. Ballard, Jean Francheteau, T. Juteau, C. Rangin, R. Larson, William R. Normark, A. Carranza, V. M. Diaz Garcia, D. Cordoba and J. Guerrero. The photograph was made by Dudley Foster of the Woods Hole Oceanographic Institution.



UNUSUAL LIFE FORMS near the hydrothermal vents on the East Pacific Rise include many of the same organisms found for the first time two years earlier on an expedition to the Galápagos spreading center. The photograph, made from the *Alvin*, shows a cluster of giant tube worms waving in cooler (20 degrees C.) hydrothermal currents, where the water is not blackened by minerals. The worms, classified as vestimentiferan pogonophorans, are distinguished by bright red plumes extending from white protective sheaths; some of the tube worms are as long as three meters. Other organisms include clams and white crabs. At the base of the food chain are chemosynthetic bacteria; the community is independent of solar energy. The photograph was made by William R. Normark of the U.S. Geological Survey.



PILLOW LAVA covers much of the sea floor near the hydrothermal vents. The pillow shapes were formed by the rapid cooling of magma extruded through cracks in the crust during a volcanic eruption. In the background is an ocean-bottom seismometer; an array of such instruments was deployed from a surface ship. The photograph was made by John A. Orcutt of the Scripps Institution of Oceanography.

are most efficiently deployed in the final stages of an undersea expedition. Time on the bottom is short (six hours or less) and expensive. Every means of mapping the sea floor, including the use of remotely operated cameras, high-resolution sonar scanners and other sensing devices, should be fully exploited so that the *Alvin* can be guided to key geologic sites. When the *Alvin* is employed in this sparing manner, it is a highly productive tool for gathering information. In the past seven years it has been used to investigate cycles of volcanic activity and patterns of geomagnetic reversal along the Mid-Atlantic Ridge and to study exposed cross sections of the crust in the Cayman Trough rift system near Jamaica. Hydrothermal vents and the associated exotic life forms were first observed in 1977 during dives made with the *Alvin* along the Galápagos spreading center off the coast of Ecuador.

We shall report here the results of the latest expedition with the *Alvin:* to the crest of the East Pacific Rise some 3,000 kilometers northwest of the Galápagos dive site. With the aid of the submersible and with instruments towed by surface vessels we measured such properties as the magnetization and the electrical conductivity of the crustal rocks, the velocity of seismic waves under the rise and the magnitude of gravitational anomalies over it. All these properties are sensitive indicators of the characteristics of the axial magma chamber thought to underlie the rift. It was during this expedition that we discovered the submarine hot springs that are the hottest yet found in the ocean.

Preliminary Explorations

The dive site we selected is near the northern end of the East Pacific Rise, just outside the entrance to the Gulf of California. The rise itself continues north up the middle of the gulf and links up with the San Andreas fault system in California. Outside the gulf it forms part of the boundary between the Pacific Plate and the Rivera Plate; the latter is a fragment of the much larger North American Plate.

The rift in the area we studied is currently spreading at a rate of some six centimeters per year, which is about as fast as human fingernails grow. The spreading rate here is three times the rate at the Mid-Atlantic Ridge, but it is only about a third of the highest spreading rate known: 18 centimeters per year, observed near Easter Island on another part of the East Pacific Rise. The site was picked because it was expected to be a typical intermediate-rate spreading center and because a considerable amount of detailed information about it was already available.

On earlier cruises we had obtained a fairly clear picture of the geologic setting of the spreading center and of its overall dimensions. Magnetic, photographic and sonar studies had been done with the aid of an unmanned vehicle, the Deep-Towed Instrument Package of the Scripps Institution of Oceanography. The studies indicated that at this point the spreading center may be only a kilometer or two wide. Bathymetric and geologic maps of the spreading center were assembled and targets for exploration were identified. It was established that the average depth of the dives would be more than 2,600 meters.

The first stage of the diving program was conducted in 1978 by a team of investigators from France, the U.S. and Mexico led by Jean Francheteau of the Center for Oceanographic and Marine Biological Studies in Brittany. Diving in the French submersible *Cyana,* the 12-member team focused on geologic investigations that called for the ability to maneuver near and visually reconnoiter rocky outcrops and other structures along the crest of the rise. Meanwhile planning proceeded for the next stage of the operation: the geophysical experiments, which were scheduled to begin in 1979 with the larger and stabler submersible *Alvin.*

The *Cyana* divers found that the spreading center actually consists of four geologic zones. Zone 1, directly on the axis of the spreading center, is a very young volcanic region approximately a kilometer wide. Almost all the new volcanic material produced at the spreading center appears to be extruded onto the sea floor within this remarkably narrow band. The basaltic lava flows found here, which are mostly in the form of the "pillows" characteristic of underwater eruptions, have essentially no sediments covering them. They exhibit a fresh, glassy luster and are comparatively unaltered by interactions with seawater.

Just outside the neovolcanic zone the newly formed crust begins to accelerate horizontally, approaching a maximum spreading velocity of three centimeters per year on each side of the spreading axis. In this region, designated Zone 2, the crust is stretched and cracked. Minor fissures tend to be lined up parallel to the general northeast trend of the rise and perpendicular to the direction of spreading. The fissured zone on each side of the central axis is between one-half kilometer and two kilometers wide.

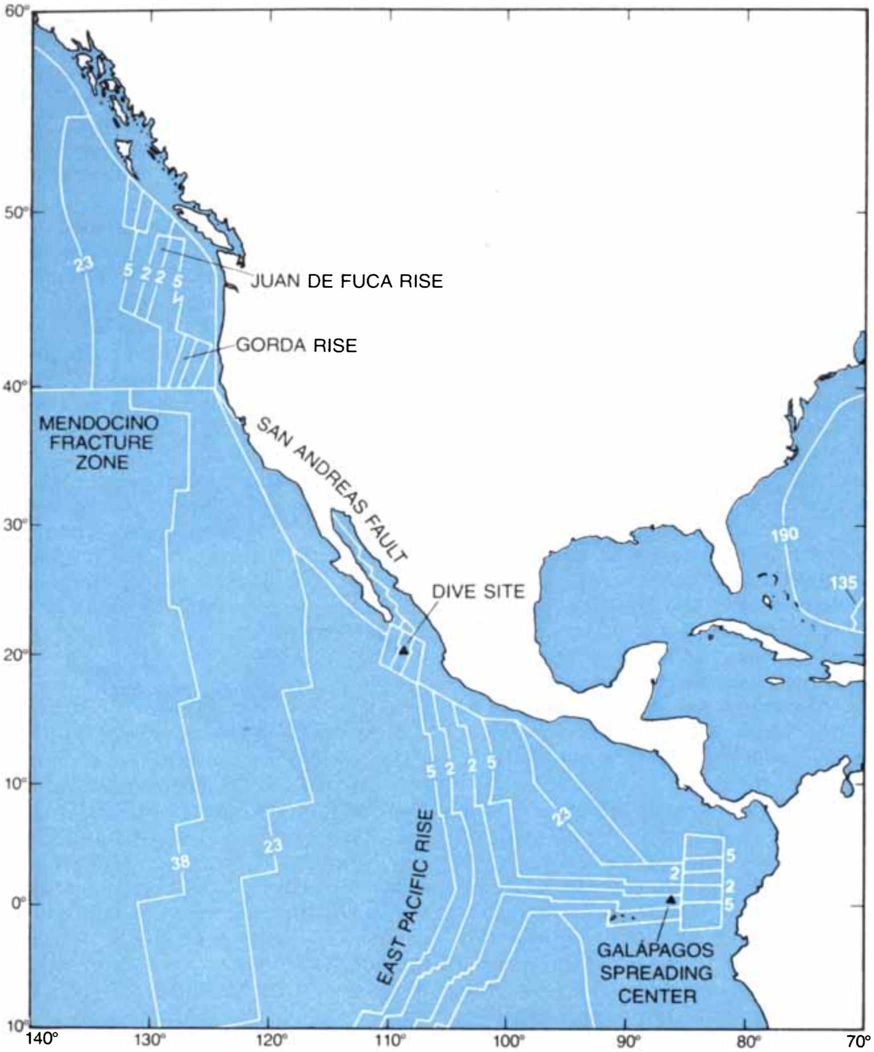
Beyond Zone 2 the crust is probably still undergoing some acceleration, although in the next region, designated Zone 3, major "normal" faults begin to develop. The faults are almost vertical and look like a huge stairway. They are caused by abrupt vertical movements in rocks where the principal stress is tensional. Slippage along the faults gives rise to frequent earthquakes with a maximum magnitude of roughly 5.5 on the Richter scale. The scarps, or exposed faces of the faults, are generally oriented toward the spreading center and are as much as 70 meters high. At approximately 10 kilometers from the spreading center, in the region designated Zone 4, active faulting diminishes sharply, and so presumably does horizontal acceleration of the crust.

The 1978 *Cyana* dives revealed unusual lava formations and mineral deposits. Solidified lava lakes, probably formed by rapid outpourings of lava, were observed. Some of the lakes are hundreds of meters long and more than five meters deep. In places the surface of a lava lake has caved in, forming a collapse pit. Pillars and walls of basalt at the edge of the lakes are marked by bands of rapidly cooled basaltic glass that may record changes in the level of the lava. The bands were probably formed either during lateral outflows from the lava lakes or during the drainage of lava back into the underlying magma chamber.

The Hydrothermal Field

Near the boundary of zones 1 and 2 a chain of mounds several meters high was discovered. The geochemists in the group, led by Roger Hekinian, found that the mounds consist of sulfides of zinc, iron and copper with a small admixture of silver. It was suspected that the sulfide mounds were created by hydrothermal venting of fluids through the sea floor. There were three other indications that hydrothermal activity might be important in the area. In 1974 and again in 1977 temperature anomalies of several hundredths of a degree Celsius had been detected, and unusually high concentrations of helium 3 had been measured over the spreading center. This light isotope of helium is generally considered to be a reliable indicator of hydrothermal activity. In addition the workers making one of the *Cyana* dives observed large clamshells, similar to shells seen at the Galápagos hydrothermal vents, although none of the shells at the more northerly site were occupied by live clams. (As it happened the *Cyana* on this dive came within a few hundred meters of the vents discovered a year later by the *Alvin.*)

In 1979, shortly before the *Alvin* was brought on the scene, we made a brief photographic and mapping survey of the axis of the spreading center to the southwest of the *Cyana* dive site. We wanted to investigate the change in the geologic structures along the spreading center and to follow up on the tantalizing signs of hydrothermal activity. The time was well spent. Under the direction of Fred N. Spiess of the Scripps Institution, the Deep-Towed Instrument Package was deployed to obtain topographic and side-scanning-sonar profiles, extending our bathymetric chart to the



EAST PACIFIC RISE forms the boundary between the Pacific Plate and the Rivera Plate (a fragment of the North American Plate) in the region off the west coast of Mexico that was selected for exploration. The triangles mark the dive sites of the East Pacific Rise project and of the earlier expedition to the Galápagos spreading center off Peru. At both sites the oceanic crust is spreading at a rate of approximately six centimeters per year. Numbered contours indicate the age of the oceanic crust in millions of years. The map is based on one prepared by W. Pitman, R. Larson and E. Herron and on a chart published by the Geological Society of America.

southwest and delineating the axis of the spreading center.

The *Angus,* a strongly built camera sled that also carried a temperature sensor, was lowered to the sea floor for a series of long traverses a few meters above the rugged volcanic terrain. Guided by Robert D. Ballard of the Woods Hole Oceanographic Institution, the *Angus* detected elevated temperatures in several places and telemetered the information to the control ship on the surface. We immediately raised the camera and eagerly awaited the development of the film. Then we quickly spun through the roll of developed film until we found about a dozen frames that showed an assortment of bottom-dwelling creatures similar to those discovered two years earlier at the Galápagos spreading center. It appeared that the Galápagos hydrothermal vents and their associated biological communities were not unique.

The evidence was striking enough for us to shift the planned diving program to the southwest. The dive team was augmented by another dozen geologists and geophysicists from the U.S., France and Mexico, including the two of us. First a triangular array of ocean-bottom seismometers was precisely positioned in Zone 1 with the aid of signals relayed by acoustic transponders on the ocean floor. Several preliminary dives made with the *Alvin* demonstrated that seismic and gravitational measurements could be made successfully. On the third dive the hydrothermal vents were seen for the first time by Francheteau and one of us (Luyendyk).

It is difficult to convey the strange quality of such an experience. First one spends two hours or so in almost total darkness, dropping by gravity more than two and a half kilometers to the sea floor. Three people are huddled in the cold and cramped confines of the *Alvin's* pressurized spherical compartment, which is only two meters in diameter. On approaching the bottom the submersible's running lights are turned on, and the illuminated water takes on a dim greenish glow. Minutes later the sea floor is sighted. As soon as the *Alvin* has reached the bottom, the team reports its position to the control ship and is given a course to steer to a bottom target. Edging ahead slowly (at about half a kilometer per hour) over the glistening volcanic rock, the investigators peer through the portholes, seeing only 10 or 15 meters into the darkness.

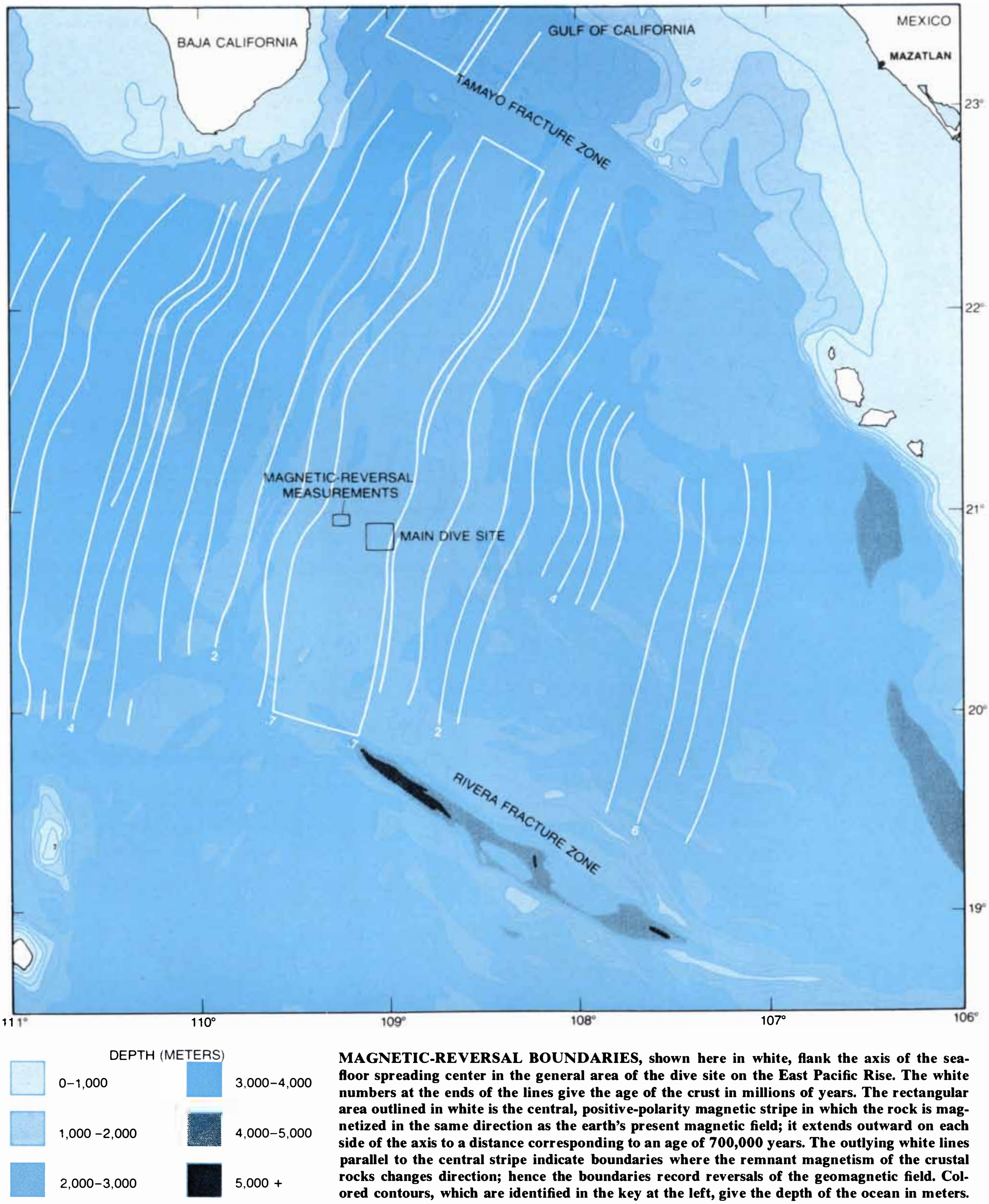
A New Ecosystem

On the dive in question we were making gravity measurements in the volcanic zone when we came on the hydrothermal field. The scene was like one out of an old horror movie. Shimmering water rose between the basaltic pillows along the axis of the neovolcanic zone. Large white clams as much as 30 centimeters long nestled between the black pillows; white crabs scampered blindly across the volcanic terrain. Most dramatic of all were the clusters of giant tube worms, some of them as long as three meters. These weird creatures appeared to live in dense colonies surrounding the vents, in water ranging in temperature from two to 20 degrees C. The worms, known as vestimentiferan pogonophorans, waved eerily in the hydrothermal currents, their bright red plumes extending well beyond their white protective tubes. (The red color of both the tube-worm plumes and the clam tissues results from the presence of oxygenated hemoglobin in their blood.) Occasionally a crab would climb the stalk of a tube worm, presumably to attack its plume.

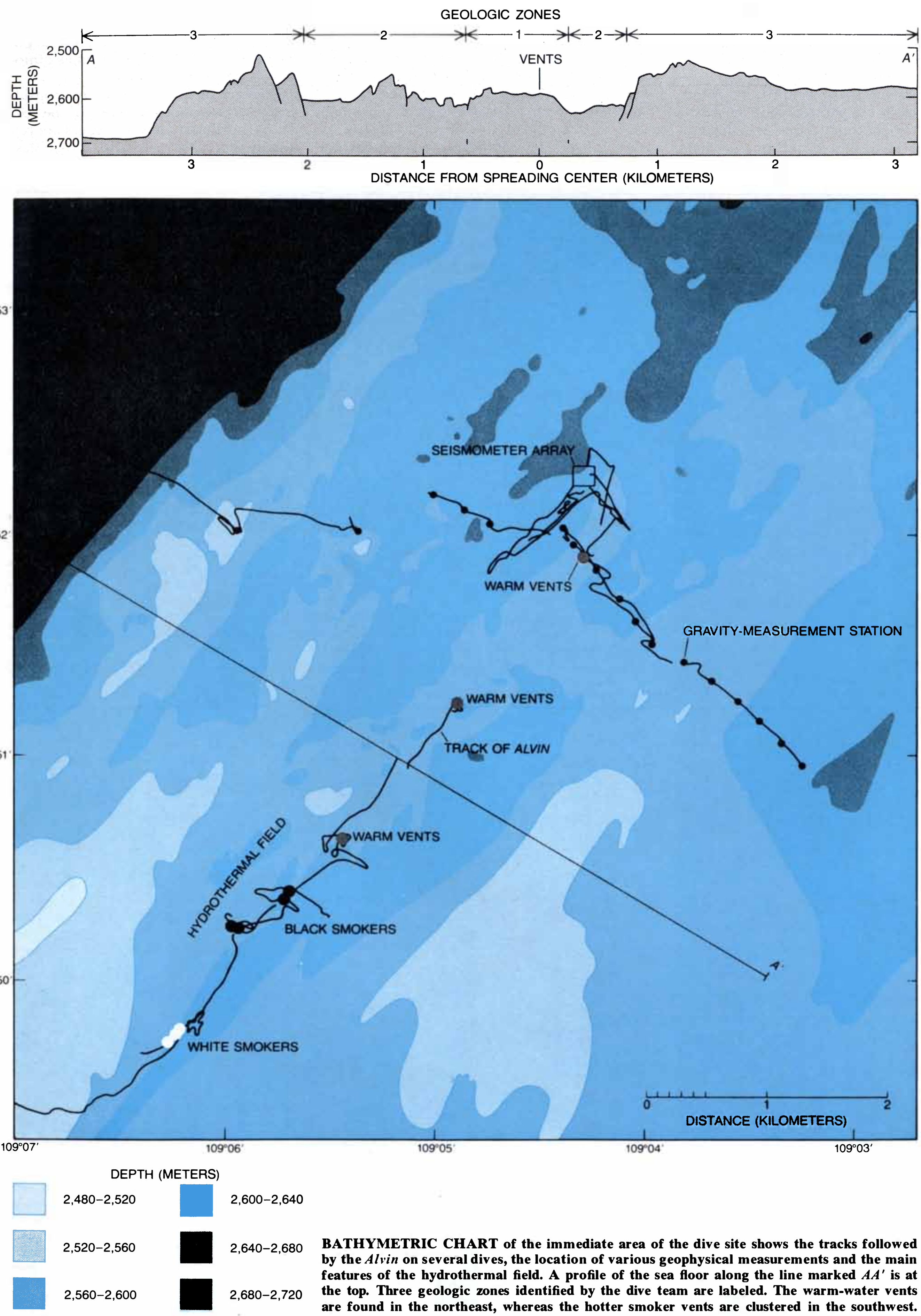
A subsequent *Alvin* dive was guided directly to another hydrothermal area identified by the *Angus,* southwest of the first vents we visited. The sight here was even more dramatic: extremely hot fluids, blackened by sulfide precipitates, were blasting upward through chimney-like vents as much as 10 meters tall and 40 centimeters wide. We named the vents "black smokers." The chimneys protruded in clusters from mounds of sulfide precipitates. A puzzling structure seen from the *Cyana* the year before was probably a fossilized black smoker of this kind.

Our initial attempts to measure the temperature of the black fluids were unsuccessful. Until then the highest temperature recorded on the ocean floor was 21 degrees C., measured only two months earlier on the Galápagos spreading center. Our thermometer was calibrated to 32 degrees C.; when it was inserted into the first chimney, the reading immediately sailed off the scale. Moreover, when the probe was withdrawn, the plastic rod on which it was mounted showed signs of melting! The temperature probe was hastily recalibrated at sea and measurements were made on several more dives; they indicated temperatures of at least 350 degrees C., an estimate that was more precisely documented later by another dive team equipped with a thermometer modified for such a temperature range. The 350-degree water does not boil because the pressure at the depth of the vents is roughly 275 times atmospheric pressure.

The hydrothermal vents show considerable variety along the crest of the rise. To the northeast the vent waters are relatively clear; they are also cooler (less



MAGNETIC-REVERSAL BOUNDARIES, shown here in white, flank the axis of the sea-floor spreading center in the general area of the dive site on the East Pacific Rise. The white numbers at the ends of the lines give the age of the crust in millions of years. The rectangular area outlined in white is the central, positive-polarity magnetic stripe in which the rock is magnetized in the same direction as the earth's present magnetic field; it extends outward on each side of the axis to a distance corresponding to an age of 700,000 years. The outlying white lines parallel to the central stripe indicate boundaries where the remnant magnetism of the crustal rocks changes direction; hence the boundaries record reversals of the geomagnetic field. Colored contours, which are identified in the key at the left, give the depth of the ocean in meters.



BATHYMETRIC CHART of the immediate area of the dive site shows the tracks followed by the *Alvin* on several dives, the location of various geophysical measurements and the main features of the hydrothermal field. A profile of the sea floor along the line marked *AA′* is at the top. Three geologic zones identified by the dive team are labeled. The warm-water vents are found in the northeast, whereas the hotter smoker vents are clustered in the southwest.

than 20 degrees C.), and they diffuse slowly through the rocks. The densest biological communities are found here. Toward the southwest the vents emit hotter fluids laden with mineral precipitates. The rate of flow also increases to the southwest, culminating in the spectacular black-smoker vents. This rather regular gradation suggests the possibility of cycles in the intensity of volcanic and hydrothermal activity along the axis.

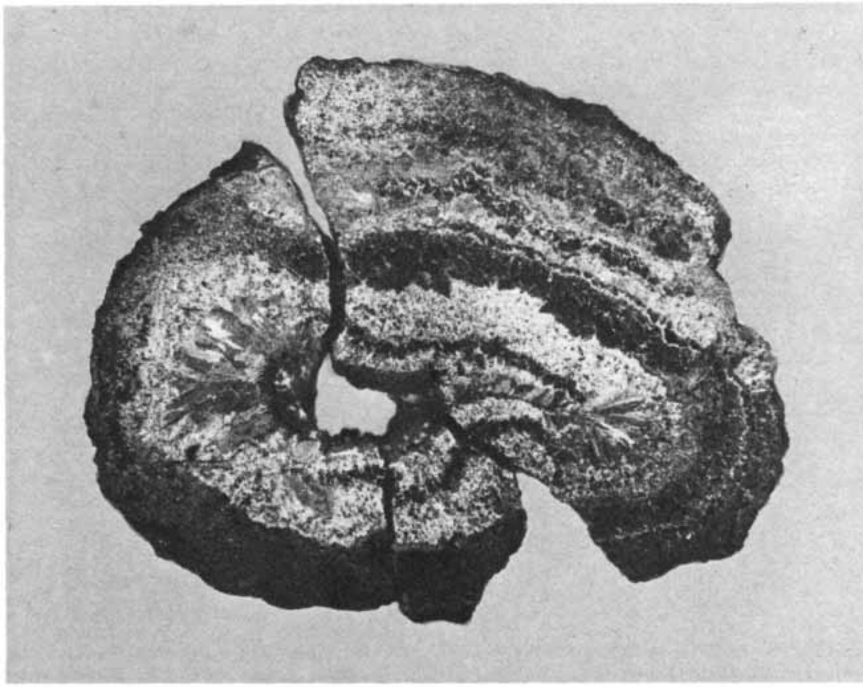
The biological community we had encountered turned out to be very similar to the one found in 1977 on the Galápagos spreading center. Certain distinctive brown mussels of the Galápagos site were absent, but sea anemones, worms called serpulids, crabs of the galatheid and brachyuran groups, large clams and giant tube worms all appeared to be the same. Each colony occupied an area roughly 30 meters wide and 100 meters long. The animals are attracted not by the warmth of the hydrothermal fluids but by the concentrated food supply. Nutrients are hundreds of times more plentiful near the vents than they are in the surrounding waters.

The food chain of this extraordinary ecological system has been analyzed by Robert R. Hessler of the Scripps Institution, J. Frederick Grassle of the Woods Hole Oceanographic Institution and others. At the base of the food chain are chemosynthetic bacteria that oxidize hydrogen sulfide emitted by the vents to form elemental sulfur and various sulfates. The bacteria harness the energy liberated by the oxidation in order to incorporate carbon dioxide into organic matter. Most of the larger organisms either feed on the bacteria by filtering or live with them symbiotically. Some are scavengers or predators. The communities are entirely independent of photosynthesis and indeed of solar energy; they rely instead on the flow of energy from the earth's interior. The fact that communities of this kind have been found both at the Galápagos spreading center and on the crest of the East Pacific Rise some 3,000 kilometers away suggests they may be distributed along much of the worldwide rift system. The communities must lead precarious lives as the hydrothermal vent systems turn on and off with sporadic volcanic cycles. Indeed, isolated piles of empty clamshells of uniform size bear witness to local mass fatalities.

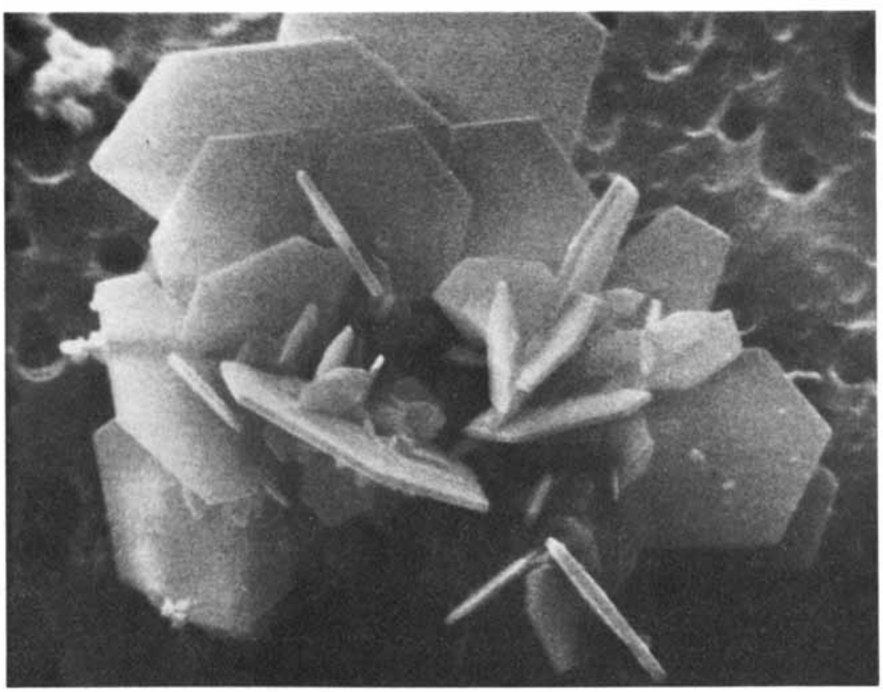
Geochemical Implications

The discovery of hydrothermal vents on the axes of two Pacific spreading centers has revolutionized theories of the chemical budget of the oceans. Formerly it was held that seawater maintains an equilibrium between input processes (mainly the efflux of rivers) and output processes (the deposition of sediments and low-temperature chemical reactions between the seawater and the ocean floor). As more became known about mineral abundances and about low-temperature reactions of seawater with sedimentary and volcanic rocks, problems arose with the "bookkeeping" for certain elements. For example, more magnesium ions and sulfate ions are supplied by rivers than can be removed from the sea by sedimentation, by the formation of clays and by the weathering of basalt. In addition the ocean floor appears to accumulate far more manganese than rivers can supply.

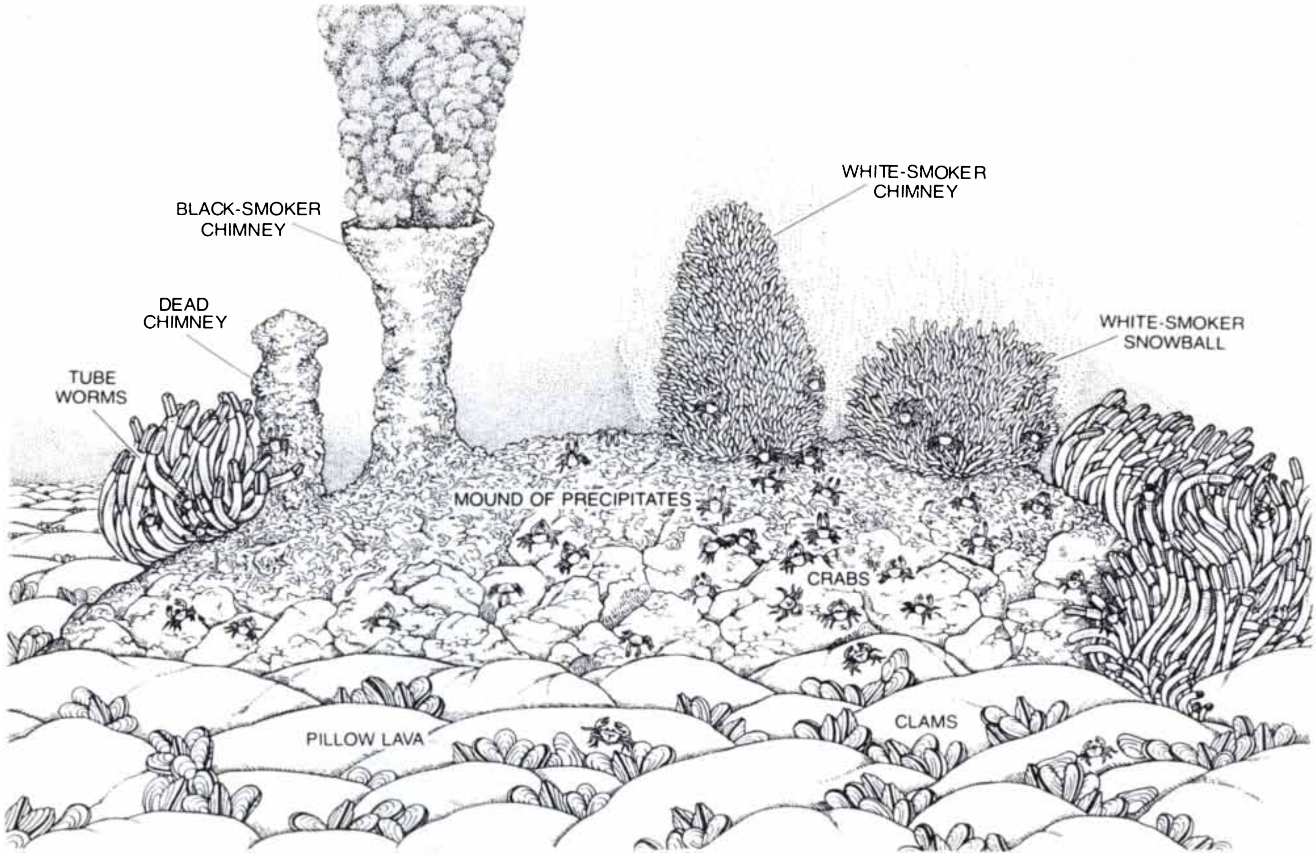
The hydrothermal circulation of sea-



SMALL CHIMNEY VENT typical of those found in the hydrothermal field is shown in cross section. The concentric bands of minerals are chiefly sphalerite, pyrite and chalcopyrite, which are sulfides respectively of zinc, iron, and copper and iron. Transitions from one mineral to another reflect changes in the properties of the fluids emitted. The photograph was made by Rachel Haymon of the Scripps Institution, who also analyzed the mineral content of the chimney.

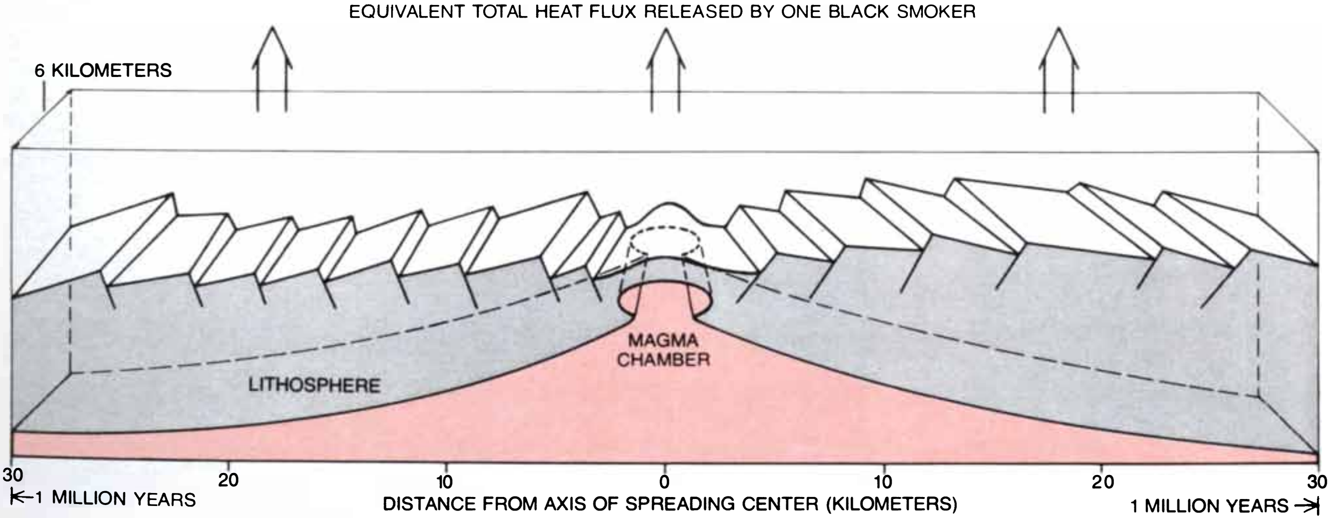


FILTERED PRECIPITATE from the effluent of a black-smoker chimney is shown in a scanning electron micrograph. The hexagonal platelets are crystals of pyrrhotite, a form of iron sulfide. The minerals recovered from the black vent water also include pyrite, sphalerite and other sulfides. The micrograph was made by J. Douglas Macdougall of the Scripps Institution.



IDEALIZED SCENE in the hydrothermal field near the high-temperature smoker vents shows an array of typical vent structures on top of a mound of precipitated minerals and organic debris. The white-smoker chimney is built up out of burrows made by a little-understood organism called the Pompeii worm. The white, cloudy fluids emitted by the white smoker have temperatures of up to 300 degrees C. The hottest water, having temperatures of up to 350 degrees C., comes from the black smokers, whose chimneys are made up of sulfide precipitates. The mound rises from a terrain dominated by glistening black lava pillows; in the crevices between pillows clams live.

water along submarine rift systems introduces a new factor: high-temperature chemical exchanges between fluids and solids. According to John M. Edmond of the Massachusetts Institute of Technology, reactions between hot seawater and basaltic rock can convert dissolved sulfates into solid sulfate and sulfide minerals; similar reactions can remove magnesium ions and hydroxyl (–OH) ions from seawater and sequester them in hydrothermal clays. The hot seawater is converted by these reactions into a chemically reduced, acidic solution that leaches calcium, silicon, manganese, iron, lithium and other positively charged ions from the rocks and releases them into the ocean. In this way hydrothermal systems can balance the budget for the major mineral constituents of seawater; the hydrothermal circulation



HEAT OUTPUT from the hydrothermal vents makes a significant contribution to the total heat budget of the earth. The heat output of a single black-smoker vent is compared here with the heat transmitted through the crust by conduction. The output of the vent is equivalent to the conductive flux of a segment of the rift system measuring some six kilometers along the axis and 60 kilometers across it.

can also account for the observed concentration and distribution of numerous minor and trace constituents.

Edmond has found that the hydrothermal effluents of the Galápagos system mix with normal seawater during their ascent through the volcanic rock. The mixing lowers the temperature of the fluids and leads to the deposition of minerals within the rocks, thereby altering the chemistry of the hot springs that discharge onto the sea floor. The high temperature and the chemical composition of the springs at the East Pacific Rise site indicate that here the hydrothermal fluids do not mix significantly with cool seawater on their way to the sea floor. Hence the fluids represent the true hydrothermal contribution to the marine chemical cycle. The water issuing from the vents has descended most of the way to the magma chamber before returning to the sea floor.

The undiluted hydrothermal fluids at the East Pacific Rise site apparently become blackened with fine-grained precipitates of iron sulfide and zinc sulfide as contact is made with cold, alkaline seawater at the ocean floor. Preliminary analyses by Rachel Haymon and Miriam Kastner of the Scripps Institution indicate that the mounds and chimneys around the vents are composed mostly of sulfides of zinc, iron and copper and sulfates of calcium and magnesium. The precise mechanisms by which the minerals are formed, the rate at which they are deposited and the ratio of water to rock at various points in the system are currently subjects of debate among geochemists. There is no doubt, however, that the vents will have a central role in models of the chemistry of the oceans.

Geophysical Experiments

Most of our geophysics program was directed toward learning more about the relation of the conjectured axial magma chamber to tectonic, volcanic and hydrothermal activity on the sea floor. We were fortunate in being able to do the experiments in an area where hydrothermal activity was proceeding at such a brisk pace. Measurements of seismic velocity, earthquake activity, gravitational anomalies, electrical conductivity and magnetic polarity were made on the crest of the rise in order to probe the subsurface structure there.

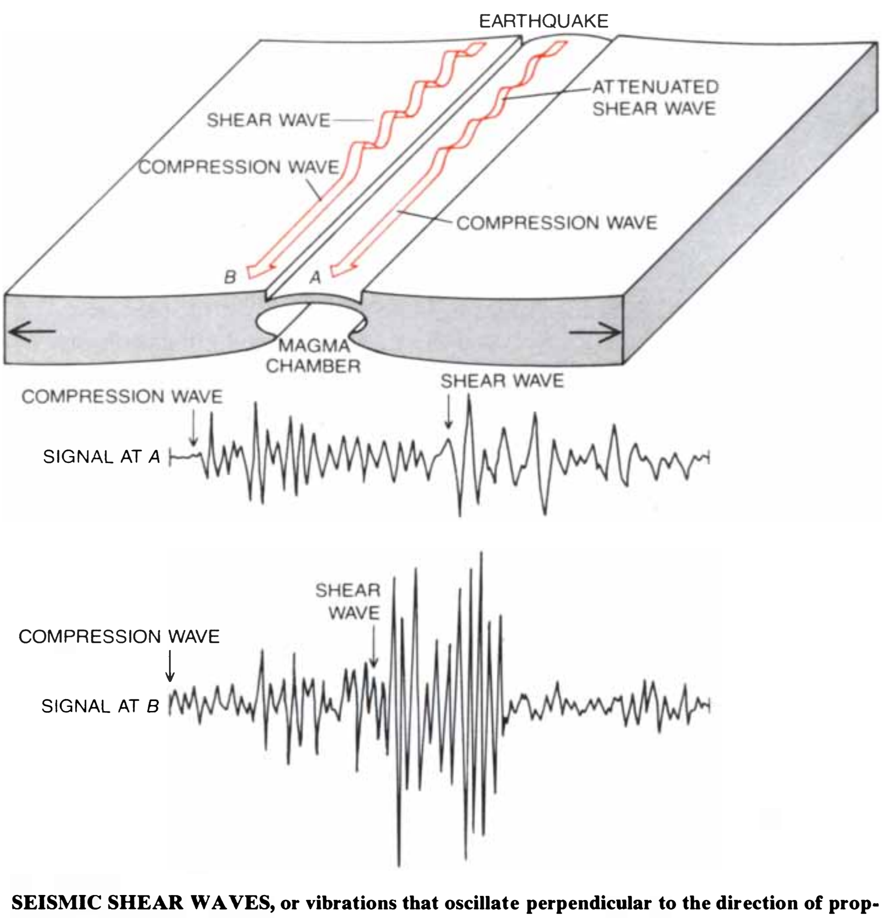
For geophysicists as well as for geochemists and biologists the most impressive finding of the expedition was the field of active hydrothermal vents. Such hydrothermal circulation on mid-ocean ridges had been proposed on theoretical grounds 15 years earlier, but it had proved difficult to study.

It is possible to calculate a theoretical rate at which newly formed lithosphere cools by means of heat conduction. The calculation in turn specifies an expected rate of conductive heat flow through the mid-ocean ridges. Measurements of purely conductive heat flow near the crest of the rise, however, yield values almost an order of magnitude smaller than the theoretical models. Are the models wrong, or is the circulation of near-freezing seawater in the hot, newly formed crust cooling the crust through convective heat transfer at a much higher rate? How deep does the seawater penetrate into the oceanic crust and how wide is the discharge zone? How is the chemical composition of the crust affected by the circulation and what minerals are deposited? A key geophysical consideration in all these questions is the depth of the cracks and fissures in the rocks at the spreading center. Bounds on the depth can be determined by measurements of seismic velocity, electrical conductivity and gravitational anomalies.

The large discrepancy between the measured conductive heat flow through the sea floor and the value predicted by models of the cooling lithosphere suggests that at least a third of the heat loss at the mid-ocean ridges is brought about by nonconductive means and presumably by hydrothermal circulation. At the Galápagos spreading center, where hydrothermal activity was observed for the first time, estimates of the heat flow were hindered by the diffuse nature of the circulation. The conditions at the East Pacific Rise site are more favorable for such measurements.

From careful viewing of motion-picture films and videotapes of the vents, flow rates were estimated. Given an average exit velocity of two or three meters per second, a single vent accounts for a heat flow of some 60 million calories per second. That is between three and six times the total theoretical heat loss across a kilometer-long segment of the mid-ocean ridge out to a distance of 30 kilometers on each side. At least 12 major chimneys were found in the southwestern part of the study area, and so the total heat flux is evidently very large. Indeed, the heat loss is so large that it suggests the lifetime of a vent is probably short. The lifetime may be only several years.

The vents appear to be confined to a narrow, linear region a few hundred meters wide and six kilometers long within the neovolcanic zone. In this band 12 temperature anomalies were detected and verified photographically, and eight vents were visited and studied with the



SEISMIC SHEAR WAVES, or vibrations that oscillate perpendicular to the direction of propagation, are attenuated by passage through the magma chamber that is thought to lie under the axis of the spreading center. When the seismic signal from a distant earthquake is recorded by an ocean-bottom seismometer on the axis (*point A*), compressional waves are strongly received but shear waves are much reduced in amplitude. On a parallel path only 10 kilometers from the axis (*point B*) both compressional waves and shear waves are transmitted efficiently. This finding suggests that a magma chamber exists under the axis and that it is relatively narrow.

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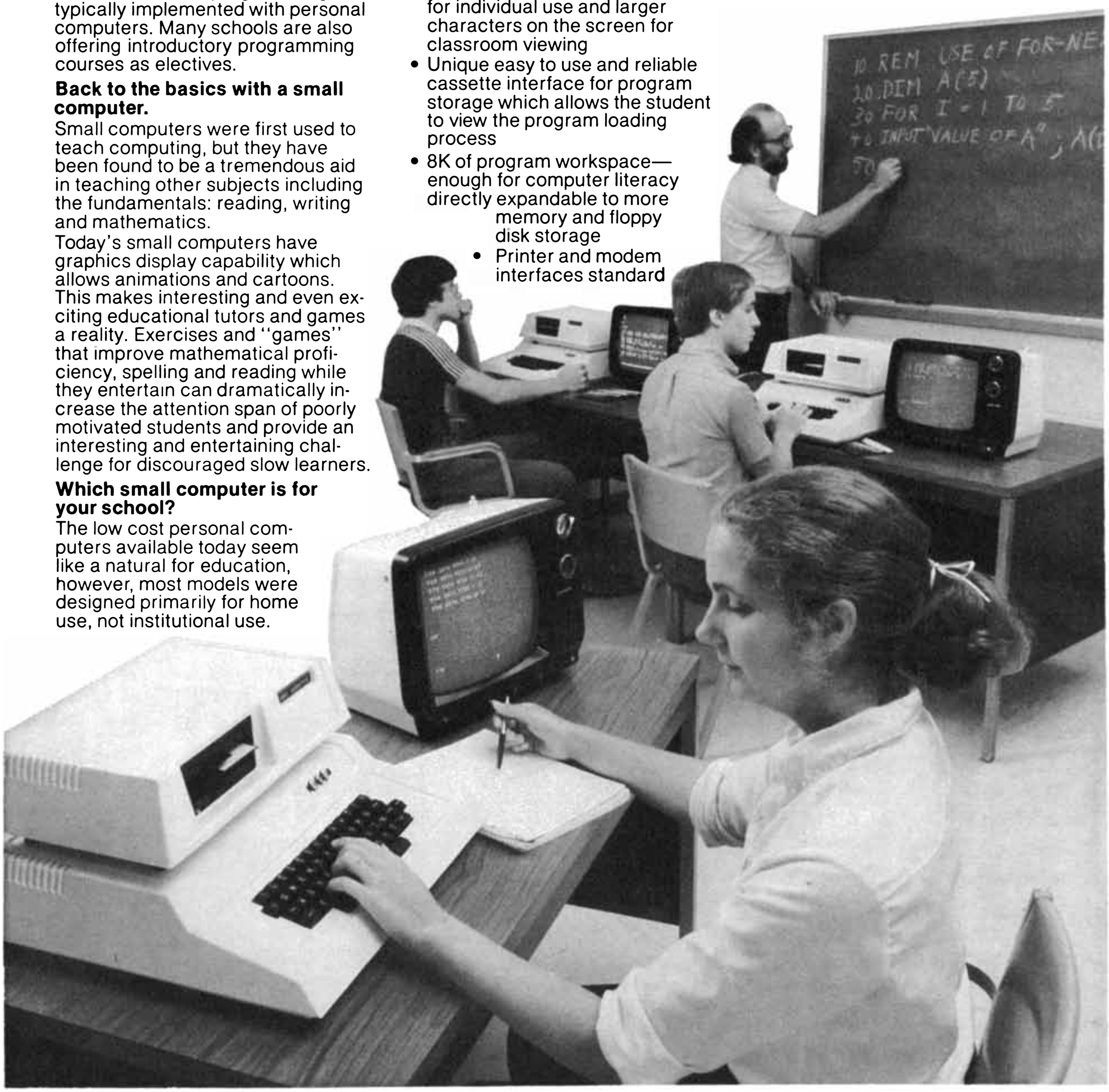


Alvin. In general the cooler vents toward the northeast are surrounded by Galápagos-style biological communities. The hottest vents near the southwestern end also have unusual life forms associated with them, but the animals tend to live at a safe distance (several meters) from the vents.

Seismic Measurements

A high-resolution seismic experiment was designed by John A. Orcutt and one of us (Macdonald) to determine the depth of the cracking and fissuring in the rocks along the crest of the rise. We proposed to measure the velocity of seismic waves in the upper crust as a function of depth. Because the spherical spreading of energy from an explosive charge detonated at the surface of the sea leads to reverberations from nearby topographic features, the resolution of seismic measurements in the top 1,000 meters of the crust is degraded. In order to overcome this difficulty it was necessary to devise a method of placing both the sources and the receivers of the seismic waves on the sea floor. For the experiment to work we also needed to time events to within a millisecond or so.

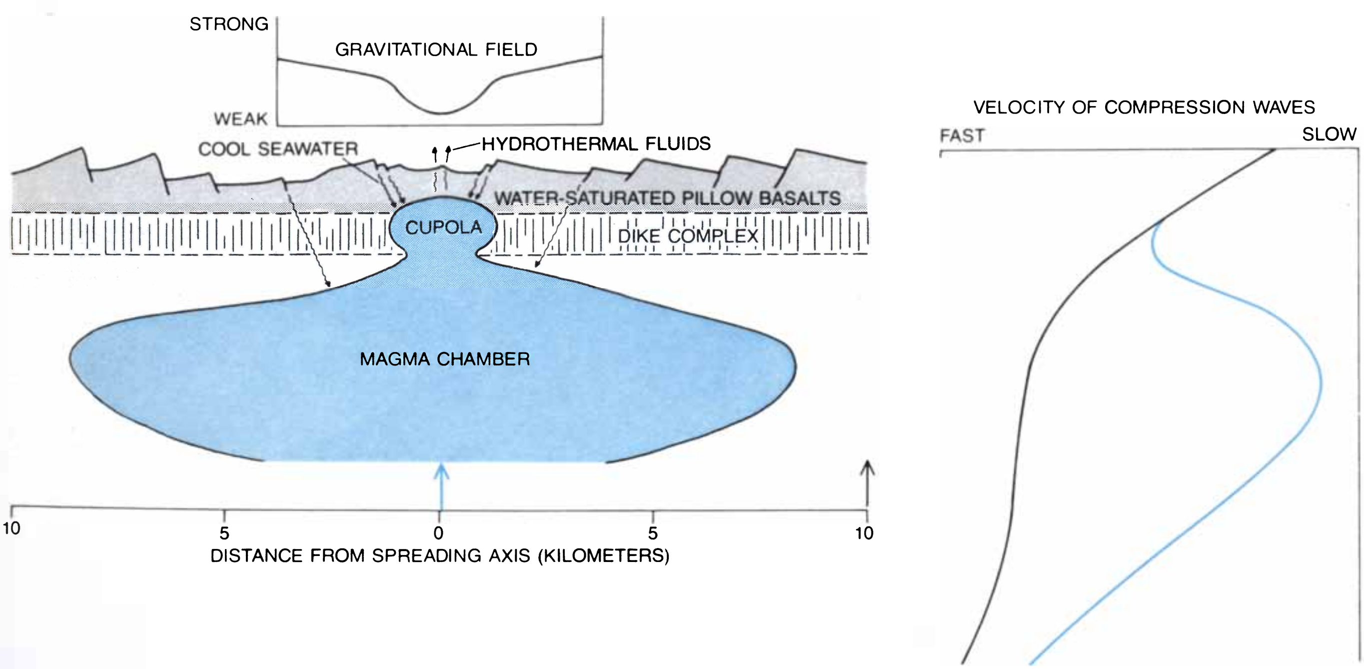
The *Alvin* provided a way of solving both problems. Explosive charges are virtually useless as seismic sources at the high pressure encountered at great depth, and so we attached a hydraulic hammer to the *Alvin* to serve as a source of seismic waves. To establish a precise time base the *Alvin* was driven up to within two meters of each of the ocean-bottom seismometers for a calibration "thump" by the hammer on the sea floor; the response was recorded by a sensor on board the *Alvin* as well as by the seismometer. The submersible returned to recalibrate each seismometer at the end of the dive.

In four dives we completed a seismic-refraction profile 1,000 meters long parallel to the spreading center and a profile 800 meters long across the spreading center. The analysis of the data is not yet completed, but simple travel-time calculations yield a preliminary determination of the velocity of seismic waves at the surface of the crust parallel to the axis of the spreading center. We obtained a seismic velocity of 3.3 kilometers per second, which is quite slow compared with the laboratory value for basalt at the same pressure (approximately 5.5 kilometers per second). Evidently the reason for the low velocity is the pervasive cracking and porosity of the rock. No major faults or fissures were traversed, but numerous hairline cracks and voids were observed in the lava pillows. Detailed conclusions concerning the degree of cracking and porosity needed to account for the observations will have to await measurements of the physical properties of the rock samples and the completion of seismic analyses at longer ranges. Of particular interest will be the depth at which the seismic velocity rises above five kilometers per second, indicating the closure of most of the fissures.

The results of an earlier seismic-refraction experiment had indicated the presence of a magma chamber at a depth of from two to three kilometers under the hydrothermal field. In the earlier experiment, which was less precise but of larger scale, explosive charges were detonated from a surface ship at ranges of up to 60 kilometers from a triangular array of ocean-bottom seismometers. At a depth of only two kilometers under the sea floor a low-velocity zone for compressional seismic waves was observed, indicating the presence of partially melted rock. At points 10 kilometers off the axis of the spreading center the seismic velocity was found to be normal for oceanic basalt or somewhat higher than normal. The magma chamber therefore appears to be confined to a zone 20 kilometers wide centered on the axis of the spreading zone.

Earthquakes and Volcanism

A second item of evidence for the existence of an axial magma chamber comes from measurements of the propagation of seismic shear waves generated by earthquakes. Where rock is partially melted, as it would be in a magma chamber, shear waves are strongly damped. Orcutt and two of his colleagues, Ian Reid and William A. Prothero, Jr., found that for paths along the spreading center shear waves from



MODEL OF THE EARTH'S CRUST under the East Pacific Rise is represented by a cross-sectional drawing based mainly on geophysical measurements. Cool seawater percolates through cracks and fissures in the rocks of the spreading center, approaching the molten rock in an elongated cupola above the main magma chamber. The water is heated by the magma and is expelled through vents along the axis of the spreading center. The existence of a cupola and of hydrothermal activity is thought to be episodic, generally following periods of intense volcanism and tectonic motion. The geophysical properties graphed at the right are sensitive both to the permeability of the crust

earthquakes are severely attenuated, whereas only 10 kilometers from the axis shear waves are transmitted efficiently. Again this finding is clear (although indirect) evidence for the presence of a shallow, narrow magma chamber under the spreading center.

Basalt samples collected with the *Alvin* have been analyzed by James W. Hawkins of the Scripps Institution; the nature of the rocks also suggests the presence of a shallow axial magma chamber. The basalt samples, collected along a six-kilometer traverse of the neovolcanic zone, were found to have a limited range of compositions, indicating they were derived from a single parent magma by fractional crystallization of the minerals olivine and plagioclase at comparatively low pressure. The results are consistent with a magma chamber less than six kilometers deep, which in turn implies that the roof of the chamber is only a few kilometers thick. This thin covering layer is densely cracked and fissured, allowing seawater to percolate deep enough into the crust to be heated to at least 350 degrees C.

How deep does the circulation extend? As a sequel to the ocean-bottom seismic measurements we returned last summer to measure microearthquakes in the hydrothermal field. Seven ocean-bottom seismometers were guided into position with the aid of moored acoustic transponders that had been left to mark the vents. If the hydrothermal flow had some telltale seismic "signature," perhaps we could determine how deep the flow extends. So far the results have been encouraging. Earthquakes in the region appear to be shallow: only two or three kilometers deep at the most. This finding is in excellent agreement with earlier indications that the roof of the magma chamber is thin, and it establishes a reasonable upper limit for the depth of the cracked part of the crust.

Among the seismic events recorded by the array were small earthquakes of a distinctive kind called harmonic tremors. Such tremors were associated with the catastrophic eruption of Mount St. Helens a year ago, and they are a sure sign of impending or recent volcanic activity. Just before and during the Mount St. Helens eruption the tremors increased in frequency until they became almost continuous. Our records for the East Pacific Rise look similar, showing as many as several hundred events per hour. It is possible that this segment of the rise is now either ending or entering an active volcanic stage.

Gravitational Anomalies

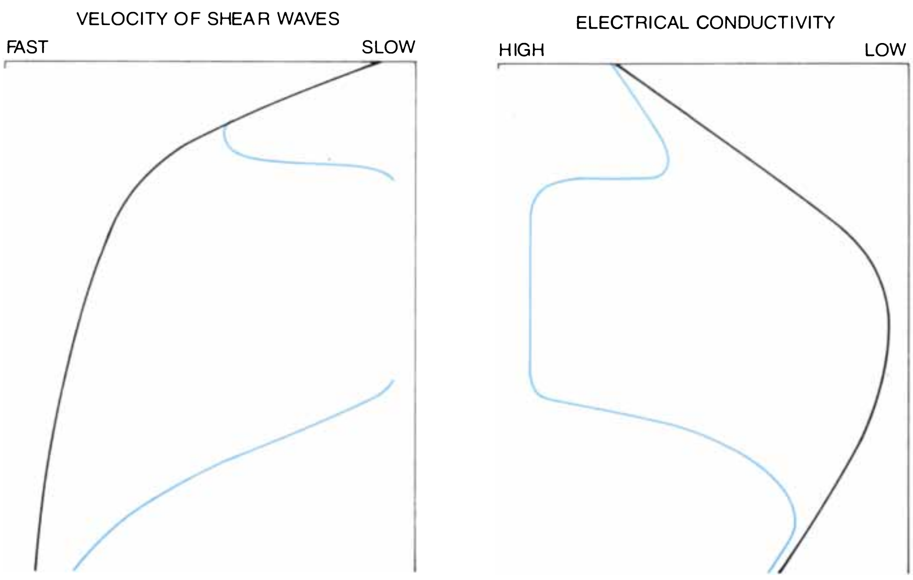
Closely associated with the seismic experiments was a series of gravity measurements conducted with the *Alvin* by Spiess and one of us (Luyendyk). As in the case of seismic waves, the local gravitational field should be altered by variations in the density of the crust caused by fissuring or by the presence of a shallow magma chamber. The expected gravitational anomalies are small, and they are difficult to measure from the ocean surface because of the considerable distance of the sensor from the source and because of spurious acceleration signals recorded by shipboard sensors. Once again the *Alvin* provided a solution. Measuring the gravitational field from the *Alvin* while sitting quietly on the sea floor had the effect of reducing the spurious accelerations. Moreover, making the measurements closer to the source enhanced the signal recorded by the gravimeter.

The gravitation measurements, which were made along a seven-kilometer profile extending from Zone 1 to Zone 3, showed a pronounced negative gravity anomaly over the neovolcanic zone. The anomaly is apparently centered on the central volcanic ridge and occupies much of zones 1 and 2. It indicates a region of lower-than-average density, which could be caused either by fissuring of the crust or by a shallow magma chamber. Geologic observations show a maximum of fissuring in Zone 2, whereas the negative gravity anomaly is centered on Zone 1, which has comparatively few fissures. This observation suggests (but does not fully demonstrate) that the gravity anomaly is caused by a shallow magma chamber.

If one assumes that the magma chamber has the shape of a horizontal cylinder with its axis parallel to the ridge and its center directly under the measured minimum in the gravitational field, the gravitational data indicate that the center of the cylinder is about 1,000 meters below the sea floor. If one further assumes that the chamber is filled with molten basalt, its density would have to be lower than the density of the surrounding rock by about .21 gram per cubic centimeter. This estimate in turn implies that the upper edge of the cylinder is about 600 meters below the sea floor. Assuming a smaller density contrast between the magma in the chamber and the surrounding rock would require that the magma body be larger and reach closer to the surface of the crust.

The seismic results make it seem more likely that the main magma chamber is much larger and deeper. Indeed, for geologic reasons it seems probable that the main, permanent part of the chamber is between two and six kilometers below the sea floor and is two or three times as wide as it is deep. The structure apparent in the gravity data may be not the main chamber but a small, transitory, elongated cupola, or dome, at the apex of the main chamber. Such a cupola could occupy all of Zone 1 and could supply the magma to feed the lava flows found there.

The magnitude of the negative gravity anomaly corresponds to a mass deficiency under the axis of the spreading center



and to the presence of the axial magma chamber. Colored curves show the variation of each property with depth at the spreading center; black curves show variation with depth approximately 10 kilometers from the spreading center. A measured gravitational anomaly is also shown schematically; such variations in the strength of the gravitational field, which were detected at the sea floor, reveal the shallow structure of the crust and of the magma chamber.

of about 90 million kilograms per meter of ridge. If the crust at the spreading center is in isostatic equilibrium (meaning that the forces of gravitation and buoyancy are in balance), a mass excess should exist somewhere on the ocean bottom to balance the deeper mass deficiency. Zone 1 is an uplifted topographic block about a kilometer wide and roughly 20 to 30 meters higher than the surrounding terrain. Even so, it is only about half as high as it would have to be to achieve isostatic equilibrium at the axis of the spreading center. Either the mass deficiency is balanced by other topographic features farther away from the axis, or friction along fault planes is holding down the central block in opposition to the buoyant force.

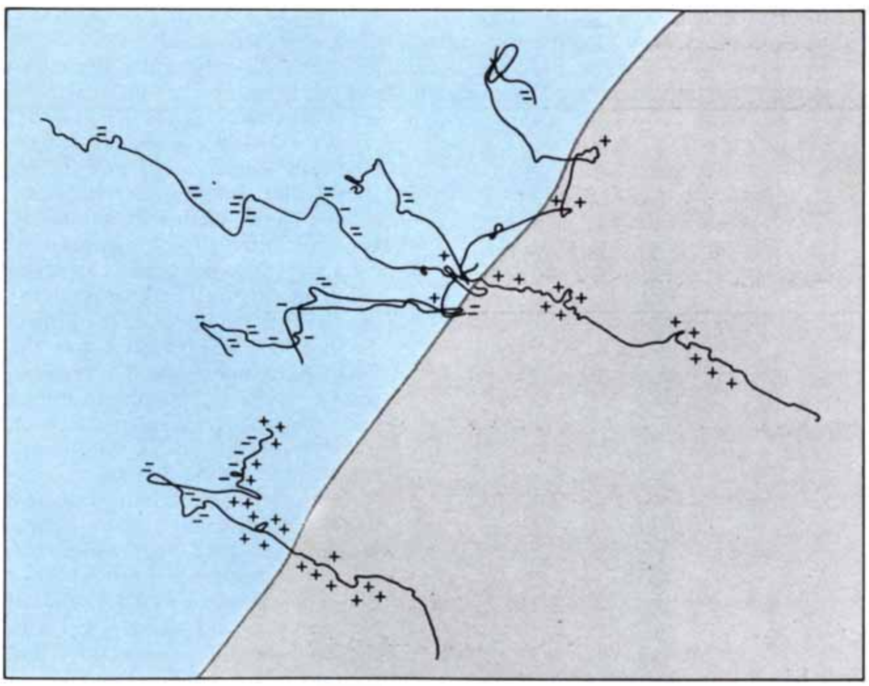
Electrical Measurements

The measurements of gravitational anomalies also yield an estimate of the bulk density of the upper 100 meters of the bottom topography. Along the crest of the rise the bulk density is about 2.6 grams per cubic centimeter, compared with a measurement of 2.9 grams per cubic centimeter for some 90 rock samples taken from the bottom. The discrepancy suggests that the topography has a porosity of about 15 percent.

The presence of water in the rocks of the crust might be detected directly by means of the electrical conductivity of water. At greater depths electrical conductivity might also be exploited to detect the axial magma chamber, because magma has a much higher conductivity than solid basalt. For these purposes a new electrical-sounding technique was developed by Charles S. Cox of the Scripps Institution. The experiment was designed to give further information on the percolation of seawater into the crust, on the depth of fissuring and on the lateral extent of the magma chamber. No similar measurements had been attempted before, nor had any other techniques been able to estimate the conductivity of the crust under the oceans.

An electric-dipole antenna 800 meters long was towed near the sea floor behind the research vessel *Melville*, which is operated by the Scripps Institution. The antenna transmitted electrical signals into the ocean and the crust at frequencies selected so that the signal would be quickly absorbed in the ocean, whereas it might penetrate to a considerable depth in the crust. Three receivers were placed on the sea floor near the spreading center. Because the experiment was our first attempt at towing a large, fragile antenna near the sea floor the rugged topography of Zone 1 was avoided. The electrical soundings were made in an area between 10 and 15 kilometers west of the spreading axis in crust that is between 300,000 and 400,000 years old.

Soundings were made to a depth of approximately eight kilometers below the sea floor. The pattern of conductivity indicates that only 10 to 15 kilometers from the spreading axis the magma chamber is less than 200 meters thick. This finding is a strong confirmation of the seismic experiments that had suggested a narrow axial magma chamber. Observations made with the *Cyana* indicate that active faulting of the crust diminishes at a distance of between 10 and 12 kilometers from the axis. Perhaps the width of the magma chamber controls the width of active tectonic faulting on moderate-to-fast spreading centers. Another finding of the electrical-sounding experiment is that conductivity comparatively near the surface of the sea bed is low. This indicates that seawater penetrates the crust to a maximum depth of from two to four kilometers.



MAGNETIC POLARITY OF THE CRUST was measured with instruments mounted on the *Alvin* at more than 250 points along a series of traverses near a magnetic-reversal boundary. Plus signs designate positive polarity (identical with the present direction of the field) and minus signs negative polarity. The measurements made on the sea floor with the *Alvin* are superposed on a map of the magnetic-reversal boundary based on data recorded from a surface ship. On this map the gray area is positive and the colored area is negative. The transition zone in each case is remarkably sharp, indicating that the oceanic crust is created in a narrow band (about a kilometer wide). The boundary suggested by the ocean-bottom measurements is about 500 meters northwest of the position calculated from the data recorded at the surface, possibly because of the spillover of positively polarized material on top of negatively polarized rock.

Magnetic Reversals

In another series of dives we carried our investigation slightly off the axis of the ridge and northwest to the edge of the youngest major magnetic-reversal stripe. The object was to see what the geometry of such a boundary could tell us about the formation of new oceanic crust along the spreading axis. Almost two decades after the Vine-Matthews model was proposed there is still no full understanding of how such stripes are formed. At one time it was widely believed most of the magnetic signal associated with the magnetic-reversal stripes was confined to the top 500 meters of the oceanic crust. Deep-sea drilling into the deeper layers of the crust has revealed a chaotic mixture of magnetic polarities and intensities that is quite out of character with the linear sequence of magnetic stripes measured from the surface of the sea.

In the first stage of this study we constructed a three-dimensional mathematical model of the magnetic-reversal boundary on the basis of earlier measurements made with a deep-towed magnetometer. From the model we calculated that the boundary was remarkably straight and narrow: less than 1.4 kilometers wide. Filtering of the data was required in order to achieve a stable solution, however, and it made us wonder if the boundary was really so well defined. To find out how the oppositely magnetized stripes are actually arrayed on the sea floor we mounted a more sensitive magnetometer on the *Alvin*. The instrument measured the components of the magnetic field in three dimensions

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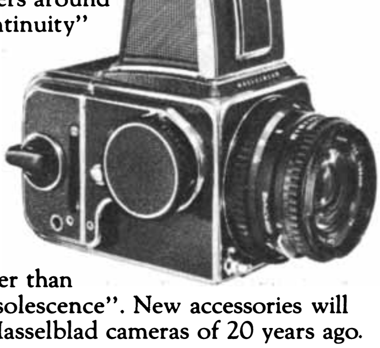

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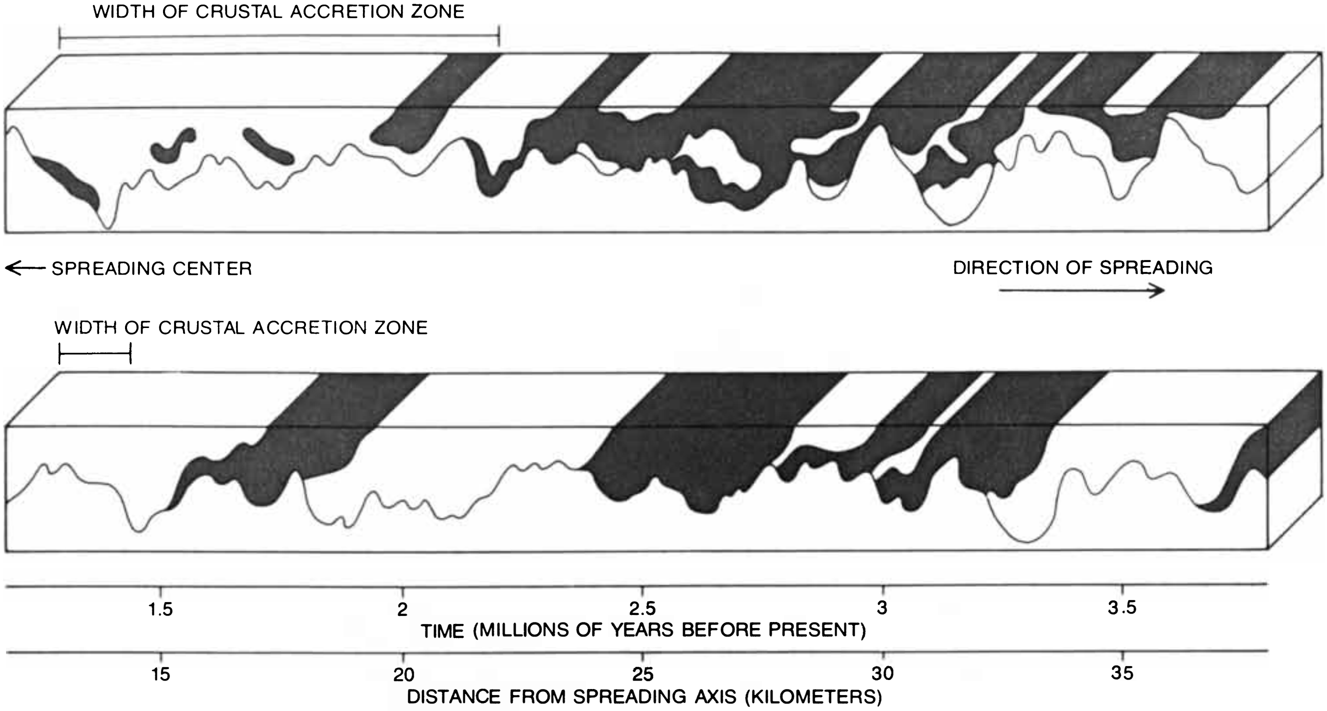


DISTRIBUTION OF MAGNETIC POLARITIES in the oceanic crust is influenced by the width of the spreading zone, as is shown in two hypothetical profiles developed statistically by Hans Schouten and Charles Denham of the Woods Hole Oceanographic Institution. In the upper diagram the rate of sea-floor spreading is assumed to be low and the accretion zone, where new crust emerges, is assumed to be large. Such conditions prevail at the Mid-Atlantic Ridge. In the lower diagram the accretion zone is narrow, as it is at the East Pacific Rise. The thickness of the crust depends on the rate of spreading and on the frequency of volcanic eruptions. The degree of mixing of oppositely magnetized sections depends on the width of the accretion zone. The zone is thought to be wider at centers that spread slowly.

and also measured the vertical gradient in the field: the rate at which the field changes with height above the sea floor. In this first attempt to study a submarine magnetic-reversal boundary at close range we were joined by Loren Shure of the Scripps Institution and by Stephen P. Miller and Tanya M. Atwater of the University of California at Santa Barbara.

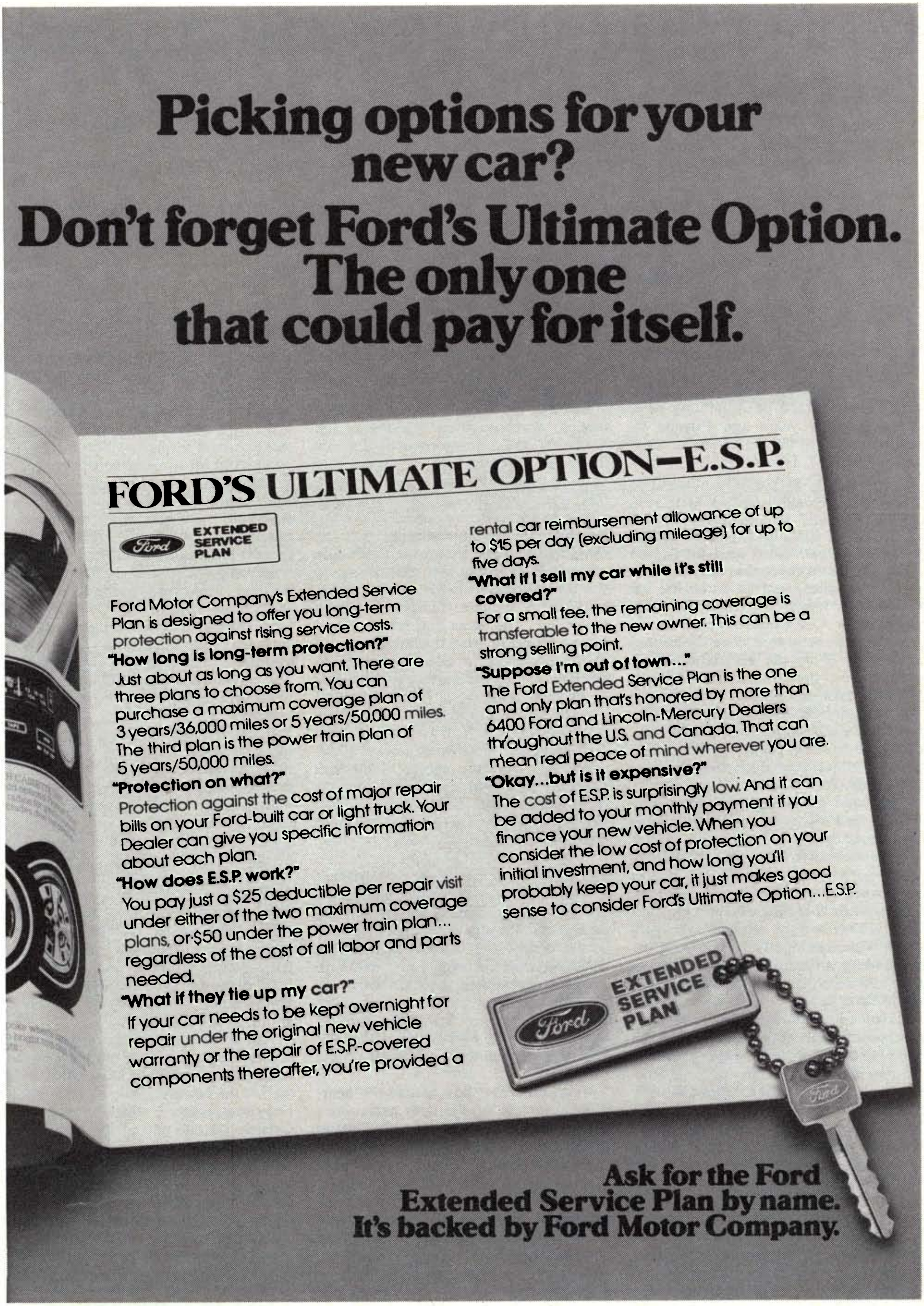
In five dives across the magnetic-reversal boundary we made more than 250 clear identifications of the magnetic polarity of the basalt outcrops. The results of the magnetic survey were striking. Even on long traverses on both sides of the boundary every magnetic target had the correct polarity, that is, the same polarity as that of the regional magnetic stripe defined by the deep-towed magnetometer. This observation was not too surprising for the younger side of the boundary, because newer positive-polarity crust (crust that has the same polarity as the earth's present magnetic field) would be expected to overlie older, negatively polarized crust. What was surprising was that there were no outlying regions of new crust on the older side of the boundary.

We found that the magnetic-reversal boundary surveyed with the *Alvin* is displaced about 500 meters farther northwest of the spreading axis than the boundary position calculated from the data collected by the deep-towed magnetometer. The calculated boundary marks the average position of the magnetic reversal in a cross section of crust to some depth. The fact that the boundary mapped directly on the sea floor is 500 meters northwest of the calculated average position indicates a spillover of basalt away from the volcanic vents over older, negatively polarized crust.

The data obtained with the *Alvin* and the earlier measurements together show that the magnetic stripes are formed in a very narrow zone. After allowing for the extension of the crust by faulting and for the finite period required for the geomagnetic field to reverse, it appears that the zone of crustal formation must be only between 500 and 1,000 meters wide. This result is in excellent agreement with the geologic observations made with the *Alvin* and the *Cyana* for the width of Zone 1, which varies from 400 meters to 1,200 meters at the present spreading axis. Hence the zone of crustal formation both today and about 700,000 years ago is sharply defined: it is barely a kilometer wide. Considering the lateral dimensions of the Pacific and North American plates, which are thousands of kilometers across, it is remarkable that the spreading center between them is so narrow and so stable.

How can this picture of well-ordered stripes be reconciled with the complex magnetic stratigraphy observed in the deep-sea drilling cores? It turns out that the holes penetrating deeper than 500 meters into the oceanic crust were all drilled in the Atlantic basin, which has much lower spreading rates. Statistical studies show that at such low rates a zone of crustal formation wider than a few kilometers generates a crustal section with a complex mixture of magnetic polarities. Given faster spreading and a narrower zone of crustal formation (the conditions that prevail at the East Pacific Rise), the magnetic stripes have a greater tendency toward magnetic homogeneity and the boundaries of the stripes are sharper.

It follows from this line of reasoning that the physical processes giving rise to new oceanic crust in the Atlantic are quite different from those in the Pacific. Further efforts to unravel the complex physical and chemical processes at work near the boundaries of the major lithospheric plates will require additional on-site experiments, in which the manned submersible will continue to have an essential part. One of the most rewarding outcomes of these studies is the unification of the many disparate fields within oceanography. Biologists, geochemists, geologists, geophysicists and physicists have all been drawn into a common quest for an understanding of sea-floor spreading at the mid-ocean ridges.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Countercurrent Systems in Animals

Exchanges between two fluids moving in opposite directions are the basis for a variety of stratagems that enable many species of animal to survive comfortably in an inhospitable environment

by Knut Schmidt-Nielsen

When a scientist gets results that cannot be explained, either the results are wrong or the scientist is on the track of something new. More than 10 years ago Eugene C. Crawford, Jr., of the University of Kentucky, Harold T. Hammel of the Scripps Institution of Oceanography and I measured the evaporation of water from the respiratory tract of the camel. It was known to us that the air inhaled by a mammal is humidified as it flows past the moist membranes that line the nose and the trachea, and so when the air reaches the lungs, it is saturated with water vapor. One would suppose the air would still be saturated when the animal exhales it. From the temperature and the volume of the exhaled air it is easy to calculate how much water vapor the air should then hold. Our results were surprising: the measured water loss in camels whose intake of water had been limited was sometimes much less than we had predicted.

The most probable explanation was that we had made an error in our measurements. In the end, however, the results turned out to be correct. With Robert C. Schroter of the Imperial College of Science and Technology in London and Amiram Shkolnik of Tel Aviv University, I verified the original findings in 1979. We relied on an accurate and fast-responding sensor of relative humidity that had recently been developed. We could now be certain we were on the track of an undiscovered physiological mechanism. The mechanism enables the camel to recapture water vapor from the air passing out through its nasal passages, so that the air it exhales can have a relative humidity of substantially less than 100 percent. The mechanism turns out to be quite simple. It is based on the same principle that allows many animals to conserve body heat. The essence of the mechanism is a countercurrent exchanger, in which heat, for example, is transferred between liquids or gases that are flowing in opposite directions. In the camel the situation is complicated because several interdependent processes are superimposed on one another. It will therefore be helpful to begin by explaining a simpler system.

Some 25 years ago the late P. F. Scholander, who was then working at the Woods Hole Oceanographic Institution, described a mechanism in whales that helps to prevent the loss of heat through the flippers and the tail flukes when the whale swims in the icy waters of the polar seas. The mechanism is based on the same physical law that leads to the loss of body heat in the first place, namely the law that heat always flows "downhill," from a higher temperature to a lower one. The veins that return blood from a flipper or from the tail to the core of the body run in close proximity to arteries. In fact, each artery is surrounded by such veins. Thus the warm blood flowing into a flipper or a tail fluke is surrounded by a jacket of cool blood flowing in the opposite direction. Much of the heat from the arterial blood does not reach the periphery; in large part it is transferred to the cooler venous blood, which in this way is prewarmed before it reenters the core of the body.

A similar countercurrent arrangement of arteries and veins is found in the limbs of many animals. It is found, for example, in the legs of wading birds and in the tail of the beaver. In the tuna a countercurrent exchanger helps to keep the swimming muscles warm by returning to them the heat the muscles produce. It thereby keeps the muscles warmer than the rest of the fish's body and warmer than the water in which the fish swims.

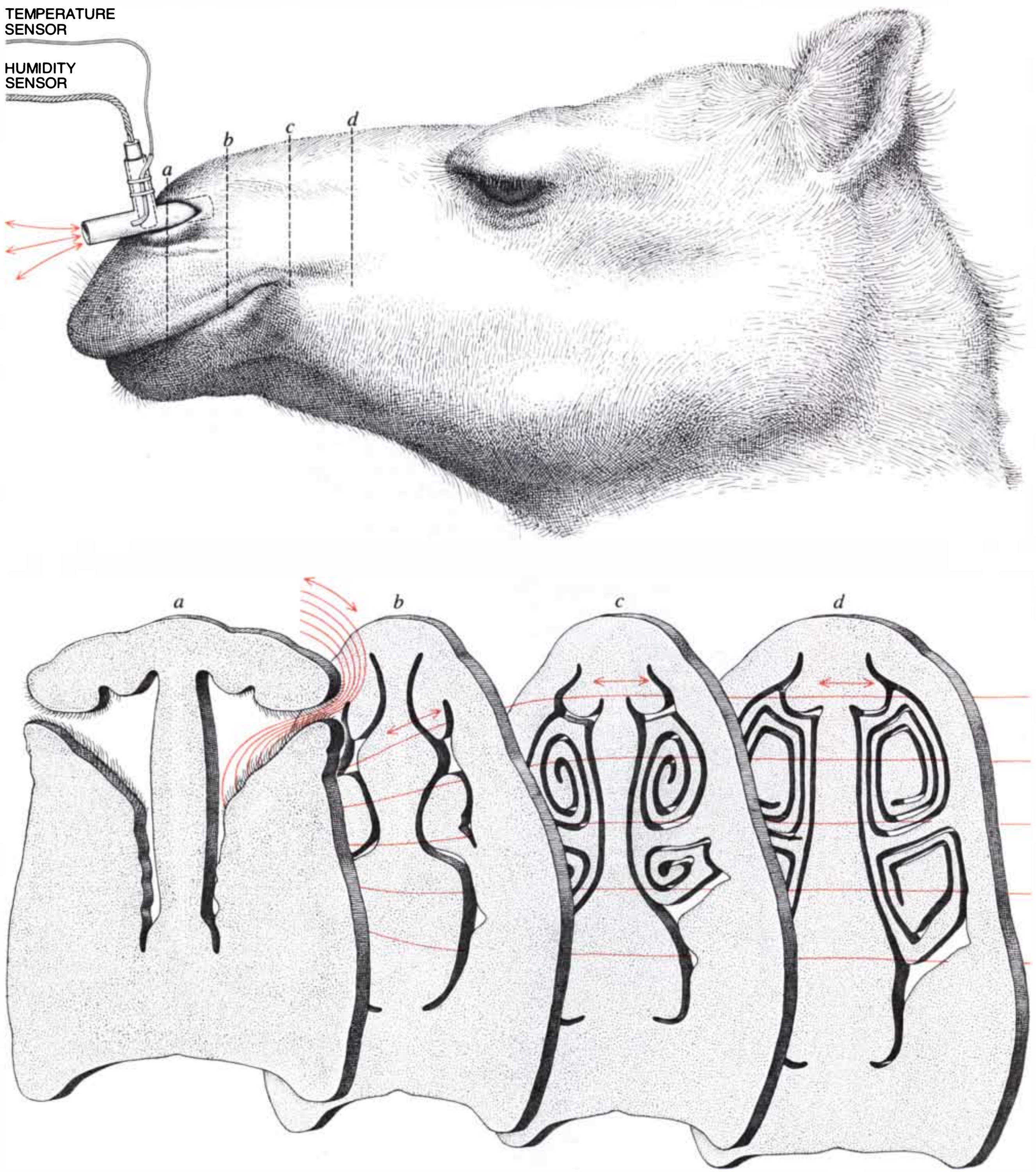
Countercurrent flow is also the operating principle of the heat exchangers that conserve heat in many industrial processes. In a heating plant, for example, a great deal of energy can be saved if high-temperature exhaust is used to preheat the air blown into a furnace. Such preheating returns to the furnace some of the heat that otherwise would be lost.

Imagine that the process of heat regeneration requires an interrupted or pulsed warming of the incoming air. To achieve this kind of regeneration one could direct the hot exhaust through a set of copper pipes and afterward direct the incoming air through the same pipes, preferably in the opposite direction. In the first part of the resulting cycle the pipes would store heat from the exhaust; in the second part the heat would be transferred to the incoming air. The situation is similar when a mammal breathes. The air that is inhaled is heated as it passes through the nose and the upper respiratory tract, so that it reaches the lungs prewarmed to the temperature of the core of the body. On leaving the lungs the warm air again passes over the surfaces of the tract, which were cooled a moment before by the air flowing in. The exhaled air therefore gives up some of its heat and the nose serves as a heat regenerator.

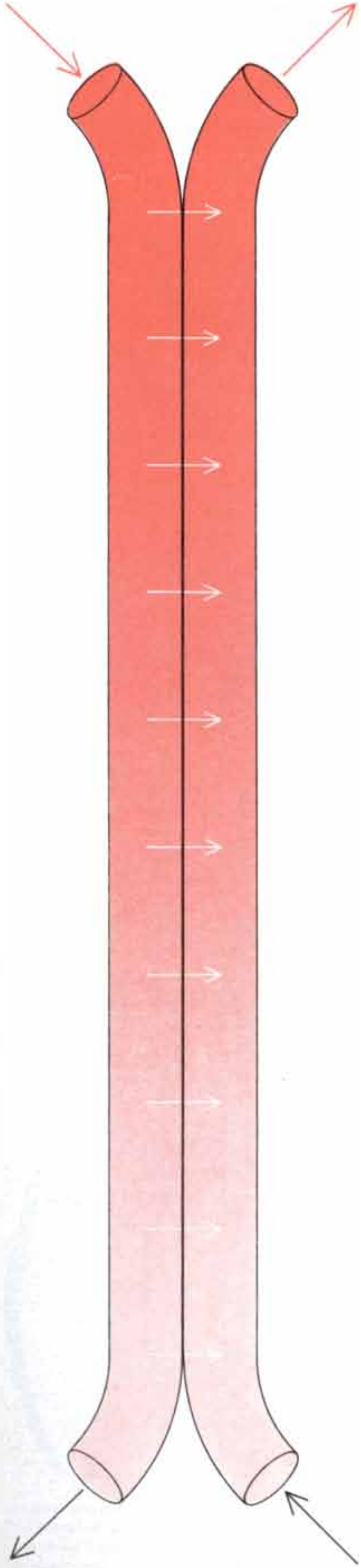
I first became aware of the importance of nasal heat exchange in studies of kangaroo rats from the Arizona deserts. The kangaroo rat never drinks, and it must economize to the utmost with the small amount of water it gets from its food. When I measured the temperature at the tip of the animal's nose with a thermocouple, I found that the exhaled air was several degrees cooler than the core of the body. I have just given the reason: the inhaled air cools the nose, which in turn cools the exhaled air. A temperature gradient thus extends inward from the tip of the nose until body temperature is reached at a depth of about 20 millimeters.

The nose of the kangaroo rat can be represented by a simple model: a narrow box open at both ends. Assume that the wall of the box is initially at the animal's body temperature, which is 38 degrees Celsius. At one end of the box the incoming air cools the wall, but since the air is warmed as it flows through the box, it cools the wall progressively less. Before the air reaches the other end of the box (the lungs) it has been heated to body temperature, and a temperature gradient extends along the wall. On exhalation the warm air gives up heat to the wall. If the heat exchange were complete, the air would leave the box at the same temperature it had when it entered.

In our experiments with kangaroo rats the temperature at the tip of the nose in dry air turned out to be several degrees below that of the entering air. For example, when a rat inhaled dry air at 28 degrees C., we found the exhaled air had a temperature of 23 degrees, for a difference of five degrees. This too is easily explained. As the animal inhales dry air, water evaporates from the moist inner surface of the nose, causing the temperature of the surface to fall below that of the air. The water vapor carries off from the surface the heat that is required to change water from a liquid to a gas. The air passages of the kangaroo rat are quite narrow: the space between their inner surfaces is only a fraction of a mil-



CAMEL'S NOSE is remarkable for the scroll-like passages called turbinates, which contribute to a surface of more than 1,000 square centimeters. The turbinates give up heat and water vapor to the air the camel inhales. On exhalation, however, they recapture a substantial fraction of both. The nose is thus the site of countercurrent exchanges that conserve both energy and water. The temperature and the relative humidity of both the inhaled and the exhaled air can be monitored by means of sensors that are inserted loosely into a nostril.



limeter. The exchange of heat between the airflow and the nose is therefore quite rapid, and the air that leaves the nose approaches within a few tenths of a degree the temperature of the tip of the nose. Hence the air is cooler when it is exhaled than it was when it was inhaled.

Since the exhaled air is cooler than the inhaled air, it might be inferred that the kangaroo rat extracts heat from the air and retains the heat to keep warm. This conclusion overlooks the fact that the cooler exhaled air is fully saturated with water vapor, whereas the inhaled air is dry. The total heat content of the exhaled air must therefore include the heat that is needed to evaporate the water. Since there is water in the exhaled air and not in the inhaled air, the animal loses water. The water loss is reduced, however, because cool air can hold less moisture than warm air.

How important for water conservation is the cooling of the exhaled air? The answer depends on the temperature of the ambient air and on the amount of water vapor already in it. Suppose the ambient air is at a temperature of 30 degrees C. and at 25 percent relative humidity. Under these conditions a kangaroo rat exhales the air at 27 degrees C. and 100 percent relative humidity. In order to make some explicit calculations, assume that over some interval the rat inhales one liter of air. Heating this volume of air to the body temperature of 38 degrees then requires 2.4 calories. Saturating the air with water vapor requires that 43.8 milligrams of water be vaporized, at an energy cost of 25.3 calories. The total expenditure of heat required to warm and humidify the air is therefore 27.7 calories.

How much of this heat is recovered? The cooling of the air to a temperature of 27 degrees releases 3.3 calories. The air remains fully saturated, but since it holds less water vapor at the lower temperature, some 23.6 milligrams of water recondenses in the nose. In condensing, the water gives up its heat of vaporization, with a return of 13.7 calories. In sum, the animal recaptures 17.0 calories, or 61 percent of the total energy that was expended to heat and humidify the air. It also recaptures 54 percent of the water.

COUNTERCURRENT SYSTEM transfers heat between fluids moving in opposite directions. A hot fluid enters a tube at the upper left; a cold fluid enters a tube at the lower right. The two tubes are adjacent, and so heat moves from the hot tube to the cold one. A temperature gradient (*color*) is thereby established, and the heat tends to be conserved at one end of the system. The principle of countercurrent exchange is employed to conserve heat in industrial processes such as distilling.

The amount of water recovered varies with the ambient conditions. At a temperature of 15 degrees and a relative humidity of 25 percent as much as 88 percent of the water that humidifies the inhaled air recondenses on exhalation. The cooling of the exhaled air in the nose is therefore of great importance in the water balance of the kangaroo rat.

Heat exchange in the airways has received little attention from physiologists studying human respiration. In the upper respiratory tract of the human body, however, the exhaled air is cooled to a temperature only a couple of degrees below that of the core of the body.

The reason for this small amount of cooling is simple. In the human body the heat exchange between the airflow and the walls of the nasal passages is far from complete, partly because the passages are wide and partly because the total surface area inside the nose is relatively small. What is probably an even more important reason is that the nasal surfaces stay warm because the blood flow in the nose is relatively great.

Since people exhale air at close to body temperature, the recovery of both heat and water is usually insignificant. The warming and humidification of the air on inhalation are, however, quite important. The importance is illustrated by a grave problem that often develops after the surgical procedure of tracheotomy, in which an opening is made from the trachea to the outside of the body. After a tracheotomy the air the patient inhales passes into the trachea without being warmed and humidified in the nose. As a result the trachea dries out and crusts form on its surface.

The best countermeasure for dealing with the problem is to humidify the inhaled air. To this end the Swedish physician Nils Toremalm has invented a device that functions like the nose of the kangaroo rat. The active elements of the device are two strips of aluminum foil, one of which is flat and the other corrugated. Each strip is four meters long, three centimeters wide and .05 millimeter thick. The two strips are rolled together and fitted inside a plastic cylinder, where they provide an area for heat and moisture exchange amounting to some 4,000 square centimeters. One end of the plastic cylinder is open; the other end is attached to the tracheal cannula, the tube placed in the opening made in the trachea. When the patient exhales, water condenses onto the foil. During the ensuing inhalation the water evaporates and is carried back to the trachea and the lungs. The loss of water from the respiratory tract is reduced to less than half of what it would otherwise be.

If the cooling of exhaled air is insignificant in man, one might think it would also be insignificant in other large ani-

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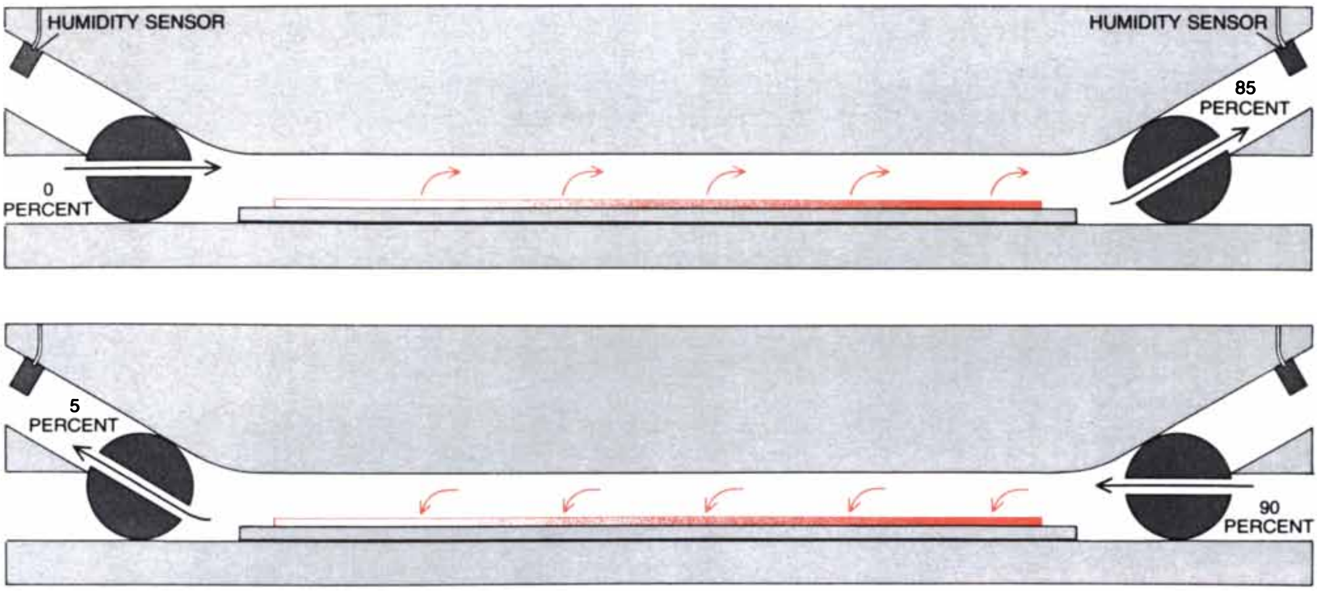

MODEL OF THE CAMEL'S NOSE was devised by the author to show how the camel, unlike man, can exhale air that is less than fully saturated with water vapor. The model consists of a narrow rectangular chamber through which air can be passed. A strip of filter paper inside the chamber simulates the absorbency of the inner surface of the nose. The model alternately "inhales" and "exhales." On inhalation (*upper diagram*) dry air enters from the left; on exhalation (*lower diagram*) moistened air enters from the right. The moistening simulates the humidification inhaled air undergoes. After a few minutes a steady state is established: the filter paper takes moisture (*color*) from exhaled air and releases it to the inhaled air. The exchange reduces the relative humidity of the exhaled air to only a few percent.

mals. For one thing, the nostrils of horses or antelopes or camels are large, like those of man. This might suggest that in large animals the exchange of heat between the air and the inner surface of the nose is poor. For several years, therefore, my colleagues and I paid little attention to large animals. This turned out to be a mistake. We had overlooked the great length of the nasal passages in most large animals and the corresponding extent of the surface area.

A few years ago Schroter and I, along with Vaughan A. Langman of Harvard University and Geoffrey M. O. Maloiy of the University of Nairobi, studied respiratory exchange in several of the large ungulates of East Africa. In the giraffe, for example, we found that when the ambient air has a temperature of 21 degrees C., the exhaled air has a temperature of 28 degrees, which is 10 degrees below the animal's body temperature. In this instance 56 percent of the water that evaporates on inhalation is recovered on exhalation. We estimated that heat exchange in the nose of the giraffe could reduce the animal's respiratory loss of water by from 1.5 to 3 liters per day. On the dry East African savanna the latter amount may be as much as a fifth of the giraffe's total daily need of water.

Although the cooling of exhaled air can result in a substantial saving of water for animals such as the giraffe and the kangaroo rat, the exhaled air is still saturated with water vapor at the lower temperature. Our measurements in the camel, however, had shown not only that the air is cooled but also that it is exhaled with a relative humidity of less than 100 percent. Those measurements would therefore remain unexplained unless in the camel some other physiological mechanism captures additional water vapor.

A distinctive property of the camel's nose is apparently responsible for the second mechanism. The inner surface of the nasal cavity is hygroscopic: it readily takes up water vapor. When exhaled air passes over the hygroscopic surface, water vapor is absorbed; during the following inhalation the drier air passing over the surface takes away water vapor. The uptake of water contributes to the humidification of the inhaled air and at the same time restores the hygroscopic quality of the surface. There is no reason this process should not operate in tandem with heat exchange, and indeed that appears to be the case.

In order to establish that a hygroscopic surface can serve as a moisture regenerator I designed a simple laboratory model through which air of controlled humidity can be made to flow in alternating directions in a manner that simulates the camel's respiration. The model nose is a rectangular chamber 30 centimeters long and seven centimeters wide. To represent the separation between the inner surfaces of a camel's nose the floor and the ceiling of the chamber were spaced two millimeters apart.

In the nose of the camel the airflow is directed through turbinates: elaborately convoluted passages that in cross section resemble scrolls. The turbinates contribute to a total interior surface area of more than 1,000 square centimeters. The surface area inside the model was about a tenth as great. The volume of air passing through the chamber in a given interval was therefore adjusted to be a tenth that in the camel. The air was passed through the chamber for five seconds in one direction and then for five seconds in the other. Hence the model "breathed" six times per minute, which is roughly the rate at which a resting camel breathes.

I tried covering the inner surface of the chamber with various combinations of salts such as calcium chloride and with other hygroscopic materials. They were all effective, but even ordinary filter paper proved sufficiently hygroscopic to demonstrate the validity of the model. A single sheet of filter paper measuring about six by 24 centimeters was placed inside the model nose. In each cycle of breathing, dry air was passed for five seconds in one direction (representing inhalation) and air at 90 percent relative humidity was passed for five seconds in the opposite direction (exhalation). After the model had been in operation for a few minutes a steady state was established. The "exhaled" air that entered the nose at 90 percent relative humidity left the other end of the nose at only 5 percent. Conversely, the "inhaled" air that entered the model nose completely dry had attained a relative humidity of 85 percent when it left the other end.

The fact that a single sheet of filter paper can alternately humidify and de-

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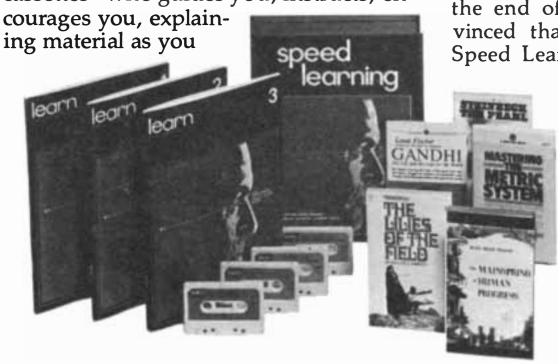

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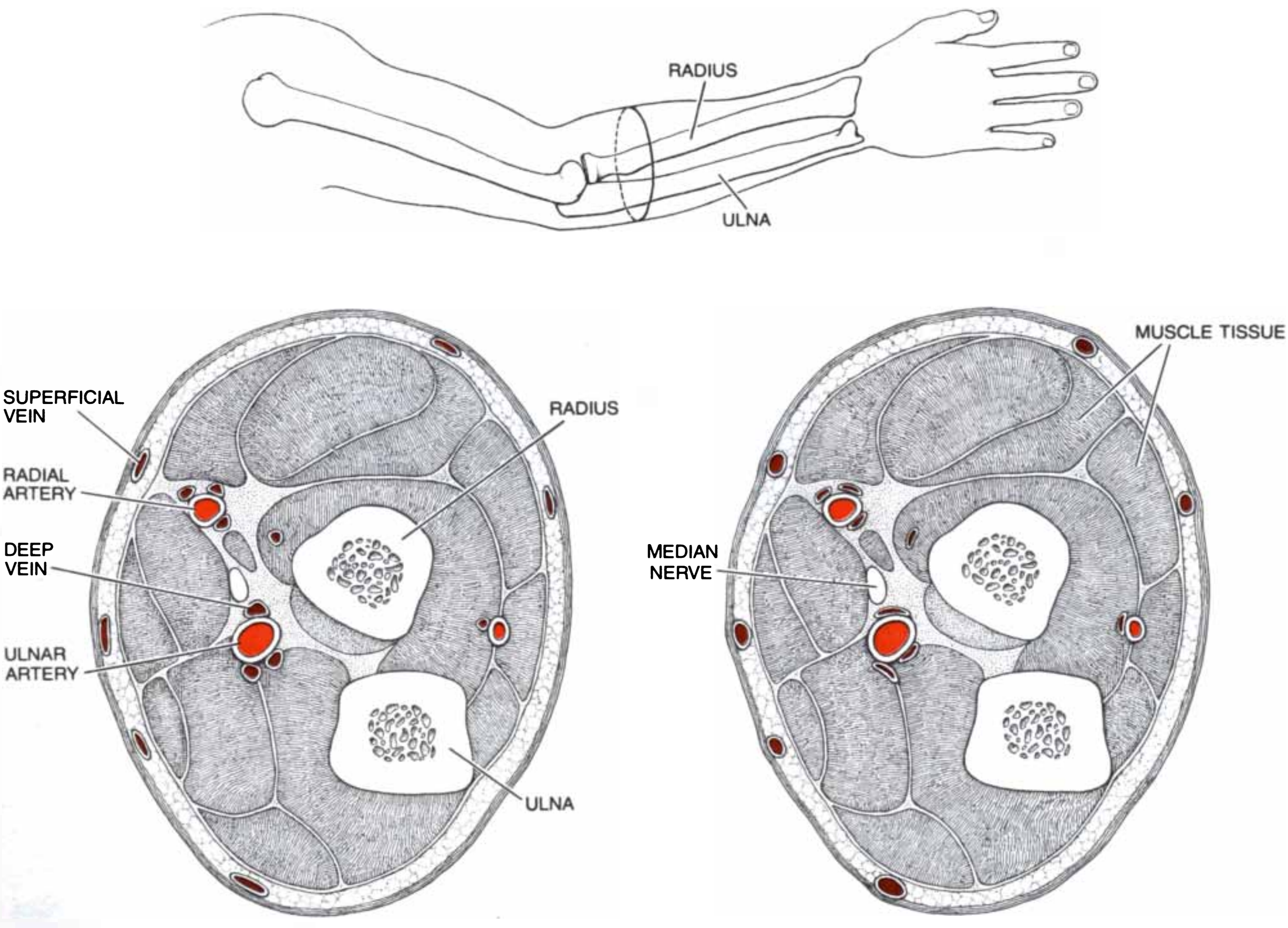
humidify the air passing over it shows that the same principle can operate in the nose of the camel. It is significant that a camel exhales unsaturated air only when it has been deprived of drinking water for a considerable period. Under such conditions the nasal membranes dry out and are covered with a layer of dry mucus and cellular debris. The layer is hygroscopic and is capable of functioning exactly as our model indicates. Herein lies the answer to the problem of how camels can exhale air at less than full saturation.

To assess the amount of water a dehydrated camel can conserve when the inner surface of its nose is dry and hygroscopic consider a period of time in which a camel consumes one liter of oxygen. (For an adult camel at rest it would be about two minutes.) To get this amount of oxygen the camel would need to inhale a total of 20 liters of air. Assume that the air has a nighttime temperature of 28 degrees C. and a relative humidity of 40 percent. If the air were exhaled at 35 degrees and 100 percent relative humidity, the camel would lose 568 milligrams of water. If the air were exhaled at 28 degrees and 100 percent relative humidity (the consequence of nasal heat exchange alone), the camel would lose 322 milligrams. If the air were exhaled at 28 degrees and 75 percent relative humidity (the consequence of both heat exchange and the action of the hygroscopic moisture exchange), the camel would lose only 187 milligrams of water.

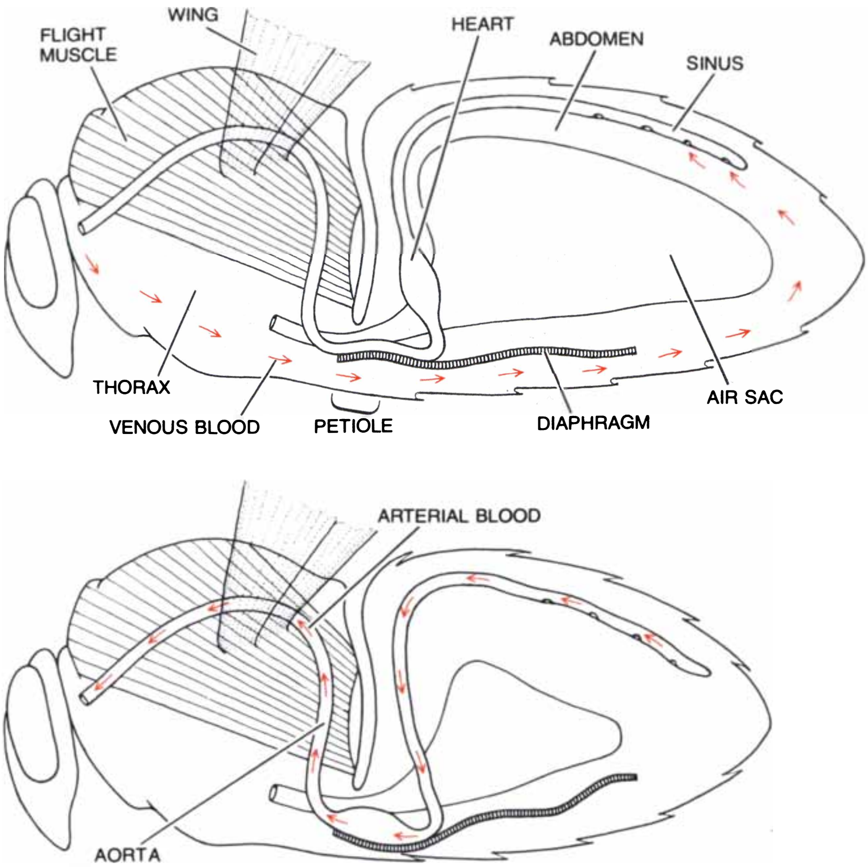
The assessment of the camel's water budget can be carried a step further. Consider that the metabolic combination of one liter of oxygen with the hydrogen in the camel's food leads to the formation of about 600 milligrams of water. The loss of 187 milligrams would therefore imply that at night a dehydrated camel loses from its respiratory tract as little as a third of the amount of water that is being formed by metabolism. It does not necessarily follow that in the long run the camel can gain water from its metabolism. After all, the camel needs water not only for respiration but also for the formation of urine. In addition some water is lost in the feces, and there is always evaporation from the skin, even when the animal does not appear to be sweating. Moreover, in the daytime, when the air temperature is high, the evaporation of water from both the skin and the respiratory tract increases.

Once it is plain that hygroscopic materials can be employed by an animal as a water regenerator, one can see that the principle has many applications other than the camel's nose. Many years ago I noticed that a kangaroo rat sometimes sleeps in a sitting position with its head tucked between its hind legs. In this position the rat breathes through the fur between its legs. At the time I wondered if this could have an effect on the water balance. I now realize that some of the water vapor in the exhaled air must be absorbed by the fur and released again to the inhaled air. To measure the process directly would be quite difficult. Still, I have found that water-stressed kangaroo rats spend more of their time with their heads between their legs than unstressed kangaroo rats do.

Undoubtedly water can be recovered whenever an animal breathes through any hygroscopic material, such as wool, fur or feathers. Sentiel Rommel of the College of the Atlantic has told me that deer in winter sleep with their heads



SPATIAL BYPASS of a countercurrent exchanger is found in the arm. In cold weather (*left*) the blood flowing into the arm returns to the core of the body through veins that run adjacent to arteries. Hence the venous blood recaptures some of the heat that leaves the arterial blood. In warm weather (*right*) the exchange is bypassed. The returning blood is shunted into veins lying near the surface of the arm.



TEMPORAL BYPASS of a countercurrent exchanger is found in the bumblebee. In warm weather the bypass deactivates the exchange that returns to the flight muscles the heat they produce. Here the action of the bypass is shown. When the bee inhales (*upper diagram*), venous blood is pulled into the abdomen. When it exhales (*lower diagram*), arterial blood is pushed toward the muscles. This reduces the transfer of heat between the venous channel and the aorta. The system was discovered by Bernd Heinrich of the University of California at Berkeley.

tucked between their hind legs. This posture undoubtedly reduces the direct loss of heat from the head, which is thinly furred. It must also reduce the loss of water through respiration. Is this saving of any importance when snow provides an unlimited supply of water? The answer is yes. If deer replaced the lost water by eating snow, heat would be expended to melt the snow, to heat the water to body temperature and then to evaporate the water.

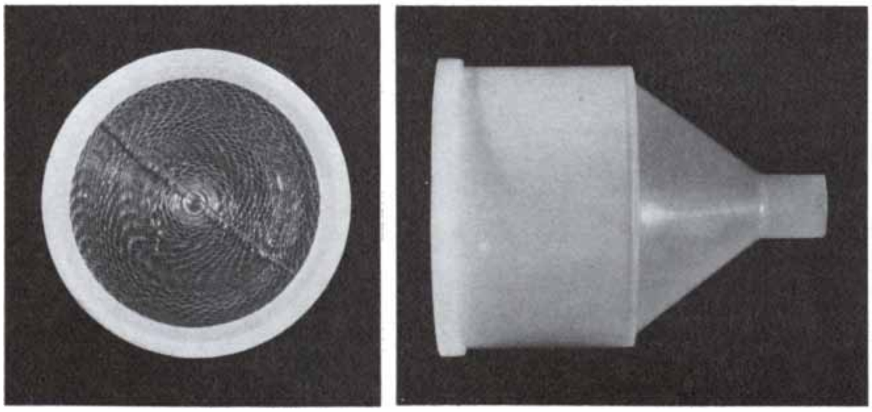
Let me pause and summarize. The countercurrent heat exchanges in the flippers of whales and in the legs of birds depend on the flow of fluid in two separate but adjacent channels. In contrast, the heat exchanges in the nose of a mammal and the moisture exchanges peculiar to the camel depend on a single channel, and instead of being separated in space the countercurrent flows are separated in time. Both the systems with spatial and those with temporal separation are entirely passive, however: they depend on the "downhill" flow of heat or moisture.

If the systems are passive, do they continue to function even when they are not needed? One can imagine a situation in which such continued operation might be detrimental, such as in circumstances where heat should be dissipated instead of being conserved. Consider a whale that swims in tropical seas rather than polar ones. The heat generated by the animal's metabolism must then be removed, and because the body of the whale is insulated by a thick layer of blubber the surfaces of the flippers and of the flukes must serve as the avenues for heat loss. The simplest way to accelerate the loss of heat from the flippers and the flukes would be to increase the rate of flow through the circulatory system, so that the blood does not stay long in the countercurrent heat exchangers. A more effective way would be to bypass the exchangers entirely.

In the whale the exchangers can be bypassed because some of the veins in the flippers run close to the surface instead of next to a deep-lying artery. If the circulating blood is shunted into the superficial veins, the blood that returns to the core of the body is cooled by the ocean water. An analogous arrangement is found in man, although it is less well developed. In man the arteries that supply the lower part of the arm run adjacent to veins. In cool weather, when the conservation of heat is useful, this arrangement serves to reheat the venous blood that returns to the core of the body. In warm weather the venous blood is shunted into veins just under the skin, which bypass the deep-lying heat exchanger.

One can imagine still another way of bypassing a heat exchange between two adjacent channels. Instead of separating the warm and the cool fluids spatially, they could be isolated temporally. In particular, one channel could cease to carry fluid when the other channel carries the return flow. A system working on this principle has been discovered by Bernd Heinrich of the University of California at Berkeley. It governs the temperature of the flight muscles of the bumblebee.

The flight muscles of the bumblebee are in the thorax and the heart is in the abdomen. The thorax and the abdomen are connected by a narrow stem, the pet-



ARTIFICIAL COUNTERCURRENT EXCHANGER humidifies the air inhaled by patients who have undergone a tracheotomy. The device is a plastic cylinder that is placed at the top of a tube that enters the patient's trachea. Inside the device two rolled strips of foil provide a surface on which water from the exhaled air can condense. When the patient inhales, the water reevaporates. The exchanger was invented by the Swedish physician Nils Toremalm.

iole. Through the petiole runs the aorta, in close proximity to the channel that carries venous blood back to the heart. The petiole is thus the site of a countercurrent heat exchanger. In cool weather the exchanger returns to the flight muscles much of the heat they generate. This return of heat is necessary because the bee cannot fly unless the temperature of its flight muscles is greater than 30 degrees C. The exchanger can keep the flight muscles at the required temperature even when the air temperature is close to zero.

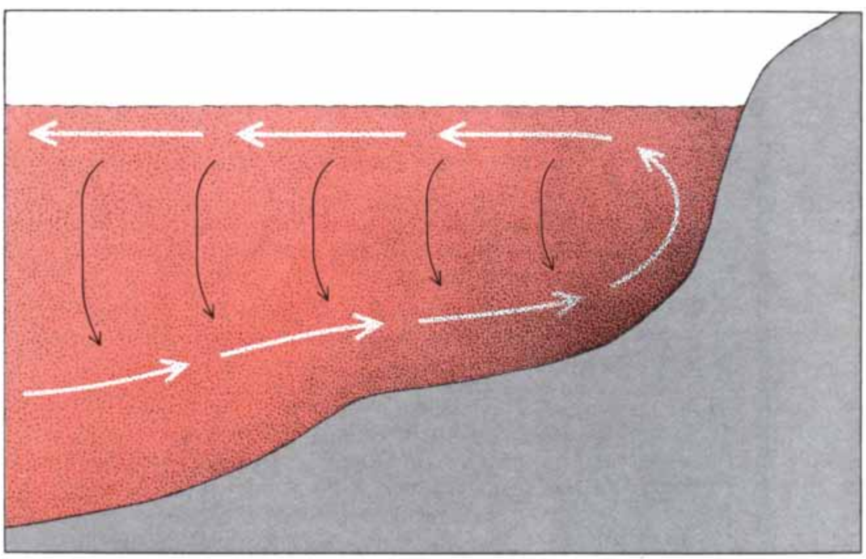
When the bumblebee flies in warm weather, the muscles must lose heat, but the petiole has no room for an additional channel to bypass the heat exchanger. Heinrich has found that at such times the flows of arterial and venous blood can alternate. When the bee inhales, the abdomen distends and venous blood is pulled into it. When the bee exhales, the abdomen is compressed and arterial blood is pushed into the thorax. The compression flattens the venous channel between the thorax and the abdomen, and blood stops flowing through it.

Certain structures that resemble the exchangers discussed here work "uphill," that is, they move a substance against its concentration gradient. These structures are known as multipliers or, to be more precise, countercurrent multipliers. In the kidney of a mammal an array of countercurrent multipliers is responsible for the concentration of urea and other substances in the urine. In the swim bladder of a fish a similar array concentrates gases in spite of the gas pressure inside the bladder.

The characteristic feature of a countercurrent multiplier is a hairpin loop. A fluid moves through the loop while a mechanism of active transport (an "uphill" transport of molecules that requires the expenditure of energy) transfers a substance dissolved in the fluid from the exit leg to the entrance leg of the loop. Even if the concentration in the exit leg is only slightly less than that in the entrance leg, the concentration inside the loop can build to a very high level.

Although I know of no technological analogue of the countercurrent multipliers found in animals, there is a multiplier in nature that operates not in a living organism but on an almost global scale. The deep ocean current that presses against the coast of Peru and deflects water up toward the surface is rich in nutrients. Off the coast of Peru, therefore, one finds a great concentration of plankton that supports a rich coastal fishery. As the water at the surface flows away from the coast, particles of organic matter sink into the underlying onshore current. In this way nutrients are constantly being trapped in a loop. The source of energy that runs this enrichment system is the energy that drives the current. The ocean currents are driven by the wind and modified by the rotation of the earth; therefore the energy needed for the enrichment ultimately comes from the sun.

This discussion has now taken us far from the riddle of how the camel dehumidifies air. It is interesting to see that the same basic principle, that of countercurrent flow, applies in a wide variety of situations, in both living systems and nonliving ones and in both nature and technology.



CURRENTS OFF PERU constitute a large-scale countercurrent system. A deep current approaches the shore and brings nutrients to the surface, where they nourish a coastal fishery. A surface current drives organic matter away from the shore. The matter sinks into the deep current, where nutrients are redissolved. In this way a concentration of the nutrients is maintained.

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Highly Excited Atoms

They are floppy, fragile and huge. Some of them have been found to have a diameter of almost a hundredth of a millimeter, which is 100,000 times the diameter of an atom in its lowest energy state

by Daniel Kleppner, Michael G. Littman and Myron L. Zimmerman

The emblem for the planetary model of the atom introduced in 1913 by Niels Bohr has become a symbol of our times. Since the 1930's, when the symbol was adopted by modernist sculptors and architects, the familiar pattern of electrons orbiting a nucleus has stood for scientific knowledge and progress. Perhaps the persistence of the ubiquitous symbol reflects its ancestry: Bohr's atomic theory imitates in part Newton's planetary theory, and the symbol could easily pass for an abstract plan of a solar system. Whatever the reason, the curious blend of traditional and modern ideas that underlies Bohr's theory has given it a remarkable vitality. The language and the spirit of Bohr's work have persisted in physical thought long after the model itself was commonly acknowledged (by Bohr among others) to have served its purpose.

Bohr's theory of the hydrogen atom had a scientifically useful life of a little more than a decade. The creation of quantum mechanics in the mid-1920's marked its demise. In the past few years, however, a new field of atomic physics has emerged from the no-man's-land between 19th-century classical physics and 20th-century quantum mechanics that was central to Bohr's early work. It is the physics of atoms in which an electron is excited to an exceptionally high energy level. Much of the appeal of the study of highly excited atoms comes from the clarity with which the atoms illustrate the continuity of thought between the world of classical physics and the world of quantum physics.

The highly excited atoms are often called Rydberg atoms, after the Swedish spectroscopist Johannes Rydberg. Any atom can be made into a Rydberg atom by promoting its outermost electron to a very high energy level. Rydberg atoms have a wealth of exotic properties. In the first place they are gigantic: Rydberg atoms have been detected whose diameter approaches a hundredth of a millimeter, which is 100,000 times the diameter of an atom in the ground state, or lowest energy level. The Rydberg atoms are so large that they can engulf other atoms. Rydberg atoms are also remarkably long-lived. An ordinary excited atom generally returns to the ground state in less than a ten-millionth of a second. On the time scale of atomic phenomena Rydberg atoms live almost forever; lifetimes from a thousandth of a second to a second are common. Ordinary atoms are scarcely affected by an applied electric field or magnetic field; Rydberg atoms can be strongly distorted and even pulled apart by a relatively weak electric field, and they can be squeezed into unexpected shapes by a magnetic field.

Powerful new experimental techniques for studying Rydberg atoms became available about six years ago, and laboratories in North America, Western Europe and the U.S.S.R. are now engaged in Rydberg-atom studies. At the Massachusetts Institute of Technology we have been particularly interested in the structure of Rydberg atoms in electric fields and magnetic fields. Our experiments have enabled us to witness dramatic atomic phenomena that had not been observed before. The experiments have also yielded some surprising new insights into the properties of simple atoms.

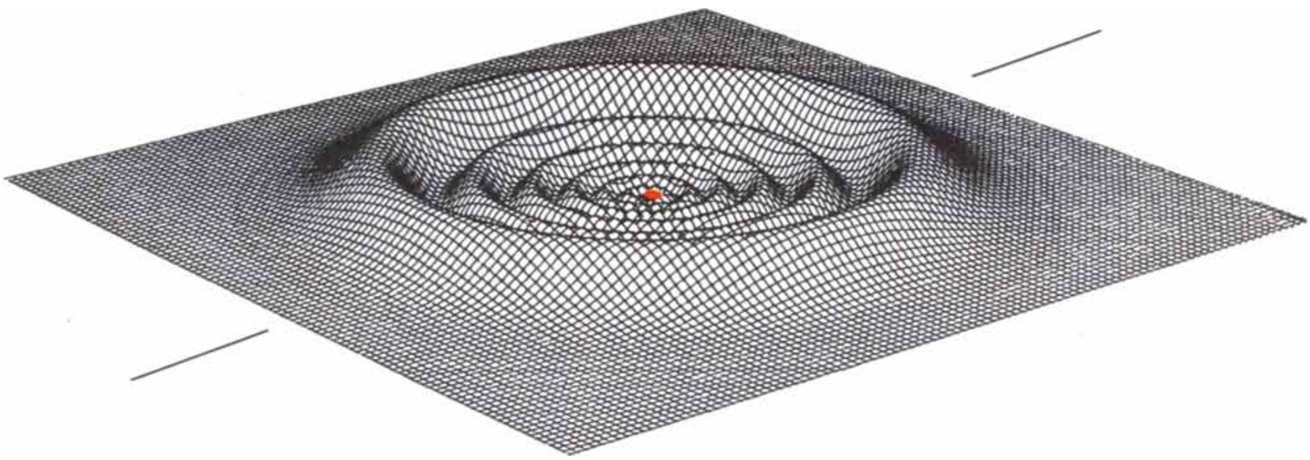
Rydberg atoms are like hydrogen in their essential properties. The similarity can be understood from the most elementary ideas of atomic structure. Every atom consists of a massive nucleus with an electric charge of $+Z$ (the total charge of Z protons, each having a charge of $+1$) surrounded by Z electrons, each having a charge of -1. Z is the atomic number of the atom. Hydrogen, for which Z is 1, consists of a single electron that is attracted to a nucleus composed of a single proton. If the outermost electron of an atom other than hydrogen is promoted to a very high energy level, it takes up a large orbit, well outside the orbit of all the other electrons. Hence the excited electron is attracted by a compact ionic core (made up of the nucleus and all the inner electrons) whose net charge is $+1$, the charge of a hydrogen nucleus. As long as the excited electron does not come too close to the core, the motion of the electron is the same as it would be in a hydrogen atom. Thus the physics of Rydberg atoms is essentially the physics of hydrogen.

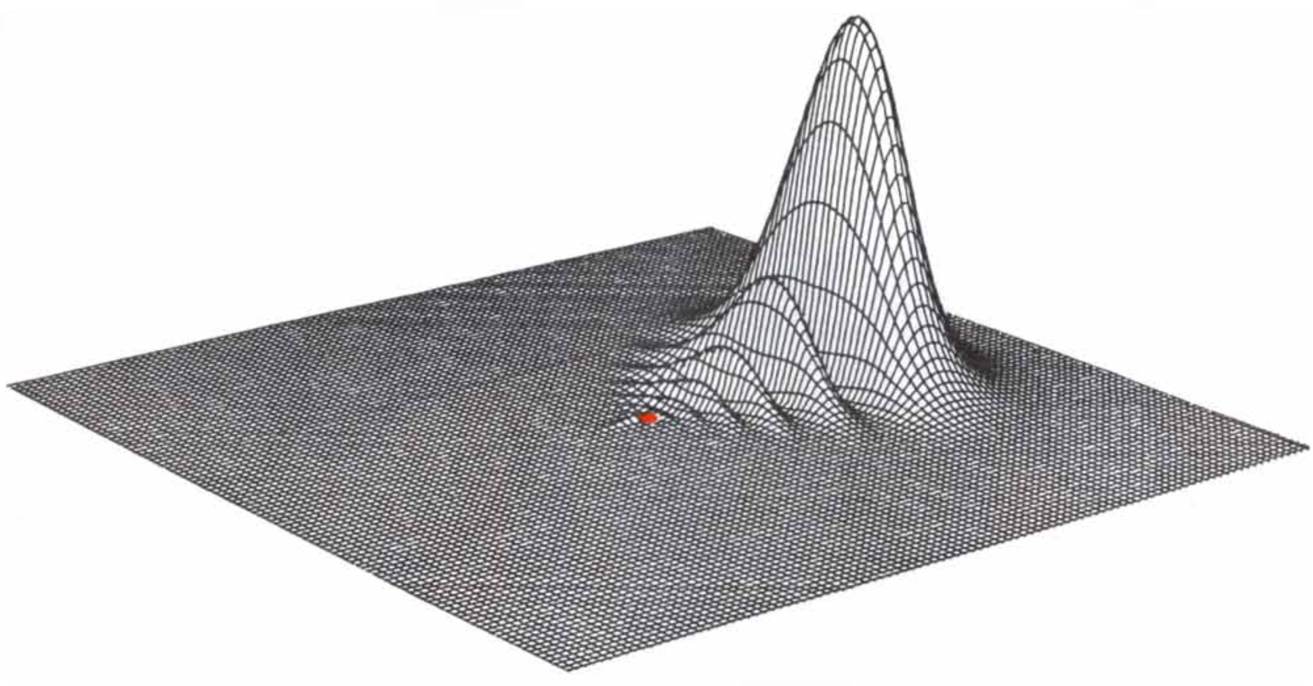
According to the Bohr theory, the hydrogen atom is a solar system in microcosm. The gravitational attraction that binds a planet to the sun and the electrostatic attraction, or Coulomb force, that binds an electron to a proton depend on distance in the same way: both forces decrease as the square of the distance. For this reason the motion of an electron around a proton is identical in form with the motion of the earth around the sun. Nevertheless, the analogy between planetary motion and the motion of the electron in a hydrogen atom is not exact. According to classical electromagnetic theory, the orbiting electron would rapidly lose energy by radiating light and would eventually crash into the nucleus.

In order to overcome this problem Bohr introduced the extraordinary idea that atoms exist only in stationary states, that is, in certain allowed energy levels. The electron cannot spiral into the nucleus. It can lose energy only by "jumping" from a higher level to a lower level, giving off the excess energy as electromagnetic radiation, until it reaches the ground state. From this lowest level no further loss of energy is possible. These simple ideas enabled Bohr to account for the stability of hydrogen as well as for its spectrum: the distinctive pattern of sharply defined wavelengths the atom radiates.

The allowed energies of the electron in a hydrogen atom are given by the expression $-E_0/n^2$, where E_0 is a constant and n is a positive integer called the principal quantum number, which designates the energy level of the electron. The constant E_0 has a value of about 13.6 electron volts. (One electron volt is the energy an electron gains when it is accelerated through a potential difference of one volt.) The energy is negative because work must be done to overcome the Coulomb force in separating the electron from the proton. The value $n = 1$ designates the ground state, and so the electron of a hydrogen atom in the ground state has an energy of -13.6 electron volts. The energy is determined by the combination of the electrostatic attraction between the electron and the proton and the kinetic energy of the electron as it whirls around the proton. Higher energy levels are designated by increasing values of n. As n approaches infinity the energy approaches zero, which is the energy of an electron and a proton that are far apart and at rest.

A Rydberg atom is an atom with a single electron in a state with a large principal quantum number. Atoms in states with n as large as 350 have been detected in outer space by radio astronomers, but in laboratory experiments n typically lies in the range between 10 and 100. Most of the interesting properties of Rydberg atoms depend on n in a simple way. The radius of a Bohr orbit is proportional to n^2, and so the area of the orbit is proportional to n^4. The separa-

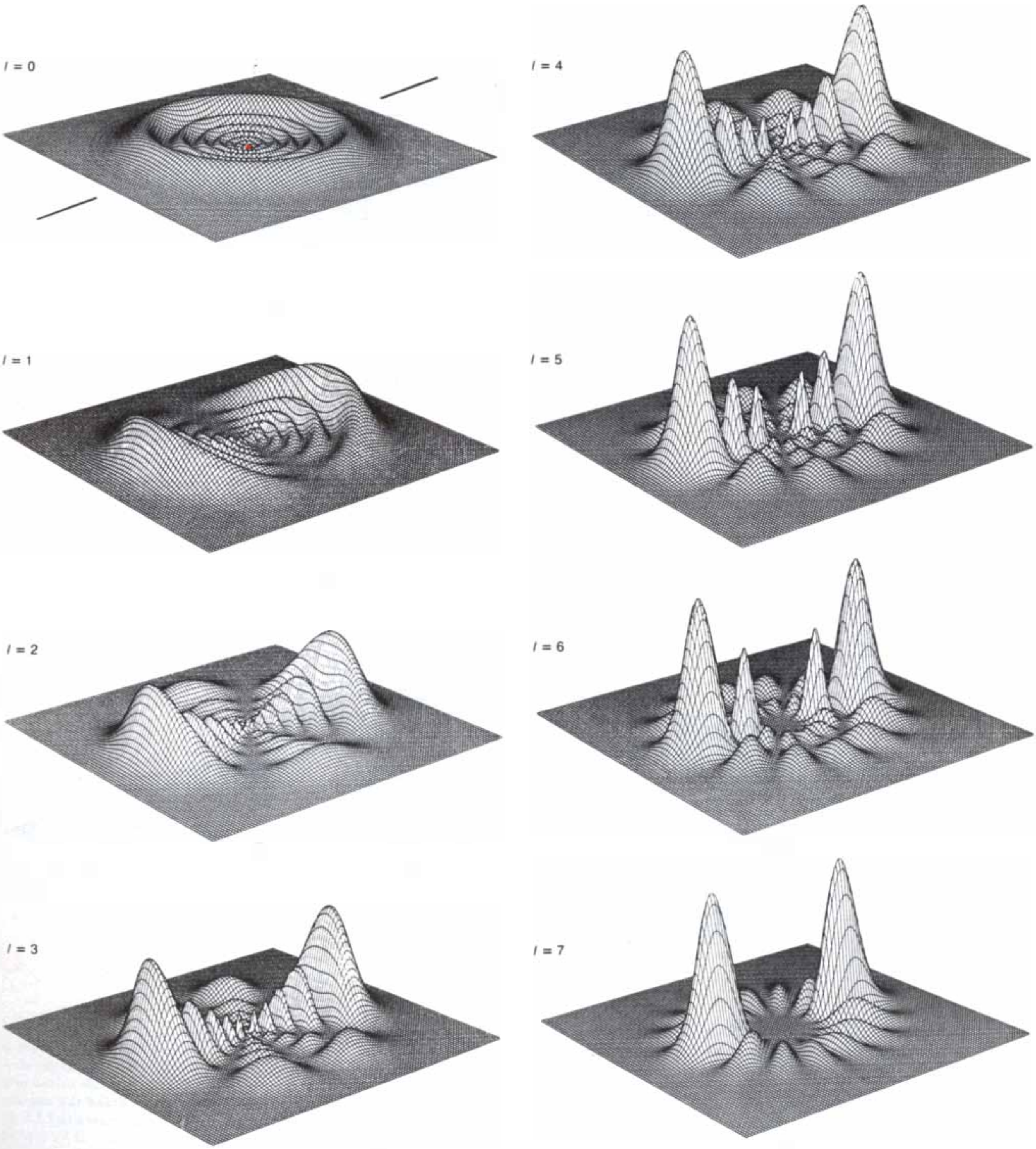




ELECTRON-CHARGE DENSITY OF HYDROGEN is graphed on a plane passing through the single proton that forms the nucleus of the atom (*colored dot*). The states of hydrogen are described by the three quantum numbers n, l and m; n is a positive integer that designates the energy level of the electron, l is an integer between 0 and $n - 1$ that corresponds to the magnitude of the eccentricity (or angular momentum) of the electron's orbit and m is an integer between $-l$ and $+l$ that describes the orbit's orientation. In the state where $n = 8$, $l = 0$ and $m = 0$ (*upper graph*) charge density is a series of concentric wavelike peaks. In three dimensions the charge density can be visualized as a series of spherical shells formed by rotating the graph about an axis passing through the nucleus. The distance from the nucleus to the edge of the plane corresponds to 2×10^{-6} centimeter, which is 380 times the Bohr radius (the radius of a hydrogen atom in the lowest energy state). In a weak electric field (*lower graph*) the electron in an $n = 8$ state of hydrogen "stands" far to one side of the proton, forming an electric dipole. (In this state $m = 0$ and the angular momentum is a mixture of all possible values of l from zero to 7.) A dipole consists of two equal and opposite charges separated by a fixed distance. Many atoms act as dipoles, but most of them are not true dipoles: there is no separation of charges but only a slight distortion of the charge cloud. In the diagrammed state the separation is real. An atom whose outermost electron has been excited to a high energy level is often called a Rydberg atom. All Rydberg atoms are true dipoles.

tion of adjacent energy levels varies as $1/n^3$ and the number of energy levels in a small range of energies increases as n^5. The dramatic properties of a Rydberg atom follow from their dependence on large powers of *n*. For example, when *n* equals 30, the area of the electron's orbit in a Rydberg atom is almost a million times the area in an ordinary atom.

In considering the analogy between the motion of an electron around a nucleus and the motion of a planet around the sun it is important to keep in mind that the most general planetary orbit is elliptical. The period of motion of a planet (that is, the length of the planet's year) depends on the major diameter of the ellipse but not on its eccentricity, or shape. This law, which was formulated by Johannes Kepler at the beginning of the 17th century, has a parallel in the



STATES OF HYDROGEN with $n = 8$ and $m = 0$ vary in angular momentum from $l = 0$ to $l = 7$. Although charge density may seem complex, the nodal lines (where the charge density is zero) are always either circles centered on the nucleus or straight lines passing through the nucleus. In three dimensions the nodal surfaces are spheres or cones. The charge-density graphs were made with the aid of a computer by William P. Spencer of the Massachusetts Institute of Technology. To make the graphs easier to interpret the charge density was multiplied by r^2, where r is the distance to the nucleus. The innermost node of the charge density is too close to the nucleus to be seen.

dynamics of the Bohr atom. The energy of an electron in a given level is identical for orbits that have the same major diameter, no matter what the eccentricity.

Because there are infinitely many different ellipses with the same major diameter, there might be an infinite number of atomic states with the same energy. Bohr argued that only a finite number of orbits should be possible for each value of n. The orbits are distinguished geometrically by their eccentricities. The physical variable corresponding to the eccentricity is the angular momentum of the electron, and Bohr postulated that the angular momentum can have only values given by $lh/2\pi$, where l is any integer from 0 to $n - 1$ and h is Planck's constant.

In creating his atomic theory Bohr invoked an original and ingenious argument, subsequently named the correspondence principle, that enabled him to derive the equations governing the hydrogen atom without any knowledge of the underlying quantum-mechanical laws. The idea of quantum jumps was so alien to traditional physics that it provided no means of predicting atomic spectra from first principles. Bohr overcame this obstacle by considering highly excited states of the hydrogen atom, or in other words Rydberg states. He argued that if n is very large, the effect of changing n by one unit must in some sense be small. For example, the jump from $n = 100$ to $n = 99$ should be much less drastic than the jump from $n = 2$ to $n = 1$. Thus changes in energy between two highly excited states should be smooth compared with the abrupt change in energy between two low-lying states.

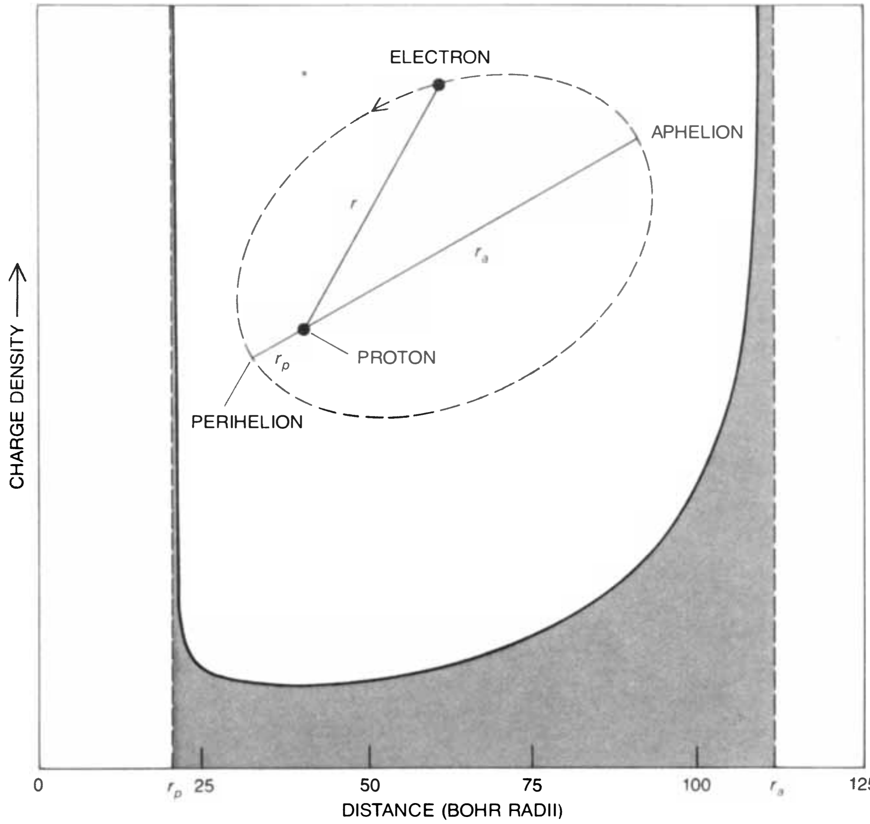
Smooth changes are characteristic of classical systems, where energy can vary continuously. The similarity suggests that highly excited atoms should have classical properties. In particular an electron in an atom should emit electromagnetic radiation with a frequency equal to the orbital frequency. The correspondence principle suggests that the frequency of electromagnetic radiation emitted as a Rydberg atom jumps to a nearby state should approach the frequency at which the electron revolves around the proton. This clue was the key to the problem. It led Bohr to the correct mathematical description of the hydrogen spectrum and to the correct expression for the energy of the electron.

Bohr's simple model accounted for the most conspicuous features of the spectrum of hydrogen, but the model incorporated such a jumble of traditional concepts and radical ideas that it could not be generalized or extended. A new point of view was needed. This point of view, which is alien to the classical outlook of Bohr's theory, was provided by quantum mechanics. The picture of an electron as a particle was replaced by an abstract vision of probability theory. According to the new mode of thought, knowledge of the electron is best expressed in terms of a wave function: a mathematical expression whose value varies in both space and time. The probability of finding the electron in some small volume V is proportional to the product of V and the intensity of the wave function there. In classical physics there is no need to speak of probability. If an electron is prepared in a known way at a given time, one can predict with certainty whether or not it will be in V at any future time. In quantum mechanics, however, if one prepares the electron in the same way and repeats the experiment many times, sometimes the electron will be found in V and sometimes it will not.

A simple artifice makes it possible to describe the electron without the encumbrance of probability theory. The idea is to view the electron not as a charged particle but as a cloud of charge. One can then imagine a fractional charge in a volume V that is the product of V and the charge density. Any single measurement of the charge in V must find either one electron or none, but if the electron is prepared in the same way and the measurement is repeated many times, the average of all the results will be the same as the fractional charge calculated from the charge density. Hence knowledge of the charge density is equivalent to knowledge of the probability that the electron is in V.

At first the concept of charge density in an atom seems to bear little resemblance to Bohr's picture of an electron orbiting the nucleus, but the two views are closely related. Consider the probability of finding an electron in some thin spherical shell surrounding the nucleus. In quantum mechanics the probability is proportional to the product of the shell's volume and the intensity of the wave function in that volume. In classical physics the average charge density is proportional to the time the electron spends in the shell. The faster the electron moves through the shell, the less time the electron spends in it and therefore the less the average charge in the shell is. In short, the classical charge density varies inversely as the speed of the electron.

In a classical elliptical orbit the distance from the nucleus to the electron varies between two extremes: aphelion

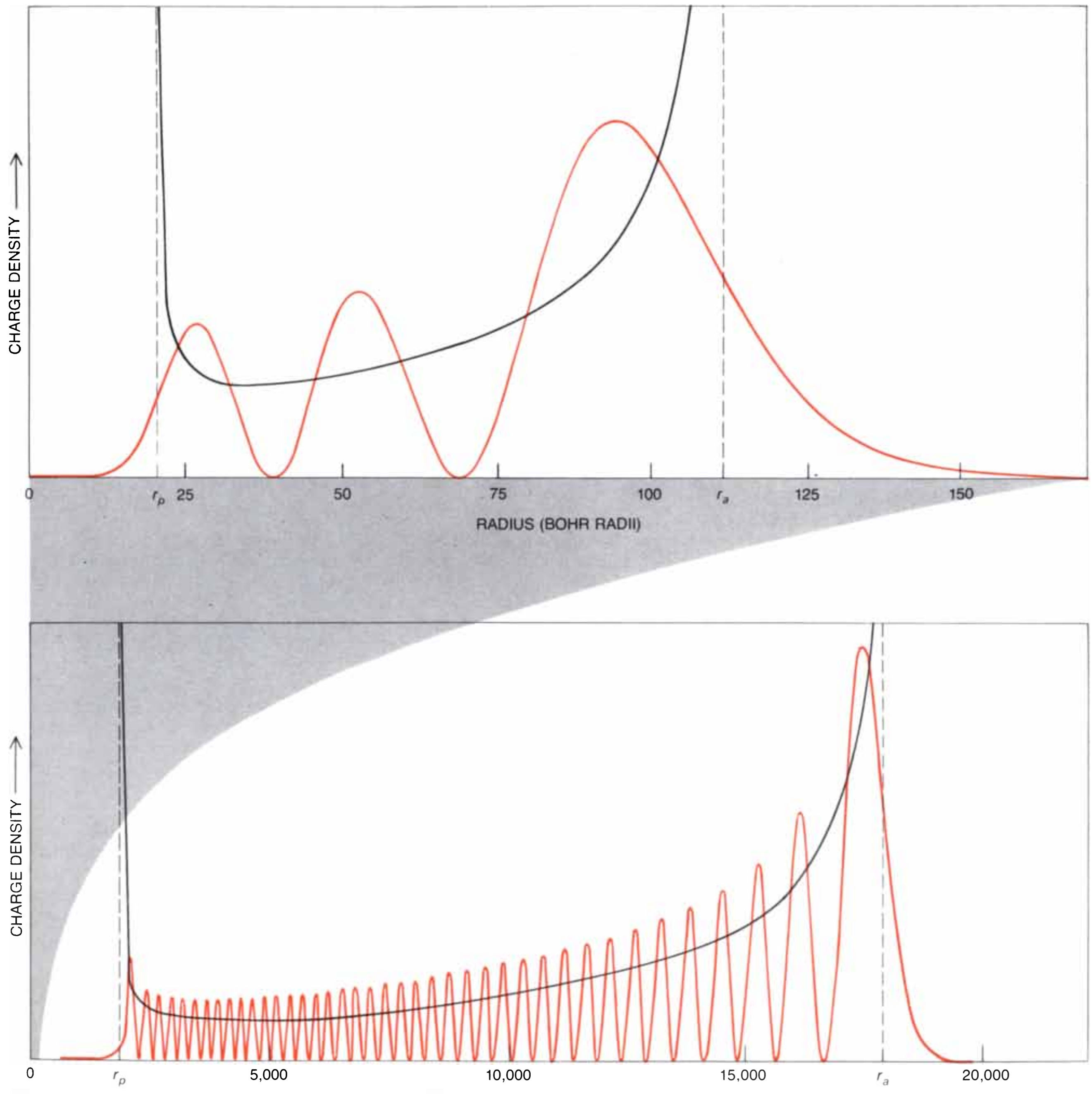


CLASSICAL BOHR ORBIT for the $n = 8$, $l = 5$ state of hydrogen is a squat ellipse (*inset illustration*). The diameter of the ellipse is 128 times the Bohr radius. As the electron moves in its orbit around the proton the orbital radius r varies between the aphelion distance r_a and the perihelion distance r_p. The classical charge density (*graph*) is proportional to the relative amount of time the electron spends at a distance r from the proton. The charge density varies inversely with the radial speed of the electron. The classical charge density diverges at aphelion and at perihelion, where the radial speed falls to zero as the electron reverses radial direction.

and perihelion, to borrow the planetary terminology. The radial speed of the electron falls to zero as it reverses radial direction at these extremes, and so the charge density has a peak there. The charge density has a minimum where the radial speed is greatest, which is close to perihelion. The charge density is zero at distances less than perihelion and greater than aphelion, where the electron never ventures.

The classical and the quantum-mechanical charge densities have little in common in a low-lying state of hydrogen such as $n = 8$, $l = 5$. As the correspondence principle predicts, however, the two charge densities are similar in a highly excited state such as $n = 100$, $l = 60$ [*see illustration below*]. Nevertheless, even in these states there are important differences between the two kinds of charge density. The quantum-mechanical charge density has wavelike features, including nodes and rounded peaks, that reflect the underlying wave properties of the electron. In the classical description the wavelike features are absent. Moreover, in quantum mechanics the electron can penetrate regions of space that are inaccessible to it in classical physics. For example, the electron can venture slightly beyond the aphelion distance.

The existence of Rydberg atoms has been known since before the turn of the century. In 1906 R. W. Wood, an American spectroscopist, observed absorption lines in sodium gas for transitions to states as high as $n = 60$. According to the Bohr theory, an atom can absorb light if the frequency of the light



QUANTUM-MECHANICAL CHARGE DENSITY (*color*) is different from the classical charge density (*black*) in a low-lying state of hydrogen such as $n = 8$, $l = 5$ (*upper graph*). In an energetic state such as $n = 100$, $l = 50$ (*lower graph*) charge densities have a similar shape.

multiplied by Planck's constant is equal to the energy difference between the initial state of the electron and an allowed excited state. When light from a lamp is passed through a gas and dispersed with a spectroscope, dark lines appear where the light has been absorbed at the frequencies satisfying the Bohr condition. There are impediments, however, to the study of Rydberg atoms by this method. Highly excited atoms are so large and so weakly bound that they rapidly break apart when they collide in a gas.

Isolated Rydberg atoms were first observed deep in interstellar space. In 1965 B. Höglund and Peter G. Mezger of the National Radio Astronomy Observatory detected radiation from hydrogen atoms undergoing transitions between levels near $n = 100$. For such large values of n the radiation is not in the optical region of the electromagnetic spectrum but in the microwave region.

Deep space might seem to be an unlikely place for finding Rydberg atoms; actually it is almost ideal because the density of atoms is so low that collisions are rare. Of course, the density must not be too low: there must be enough atoms to provide a detectable signal. A radio telescope can look so far into space that there are many atoms along the line of sight in spite of the low density. The atoms are created when free electrons and protons recombine to form hydrogen. This process of recombination is one of the dynamical mechanisms that govern the delicate balance between neutral matter and charged particles in the galaxy. The atoms radiate as they cascade to lower Rydberg states. Such recombination radiation is emitted from many regions of the galaxy.

Rydberg atoms can be created in the laboratory by a number of techniques. The bombardment of a gas with charged particles promotes atoms in the gas into a wide range of excited states, including Rydberg ones. Many laboratories, however, including our own, rely on another technique. A tunable laser is used to excite the atoms. This method makes it possible to select a particular Rydberg state, an advantage that has revolutionized the field.

Most experiments with Rydberg atoms have been done with the atoms of the alkali metals: lithium, sodium, potassium, rubidium and cesium. These elements are commonly chosen because they are easily turned into a gas, because their spectral absorption lines are at wavelengths conveniently generated by laser light and because they absorb light efficiently. The alkali metals are the workhorses of atomic physics.

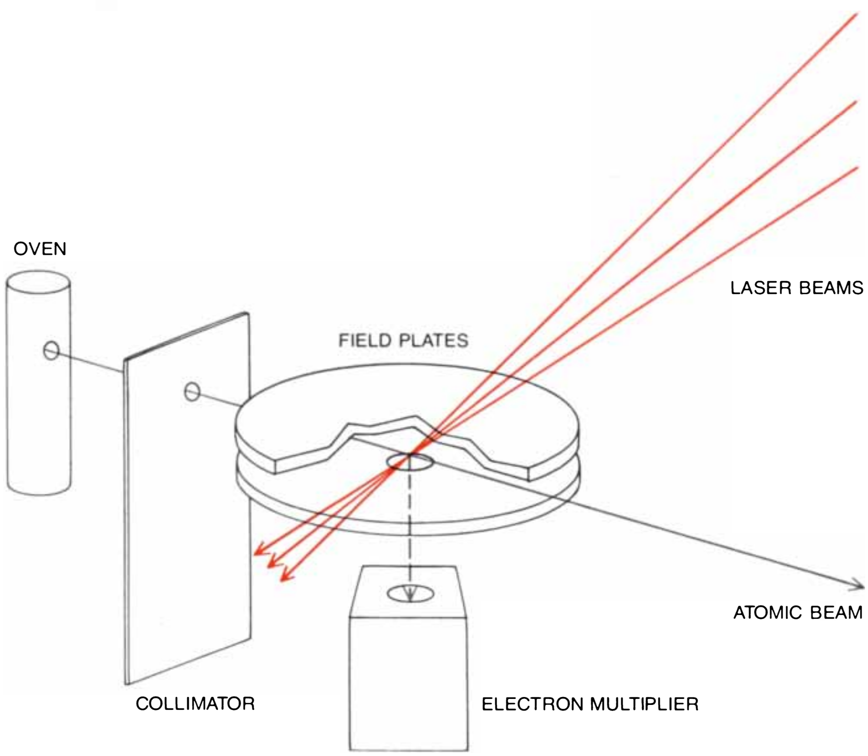
In our laboratory we excite the alkali atoms to Rydberg states with pulsed tunable dye lasers. The lasers generate brief but intense flashes of highly monochromatic light. Usually we excite an atom with pulses from three lasers. The first two pulses excite the electron to an intermediate state, and the final pulse "kicks" the atom into a Rydberg state. In lithium, for example, two lasers excite the electron to the state $n = 3, l = 0$, and the third laser, whose frequency can be tuned over a wide range, drives the electron into a Rydberg state with a large value of n and with l equal to 1. The lasers are fired about 10 times per second, and each pulse lasts for about 5×10^{-9} second. The light is so bright that most of the atoms in the interaction region (whose volume is a cubic millimeter) can be made into Rydberg atoms.

In order to keep the Rydberg atoms from colliding we do the experiments with an atomic beam. In the case of lithium the metal is turned into a vapor by heating in an oven to a temperature of about 650 degrees Celsius. The vapor flows through a small hole into a vacuum chamber; a blocking plate with a small aperture collimates the vapor to form the atomic beam. The vacuum is good enough for an atom to cross the chamber without a single collision.

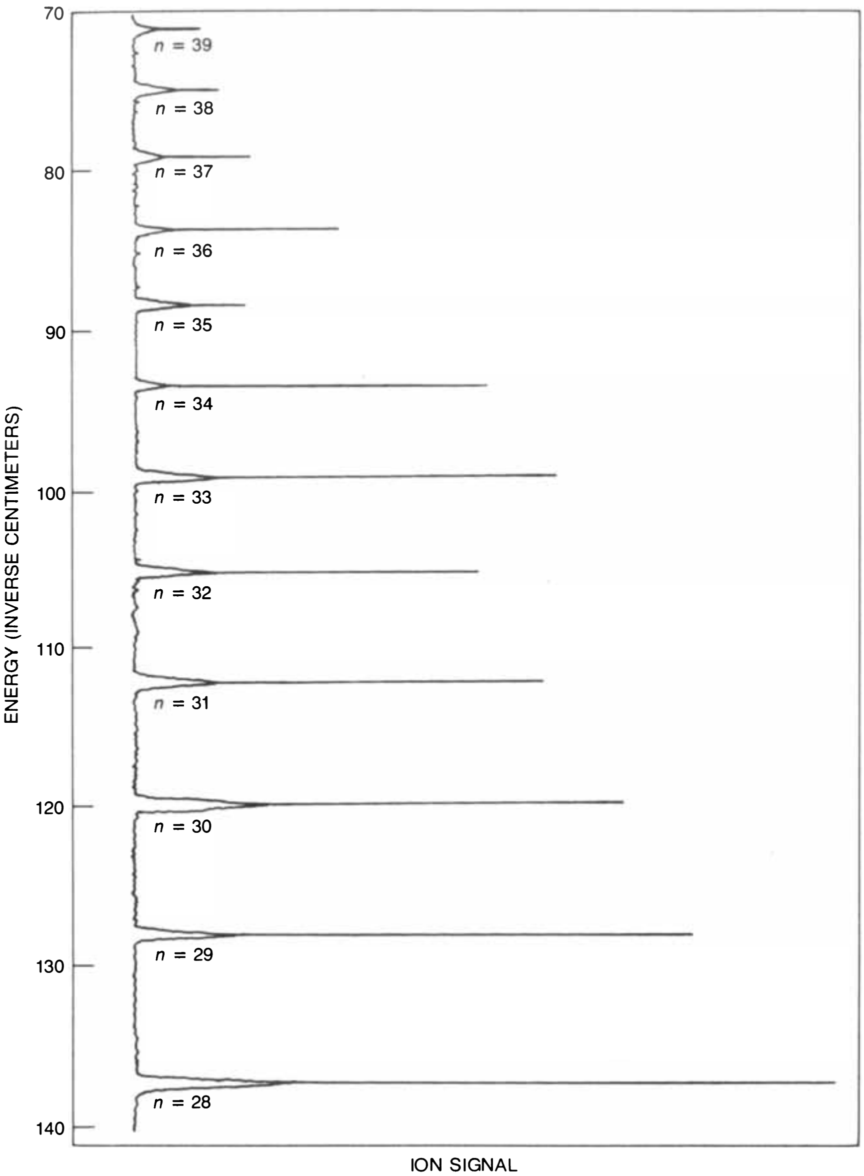
The detection of electrically neutral atoms is usually a troublesome problem, but that is not the case with Rydberg atoms. We ionize them by applying an electric field large enough to tear away the excited electron. Ionizing a ground-state atom requires an extraordinarily large field (perhaps 300 million volts per centimeter), but a field of only a few hundred volts per centimeter is sufficient to ionize many Rydberg atoms. The field is generated by applying a pulse of voltage across two parallel conducting plates centered on the interaction region. The freed electron or the ion passes through a grid in one of the plates and actuates a detector. The technique, which is called field ionization, is so sensitive that we can do experiments with one Rydberg atom per laser pulse, although we usually detect thousands of atoms per pulse.

To display a series of Rydberg-atom energy levels we slowly vary the frequency of the third laser and record the field-ionization current. Whenever the laser frequency multiplied by Planck's constant equals the energy needed to excite an atom to an allowed state, some atoms are converted into Rydberg states and are then promptly ionized. The result is an experimental "picture" of the energy levels.

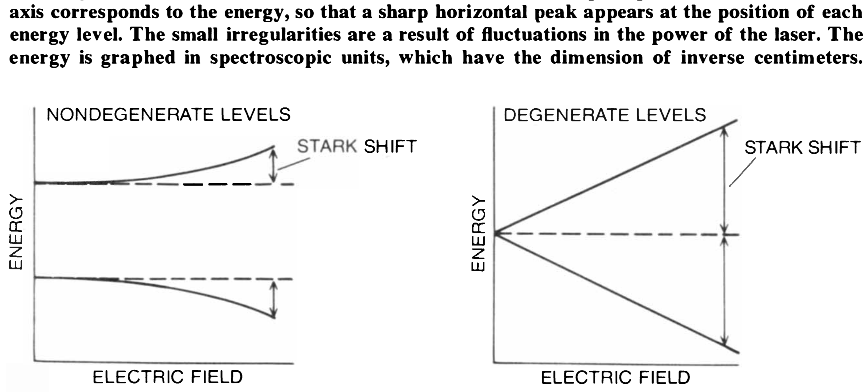
We have employed these techniques to study a fascinating aspect of Rydberg atoms: their properties in an electric field. If an electric field is applied to



THREE LASERS are employed to excite atoms of the alkali metals (lithium, sodium, potassium, rubidium and cesium) to Rydberg states in the authors' laboratory at M.I.T. The metal is heated in an oven to convert it into a vapor. The vapor flows through a small hole into a vacuum where the density is low enough for an atom to cross the entire apparatus without collision. A collimator forms the vapor into an atomic beam. Two or three laser pulses excite an atom to a Rydberg state. The Rydberg atoms are easily detected by the technique called field ionization. A pulse of high voltage is applied across two plates centered on the interaction region.



RYDBERG STATES OF LITHIUM are displayed experimentally by slowly varying the frequency of the light in the final laser pulse and recording the field-ionization current. When the frequency corresponds to the energy needed to excite an atom, the atom can absorb a photon, or quantum of light, and become a Rydberg atom, which is promptly ionized. The vertical axis corresponds to the energy, so that a sharp horizontal peak appears at the position of each energy level. The small irregularities are a result of fluctuations in the power of the laser. The energy is graphed in spectroscopic units, which have the dimension of inverse centimeters.



STARK EFFECT is a shift in the energy levels of an atom in an electric field. The extent of the shift depends on whether or not the energy levels are degenerate. Degenerate levels are states with different quantum numbers that nonetheless have the same energy. In nondegenerate states (*left*) the Stark effect is small and varies with the square of the applied field. Adjacent energy levels tend to repel each other: the upper level is shifted up and the lower level is shifted down. In degenerate states (*right*) the Stark effect is large and varies linearly with the applied field. Rydberg atoms have many degenerate states that often have a large Stark effect.

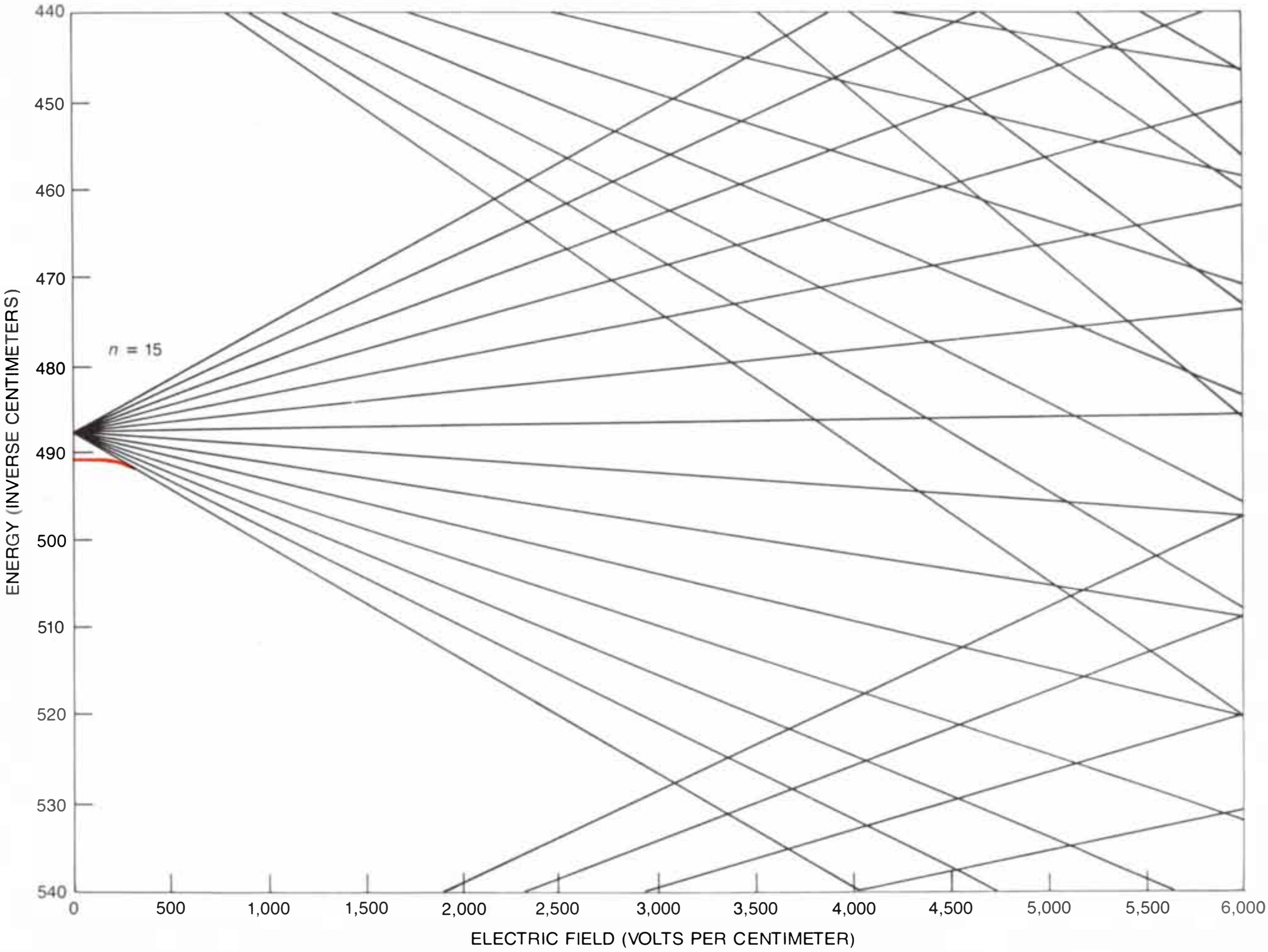
an ordinary atom, its energy levels are shifted slightly; the shift is called the Stark effect. The amount by which a given level is shifted depends chiefly on the proximity of a neighboring level. The nature of the shift is altered radically if the energy levels happen to be degenerate. Two states are said to be degenerate if they are physically distinct (that is, if they have different quantum numbers) but nonetheless have the same energy. In nondegenerate states the Stark effect is small and varies quadratically, or as the square of the applied electric field. In degenerate states the Stark effect is large and varies linearly, or by simple proportionality, with the field. Rydberg atoms are highly degenerate, and they can display spectacular Stark effects.

The degeneracy of Rydberg states follows from a unique property of hydrogen: for a given principal quantum number the states of different angular momentum all have the same energy (given by $-E_0/n^2$). The states of hydrogen are also degenerate with respect to another quantum number, m, that describes how the angular momentum is oriented in space. The value of m can be any integer from $-l$ to $+l$. Thus the state of a hydrogen atom is specified by the three quantum numbers n, l and m. (Other quantum numbers are needed to describe the spin of the electron and the spin of the nucleus, but they can be neglected here.) In hydrogen, for each value of n the states with all possible values of l and m are degenerate.

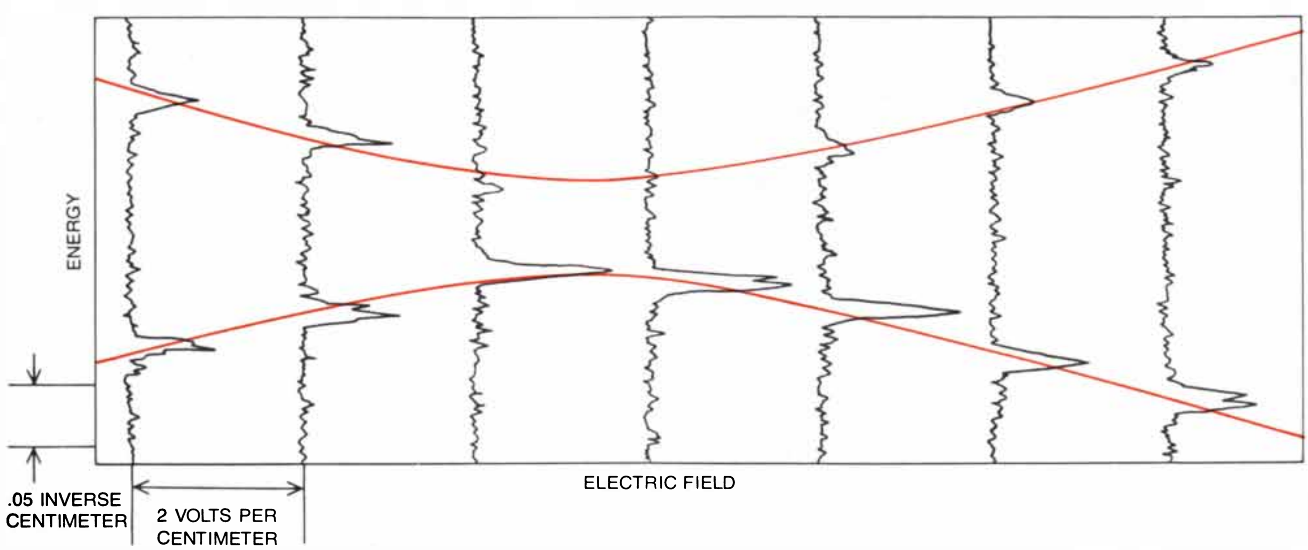
Rydberg states of hydrogen and many Rydberg states of other atoms have gigantic Stark effects because of the high degree of degeneracy and the large size of the atoms. In an electric field the degenerate levels for each value of m split into a series of groups, each group having a single value of m. If the energy of a group is graphed as a function of the electric field, the levels form a fanlike pattern in which some levels increase with the field and others decrease.

A Rydberg atom of an alkali metal such as lithium has a Stark effect that seems similar to that of hydrogen, although there are differences. Among the $m = 1$ levels, for example, the states in which l is greater than 1 resemble the states of hydrogen: they are degenerate and have a linear Stark effect. An electron in the state $l = 1$, however, passes so close to the core of the atom that the electron's energy is slightly lowered. As a result the $l = 1$ state is nondegenerate and has a typical quadratic Stark effect at low fields. In higher fields the shift becomes linear and the entire system resembles hydrogen.

We have studied the Stark effect in Rydberg atoms by applying a steady voltage across the plates centered on the interaction region. Again we slowly varied the frequency of the laser and detected the excited atoms by ionizing them



FANLIKE PATTERN is generated when the Stark effect splits the degenerate energy levels of a Rydberg atom. For hydrogen a series of levels with $n = 15$, $m = 1$ and a mixture of values of l is shown. In addition levels with $n = 14$ and $m = 1$ enter the map from below and levels with $n = 16$ and $m = 1$ enter it from above. The Stark-effect map of the comparable states of lithium resembles the map of hydrogen except for two features. If there is no external field, the $n = 15$, $l = 1$ state of lithium is not degenerate with the other angular-momentum states where n equals 15. The reason is that the $l = 1$ orbit approaches the ionic core (the inner electrons and the nucleus). As a result an electron with l equal to 1 is subject to a slightly stronger field than it is in a hydrogen atom. The $l = 1$ state is not precisely degenerate in a weak field, so that it is subject not to a large linear Stark shift but to a small quadratic one (*color*). In a field stronger than 300 volts per centimeter the shift becomes linear and the $l = 1$ state resembles the corresponding state of hydrogen. The other difference between the two maps is subtle but significant. In the Stark-effect map of lithium the energy levels never cross, as they always do in the map of hydrogen.



AVOIDED CROSSING in the Stark-effect map of the lithium atom is shown in a high-resolution view of the close approach of an $n = 18$ level and an $n = 19$ level. The colored lines represent theoretical calculations of the Stark-shifted energy levels made by the authors.

with a high-voltage pulse a microsecond or two after the lasers were turned off. The energy-level diagram was recorded and the process was repeated at increasing values of the applied field. A map of the shifted energy levels made from the data resembles a map we constructed from the theoretical methods of quantum mechanics [*see illustration below*].

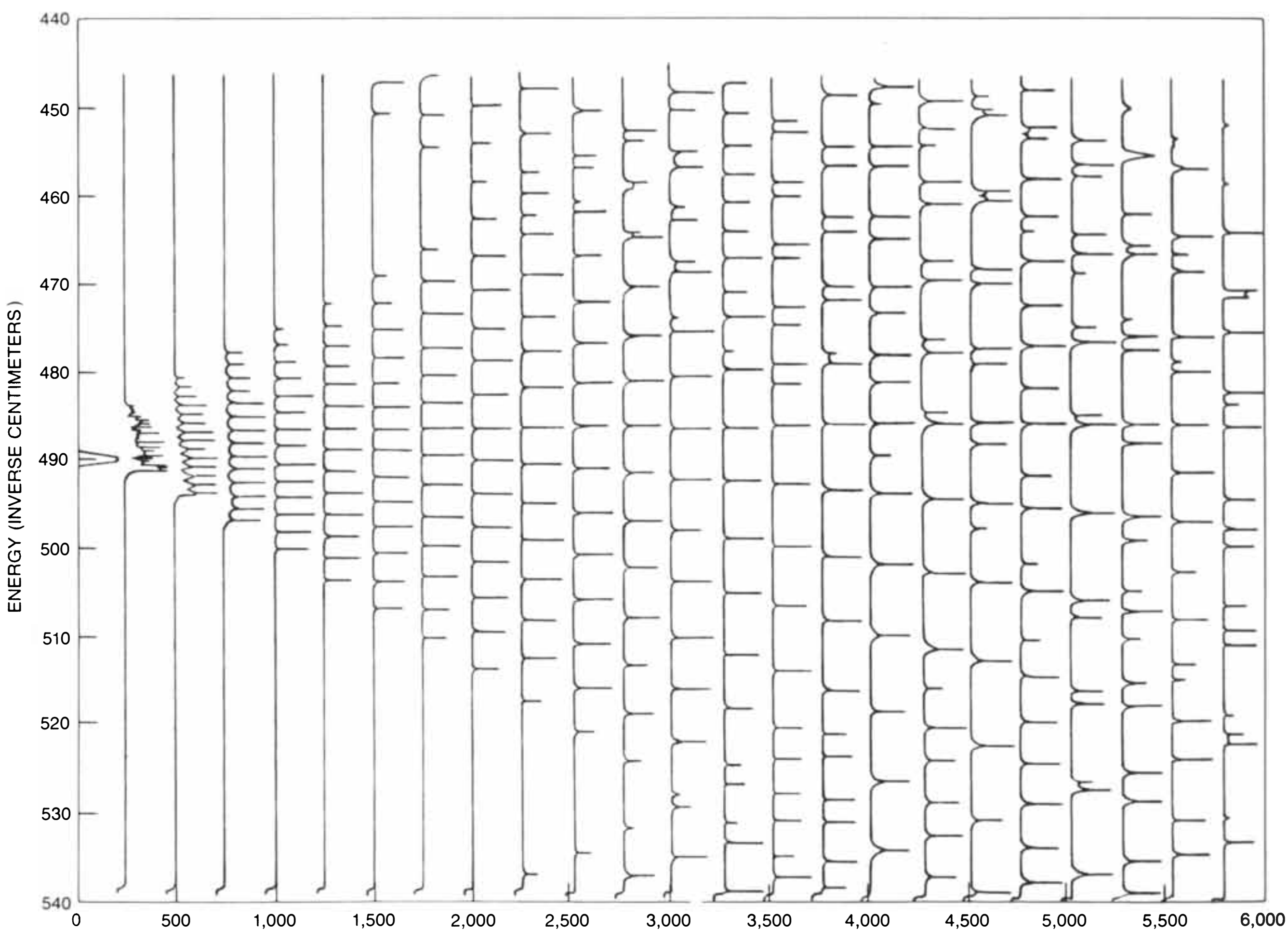
There is a subtle but important difference between the Stark structure of hydrogen and that of lithium. As the applied electric field increases, the energy levels of hydrogen cross one another. At a value of the field where two levels cross they are degenerate. It should be emphasized that degeneracies are not the rule in quantum mechanics but the exception. Wherever a degeneracy is found there is some underlying symmetry, or simplicity, in the problem. For example, the degeneracy in hydrogen of all the angular-momentum states of a given *n* follows from the exact inverse-square nature of the Coulomb force.

An analogous symmetry in planetary motion is connected with the fact that the orbit of a planet is an ellipse whose orientation is fixed in space. If the inverse-square gravitational force is even slightly perturbed, however, the orientation is no longer constant; the ellipse slowly precesses, or changes its direction in space. The precession of the perihelion of Mercury is a famous example caused in part by small relativistic effects.

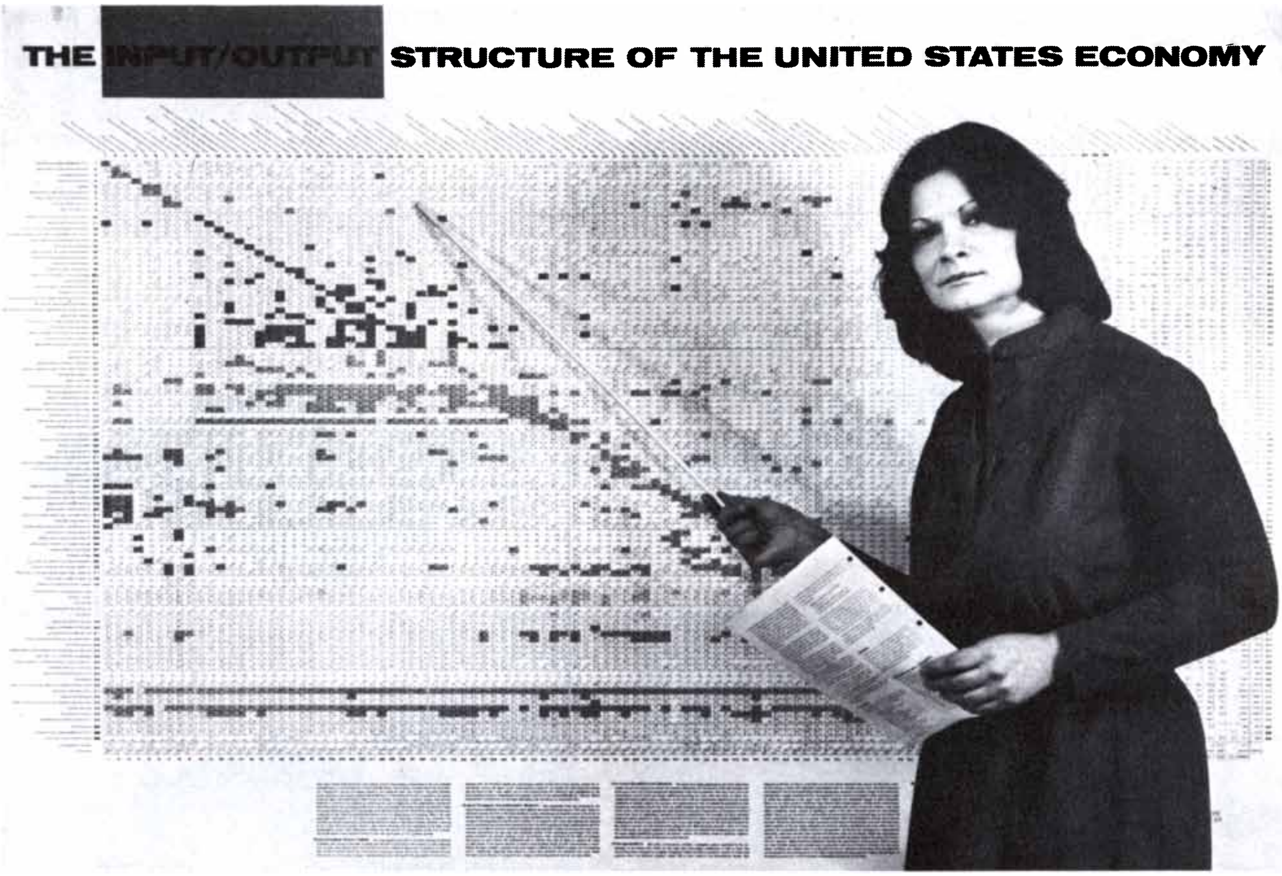
If the pure Coulomb field is slightly perturbed, the underlying symmetry of the Stark structure is lost. Such is the case in lithium. Near the ionic core of lithium (or of any atom other than hydrogen) the inverse-square law does not hold exactly because of the influence of the core electrons. The consequences are dramatic: when the levels are shifted by the Stark effect, none of them cross. Two levels can come close, but at some point they repel each other and turn away. By observing such avoided crossings we can obtain a sensitive test of the accuracy of our calculations. Alternatively we can use the data to reveal the presence or absence of an underlying symmetry of the system.

Although the energy-level map of the Stark structure may look complex, it illustrates a simple idea about the distribution of the electric charge in a Rydberg atom. The most striking feature of the map is the linear variation of the energy with the field. Such a variation is characteristic of an electric dipole: a configuration of two equal and opposite charges separated by a fixed distance. Many atomic and molecular systems exhibit the characteristics of a dipole, but most such systems are not true dipoles: there is no actual separation of charges but only a slight distortion in the shape of a charge cloud. In Rydberg atoms, however, the separation of charges is quite real [*see illustration on page 131*].

Field ionization is often employed to detect Rydberg atoms because it is simple, efficient and essentially free of noise. The physical process that underlies field ionization is quite interesting in itself. It is the process of tunneling, which is purely quantum-mechanical;



STARK-EFFECT MAP OF LITHIUM is made by recording the field-ionization signal as the electric field increases in strength. The horizontal peaks mark the ion signals that are generated when the frequency of the final laser pulse, which is slowly varied, matches an energy level of the atom. The energy levels (that is, the straight lines along which the horizontal peaks fall) can be clearly seen by turning the page sideways and looking along the surface. The levels are the same as the ones in the top illustration on the preceding page.



WHAT MAKES THE U.S. ECONOMY TICK?

The editors of SCIENTIFIC AMERICAN have prepared a wall chart displaying for the 1980's the Input/Output Structure of the U.S. Economy based on the latest interindustry study from the U.S. Department of Commerce.

The SCIENTIFIC AMERICAN Input/Output wall chart does for economics what the table of elements does for chemistry. It answers at a glance questions about the linkage between the microeconomics of the firm and the macroeconomics of the system; about the web of technological interdependencies that tie industry to industry; about the industry-by-industry direct and indirect consequences of swings in public and private spending; about the impact of change in technology, and about any other topic you can think of. You are rewarded by surprise as well as by confirmation of your hunches. For teaching and practical and theoretical studies, here is a powerful, graphic tool.

In the familiar format of the SCIENTIFIC AMERICAN Input/Output wall charts for the 1960's and 1970's, the wall chart for the 1980's measures 65″ × 52″ and is printed in eight colors. Each of the nearly 10,000 cells in the 97-sector interindustry matrix shows (1) the interindustry commodity flow, (2) the direct input/output coefficient and (3) the "inverse" coefficient. Where the direct input/output coefficient exceeds .01, the cell is tinted in the color code of the industrial bloc from which the input comes. This device, combined with triangulation of the matrix, brings the structure of interindustry transactions into graphic visibility.

A supplementary table displays, industry by industry, the capital stock employed; the employment of managerial, technical-professional, white-collar and blue-collar personnel; the energy consumption by major categories of fuel, and environmental stress measured by tons of pollutants.

The editors of SCIENTIFIC AMERICAN are happy to acknowledge the collaboration, in the preparation of this wall chart, of Wassily Leontief, originator of input/output analysis—for which contribution to the intellectual apparatus of economics he received the 1973 Nobel prize—and director of the Institute for Economic Analysis at New York University.

Packaged with the chart is an index showing the BEA and SIC code industries aggregated in each of the 97 sectors.

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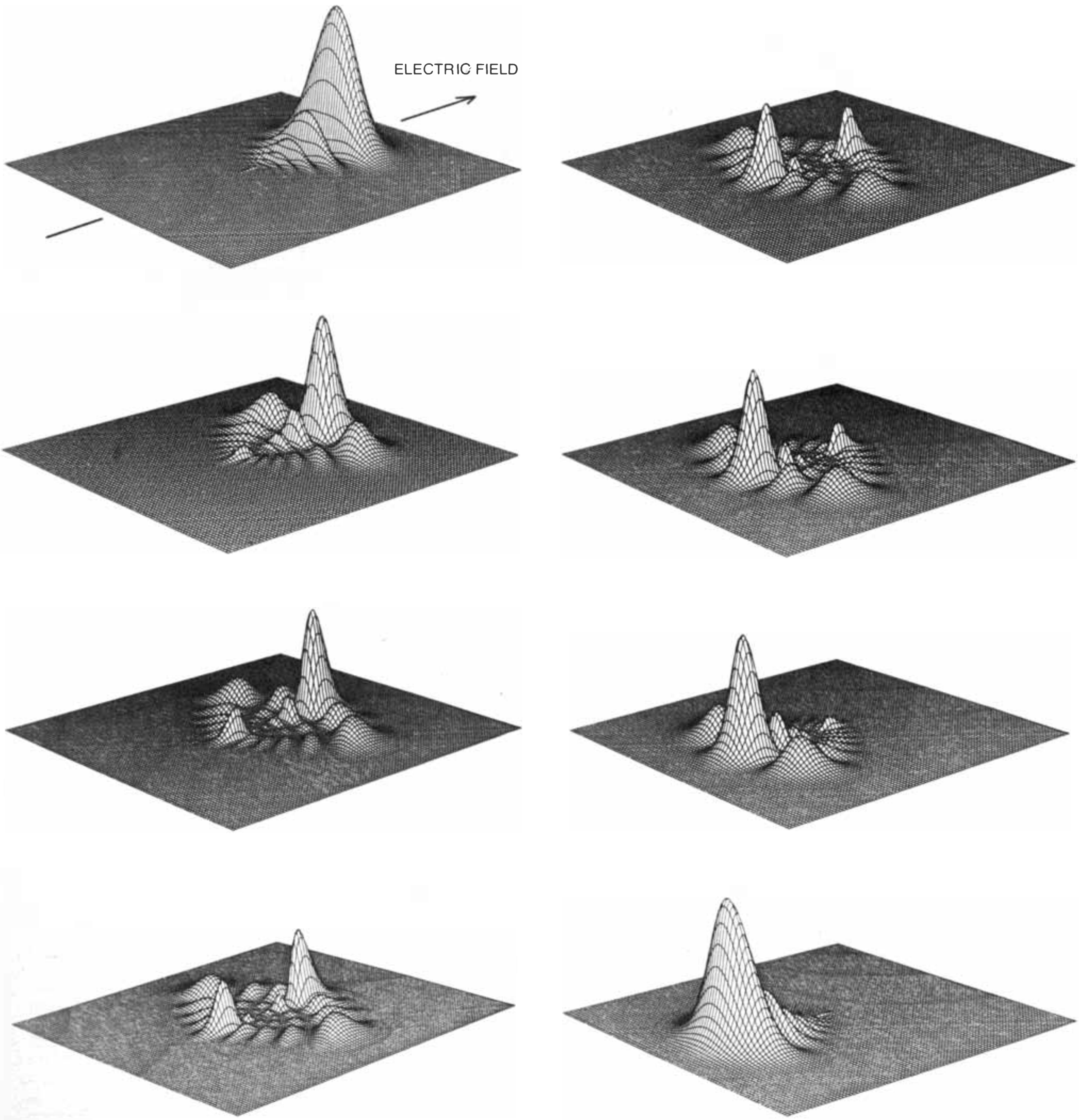
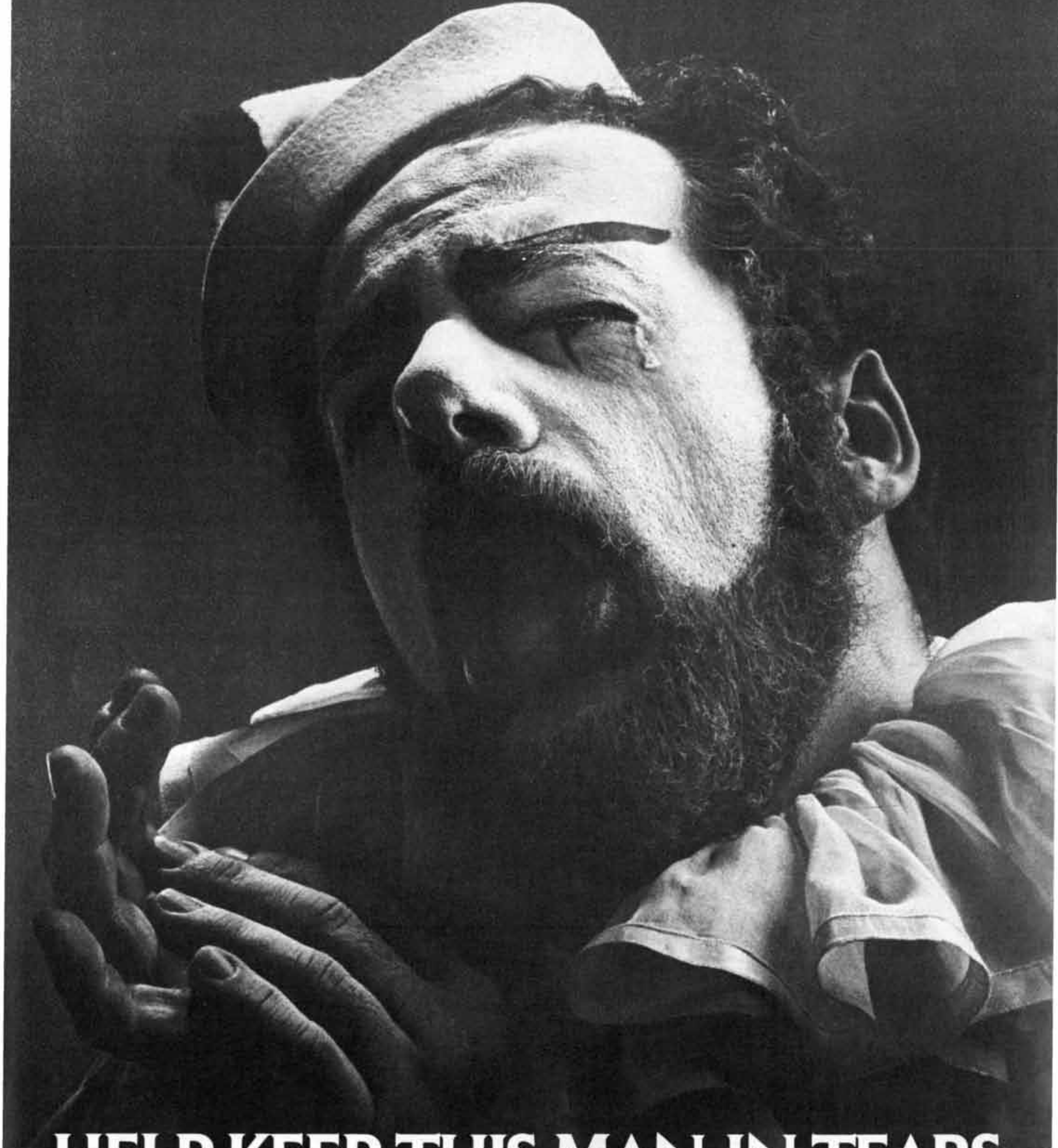
there is nothing like it in classical mechanics. Tunneling is the motion of a particle through a region where classical mechanics does not allow it to be.

In both quantum mechanics and classical mechanics the total energy of a particle has two components: kinetic energy and potential energy. For a hydrogen atom both components of the energy can be represented in a graph that gives the energy of the electron as a function of distance from the nucleus [*see illustration on page 142*]. Since the total energy, $-E_0/n^2$, is constant for any given value of n, it is plotted as a horizontal line. The potential energy varies inversely with distance and forms a hyperbola. Where the curves representing the total energy and the potential energy intersect, the kinetic energy is necessarily zero, and so the electron's velocity is also zero. An electron moving away from the proton comes to rest there and then starts falling back toward the proton under the attraction of the Coulomb force. The intersection is called a turning point. According to



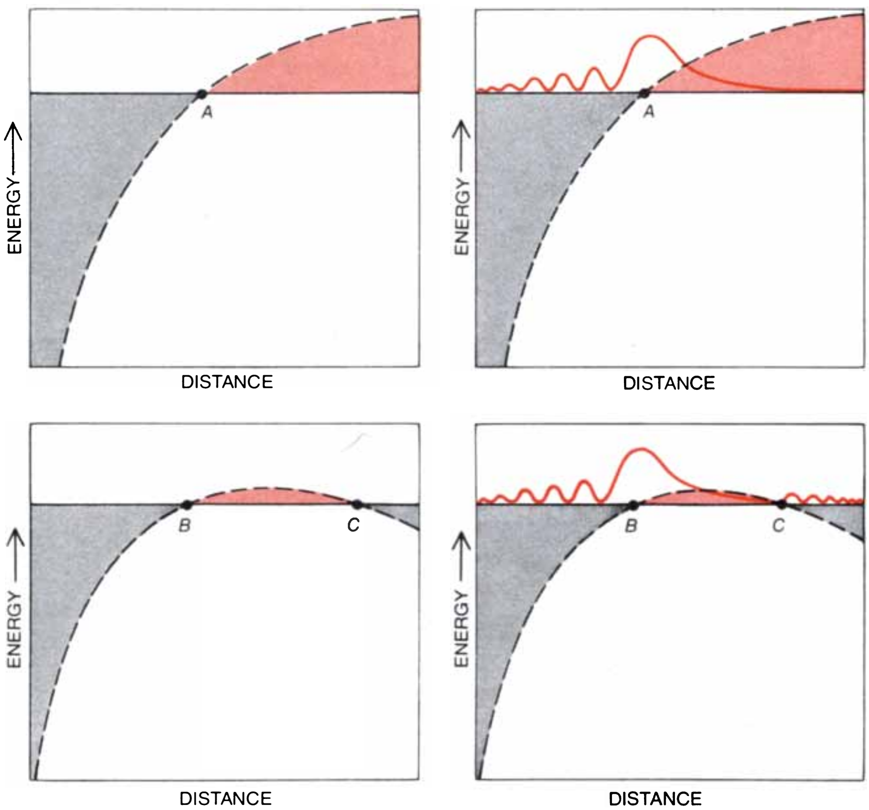
HYDROGEN ATOM IN AN ELECTRIC FIELD can assume many shapes because of its high degree of degeneracy. The charge distribution for the $n = 8$, $m = 0$ states can have any of the eight shapes shown. In each state the angular momentum has a mixture of values from $l = 0$ to $l = 7$. The specific shape a Rydberg atom assumes depends on the experimental conditions under which it is formed. The same family of states is shown in the illustration on page 132. The electron-charge cloud is displaced from the proton, giving rise to a linear Stark effect. The Stark effect is proportional to the average distance between the proton and the electron, which is different for each state. In three dimensions the charge distribution has a cylindrical symmetry about colored axis; nodal surfaces are paraboloids of revolution.



classical physics, the electron cannot go beyond the turning point because the kinetic energy would be negative there. (The kinetic energy is proportional to the square of the velocity. In classical physics it can never be negative.)

The energy diagram must be modified somewhat when a hydrogen atom is put in an electric field. Near the origin the force on the electron stems chiefly from the influence of the proton, but at large distances, where the Coulomb force is small, the force associated with the applied field dominates. The potential-energy curve, which is determined by both the Coulomb force and the applied field, has a maximum where the two forces balance. If the total energy is less than the maximum, the potential-energy curve forms a barrier to the motion of the electron. The horizontal line representing the total energy meets the potential-energy curve at both an inner turning point and an outer one. An electron at rest at the outer turning point would start to move radially outward, accelerated by the applied field. In classical physics an electron that is between the proton and the inner turning point is trapped forever by the potential barrier; it cannot escape unless its energy is boosted to a level higher than the top of the barrier.

When the quantum-mechanical distribution of charge is superposed on the energy diagram, the "tail" of the distribution extends beyond the outer turning point, which indicates that the electron can escape from the atom. The quantum-mechanical state is no longer a stationary state; sooner or later the electron will tunnel through the barrier and be carried away by the applied field.



TUNNELING OF AN ELECTRON through a potential-energy barrier is the quantum-mechanical mechanism that underlies field ionization. At the top left is a graph of the total energy (*solid line*) and the potential energy (*broken line*) of the electron in the hydrogen atom. The energy is graphed as a function of the electron's distance from the nucleus. The kinetic energy (the difference between the total energy and the potential energy) can never be negative in classical mechanics, and so the electron is confined to the region (*gray*) between the proton and the turning point (*A*), where the potential energy is equal to the total energy. According to classical physics, an electron moving away from the proton would come to rest at the turning point and then start falling back toward the proton; the electron cannot pass into the region beyond the turning point (*color*). At the top right the quantum-mechanical charge density is superposed on the energy diagram. The charge distribution has a "tail" that extends beyond the turning point, and so there is a finite probability of finding the electron in the classically forbidden region. At the bottom is the energy diagram for a hydrogen atom in an electric field. The potential-energy curve is determined by both the Coulomb-force field and the applied electric field, and as a result there are two turning points (*B, C*). At the bottom left is the situation in classical physics. An electron cannot go from the region between the proton and the inner turning point (*B*) to the region beyond the outer turning point (*C*) because it would have to pass through the forbidden region (*color*). The electron is permanently bound to the proton. The quantum-mechanical charge density at the bottom right shows that the tail of the charge distribution extends beyond the outer turning point. Therefore the electron can tunnel through the potential barrier and escape from the atom. That happens when the atom is ionized by an electric field.

Tunneling is the fundamental mechanism of field ionization. It also governs physical phenomena ranging from the radioactive decay of nuclei to the emission of electrons from a sharply pointed conductor. The lifetime of the electron (the average time for it to tunnel through the barrier) varies with the height of the potential barrier in a spectacular way. In the case of alpha-particle emission by a nucleus the lifetime ranges from microseconds to billions of years depending on the energy of the alpha particle. In the field ionization of a Rydberg atom the lifetime typically decreases by a factor of a million when the field is increased by only 20 percent.

The Rydberg atom is an ideal system in which to study tunneling because the lifetimes can be calculated precisely and can be varied simply by turning the knob that controls the applied voltage. In our laboratory we have measured the lifetimes of Rydberg states of sodium. The experiment is simple in concept. A Rydberg atom is formed in the applied field by a short laser pulse, and the time it takes for an ion to appear is measured by an electronic timer. The measurement is repeated thousands of times and the average lifetime is calculated. To avoid confusion no more than one atom is observed in each laser pulse. (As we mentioned above, single-atom experiments are quite practical.) Our results are in good agreement with theoretical predictions. We have found that the measured lifetimes are so sensitive to changes in the strength of the field that the lifetimes can be employed to determine the field with a high degree of accuracy.

Unlike atoms in strong electric fields, atoms in strong magnetic fields are not well understood. It is surprising that such an elementary problem in atomic physics remains unsolved. In the case of hydrogen the physical system (an electron, a proton and a magnetic field) is not complex and the equations that describe the system are simple. General methods for solving the equations have not yet been developed, however, and much of the physics remains a mystery. It is a mystery worth some effort to solve, because it will almost certainly lead to the discovery of interesting new phenomena.

An electric field tends to pull an atom apart, and when the field exceeds some critical strength, the atom simply ionizes. In contrast, a magnetic field squeezes an atom, which remains stable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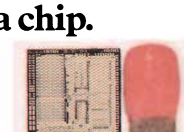

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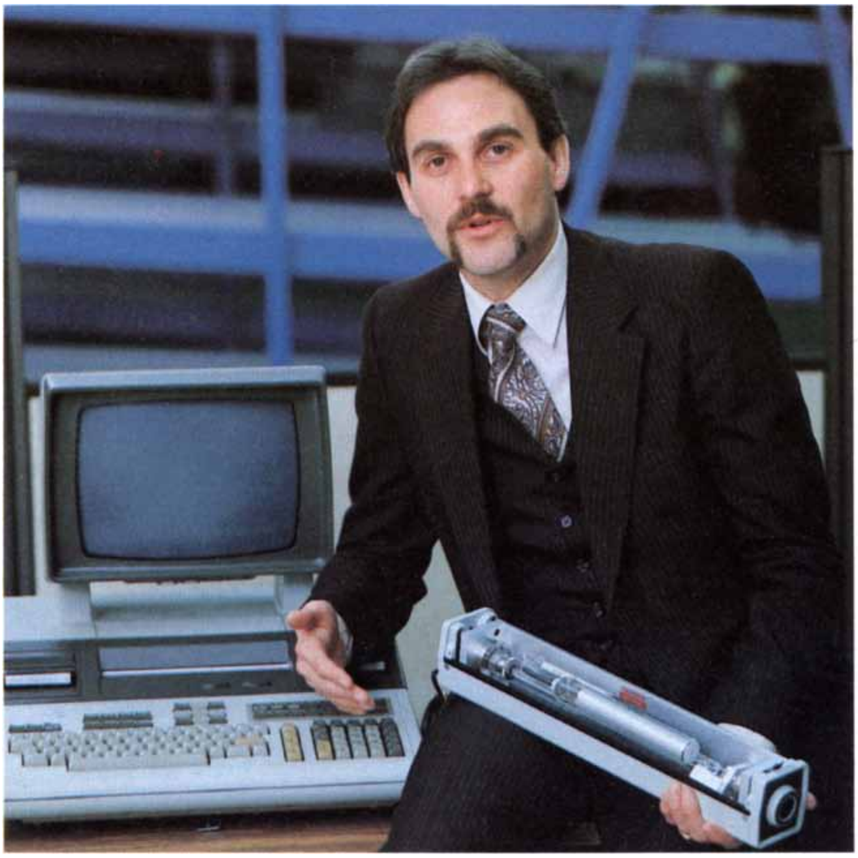

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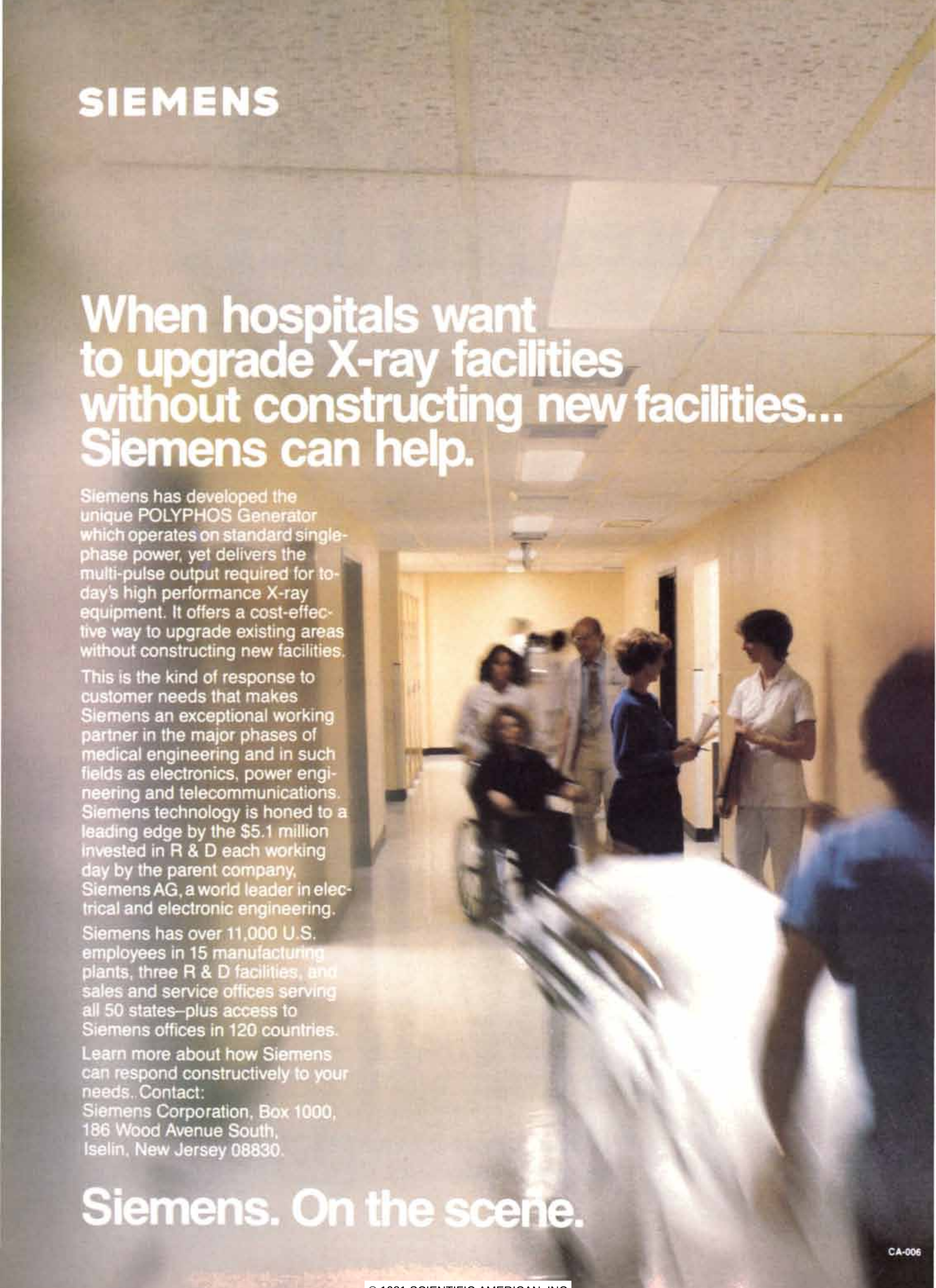
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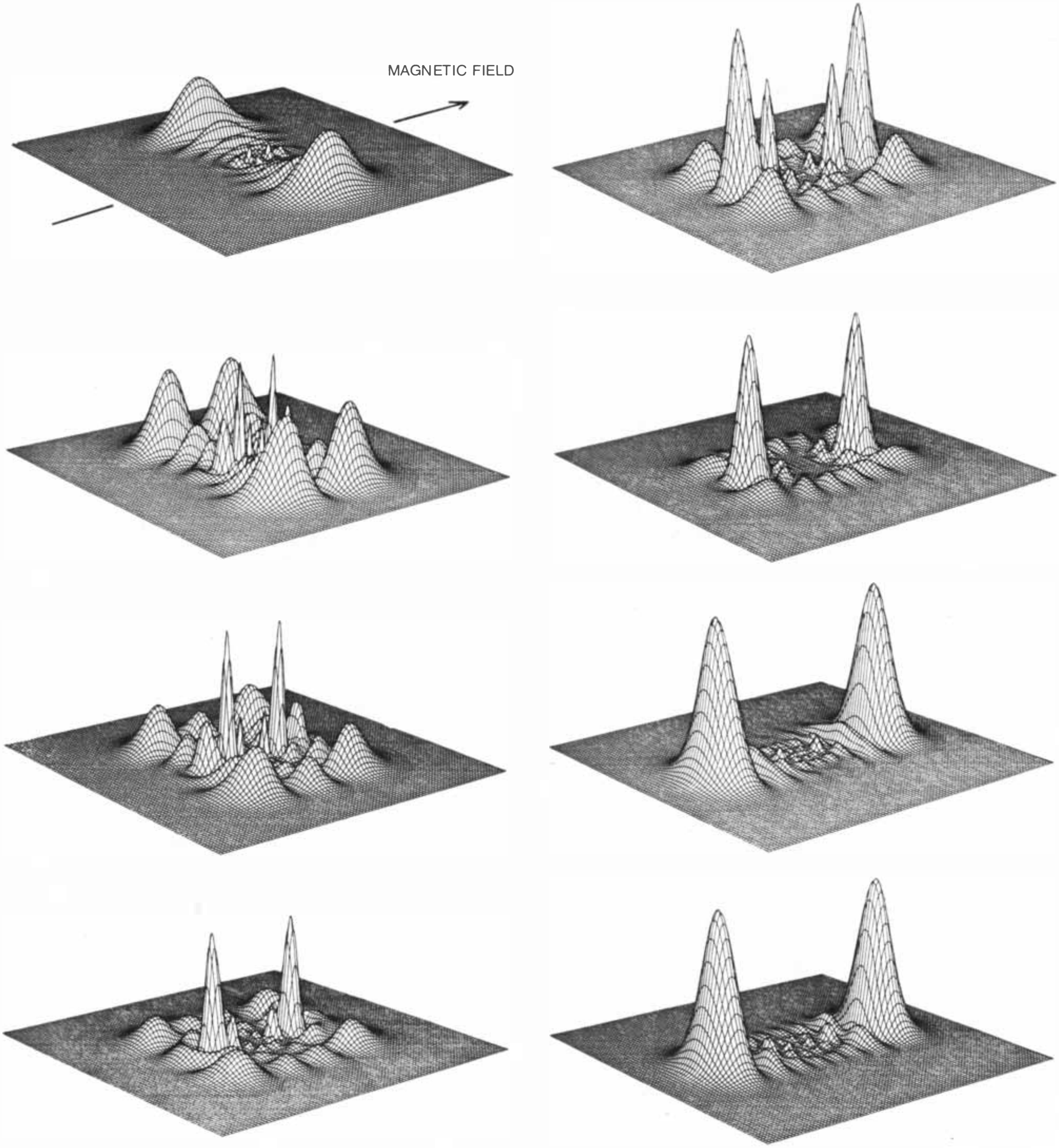
even in an arbitrarily strong field. Eventually the magnetic force exceeds the Coulomb force and the electron charge cloud assumes a new shape. Atoms under these conditions are sometimes called magnetic atoms.

Magnetic atoms are a tempting subject of study because their structure is quite different from that of ordinary atoms. They have not been studied in detail mainly because the magnetic field needed to convert a ground-state atom into a magnetic atom is more than 1,000 times as strong as the strongest field that can be created in the laboratory. Nevertheless, the subject has attracted considerable interest.

Some years ago it was discovered that when a solid-state analogue of the hydrogen atom called an exciton is put in a magnetic field, it exhibits the properties



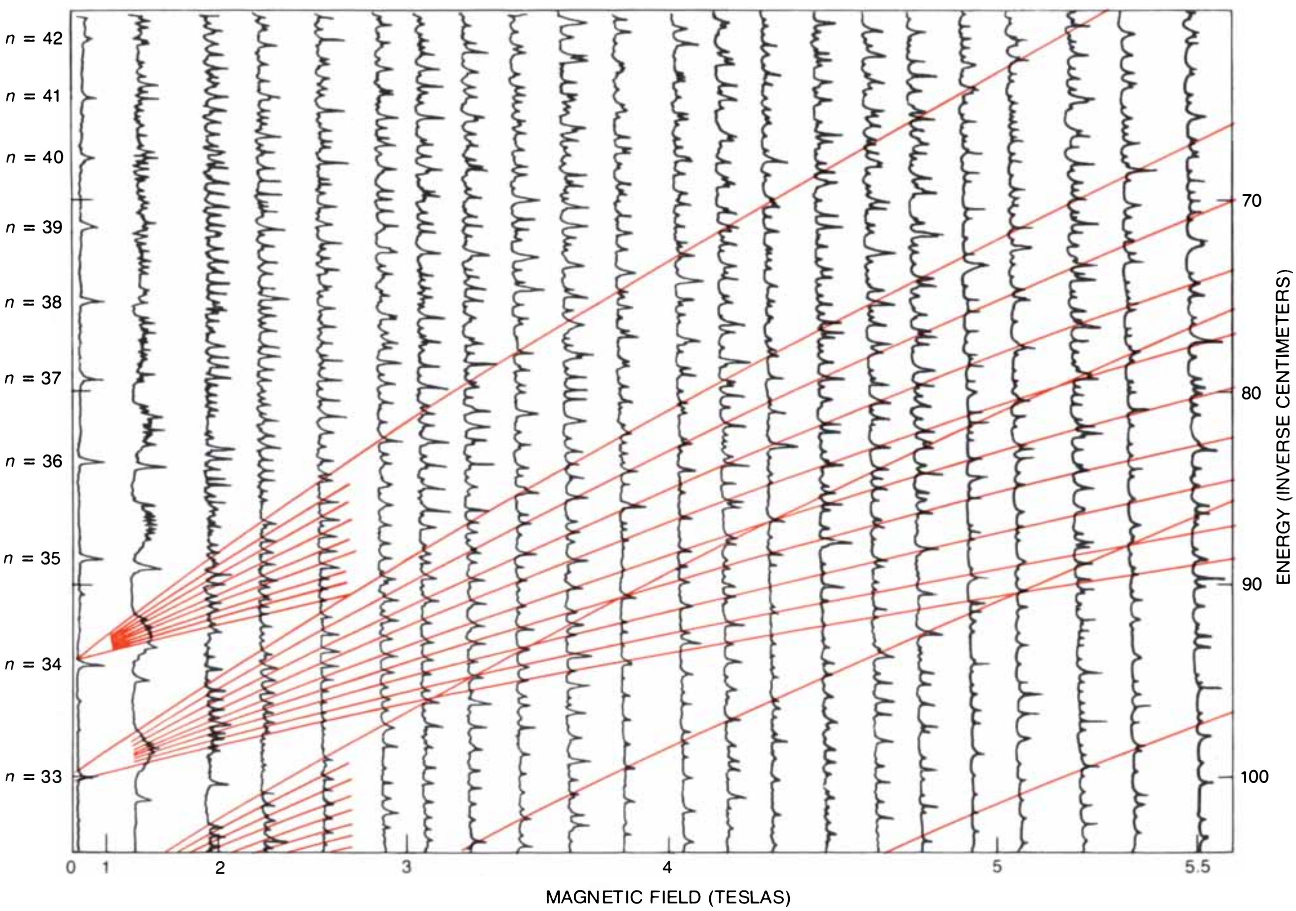
HYDROGEN IN A MAGNETIC FIELD can assume a third set of shapes for the family of $n = 8$, $m = 0$ states, where the angular momentum has a mixture of values from $l = 0$ to $l = 7$. (Other shapes for the same family of states are shown to the same scale in the illustrations on pages 132 and 140.) Little is known about the properties of atoms in a strong magnetic field. In the hydrogen atom the system is quite simple and the equations describing the system are easily stated, but no general methods for solving the equations are known. The difficulty in developing a general theory of magnetic atoms is in part that the nodal lines cannot be described by any known coordinate system. Near the proton the nodal surfaces are spherical because the Coulomb force dominates, but far from the proton the nodal surfaces are cylindrical because the magnetic force is more important. (The magnetic force is directed not toward the proton but to the axis of the field.)

of a magnetic atom. (Excitons are observed in semiconductors, where charge is carried both by electrons and by "holes," the positively charged voids formed by the absence of an electron. An exciton consists of a single electron and a single hole bound by the Coulomb force. Significantly, the exciton is an exceptionally large atom.) More recently astrophysicists realized that neutron stars (stars so dense that the electrons of their atoms have been squeezed onto the protons, neutralizing their electric charge) can have a magnetic field up to 10 million times stronger than the strongest field man can create. These discoveries have stimulated much theoretical work on the structure of magnetic atoms. Relatively little spectroscopic information has been obtained from excitons or from stellar objects with strong magnetic fields, so that much of the theory remains untested.

In the past few years magnetic atoms have been formed in the laboratory by applying a moderate magnetic field to Rydberg atoms. To understand the properties of Rydberg atoms in magnetic fields it is helpful to view atomic magnetism from the elementary perspective of the Bohr theory. Two magnetic interactions are associated with an electron in a Bohr orbit. (We shall neglect some small effects that are the result of electron spin and nuclear magnetism.) The first interaction comes from the orbital motion of the electron. An electron moving in an orbit is equivalent to a small current flowing in a loop of wire; the moving electron is a tiny electromagnet. The strength of the magnet, called the magnetic moment, is so small that even in a strong applied field the interaction is feeble. Nevertheless, the interaction can be detected: it causes the lines of the atomic spectrum to be shifted in frequency, although the shifts are so small that some skill is needed to observe them. They were first seen by the Dutch physicist Pieter Zeeman and are called the Zeeman effect.

The second magnetic interaction is a result of the law of electromagnetic induction formulated by Michael Faraday: A changing magnetic field gives rise to an electric field. If a magnetic field perpendicular to a loop of wire increases, the induced electric field causes a current to flow in the loop. The current is proportional to the area of the loop and is called the diamagnetic current. Similarly, the diamagnetic current induced in a Rydberg atom by an external magnetic field is proportional to the area of the orbit of the excited electron. Since the area of a Rydberg orbit increases as n^4, the diamagnetic interaction also increases as n^4. On the other hand, the electrostatic energy that binds the electron to the nucleus varies as $1/n^2$. Thus the ratio of the magnetic energy to the electrostatic binding energy increases as n^6. For $n = 30$ the ratio is almost a billion times larger than it is for $n = 1$. The ratio for $n = 30$ is so large that the magnetic force can no longer be thought of as a small perturbation to the electric force of the nucleus. On the contrary, it is the electric force that is the small perturbation.

The situation is actually more compli-



MAGNETIC STRUCTURE of a Rydberg atom is found by varying the strength of the applied magnetic field and recording the ionization signal. The energy-level diagram may seem chaotic, but actually it has strong regularities. The energy levels form families of smoothly varying curves. Colored lines have been drawn through several of the curves. The lines can be seen best by viewing the illustration diagonally from the lower left. The fact that the energy levels cross without any visible repulsion indicates there is an underlying symmetry in the system. The symmetry is not known, but if it could be identified, it might provide the key to a general solution to the magnetic-field problem. The data were gathered by Jarbas C. Castro and Randall G. Hulet of M.I.T. The horizontal scale has been made proportional to the square of the magnetic field because the interaction of the atom with the field is proportional to the square of the field.

cated. The magnetic force on the electron is huge when the electron moves perpendicular to the magnetic field, but it is zero when the electron moves parallel to the magnetic field. Therefore the magnetic force dominates motion in the plane perpendicular to the field, whereas in the third dimension (that is, in the direction of the field) the electric force reigns. As a result the motion is extraordinarily complicated and the present theoretical understanding of it is incomplete. It seemed to us, however, that a system as basic as an electron, a proton and a magnetic field should not be complex but simple. We decided to measure the energy levels of Rydberg atoms in strong magnetic fields in the hope that the data would lead to some new understanding.

We plotted the energy levels at numerous values of the magnetic field in much the same way as we took data in the case of an electric field. The results came as a pleasant surprise [*see illustration on opposite page*]. The energy-level map has so much structure that to the casual eye there is no rhyme or reason (as one might expect for some extremely complicated motion); actually, however, the map shows great regularities. If one views the energy levels from the proper perspective, a simple pattern emerges. Each energy level is shifted as the magnetic field increases, but the sequence of shifted levels forms a pattern of straight lines. Furthermore, the levels from different groups appear to cross freely. As we pointed out in our discussion of Stark structure, levels can cross only when there is some special symmetry in the problem. The existence of such a symmetry suggests that there is an underlying regularity in the motion. If we could identify the regularity, it should provide the key to a complete solution to the problem.

Our findings came as a surprise because no one has been able to identify a special symmetry in the magnetic-field problem, and it is widely thought that none exists. Our findings do not actually contradict this view, because we have found that the symmetry is not exact. If we examine not Rydberg states but low-lying states, the symmetry is conspicuously absent: the energy levels are disordered and the system looks discouragingly complex. The symmetry is never exact, but it becomes a better approximation as n increases. For the values of n we studied, the symmetry is exact for all practical purposes.

We are still searching for the symmetry and attempting to understand the implications of our findings. Whether or not we manage to solve the magnetic-field problem, the experiments have already taught us much. Apparently nature still has surprises in store even in the simplest systems, provided we make the effort to look.

The Sunflower Crop

In the past decade the sunflower, grown mainly for the oil in its seeds, has become a major factor in U.S. agriculture. Worldwide it ranks second only to the soybean as a source of vegetable oil

by Benjamin H. Beard

In 1716 an English patent was granted to Arthur Bunyan for a process whereby "from a certaine English seed might be expressed a good sweet oyle of great use to all persons concerned in the woollen manufacture, painters, leatherdressers, etc. . . . such oyle so to be made is to be expressed from the seed of the flowers commonly called & knowne by the name of sunflowers of all sorts, both double & single." It was the first record in Europe of a development that has now put the sunflower second only to the soybean as a source of vegetable oil and made it a major commercial crop in many countries. A measure of its increasing significance is the fact that in the U.S. the acreage planted to sunflowers rose from a few thousand in 1970 to about four million in 1980. Most of the harvest of seed went into the manufacture of what has come to be known as "sunoil," the production in 1979–80 amounting to 5.6 million tons.

The U.S.S.R. has led the world in the production of sunflower seed for many years, harvesting from 4.5 to five million hectares per year. (A hectare is 2.47 acres.) The production there has remained fairly stable since 1960. Argentina ranks second, having planted slightly more than one million hectares to sunflowers annually since 1965. The U.S., Australia and Canada follow in importance. The total amount of land given over to sunflowers in some 35 countries increased from 6.5 million hectares in the 1950's to more than 9.8 million in 1977.

The sunflower is a member of the Compositae family, which is the largest family of vascular plants, numbering among its members also asters, chrysanthemums, dahlias, lettuce, marigolds, ragweed and zinnias. The sunflower's characteristic of turning toward the sun during the day accounts for both its common name and its botanical name, *Helianthus* (from the Greek *helios,* sun, and *anthos,* flower). The heliotropic movement of the sunflower's head results from a bending of the stem and is termed nutation. After sunset the stem gradually straightens, so that by dawn the head is again facing east. When the plant reaches the stage of anthesis (the opening of the flower), nutation ceases; thereafter the head faces only eastward.

About 100 species of *Helianthus* are known, 50 of them native to North America and 15 to South America. A plant of the genus has many small flowers aggregated together on the capitulum (the botanical term for the head). The rear side of the head is covered with small green bracts called phyllaries. Above them are the familiar yellow petal-like structures, which are called rays or ray flowers. They play no role in the reproduction of the plant except insofar as they might serve as a signal for bees and other pollinating insects.

Inside the rays are many small complete flowers known as disk florets. Each floret has the potential to develop an achene, or seed, which is botanically a fruit. A mature plant has from 250 to 1,500 seeds arrayed in a spiral pattern in the large circular structure the rays surround.

The commercial importance of the sunflower arises from the fact that in many places the plant produces more oil per unit of land than any other crop. The yield of seed from modern cultivars of the sunflower can exceed 3,000 kilograms per hectare, although the average is usually less than 1,500. About 40 percent of the seed (in plants that are grown for oil) is oil of high quality and without toxic constituents.

The earliest published description of the sunflower is in a herbal of 1568 by Rembert Dodoens. Although it and later herbals cite Peru or Central America as the plant's place of origin, modern authorities believe the common sunflowers are native to North America, probably to what is now the U.S. Southwest. Archaeological explorations at several sites in North America have found evidence of sunflowers, some of which grew wild and some of which were cultivated. Evidence of cultivation dates from as early as 3000 B.C. at sites in Arizona and New Mexico.

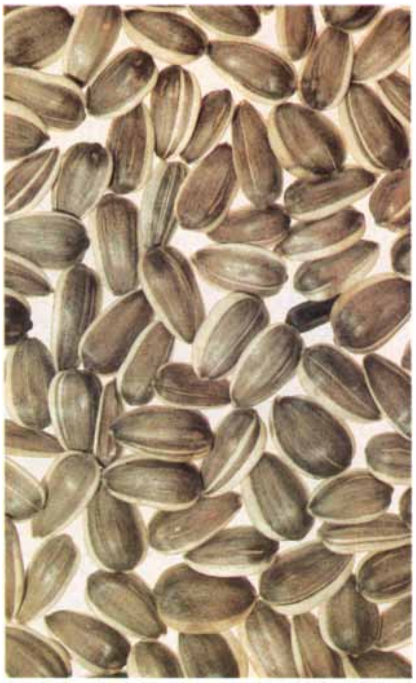
Several of the early European explorers in North America recorded the use of sunflower seeds by the native inhabitants. Some tribes were reported to gather the seeds from wild plants, others to cultivate the flower along with other crops. Even before the arrival of the Europeans the American Indian had recognized the value of the single-stem plant (the crop type), which has a larger head and larger seeds than the branched-stem ornamental plant, and had preserved it. In effect the Indians did the first breeding of sunflowers, perhaps unwittingly or perhaps by a form of selection based on the preferences of different tribes.

Sunflower seeds were taken to Europe during the latter part of the 16th century (they are recorded as having first reached Spain in 1581) and were grown in gardens as a novelty or as an ornamental plant. Gradually the practice spread across Europe to Russia. There the sunflower soon became an important crop, perhaps in part because of a church restriction that forbade the consumption during Lent of nearly all foods rich in oil. The sunflower had been introduced too recently to be included on the list.

As the crop became more important in Russia efforts at deliberate selection were begun. By 1880 the "Mammoth

FIELD OF SUNFLOWERS on a farm near Fargo, N.D., appears in the photograph on the opposite page. At this stage, from 30 to 45 days short of maturity, the flowers face eastward all day. Before the flower appears the head follows the sun during the day, turning by a bending of the stem so that at sunset it is facing west. During the night the stem straightens so that by dawn the head is again facing east. The farming techniques for growing sunflowers on this large scale resemble those for growing corn. The crop is ordinarily harvested with a combine.

SUNFLOWER IN ANTHESIS, the flowering stage, displays two types of flowers: ray flowers, which are the yellow structures, and disk florets, which are the small objects surrounded by the ray flowers. The achenes, or seeds, of the plant develop in the disk florets. Here the disk florets are at different stages of development; the ones near the center have not opened.



SUNFLOWER SEEDS are produced in two types, the oilseed (*left*) and the confectionery or nonoil seed (*right*). Oilseeds are black and have an oil content of 40 percent or more. The residue after the oil has been extracted is a protein meal that serves as a food for animals. The nonoil seeds are gray or white with black, gray or brown stripes. The oil content is about 30 percent. The larger nonoil seeds serve as snack food, the smaller ones as a feed for birds and poultry.

Russian" cultivar was being offered for sale by seed companies in the U.S. In the 1890's more cultivars from Russia were introduced in the U.S. and the sunflower attracted a good deal of attention, but it did not become a significant factor in agriculture.

Nevertheless, plant breeders began as long ago as the 1890's to seek improvements in the sunflower. The first attempt was directed at developing resistance to a moth (*Homoeosoma nebullela*) that in the larval stage eats growing sunflower seeds. The major advances achieved by the first breeding programs were toward earlier maturity and an increase in the oil content of the seed.

Later a particularly successful breeding program was developed by V. S. Pustovoit in the U.S.S.R. In 1940 the average oil content of most sunflower seeds grown commercially was about 33 percent; by 1965 Pustovoit was testing strains with an oil content of more than 50 percent. He had also developed sunflowers resistant to broomrape, a parasitic herb that grows on the roots of plants. He obtained the resistant trait from wild species.

In 1942 Eric D. Putt of the Canadian Department of Agriculture developed a shorter, early-maturing cultivar named Sunrise. It was successful as an oilseed crop from 1943 to 1948, but then unfavorable weather and an attack of rust discouraged farmers from planting the crop. By 1955 Putt and Waldemar E. Sackston had discovered sources of rust resistance in some wild species. The development of new cultivars incorporating the resistance to rust made the crop attractive again.

Through the 1950's and 1960's even the best cultivars were extremely variable. For example, different plants in the same field would reach anthesis over a period of from three to five weeks. The harvest had to be delayed until most of the seeds had matured, and the delay was often costly. Moreover, if measures were needed to protect the crop against insects or disease, more than one application of the material was usually needed, which added to the cost of production.

Putt had shown that seeds from cross-pollinations between two different homozygous lines gave rise to plants with yields as much as 25 percent higher than those from openly pollinated cultivars in which the pollen can come from any source. Alternate forms of a particular gene are termed alleles. A pair of allelic genes, one from each parent, is described in genetic shorthand as, for example, *Aa*. A plant with two identical genes, *AA* or *aa*, is homozygous for that allele; if the genes differ, *Aa*, the plant is heterozygous. Putt's observations, together with the successes that had been achieved with hybrid corn, indicated

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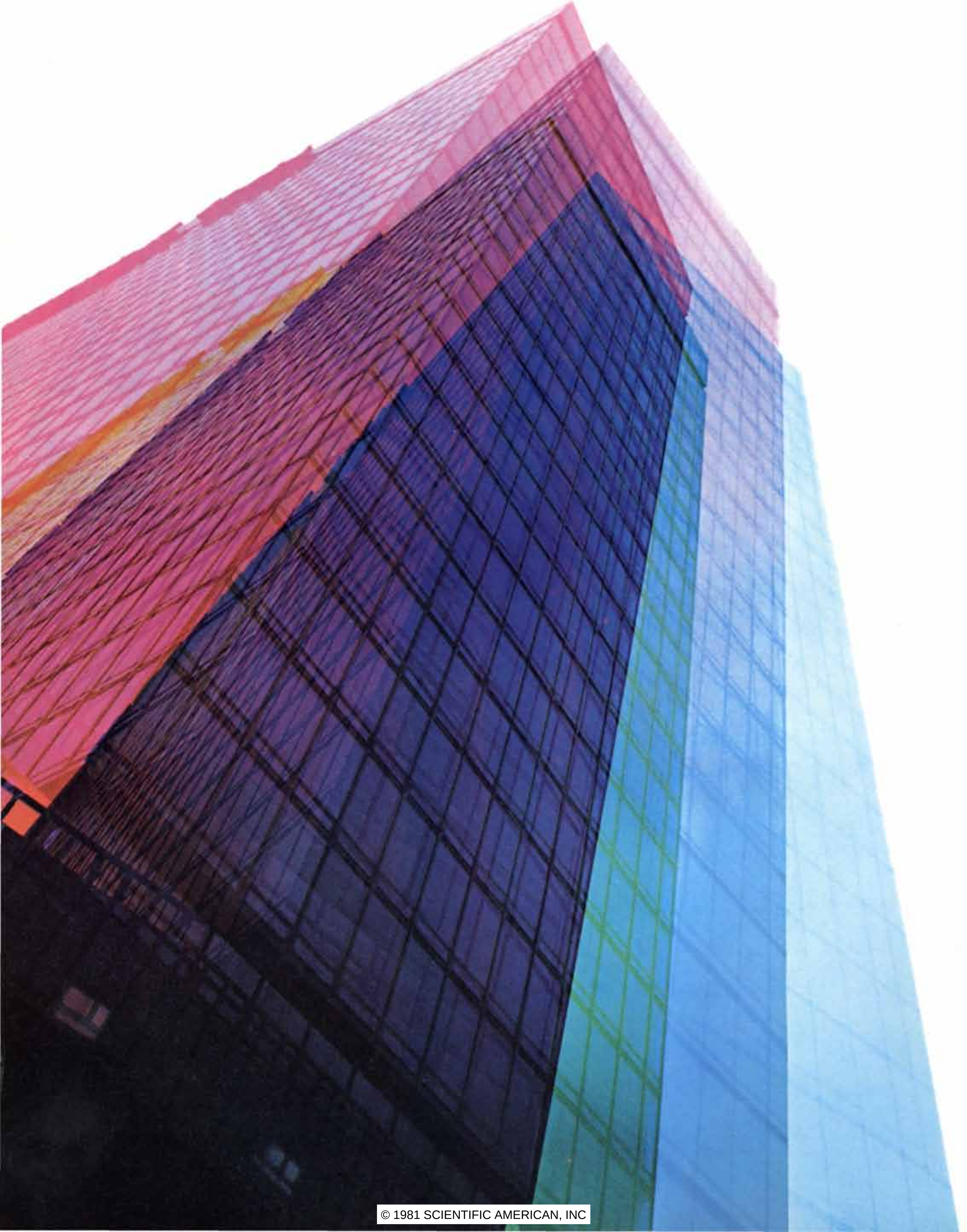
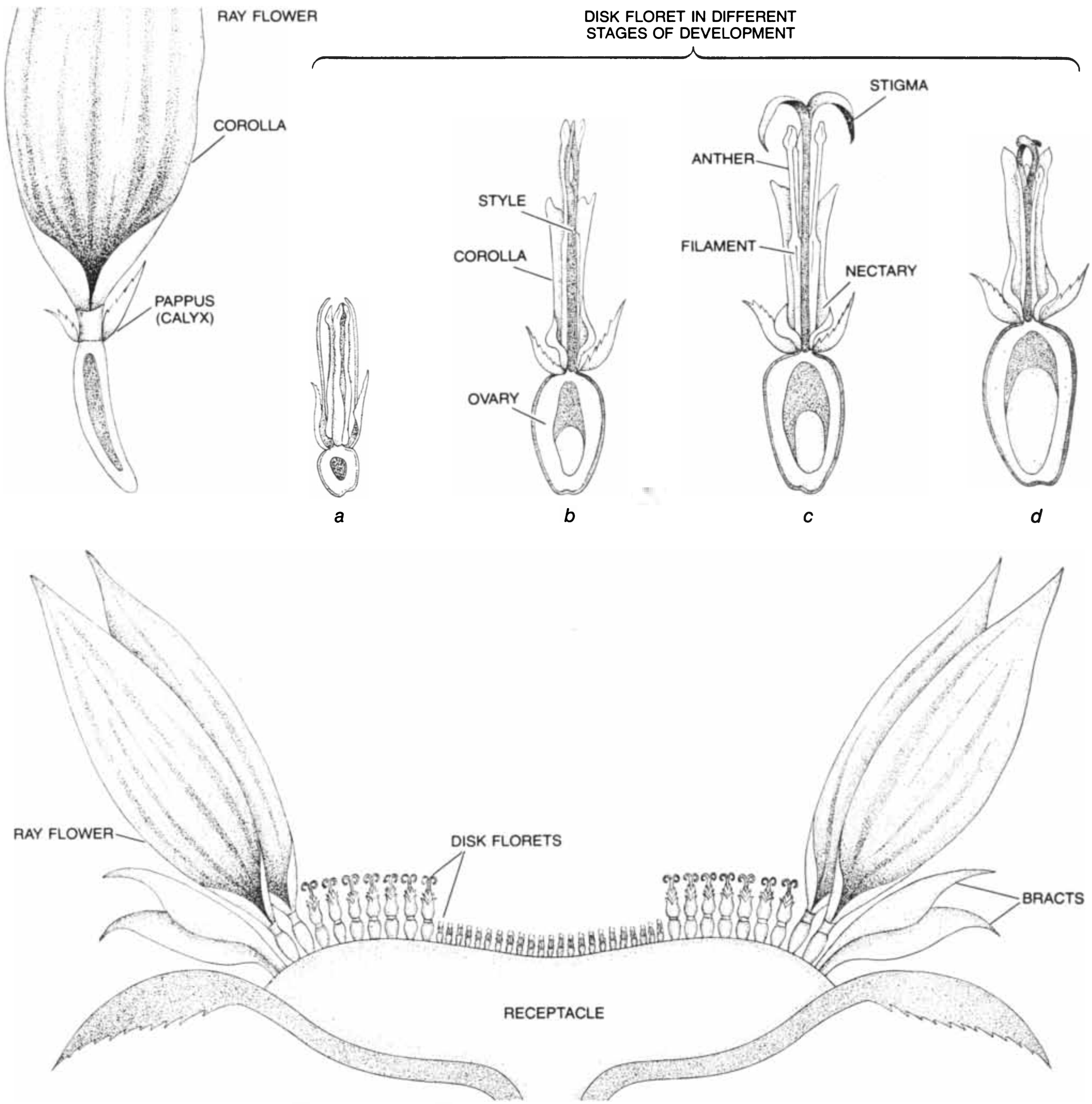


that the best way to increase uniformity and improve yield in the sunflower was to develop a system to economically produce hybrid seed.

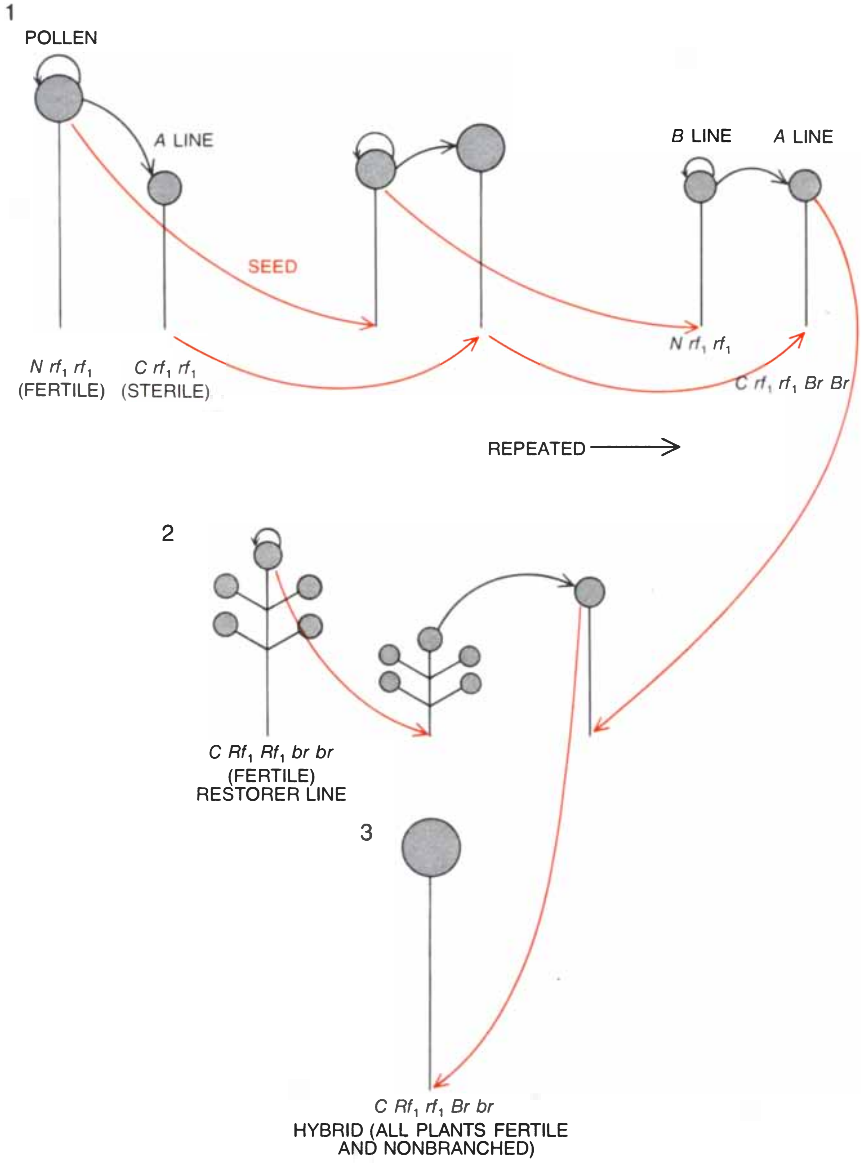
In order to obtain hybrid seed the breeder must eliminate selfing and sibbing, that is, self-pollination and pollination by a brother or sister plant. The aim is to achieve a "female" line that is capable of accepting pollen from another line (cross-pollination) but does not reproduce its own line. The most straightforward way is by emasculation, which entails eliminating the pollen-bearing organ. This process usually requires a great deal of hand labor. Another technique is to achieve male sterility by various means.

Several workers, including Murray L. Kinman of the U.S. Department of Agriculture, tried to develop a hybrid system based on the self-incompatibility of sunflower lines. Self-incompatibility is a characteristic of certain plants that prevents the pollen from functioning on stigmas of the same plant. The idea was to develop a line in which all plants would have this characteristic, so that selfing or sibbing within the line would be prevented. If two such lines were planted in an isolated field, all the seed on all the plants would be hybrid. The only functioning pollen on any plant would be from plants of the other line. The method did result in a high percentage of hybrid seed, but it also failed to fully prevent selfing. The seed therefore did not meet the legal requirements for the hybrid label.

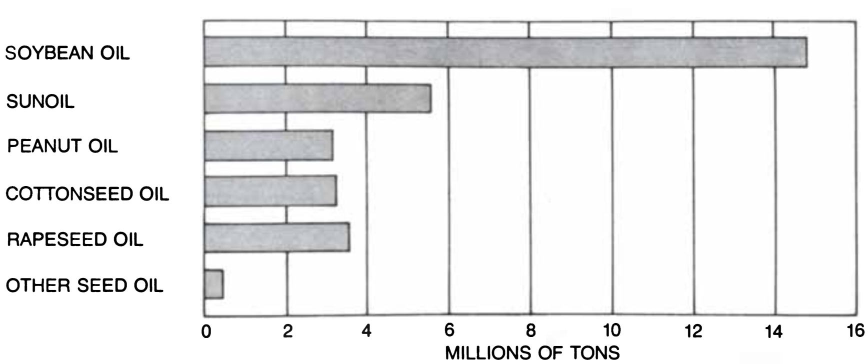
A. V. Vranceanu in Romania was able to obtain hybrid seed through a genetic male-sterile system, that is, by working with plants that lacked the male function because of the action of a particular gene. In this system one inbred line that



HEAD OF SUNFLOWER is portrayed in cross section, with details of a ray flower and disk florets above it. The disk florets are shown at four stages of development: not yet open (*a*), when pollen is shed (*b*), a day or two later (*c*) and about two days after pollination (*d*).



HYBRID SEED, which results in sunflower crops with superior qualities, is grown mainly by the cytoplasmic male-sterile system, a term reflecting the fact that a factor in the cytoplasm of the plant cells gives rise to male sterility (*C* rf_1 rf_1). Plants with normal cytoplasm (*N*) or with the capability of restoring the male function (Rf_1) also figure in the process. The conversion of normal plants into cytoplasmic male-sterile inbred ones begins (*1*) with a normal line that is bred to a male-sterile line. The process is repeated for four or more generations to give rise to an inbred *A* line that is cytoplasmic male-sterile and carries a gene for nonbranching (*Br Br*). Plants grown from its seeds and the seeds of a restorer line are crossed (*2*) in an isolated field, and the resulting seed yields hybrids (*3*) that are all fertile and nonbranched.



RANK OF "SUNOIL" among the major sources of vegetable oils is shown according to the estimated data for the 1979–80 crop year. "Other" seed oils include safflower, sesame and corn.

serves as the female is planted in the seed-production field. The line segregates in the ratio of one male-fertile plant to one male-sterile plant. In Vranceanu's system the fertility allele was closely linked to a dominant gene that caused the formation of the reddish pigment anthocyanin in the seedling plants. This marking agent made it easy to remove the fertile plants before they shed any pollen, leaving only sterile plants for seed production. The method requires additional labor, however, and increases the cost of the hybrid seed. Moreover, some plants that lack anthocyanin are nonetheless fertile, and so the effectiveness of the system is diminished.

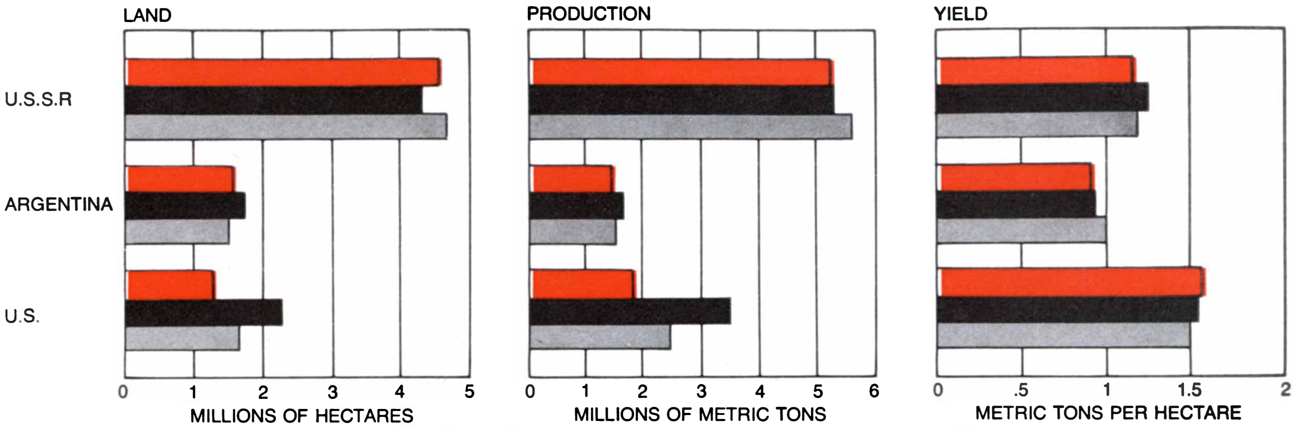
A fair amount of hybrid seed was produced by this method and the system was employed commercially in many countries in the 1970's. In most places, however, it has been abandoned in favor of the cytoplasmic male-sterile system. Here a factor in the cytoplasm of the cells of the plants gives rise in the next generation to plants that are all male-sterile.

Cytoplasmic male sterility had been reported in the sunflower as early as 1958, but the plants always had some fertile progeny as a result of pollination from ordinary fertile lines. In 1969 Patrice Leclercq in France reported finding cytoplasmic male sterility in the progeny of a cross of *Helianthus petiolaris* Nutt. and *H. annuus*. The seed was distributed to plant breeders around the world and has been found to be satisfactory for the commercial production of hybrid sunflower seeds. Kinman and others provided the missing link by discovering the necessary fertility-restoring lines in about 1970.

The first hybrid seeds from this system became available in 1972. By 1976 about 80 percent of the sunflower crop in the U.S. came from hybrid seed. The best hybrids yielded up to 20 percent more than the best openly pollinated cultivars. As a result of the higher yield, together with the higher oil content of the seeds and the uniform attainment of maturity, the crop could be grown with modern farming techniques.

The first hybrids were susceptible to a number of diseases. Gerhardt N. Fick and David E. Zimmer of the U.S. Department of Agriculture found dominant genes for resistance to many of the diseases. As a result the losses due to disease have been greatly reduced.

Fields given over to the production of hybrid seeds are planted in various patterns according to what equipment is available. A common pattern when the planting machine is designed to plant six or eight rows at a time is to fill one hopper at one end with seed of the restorer male line and the other five or seven hoppers with the seed of the sterile inbred. After two passes by the machine



SUNFLOWER FARMING is done on an extensive scale, as is indicated by these charts reflecting the activity of the three major producing countries in 1978 (*color*), 1979 (*black*) and 1980 (*gray*). A hectare is 2.47 acres and a metric ton is 2,205 pounds. The figures for production and yield refer to the amount of seed harvested annually. A metric ton of high-quality oilseed will yield about 880 pounds of sunoil.

the planting pattern is then two rows of the male line and 10 or 14 rows of the sterile female. The distribution of pollen to the female plants is almost entirely dependent on bees and other insect pollinators.

The production of superior hybrid seed depends not only on the use of high-quality seed from special inbred lines but also on the adequate isolation of the seed-production field from other sunflowers, including wild ones. Because the pollen is carried by insects and is viable for a long time the determination of the proper isolation is difficult. At present the Association of Official Seed Certifying Agencies requires an isolation of .8 kilometer (almost half a mile). Some states have different requirements. Producers in California have agreed to an isolation of from 3.2 to 6.4 kilometers, depending on the type of sunflower plants in the vicinity that might contaminate the hybrid seed. Isolation can also be achieved by time, that is, by growing plants that come to anthesis at different times. Here a separation of anthesis by one month is regarded as adequate.

The modern farmer grows sunflowers in much the same way as he does corn. The seeds are planted with a corn planter and harvested with a combine. Weeds are controlled by herbicides and cultivation. The crop is physiologically mature when the back of the heads turns yellow and the phyllaries turn brown. To make harvesting with a combine possible the plants are sometimes dried with a desiccant, or they are harvested after the first frost, which usually results in the same degree of drying.

The standard machine for harvesting sunflowers is a combine of the kind designed for harvesting cereal grains, but a picker-sheller designed for corn is also satisfactory. For harvesting sunflowers a combine must be fitted with pans (large metal trays) that pass between the rows of plants and catch the seeds that fall from the head before the cutter bar reaches the plant. The trays also guide the stem into the cutter bar so that only the head and a short piece of the stalk are cut off. The head and stalk then go into the threshing cylinder of the machine. All modern combines can be adjusted to thresh and clean sunflower seeds with little loss from shattering and cracking. Before storage the seeds are dried.

Two types of sunflower are grown commercially. The confectionery type, which is also sometimes called the nonoil sunflower, grows as plants that reach a height of from eight to 12 feet and mature late. The seeds are large and have an oil content of about 30 percent. The color of the hull is usually gray or white with varying amounts of dark gray, brown or black stripes.

The other kind of sunflower grown commercially is the oilseed type. Its plants usually reach a height of from six to eight feet and mature fairly early. Their seeds are black and have an oil content exceeding 40 percent. It would be easy enough through breeding to make all sunflower seeds look alike. The differences in coloration between oil-variety seeds and confectionery seeds are imposed by breeders to help in distinguishing the varieties for marketing purposes. It is also believed people who eat the confectionery seeds as snacks prefer seeds with light gray or white stripes.

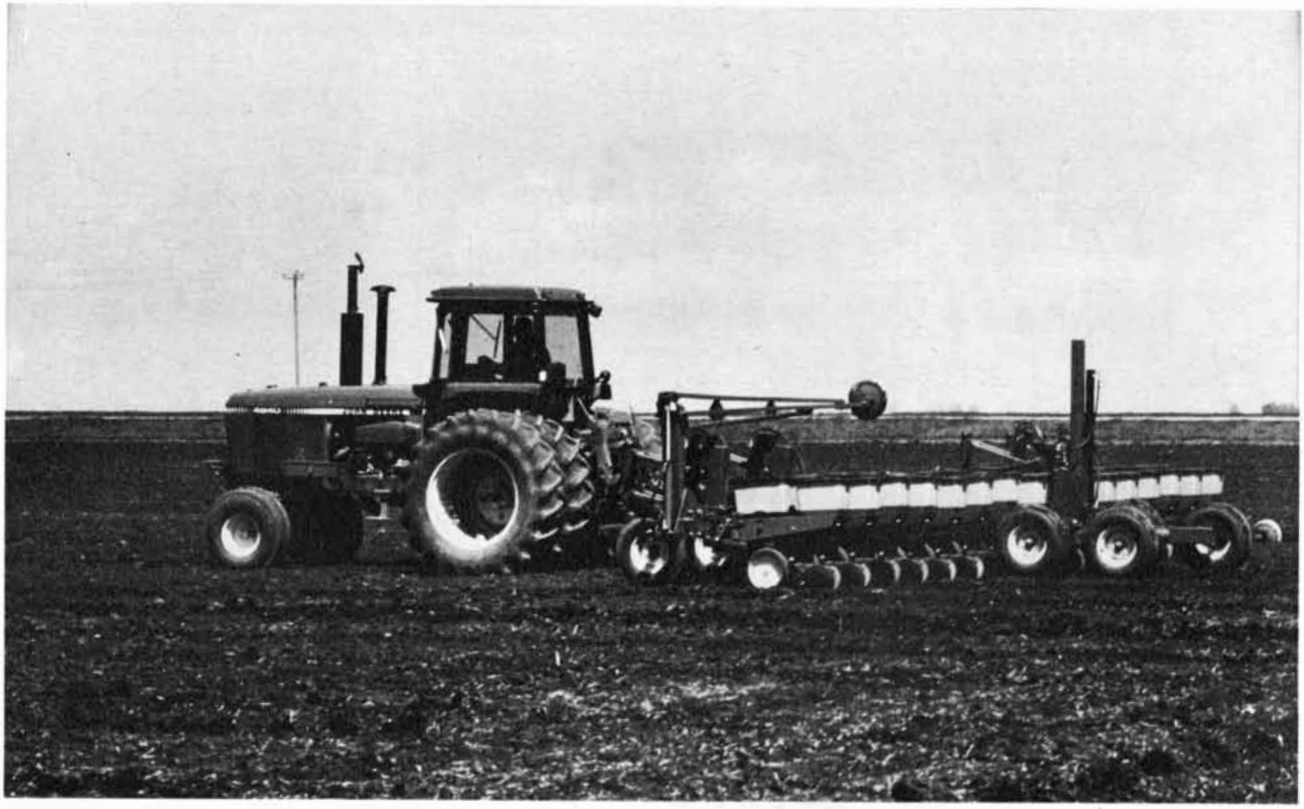
The two types of sunflower are grown in similar ways except for the spacing of plants. A premium is paid for large seeds of the nonoil type. Since seed size is correlated with head size and head size is dependent on the spacing of plants, nonoil sunflowers are grown at a rate of from 40,000 to 45,000 plants per acre, whereas the rate for oilseed plants is about 85,000.

Until 1970 most of the sunflowers grown in the U.S. were of the confectionery type. The size of that crop has changed little over the years. After the harvest the largest seeds are segregated so that they can be roasted and sold as snack food, sometimes in the hulls and sometimes with the kernels separated from the hulls. The smaller seeds are sold as bird feed or as an ingredient in poultry feed.

Oilseed sunflowers began to become significant as a commercial crop in the U.S. in the late 1960's. Their production rose swiftly during the 1970's, stimulated by a growing market in Europe and by improvements in the plant that increased the oil content of the seed and so made it possible for the farmer to receive more income from a crop of a given size. Harvested seeds are crushed and the oil is extracted by pressing and by the use of solvents. The result is not only a vegetable oil of high quality but also a crude meal that is high in protein.

Sunoil, which is high in polyunsaturated fatty acids and low in saturated ones, serves as other vegetable oils do in a variety of foods (margarine, salad dressing and mayonnaise among them) and as a cooking oil. It is also employed in paints and varnishes and in the manufacture of plastics. Recent tests on a small scale indicate that the crude oil will work as a fuel in diesel engines. It could present starting problems if it was the only fuel, but mixtures of diesel oil with from 25 to 50 percent sunoil were satisfactory in all tests. At present sunoil costs slightly more than diesel oil, but the difference is diminishing. If the yield of oil per hectare can be increased by improvements in the plant and in growing practices, sunoil might become a renewable source of high-quality fuel for diesel engines.

The crude meal, which has a protein content of from 38 to 40 percent, is a valuable protein supplement for cattle and sheep. It can be made with less crude fiber if the hulls are removed from the seeds before the oil is extracted. The



SUNFLOWER SEEDS ARE PLANTED on a farm with a multiple-row planting machine of the type also employed in planting corn and cotton. Sunflower rows are spaced from 30 to 42 inches apart. It takes from 90 to 120 days after planting for the crop to grow to maturity.

SUNFLOWER CROP IS HARVESTED by a combine. The combine has been adapted to sunflowers by the addition of large metal trays that pass between the rows to catch seeds that fall off prematurely. The trays also guide each stalk into the cutter, which cuts off the head of the sunflower. Next the machine threshes and cleans the seeds. Harvesting is usually done after the first frost or after the application of a desiccant to the plants, since the combine works best when the mature sunflower plants have become fairly dry and brittle.

meal that results from this procedure has a protein content of from 40 to 42 percent and is suitable for poultry and swine. By careful screening to remove all the hulls a meal can be made that is 51 or 52 percent protein. Sunflower meal can also be processed so that it is suitable as human food, but little of it has been put to this use so far.

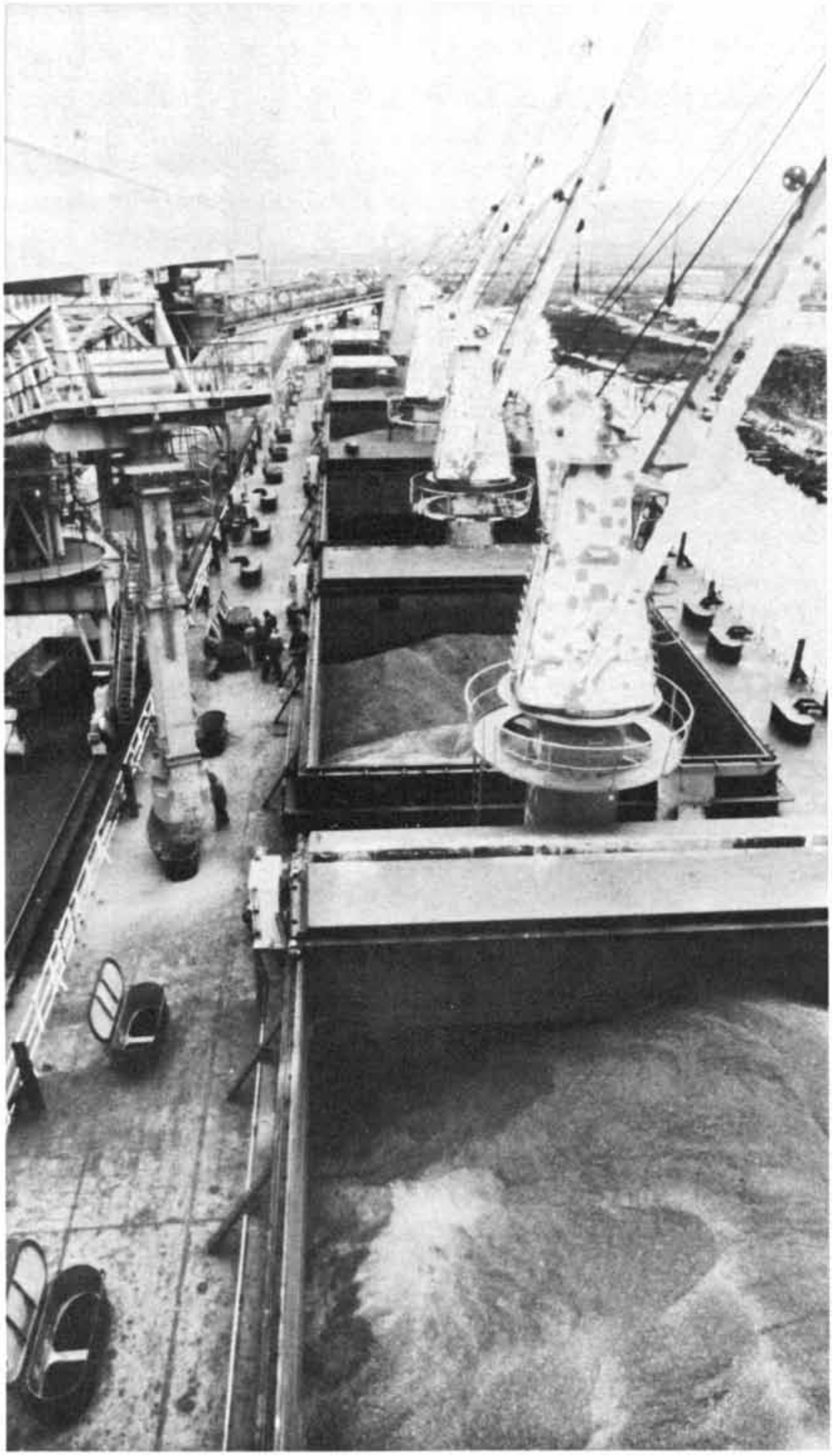
The hulls from the dehulling and the heads after the removal of the seeds can be processed to yield pectin, the gelling agent in jelly and jam. Hulls have also been employed as a roughage ingredient in feedlots for cattle. Some processing plants have burned hulls as the only source of energy for running the plant. Hulls have also been compressed into "logs" for fireplaces. On a small scale sunflower stalks have been shredded to make a fiberboard for construction purposes.

It is also possible to harvest and process the entire sunflower plant for silage. In the 1930's and 1940's this practice was followed to some extent in the U.S., but it has been discontinued because other silages such as corn have higher yields per unit of land. Sunflower silage is nearly equal to corn silage in nutrient value and is still made widely in Europe.

Various other species of *Helianthus* are cultivated on a smaller scale. Probably the best-known among them is the Jerusalem artichoke (*H. tuberosus* L.), a perennial native to North America that is grown both as an ornamental plant and for its fleshy tubers, which people cook and eat. The flavor is said to resemble that of the artichoke. Other species grown mainly as ornamentals are *H. argophyllus*, the silver-leaf sunflower; *H. maximiliani*, Maximilian's sunflower; *H. salicifolius*, the willow-leaf sunflower; *H. debilis*, the beach or cucumber-leaf sunflower, depending on the subspecies; *H. petiolaris*, the prairie sunflower; *H. rigidus*, the stiff sunflower, and *H. atrorubens*, the dark-eye sunflower.

Species of sunflower that grow wild have been important sources of pest resistance and have contributed valuable germ plasm for various other desirable genetic traits. The potential of wild-sunflower species in plant breeding, however, has not been fully exploited. Moreover, modern living practices are decreasing the wild habitats (woods, prairies and other undisturbed places) of many of these potentially valuable species. One species of *Helianthus* (*H. nuttallii* ssp. *parishii*) is now extinct, and at least one other (*H. exilis*) is on the endangered-species list. A few institutions maintain collections of sunflower species for breeding purposes, but no plans for a permanent collection have been made. Unfortunately the maintenance of a sunflower collection not only is difficult and expensive but also requires special environmental conditions. A permanent collection of all wild species, with many accessions of each one from widely scattered locations, should be established with enough money and appropriate facilities for continuous and permanent maintenance.

It seems likely that the acreage planted to sunflowers in the U.S. will continue to grow, probably with fluctuations, until it reaches about 10 million acres. I envision the price of sunoil as being close to but slightly higher than the price of soybean oil; up to now the price of sunoil has ranged from almost that of soybean oil to as much as 10 cents per pound higher. If the demand for a highly unsaturated oil as a constituent of the human diet continues to rise, sunoil will be the best and most economical vegetable oil available to meet it.



MERCHANT SHIP *Menhir* is loaded with sunflower seeds in Duluth, Minn. This load was sent to Europe, a major market for the U.S. crop. The ship's capacity is one million bushels.

Chinese Building Standards in the 12th Century

In the Sung period the emperors promulgated a code for all public buildings. It standardized features of the traditional architecture that were brilliantly adapted to Chinese environmental conditions

by Else Glahn

For several thousand years all public buildings in China, whatever their size, were built to a standard plan. Their setting was a walled enclosure oriented with respect to north and south. The most important building in the enclosure was placed at the center of the enclosure's north-south axis; the building faced south and its long axis was on an east-west line. Secondary buildings to each side of the main structure faced east and west, enclosing an open courtyard. The walls of the structures were what are now called curtain walls, bearing no load other than the weight of their own material, and in the main building the south wall was usually the only one with windows and entrances. Its massive tiled roof, characteristically curved in both front and side view, ended in broad overhanging eaves that shielded the entire structure from summer sunlight but let the rays of the low winter sun strike the south wall. The weight of the roof was ultimately supported by a series of wood columns, but poised between each roof beam and column head were elaborate sets of blocks and corbeled bracket arms, in a variety of standardized shapes and sizes and fitted together in mortise-and-tenon fashion. The columns in turn were not fixed in the foundation of the structure but rested on wood plinths and stone footings supported by heavy flagstones.

Some Chinese buildings erected nearly 1,000 years ago, in the ninth and 10th centuries A.D., still survive. The design proved equally suited to a variety of climates, ranging from the severe cold of winters in northern China and Manchuria to the tropical heat of summers in southern China. Moreover, the structures that have survived over so many centuries are proof that the standard plan gave protection against two kinds of natural calamities: the great windstorms that could ravage coastal areas and the earthquakes that might strike anywhere. This durability derived from a number of interrelated factors.

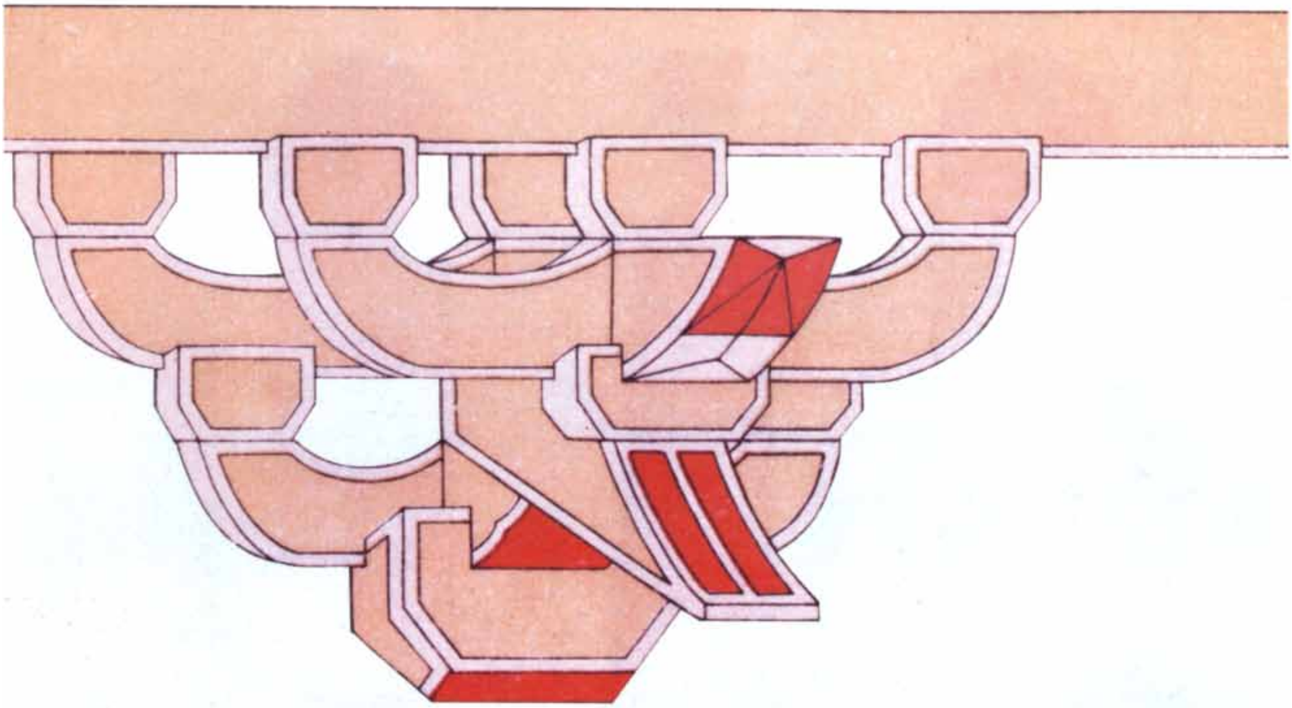
The first of these factors is that pound for pound white cedar (the wood most commonly used for construction in traditional Chinese buildings) has about four times the tensile strength of steel, and its resistance to compression is about six times that of concrete. A second factor is that a timber frame incorporating many joints and few nails is surprisingly flexible. Therefore when the frame is shaken by the oscillations of an earthquake, the internal friction of the various joints has a damping effect. The building will sway, but because its period of vibration is considerably longer than that of the earthquake it will not resonate. The sets of blocks and bracket arms and the ties in the roof frame brake horizontal movements. And because the feet of the columns are not anchored to the foundation any horizontal movement that does take place does not result in a breaking strain.

On the other hand, a building with deep eaves supported by unanchored columns would normally be vulnerable to the high winds of a typhoon. The heavy dead load of the traditional Chinese roof, however, counterbalances the forces of the wind. In Western construction the weight of a tile roof is calculated at 100 kilograms per square meter. The weight of a traditional Chinese tile roof ranges from 280 kilograms per square meter in a small structure to 400 kilograms in a large one.

The strong aesthetic appeal of the curved Chinese roof has been the subject of much speculation among art historians. The massive structure seems to float weightlessly in the air. The commonest view is that the striking curvature of the roof was a conscious imitation of the natural sweep of a tent. Actually it may have been intended to withstand windstorm stresses. For example, the concave sweep from the ridgepole to the eaves calls for a series of short rafters rather than long straight ones, which increases the flexibility of the roof frame. Moreover, the corbeled bracket sets that help to damp earthquake oscillations also uniformly distribute the weight of the wide eaves, making those parts of the structure less vulnerable. Finally, the slope of the roof provides efficient drainage for storm waters. All in all, what has seemed to be a matter of aesthetics could have originated in purely rational considerations.

How do we know that public construction was standardized in ancient China? By a fortunate chance. In the first, or northern, half of the Sung Dynasty (A.D. 960–1125), when the imperial capital was Kaifeng in Honan province, the emperor Che Tsung reinstituted in A.D. 1093 a period of reform that had been interrupted after the death of his father, the emperor Shen Tsung (1068–1085). Among Che Tsung's actions was an order, delivered to the imperial department of construction in December of 1097, to revise an earlier construction guide titled *Ying-tsao fa-shih,* or "Building Standards." This work, begun two decades earlier and finished in 1091, had never been printed.

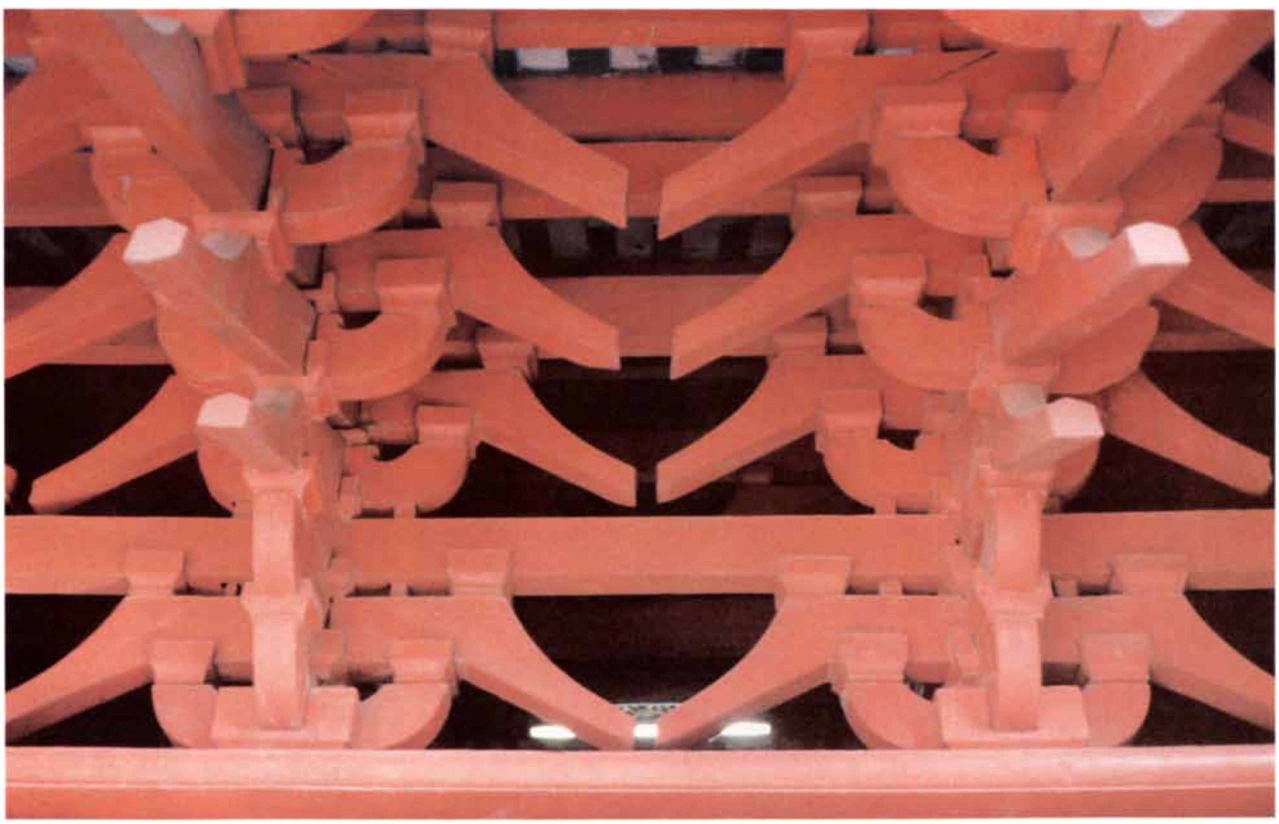
The task of producing a new manuscript fell to one of the two assistants in the department of construction, one Li Chieh. It took Li three years to complete the job; the manuscript was presented to the throne in 1100, the last year of Che Tsung's reign. The emperor's successor, his younger brother Hui Tsung, gave Li permission to print the revision in 1103. The 1,078-page work, consisting of a preface and a foreword by Li and 34 chapters, was reproduced by wood engraving, one block bearing 11 lines of 22 characters per manuscript page of text. The illustrations, an important part of the work, appeared only in the last five chapters.



SIMPLE DECORATION of a bracket-arm set, based on only three colors, is one of several that are specified in the Sung Dynasty construction code, *Ying-tsao fa-shih,* assembled by Li Chieh at the end of the 11th century. The arm set at an angle to the rest is a "lever arm."

FLORID DECORATION of an identical bracket-arm set, making use of numerous colors, is another of those specified in Li Chieh's code. Many elaborate painted decorations were included in the code, but the use of expensive materials such as gold leaf was shunned.

THREE-TIER ROOF of a temple gateway near Canton is supported by 12 columns. The load of each roof component is distributed to the columns by means of a series of corbeled sets of bracket arms, joined in mortise-and-tenon fashion, that support the roof timbers and tiles. The weight of the tile roofing in such a traditional Chinese structure ranges from 280 to 400 kilograms per square meter.



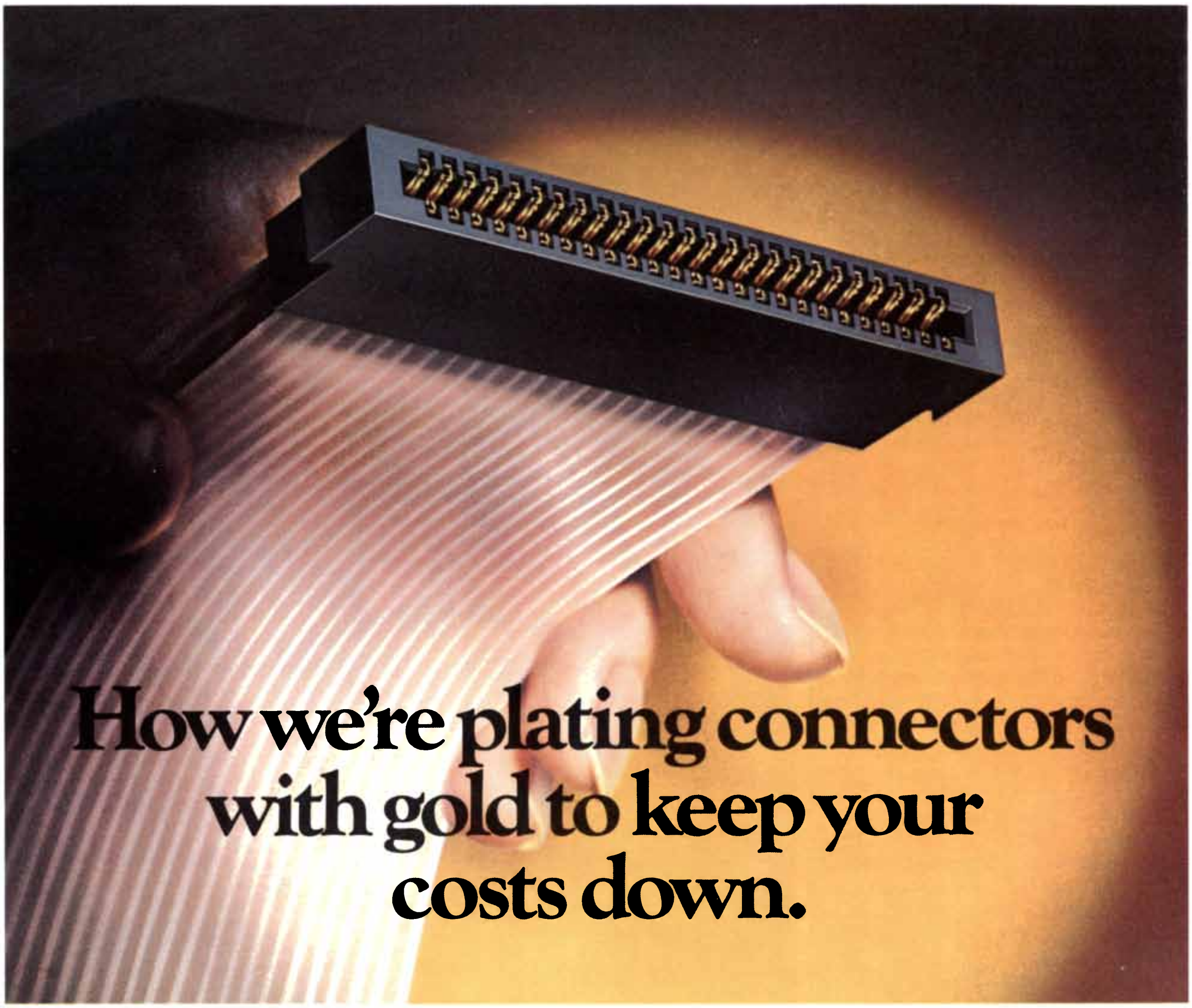
BRACKET-ARM ARRAY, seen from below, rises repetitively to support the roof beams of another building in the same temple complex near Canton. The structures were built in the 19th century, but the bracket-arm system can be traced back more than 2,000 years.

No printed copies of Li's great work survive today. A coalition of tribes from Manchuria, mistakenly considered by the emperor to be Sung allies, entered northern China a few years after the book was printed, and in 1122 their leader declared himself emperor. Three years later he sacked the Sung capital and took captive all the members of the imperial court except one junior prince. The refugee Sung prince became emperor and reestablished the dynasty in the south, selecting Hangchow in Chekiang province as the new capital. The emperor, who wanted to develop the capital, known then as Lin-an, in a standardized manner, ordered the preparation of a second edition of Li's "Building Standards." That edition was printed in 1145, nearly two decades after the Sung shift from the north to the south. In the years that followed all but three chapters and nine pages of the second edition were also lost. With these exceptions what have come down to us are copies of copies of manuscript copies of the 1145 edition.

The 1091 manuscript that Li replaced encompassed much that had been traditional in China. For example, the first two chapters of Li's 1103 edition, which list a number of technical building terms, cite as their authority texts from the time of the Han Dynasty (202 B.C.–A.D.220) and even of the Chou Dynasty (1000–256 B.C.).

Citations such as Li's apart, evidence of the antiquity of Chinese construction concepts is given by archaeological findings. For example, the use of wood columns that rest on stone supports is a practice at least as old as Neolithic times in China, dating to about 5000 B.C. Nearer to the present, some bronze vessels of the Warring States period (475–221 B.C.) bear depictions of buildings with bracket sets interposed between the head of columns and the roof frame. Similar depictions are found on stone slabs in tombs of Han Dynasty times, and so one may conclude that the practice was well established more than a millennium before Li's time. Li's book is nonetheless the oldest standardized building manual known, and the context of its preparation is significant.

The emperor Shen Tsung was served for many years by one of China's more remarkable statesmen, Wang Anshih (1021–1086). Wang undertook to reform the empire's tangled economics and in particular to reduce the seriously bloated imperial expenditures. Up to that time most government revenues consisted of payments in kind or in services: *kung,* a term usually translated as corvée, the French word for unpaid labor. The periods of free service were donated to such public-works projects as canal maintenance, road construction and the erection of public buildings.



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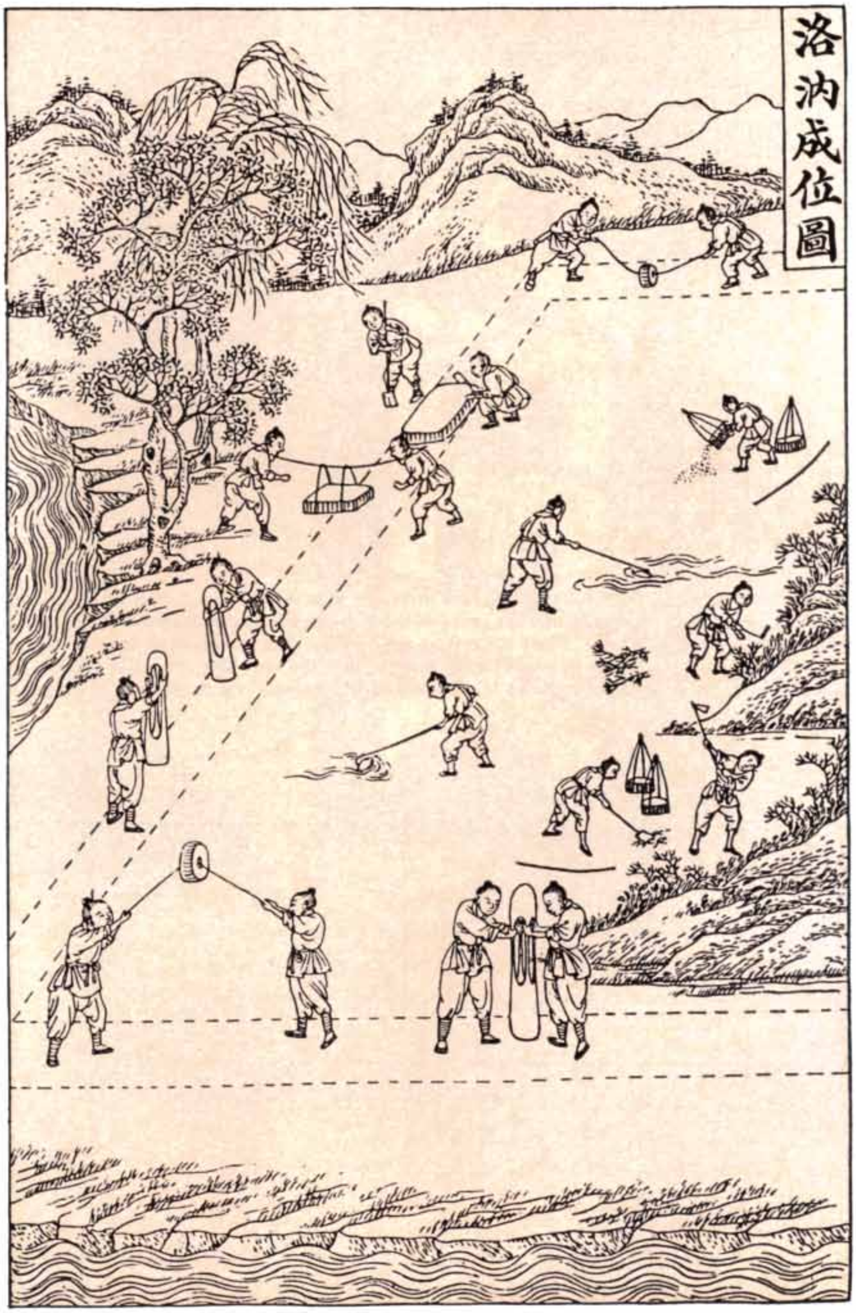
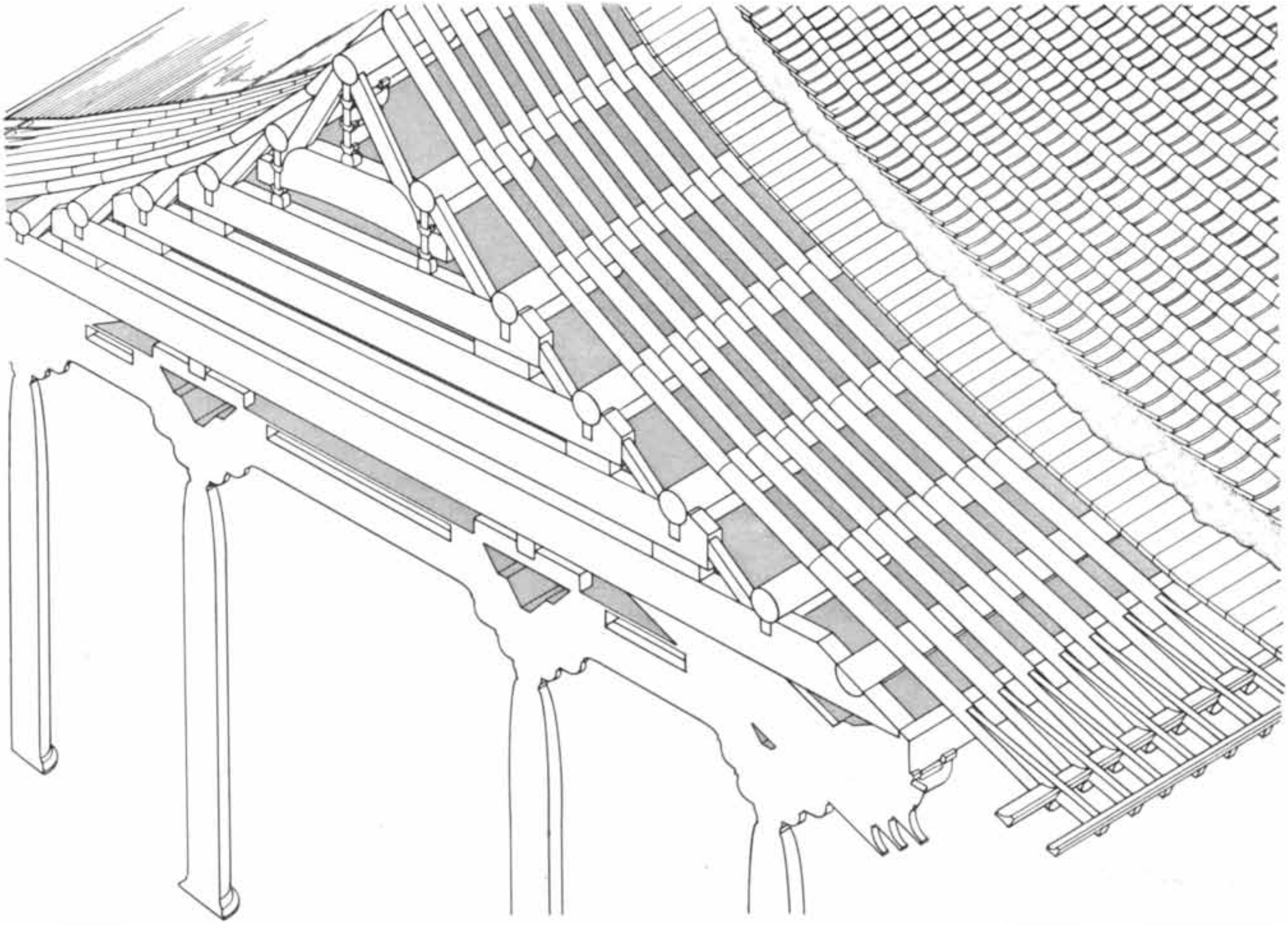
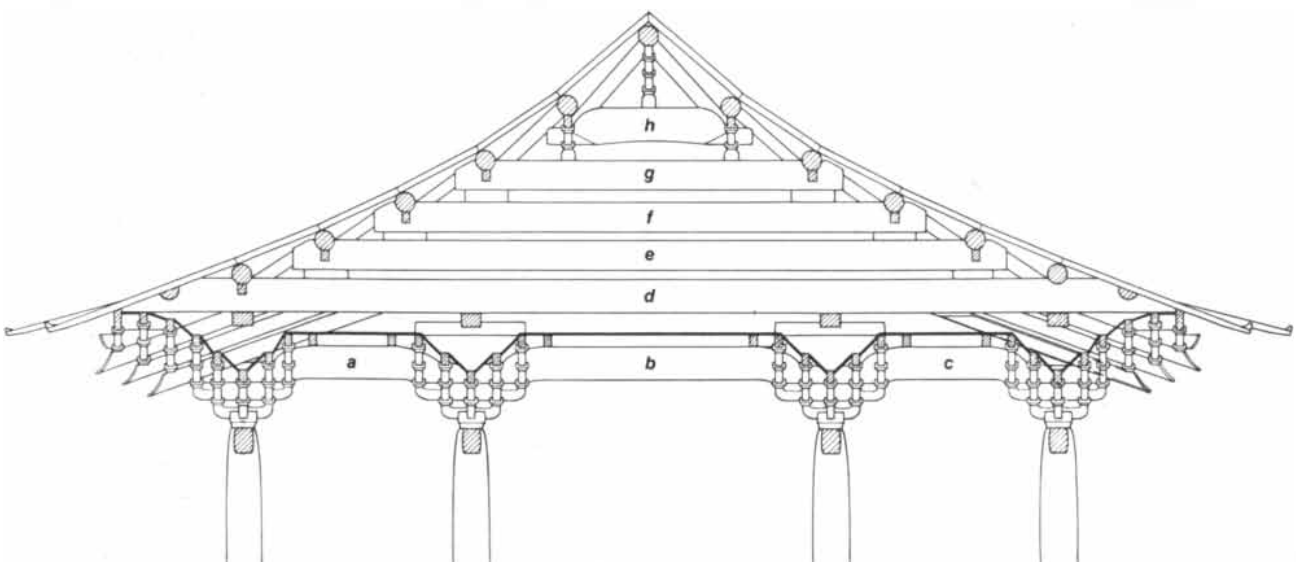
Wang's reforms, which encountered vigorous conservative opposition and caused a spate of mandarin resignations, included a 50 percent cut in the size of the standing army, a raise in pay for lower bureaucrats (so that they could afford to give up graft and extortion), price controls on grain and a ceiling on the interest that could be charged on agricultural loans. Another change was the replacement of the old corvée system with tax assessments payable in cash. The revenue generated by this change enabled Wang to pay wages to craftsmen who were employed on government projects. Included among these were carpenters, masons and other builders, and the "Building Standards" manuscript of 1091 may have been compiled at Wang's urging as a means of monitoring the expenditures of the department of construction. Certainly



SITE PREPARATION for a major structure is shown in this illustration. The first task was to line up the ground plan so that the long axis of the structure ran on an east-west line. This placed the focus of the building in the "direction of superiority," the north, opposite the entrance at the center of the south side. A footing of rammed earth and compacted rubble in alternating layers was prepared with one-man tampers and heavy stone rings. The footing was then covered with flagstones. Other workers leveled high spots, using the earth to fill in hollows.



TRADITIONAL ROOF STRUCTURE is shown in this cutaway view of one end of a public building. The pillars and bracket-arm sets that support the bottom roof beams are shown only in outline. Five progressively shorter beams rise above the sets and support the roof purlins: timbers that extend the length of the building. A series of short rafters, each no longer than the distance between two purlins, establishes the curve of the roof, which is accentuated by a final false eave. When the rafters are in place, they are planked over. Mortar is then spread on the planking and the roof tiles are set in place. The roof is shown in elevation in the illustration at the bottom of the page.



SIX TIERS OF BEAMS are supported by four bracket-arm sets. The three bottom beams (*a, b, c*) and the top one (*h*) are curved in "moon" fashion. Two small bracket-arm sets support the top beam and the highest purlins; a third set supports the ridgepole. One of the lever arms that help to support the overhanging roof eave is outlined in color at the right. The load on a purlin counterbalances the eave load.

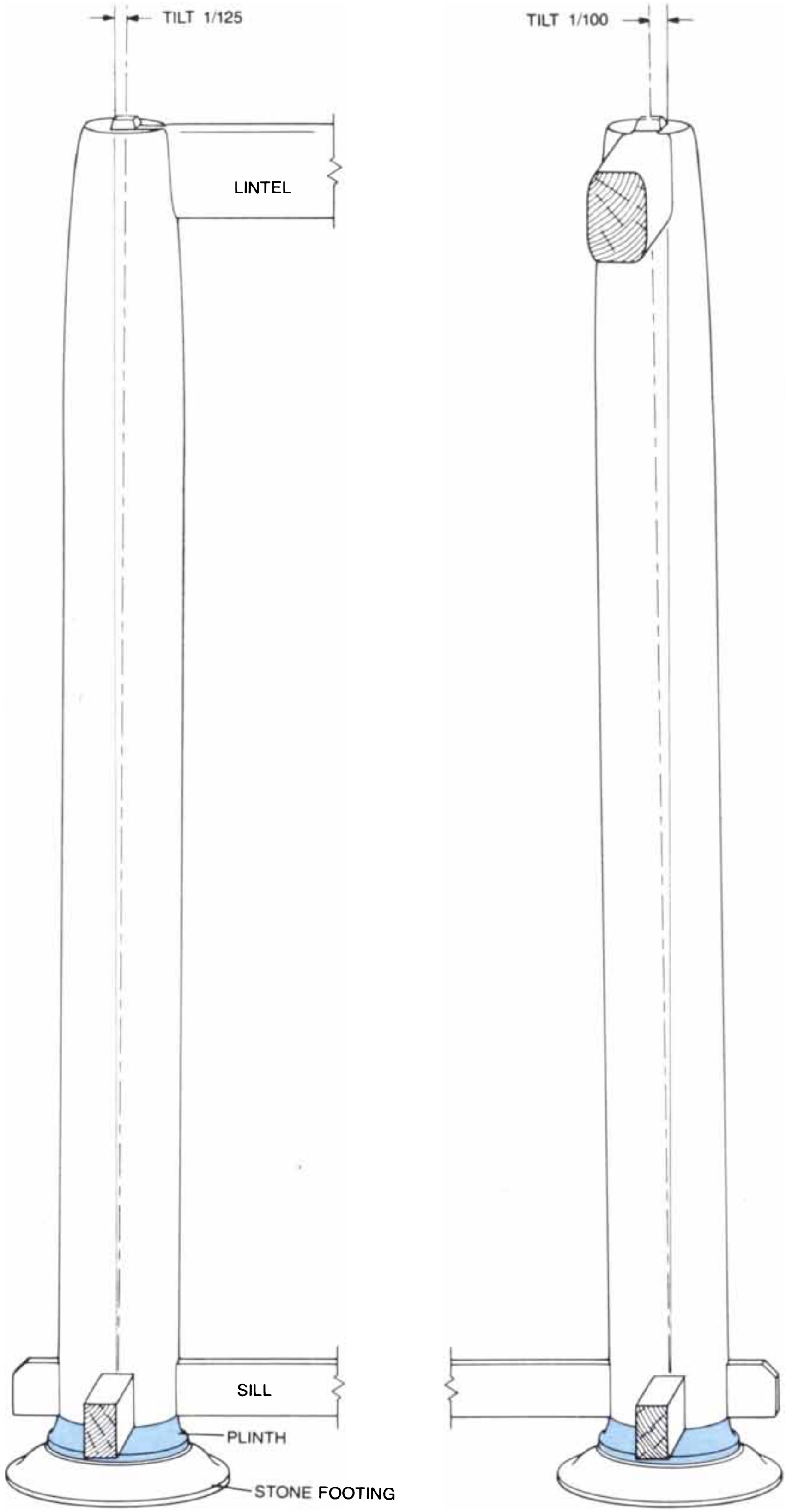
the version that has come down to us echoes the reformer's demand for the control of imperial spending. It includes instructions for calculating, down to the smallest detail, the exact amount of labor and materials required to erect all kinds of public buildings. The text was not intended to teach the principles of architecture to members of the department staff but to instruct them in managing construction accounts. After all, the craftsmen employed by the department knew perfectly well how to build.

In any event, the man whose version of "Building Standards" was printed in 1103, Li Chieh, became a considerable figure in Kaifeng. His father, a high official in Shantung province, had sent the young man to the imperial court in 1085, where he was given a largely honorary post as one of the officials charged with ceremonial offerings to heaven and earth. In 1092 Li joined the department of construction as one of the two registrars, officials of the lowest rank. By 1096 he had advanced to the next rank, that of assistant, and soon thereafter he began his compilation. In 1102, after the manuscript was completed but before it was printed, he was promoted to vice-director. He supervised the construction of several important public buildings in Kaifeng and was made director of the department in 1105. He died, full of honors, in 1110 at the age of 45.

As the text of Li's fourth chapter makes plain, public buildings then fell into one or another of eight categories, depending on their size. Grade 1 buildings had 10 to 12 columns along the east-west axis and therefore had nine to 11 bays, or spaces between columns. Grade 2 buildings had six to eight columns and five to seven bays. Grade 3 buildings had four to six columns and three to five bays. Included in Grade 3 were lesser structures called *ting-tang,* residences with eight columns and seven bays. Li's list concludes with Grade 8 structures, which are defined as "canopy ceilings," elaborate vaulted structures that were raised over a ruler's or an official's throne or a deity's image.

It seems logical to assume that one reason for defining the eight categories was to allow the stockpiling of structural timbers precut to the size required for each category. If building timbers are not to swell when the weather is damp and not to shrink when it is dry, they should be seasoned for at least two years. Cutting them to size before seasoning means a minimum waste of materials and labor. Whether or not such was the case, Li's text certainly specified precise dimensions.

The sizes are expressed in *ts'ai,* or "units," which are subdivided into *fen,* or "sections," 15 to a standard unit. Using two bracket-arm elements as examples, Li specifies their cross-sectional

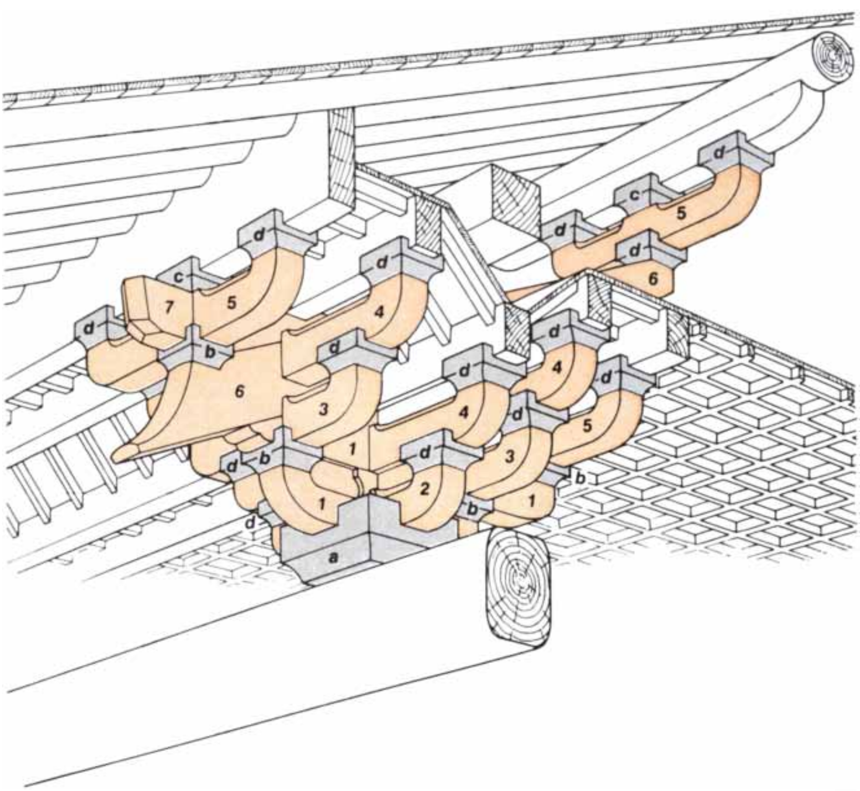


TRADITIONAL COLUMNS rested on a wood plinth (*color*) supported by a stone base, but the columns were not anchored to a foundation. The perimeter columns were stabilized at the base by timber sills that ran from one column to the next and at the top by heavy lintels. They gained additional stability by being tilted slightly inward; the tilt was 1/125th of the height of the column on the north-south axis and 1/100th of the height on the east-west axis. A cap block was mortised to the top of each column; the lowest bracket arms nested into the block.

dimensions in each of the eight building categories. The proportions of the bracket arm remain the same in all the categories, but the actual dimensions get progressively smaller. The proportion is as three is to two but is expressed in "sections." Hence the cross-sectional dimensions of a "standard" bracket arm are 10 sections from side to side and 15 sections (one standard unit) from top to bottom. When a stiffening member of the same proportion but smaller size is joined to the top of a standard bracket arm, the combined top-to-bottom measurement constitutes a "full" unit (21 sections) as follows. The stiffener cross-sectional dimensions are four sections from side to side and six sections from top to bottom. Six sections plus 15 sections equals a depth of 21 sections, or one full unit.

Although Li uses the cross-sectional depth of a standard and a stiffened bracket to define standard and full units, the same notation (in units and sections) is used to describe almost all the measurements that appear in "Building Standards." Let us see how this kind of proportional notation converts into actual measurements. The following examples are for the eight classes of buildings defined in Chapter 4. "Of the rules whenever a building is raised," Li wrote, "in every case the timber dimension [*ts'ai*] is basic. There are eight *ts'ai,* and they are used according to the size of the building. Grade 1: The depth of the bracket is nine inches and the width is six inches; one section is .6 inch. Grade 2: The depth is 8.25 inches and the width is 5.5 inches; one section is .55 inch. Grade 3: The depth is 7.5 inches and the width is five inches; one section is .5 inch." So the specifications continued, with the bracket cross-sectional dimensions gradually diminishing, until for Grade 8 ("canopy ceilings") the bracket depth and width are only half those of Grade 1 (4.5 inches by three inches), and a section measures .3 inch.

The Sung "inch" was a little more than 1.3 English inches (3.2 centimeters). Hence the Grade 1 bracket dimensions are approximately 11 by 7.5 English inches, and the size of a section is .75 inch (respectively 28.8 by 19.2 centimeters and 1.9 centimeters). The Grade 8 dimensions are half these. The virtue of having units and sections rather than specific measurements in feet and inches, of course, is that proportional descriptions are applicable to a structure of any kind and size.

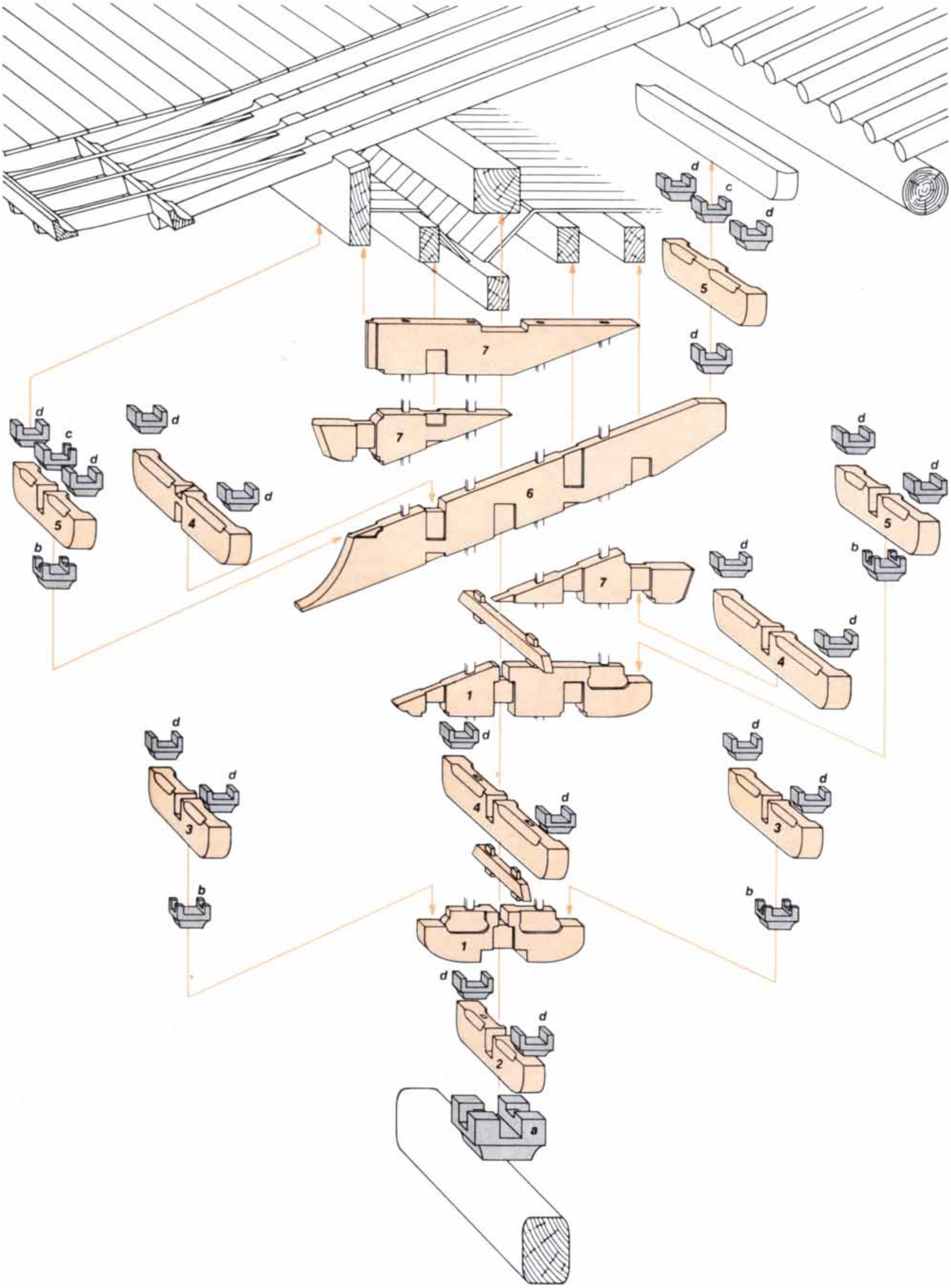


BRACKET-ARM SET typical of those placed on lintels includes a visible total of 20 blocks (*gray*), one wedge and 11 arms (*color*) as follows (in upward order, starting at the bottom): one cap block (*a*), a petal arm (*1*), one wall arm (*2*), two connection blocks (*b*) and two oval arms (*3*), two small blocks (*d*) and two long arms (*4*), seven more small blocks (*d*) and three regular arms (*5*). These arms support a total of five more small blocks (*d*), two center blocks (*c*) and one lever arm (*6*), with a connection block (*b*) at its end, resting on a petal arm (*1*). The end of the wedge above the lever arm (*6*) forms a "nose." Blocks on the front and rear regular arms, which rest on the lever arm, support an eave board at the left and a cushioned purlin at the right.

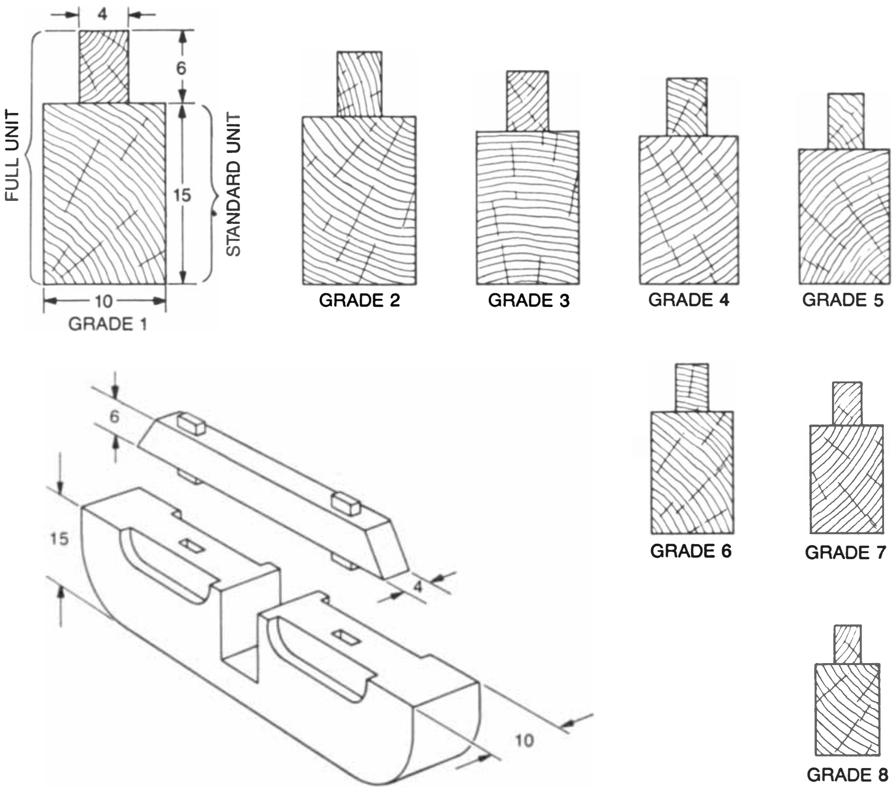
How was a traditional Chinese building erected? Before the work could start it was necessary to determine the cardinal points at the construction site. As we have seen, this was so that the front of the main building in the enclosure would face south. Although this orientation is advantageous for summer shade and winter sunlight, the basic motive seems to have been different. Evidently it was to ensure a northern position (north being the direction of superiority) for the main element of the structure. That element was the central bay. In a temple the central bay was where the deity was placed; in a palace it was where the emperor was enthroned, and in a government office it was where the senior official was seated.

Once the long axis of the enclosure was established on a north-south line it was time to grade the building site by cutting down the high spots and filling in the hollows until the area was level. A footing for the outside columns was made at the perimeter of the building site by alternating layers of rammed earth with layers of gravel and broken brick. The earth was beaten down with a barrel-like wood tamper; the gravel and brick were compacted by teams of two men who tossed a millstone-like weight up in the air at the end of ropes and let it fall. The footing was then covered with stone flagging. Stone bases for each column, twice the diameter of the column, were placed on the flagstones. The central bay of the structure was wider than the bays to each side. The location of the interior columns was not necessarily related to the positioning of the perimeter columns. Where the interior columns stood depended on the function of the building; for example, in a temple they were closer to the north side than the south, in order to leave more space in front of the deity for worshipers.

On the stone bases of the columns were placed wood plinths 10 sections high. The columns, three units in diameter in a Grade 1 building and up to two units in diameter in a smaller structure, were pegged to the plinths with a dowel. If there was rot at the interface of the wood and the stone, only the plinth had to be replaced. The perimeter columns were stabilized at the base by sills that ran around all four sides of the structure. The ratio of width to depth in the cross section of a sill timber was the usual two to three and the depth was 17 or 18 sections. The columns were also stabilized at the top by means of heavy lintels with the same two-to-three ratio of width to depth. The lintels were



EXPLODED VIEW of the bracket-arm set shown in the illustration on the opposite page shows the complexity of the mortise-and-tenon joins used by traditional Chinese woodworkers. The corbeled sets included dowels but were stabilized mainly by the weight of the roof.



EIGHT TS'AI, or "timber dimensions," were fundamental to traditional Chinese building. They are shown as schematic cross sections of a series of wall-arm-and-stiffener combinations of diminishing size. An actual combination is shown in perspective at the bottom left. The proportions of all the arms and stiffeners is the same: a ratio of breadth to depth of two to three. As the Grade 1 example at the top left shows, however, the ratio was regarded as being 10 to 15 for arms and four to six for stiffeners. The reason is that one "standard" proportional unit consisted of 15 *fen,* or "sections," which were assigned different dimensional values in each of the eight grades. Hence the section value in Grade 1, the heaviest construction, was .6 Sung inch (1.92 centimeters). The section value in each subsequent grade was a smaller fraction of a Sung inch. Thus the lightest construction, Grade 8, had a section value one-half that of Grade 1: .3 Sung inch. Most of the timber dimensions that are specified in the Sung construction code are expressed as so many "standard" units and fifteenths thereof or as "full" (21-section) units.

30 sections deep. If a colonnade was planned for the façade or for all around the building, a second set of lintels, slightly shallower than the first, was installed lower on the columns to support the inner edge of the colonnade roof. The upper third of each column tapered gradually. At a point four sections from the top the column was trimmed to fit the bottom opening of a bearing block that would support a bracket set.

The east-west columns were not equal in height; the two at the sides of the central bay were the shortest and the corner columns were the longest. The others were progressively longer the farther they stood from the central bay, so that a line connecting the tops of the columns took the form of a gentle upward curve. In a Grade 1 building the corner columns were 10 inches higher than the central pair, in a Grade 2 building the difference was eight inches, and so forth. The upward curve from the center to the corner emphasized the front-view curve of the roof. In addition the perimeter columns did not stand exactly upright but leaned slightly toward the center of the structure. Along the east-west axis of the building the angle of tilt was 1.65 degrees away from the vertical; along the north-south axis the angle was 1.3 degrees. This inward lean must have further stabilized the unanchored columns.

Once the top of each column had received its bearing block the time had come to mount the bracket sets that would support the roof timbers. Li devotes more space in "Building Standards" to these mortise-and-tenon structures than he does to all the other building timbers—plinths, columns, sills, lintels, beams, purlins, rafters and the like—combined. As a generalization, a bracket set might include two or more of the following structural members: a basic support, the bearing block, which could take any one of four forms; a bracket arm, which could take any one of five forms; a lever arm, either long or short, and perhaps a "nose." In bracket sets on the top of a column the nose was the end of a beam. In bracket sets with lever arms, however, the nose was merely decorative.

Consider first the different kinds of bearing blocks. The largest were called cap blocks. These tenoned into the tops of columns; they were 32 sections long, 32 wide and 20 deep. The next-largest were the connection blocks. These fitted on top of lever arms or at the ends of a special bracket arm that was set perpendicular to the axis of the building; they were 18 sections long, 18 wide and 10 deep. The center blocks were slightly smaller. These were placed at the center of a bracket arm to receive the center of a second arm placed above it; they were 16 sections long, 16 wide and 10 deep. The last and smallest were the end blocks. These were placed at the ends of bracket arms set parallel to the axis of the building; they were 16 sections long, 14 wide and 10 deep.

Bracket arms were made in five basic models. In the ascending order of their position, the most specialized of the five was one of the two lowest and the only one that was set perpendicular to the axis of the building. It was known as a petal arm; its length was 72 sections and its depth a full unit: 21 sections. Its sides were indented at the center, and so was the bottom; that allowed it to be tenoned with a second kind of bracket arm, known as the wall arm. This arm was installed parallel to the axis of the building; it was the standard 15 sections deep and 62 sections long. When these two lowest bracket arms were fitted together at a right angle, they would snugly tenon with a cap block to form an *X* 62 by 72 sections long on which still other bracket arms could be placed. The mortise cut into the wall arm was very deep, and so a stiffener was usually added to strengthen the arm after it was joined to the petal arm.

In this progression the next bracket arm was one known as an oval arm. It was the standard 15 sections deep, and like the wall arm it was 62 sections long. Two oval arms were tenoned to connecting blocks set at the ends of a petal arm, thereby adding two more brackets to the array. In the next tier upward, resting on a center block, was the longest bracket arm of all, called the long arm. It was only the standard 15 sections deep but measured 92 sections from end to end. At the summit of the array was a bracket called a regular arm. It rested on a center block. The regular arm supported three more blocks: another center block and at each end a small block. These three blocks carried the weight of a purlin, one of the roof timbers that ran parallel to the long axis of the structure and perpendicular to the roof beams.

What I have described here is an idealized bracket set, such as might be placed on the top of an interior column. Bracket sets on perimeter columns included a sixth element: the lever arm.

This timber, of considerable length, was not fitted among the bracket arms in a horizontal position but slanted downward toward the exterior of the building, supported in that position by a wedge-shaped timber under it. At its lower end were a connecting block and a bracket set that bore the load of the eaves. At its upper end were a block and a bracket arm that supported the next purlin inward from the eave purlin. These tilted arms were called lever arms because the load of the roof on the purlin pushed the upper end of the lever arm down, thereby thrusting its lower end up against the load of the eave.

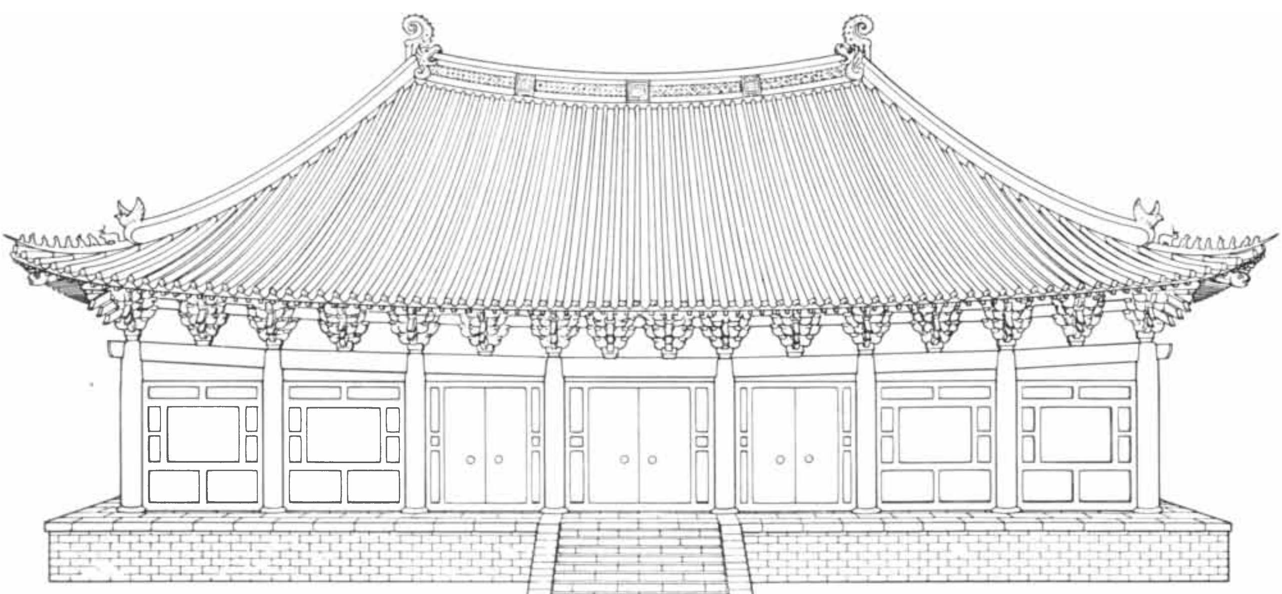
Bracket sets were not placed only at the top of columns. One of their most important functions was to support the key timbers of the roof frame: the purlins that spanned the long axis of the structure and the beams that bridged the short axis. The lowest of the roof beams were the largest. They ran the width of the building, with one end supported by the bracket set on top of a column in the north row and the other end supported by the bracket set of the corresponding column in the south row. In a large building these lowest beams, with the usual width-to-depth cross-sectional ratio of two to three, could be three units deep. On top of and near each end of these lowest beams was a supporting member called a camel hump. A connection block was fitted on each camel hump; the next-higher beam, only two units deep, spanned the distance between the two camel humps. The same connection blocks also supported one or more bracket arms that carried the load of the next pair of purlins. The intended curve from the ridgepole to the eaves determined the length and number of the higher beams; the highest of the beams carried the bracket set that supported the ridgepole.

Purlins were circular in cross section. In a large building they might be two units in diameter, in a smaller building only 16 or 17 sections. They rested not directly on the supporting bracket arms but on cushion timbers that fitted into the arms. The cushion timbers were one of the few structural elements that did not preserve the two-to-three cross-sectional ratio. They were 10 sections wide by 12 deep and ranged in length from six units to a little more than seven. The ends of each purlin bore a timber shaped like a shallow wedge; it was one unit high at its large end. Its gradual taper over a distance of one bay accented the front-view curve of the roof already established by the different heights of the pillars.

With the erection of the roof frame the structure was almost finished. To give further support to the purlins short struts were set in place, running diagonally from the sides of the circular timbers down to the beam below. Horizontal ties were also set in place between pairs of bracket sets in alternating bays. Only rafters remained to complete the roof frame. Except for the eave rafters these were short timbers, three inches in diameter and just long enough to run from purlin to purlin. They were set as close together as "the teeth in a comb" in order to support the roof tiles. The upper end of each rafter was fixed to the purlin above it with a nail and the lower end rested free on the purlin below. At the corners of the roof the rafters were spread like a fan, their upper ends tapered to fit closely. Next the rafters were covered with wood sheathing and the sheathing was covered with mortar to hold the roof tiles in place. Tiling the roof finished the construction of the building.

In the centuries that followed Li's great codification a number of construction methods underwent change. It became the practice to line up any interior columns on the same grid with the peripheral columns, and both the inward slant of the peripheral columns and their increasing height toward the corners of the building were discontinued. The latter change made the curves of the roof less pronounced. The oblique struts also disappeared.

The greatest changes, however, were in the bracket sets supporting the eaves of the roof. Lever arms lost their shape and became mere elements of decoration. The number of bracket sets not associated with columns increased, but their functional importance decreased. An example is the restoration of the audience hall in the Imperial Palace in Peking, undertaken in 1734. In "Building Standards" it is stated that the central bay should have two of the intercolumnar bracket sets and the other bays only one. The restored central bay of the audience hall ended up with eight bracket sets and each of the other bays with five. Function had been overtaken by decoration.



SOUTH ELEVATION of a Grade 2 building constructed in the 10th century shows the typical curves of a hip roof and a single bracket-arm set, resting on the lintel, between each pair of columns (except at the central bay, where there are two sets). By the 18th century the tradition was dead; a restoration of a palace building in 1734 put five sets between the columns and a total of eight in the central bay.

THE AMATEUR SCIENTIST

About phosphenes: luminous patterns that appear when the eyes are closed

by Jearl Walker

If you press your forefinger gently against your closed eyelid for a minute or less, you will probably start to see phosphenes: shapes and colors that march and swirl across your darkened field of view. Phosphenes can also appear in flickering light, in darkness and when you accidentally bump your head. You may also be able to see them simply by tightly closing your eyes. I first noticed them as a child when I cried with my face buried in a pillow.

Phosphenes were among the many subjects investigated a century ago by Hermann von Helmholtz. I shall review here a few of the experiments he described in his *Treatise on Physiological Optics.* I shall also discuss some recent experiments reported by Christopher W. Tyler of the Smith-Kettlewell Institute of Visual Sciences in San Francisco. In reviewing these studies I have been stimulated to experiment with phosphenes myself, and I shall report some of my observations. Your observations will be of interest too, because not all people see the same types of phosphenes. Let me strongly warn you, however, against hurting yourself. If pressing your eyes hurts, stop. Even if it does not hurt, do not press for more than a minute. Do not stare into bright lights. If your eyes hurt when you look toward a bright light with your eyelids closed, abandon the experiment. Nothing you can learn about phosphenes is worth the slightest harm to your eyes.

Helmholtz described some of the observations of phosphenes made by earlier workers, notably Johannes Purkinje in 1819. Helmholtz also made observations of his own. He pointed out that when a steady pressure is applied to a spot on the eye, a continuous phosphene appears at the opposite side of the visual field. For example, pressing a closed eye near the temple gives rise to a distinct phosphene toward the nose. The phosphene has a bright center surrounded by a dark ring and a bright outer ring.

When Helmholtz looked to the left with his right eye closed, the phosphene became less bright. He could not quite make the phosphene overlap his foveal vision. (The fovea is the tiny area of the retina where the packing of cones is densest. When you look directly at something, its image falls on the fovea.)

In one experiment Helmholtz stared at his nose with his right eye and held a sheet of white paper in front of his face. The paper served as a diffuse and evenly illuminated surface. He pressed against his right eyelid near the temple, being careful to have his finger about halfway up the eyeball.

The phosphene, which appeared on the nose side of his field of view, consisted of a dark spot surrounded by a bright curved band. To the right of the band were thin dark stripes. At the point of view corresponding to the fovea was a dull gray area. Farther to the right, at the region corresponding to the point where the optic nerve enters the retina, was another indistinct dark spot. When Helmholtz did the experiment again with a dark background instead of the illuminated paper, the disposition of the phosphene images was similar but the bright and dark regions were interchanged. The sensation of a phosphene in the foveal vision was absent.

In repeating the experiments I illuminated my field of view with the diffuse screen of a slide sorter. I closed my left eye and kept my right one open. It was easy to create a phosphene on the nose side of my visual field with a light touch against my right eyelid near the temple. The phosphene appeared to be purple or dark blue. I could not readily identify as much structure as Helmholtz described. At the foveal area in my field of view was a small gray spot surrounded by a brighter region. Off to the right was a gray area shaped somewhat like an arrowhead pointing toward the foveal region. All these features were easier for me to see if I periodically varied the pressure on my eyelid. As I did so the nasal phosphene and the bright spot at the foveal region oscillated horizontally and out of phase with each other.

With a prolonged and heavier pressure on a closed eye the phosphene display can be far more complex. Colors and forms float kaleidoscopically across the field of view; the images are bright, colored and constantly changing. Purkinje wrote that the "background generally consisted of fine quadrangles in regular array, on which there were either stars with eight rays, or dark or bright rhombs with vertical and horizontal diagonals; and the patterns were surrounded by alternately bright and dark bands."

Helmholtz saw less regularity. He likened the displays to fine leaves or mossy surfaces. Sometimes complex mazes appeared. Often bright blue or red sparks flashed across the display. Even when he released the pressure, still keeping his eye closed, the display continued for a while. If he opened his eye after releasing the pressure, he was first unable to see anything. Then the brighter objects in his visual field became brilliant. Superposed on these objects he still saw parts of the phosphene display, but now the bright and dark regions were reversed. Eventually his vision returned to normal.

Several experimenters had reported

The finger-pressure method of generating phosphenes


How many pearls lay in our catch we had not yet ascertained. Palo seemed hopeful, but now, diving deeper, he slipped from view.
The shark warning was still fresh in my mind when suddenly a form rose swiftly toward the canoe. It was Palo. As his net broke the surface, I saw at once our expedition would not go unrewarded. There in the net rode three cold bottles of San Miguel Beer.
With feline grace and economy of motion Palo gathered himself into the canoe, pulling in the extraordinary cargo along with the weighted foot rope that had aided his descent. As I began paddling for shore, Palo drew his knife and opened us each a San Miguel, explaining how he kept a supply of this hearty beer hidden in a crevice among the rocks at considerable depth, protected and well-chilled. It was clear he knew his business.
We paddled for the island leisurely, paying scant attention to the nacreous wealth within the shells, rewarding ourselves instead with gratifying sips of San Miguel.*
*Inspired by Jules Verne's 20,000 Leagues Under the Sea.
San Miguel
Classic beer of the Pacific.
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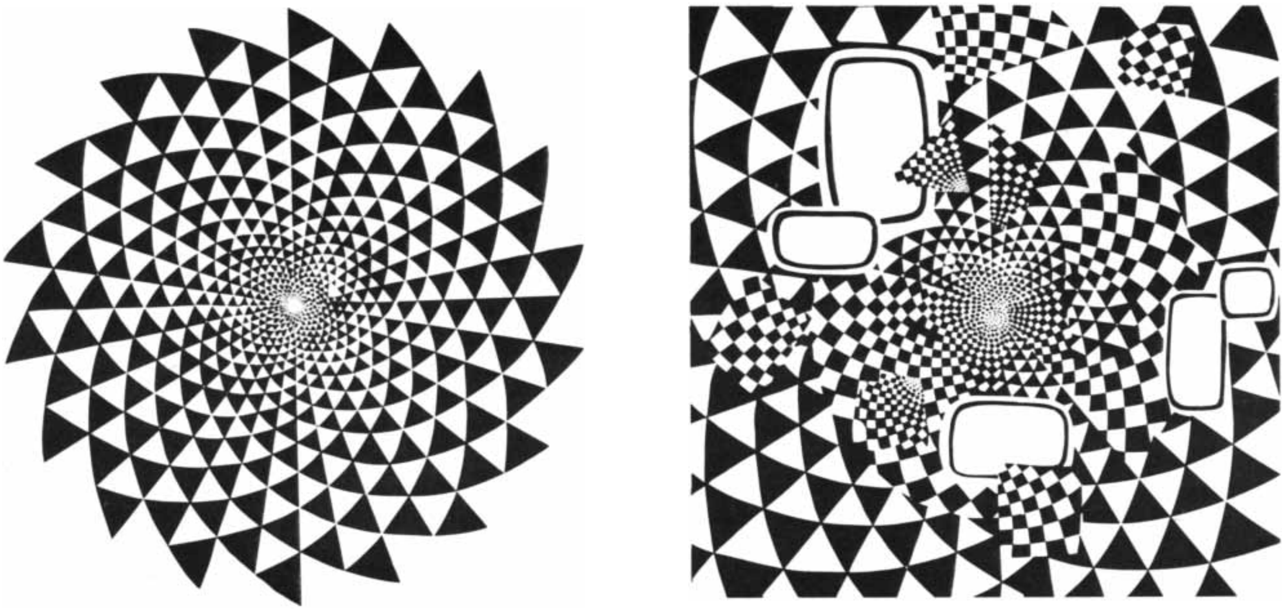
Wolfe

seeing an image of the circulatory network in the retina when they pressed a finger against a closed eye. Helmholtz, apparently unable to repeat the observation, was skeptical that the retinal network was involved. Nevertheless, some people do see it. W. A. Nagel, who wrote footnotes to Helmholtz' *Treatise,* noted that he could easily see "a dense network of bright lines on a dark ground" when he kept an eye shut for at least 20 minutes. Pressure was not necessary. Once the lines appeared he could distinguish a flickering in them, presumably because of the pulsation of blood through the retinal capillaries.

When I press fairly hard on my eye, my vision blurs noticeably and the foveal region in the visual field becomes alive with pulsating pathways. I am probably disturbing the circulation of blood in the fovea. As a result I am seeing a pulsating image that reveals the circulatory network there. The retinal network lies in front of the photoreceptors and thus shadows part of the retina, but the shadows are normally ignored by the brain because they are constant. You consciously perceive only scenes that change, either because the objects move or because your eyes scan the scene. If the circulation through the network is disturbed, an indistinct outline of the network can be seen.

Phosphenes can also be seen if the eyes are turned quickly to one side. If the background is dark, the images appear as bright spots or rings around the position of the blind spot in the field of view. The appearance of the phosphenes is not the same for both eyes. The eye that turns toward the nose "sees" a duller phosphene than the eye that is turned toward the temple. If the background is bright, the spots are dark.

This type of phosphene has been attributed to stretching or compression of the optic nerve. When the eyes are turned quickly to the side, the nerve bundle in one eye is compressed and the bundle in the other eye is stretched. The resulting phosphene is momentary. Some observers see its shapes as rings or partial rings centered on the area of the



Binocular

Small dots are yellow, large dots violet.

Monocular

Phosphenes described by Christopher W. Tyler as resulting from strong pressure

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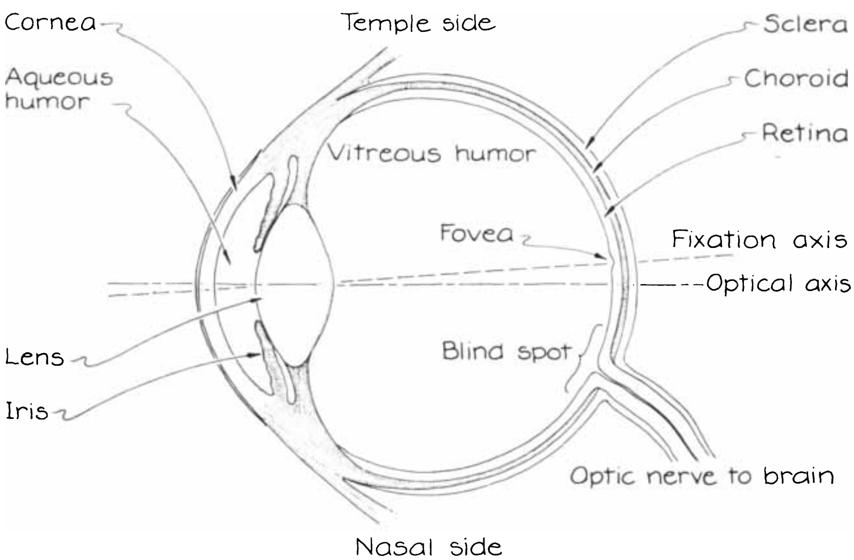

A cross section of the right eye as viewed from above

blind spot. Purkinje described concentric bright bands toward the center of the visual field. With one eye turned strongly toward the nose, the display was continuous. For Helmholtz the display was brief even when an eye was turned strongly.

Phosphenes can also appear when the eye suddenly changes its accommodation, or distance of focus, but they are not as apparent as the others I have described. Helmholtz suggested focusing on an object just outside a window and switching after a few minutes to a distant object. As the eye accommodates to the distant view a small bright border can be seen around the field of view. The sudden relaxation of the muscles of the eye apparently causes pressure variations that generate the phosphenes. Purkinje could also create the luminous border when he suddenly released pressure on his eye, but Helmholtz was unable to repeat the observation.

Of all the phosphene images described by Helmholtz the strangest are the ones that appear to a person who sits for a while in total darkness. These displays, which have been called the "prisoner's cinema," require no pressure on the eyes. Phosphenes can appear whenever there is an absence of variation in the visual field. The situation can be total darkness or continuous brightness (such as a snowstorm).

Helmholtz saw the darkness images as interfering waves that blended together. The waves moved slowly compared with some of the other displays. Helmholtz was able to demonstrate that the wave motion was synchronous with his breathing. The general background of the waves was never totally dark. He saw small luminous areas that appeared and disappeared with each breath.

I see this type of phosphene when I spend the night in a cave during a spelunking trip. After I put out my lights to prepare for sleep the darkness is absolute. In 10 minutes or so, however, I see vague splotches of light. With no reference lights to guide me the phosphenes seem to be real lights just beyond my reach.

Tyler recently published new observations on phosphenes. His paper is listed in the bibliography for this issue [*page 186*]. When someone strongly converges his eyes, as in staring at the tip of his nose with his eyes crossed, two types of phosphenes can appear. If the convergence is rapid, you can see two large rings that momentarily surround the area of the blind spot. They are the rings seen by Purkinje during a rapid rotation of both his eyes. Since the rings appear when both eyes are turned toward the nose, they must be caused by a stretching of the optic nerve.

Another type of phosphene materializes if the convergence is done in front of a uniform light source and is strong and continuous. In the center of the field of view is a red dumbbell. Some observers report red disks rather than an entire dumbbell. Stresses from the convergence are responsible for the phosphene, but apparently external light is also required. The light could reach the retina either by passing through the pupil or by passing around the eyeball through the sclera, the white exterior layer of the eyeball.

A simple check reveals the path of the light. If the fingers are placed on the nose side of each closed eyelid, the phosphene disappears, whereas if the fingers are placed on the temple side, the phosphene is unaltered. The light participating in the phosphene image therefore comes into the visual system through the pupil. The phosphene appears even if one eye is covered.

Many different phosphenes can be created by pressing the palms against

The retinal vessels of the right eye, which sometimes can be seen as phosphenes

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the closed eyes for about a minute. Tyler has classified the displays according to where the image is likely to be created in the visual pathway. With a mild pressure the display consists of colored swirls, which are probably caused by the decrease of oxygen in the retina as the pressure inhibits the flow of blood. The effect may be produced at the depth of the photoreceptors (the rods and the cones) or somewhere closer to the surface of the retina, as at the ganglion cells. Sometimes the fovea is surrounded by a blue ring or halo. Neither the structure nor the color is understood.

With a bit more pressure that is then released you might see the retinal circulation pattern. The variation of pressure on the retina causes a variation in the flow of blood through the network. If as a result the nerve activity near the vessels is different from the nerve activity farther away, the outline of the vessel system might materialize.

With still deeper pressure and its release you might see the circulatory network in the choroid coating between the retina and the sclera. This system, which appears as red on a black background, may show up best just as the pressure is released and the blood again flows through the network. This is one of the few ways the choroidal circulatory system can be observed directly.

Two types of stationary point arrays can also be seen with deep pressure. Sometimes both are seen together. In one of them yellow points are randomly strewn across a dark background. In the other bright violet points appear on a darker background. The yellow points are of uniform size but the violet points become larger toward the periphery of the field of view. The arrays can be seen with either eye and do not require deep pressure on both eyes. Tyler argues that since the blood circulation has already been stopped by the pressure, these point arrays are probably produced somewhere farther along in the visual pathway than the photoreceptor level.

When both eyes receive such deep pressure, the observer can see several complex displays. One possibility is a regular cellular grid resembling either a chessboard or an array of triangles. Another possibility is a similar cellular structure on a finer scale. Sometimes both structures can be observed, one superposed on the other. A few blank areas that Tyler likens to blank television screens are sometimes included.

Since these complex displays require deep pressure and binocular viewing, they are probably produced relatively far up in the visual pathway. Tyler suggests they originate in the visual cortex, but where or how they are created is not understood. Some elements of the visual system seem to be designed to recognize lines, but as yet no elements are known that recognize squares, hexagons or any of the other geometric patterns seen in the phosphenes.

If the pressure on the eyes did set off line-recognizing elements at random, one would expect to see a random array of lines rather than geometric patterns in phosphenes. Somewhere in the visual process, below the conscious level, there may be elements that respond to certain periodicities and shapes. In a rough analysis of the geometric phosphenes one might guess that such elements are being excited by the deep pressure on both eyes.

Part of the fascination of a repetitively flashing stroboscopic lamp at a discotheque may lie in the phosphenes that result, even when the eyelids are closed. A light flashing at rates of between 10 and 30 hertz can induce vivid geometric arrays filled with strong colors. (My use of "phosphene" here may be inappropriate. Although the patterns one can see in some flickering lights are similar to the phosphene images arising from deep pressure on the eyes, I am not certain the effects are the same. Nevertheless, I shall make the assumption here that they are.)

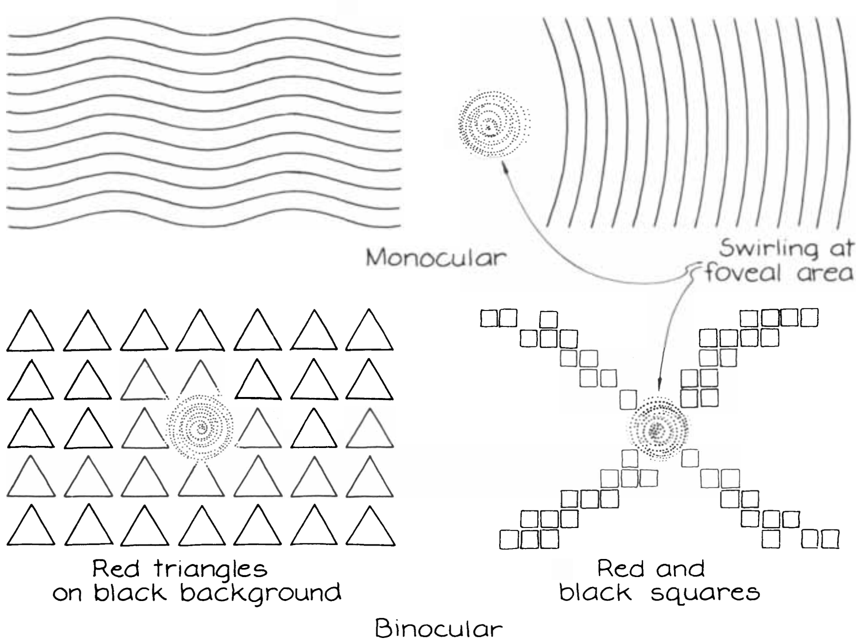
In recent studies with flickering lights observers viewed a screen lighted from the rear. A rotating wheel intersected and chopped the light falling on the screen, thereby producing a flickering but featureless illuminated surface. At a rate of about 30 hertz at least two types of structure could be perceived. One type consisted of squares laid out somewhat like a chessboard, the other of hexagons. Both lasted for five seconds or so before fading into another pattern or into an uninterpretable field. With the hexagon display the observers could distinguish a fine-scale array that was surrounded by an array of larger hexagons.

These are only a few of the possible patterns one can see in a flickering light. At lower frequencies, near two hertz, the flickering may at most produce swirling gray-and-white regions. At higher frequencies (60 hertz or more) the flickering becomes less apparent as the individual pulses of light fuse to give a perception of continuous illumination on the screen.

For most observers the colored geometric patterns become evident when the frequency is between 10 and 30 hertz. The patterns are believed to appear only if both eyes receive the flickering light. The need for binocular vision implies that the patterns are created farther along in the visual pathway than the eye, otherwise one eye would suffice. Perhaps the patterns are generated in the visual cortex, where complex shapes are perceived. The frequency of the flickering presumably matches some frequency or periodicity in the visual process there, and the brain is fooled into seeing the patterns.

I first tried to see these phosphenes by the simple expedient of holding my hands in front of my face with the palms toward me and the little fingers touching. Behind my hands was an incandescent lamp. With my eyes closed I continuously separated and rejoined my hands to create a flickering effect. I found that I got more light if I lifted my eyebrows. I was careful not to look directly at the lamp with my eyes open because the result would be a strong afterimage when I closed my eyes for the demonstration.

When I interrupted the light from the lamp at a frequency of about eight hertz, my field of view broke up into strikingly clear red and black squares, resembling a chessboard. The squares were aligned along diagonals that crossed the center of my field of view. The creation of this



Patterns seen in flickering light

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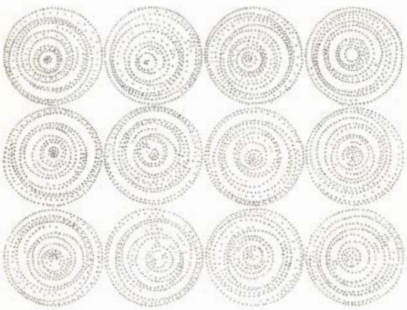

The tortoiseshell pattern

pattern called for a fairly strong light; the lamp was a 100-watt one, and I was about 10 centimeters from it.

I could not see the squares when I moved to a greater distance. What I saw instead were globular blue phosphenes in the lower half of my field of view. The change may be due to the decreased illumination. The intensity must exceed a certain threshold in order to produce geometric patterns.

Next I worked with a stroboscope. Its output was relatively bright and the frequency of the flash could be varied from one hertz up. I was careful not to look at the flashing light with my eyes open, not only to avoid afterimages but also to avoid damaging my eyes. (Some people are adversely affected by flashing bright lights. Do not do these experiments if you are thus affected.)

In my first trials I covered my left eye and faced the strobe with my right eye closed. As I increased the flash frequency from a starting level of one hertz I began to see a vortex that seemed to be in the foveal area of my view. At a frequency of a few hertz vague radial lines stretched from the vortex, but otherwise the field was featureless.

At about six hertz I saw what resembled a venetian blind. The foveal vortex was still there, but it was now brighter. With another small increase in frequency thin waves appeared, each one centered on the foveal region. The background was spotted. At a frequency of about 11 hertz chaotic bright places spotted the field. Dull colors appeared at the foveal region, which began to show vigorous pulsations. At 12 hertz the entire field pulsated with bright yellows and other colors that were duller. The field to the right of the foveal region formed an arrowhead that pointed to the fovea.

Now I covered my right eye so that neither eye received light. The field of view broke up into a cellular mosaic that reminded me of a tortoiseshell. When the afterimage faded, I again uncovered my closed right eye, and the field again developed vivid colors and rapid pulsations. Thin capillary waves formed and disappeared.

At the same frequency I covered my right eye and exposed my left eye, which

```
15 INPUT "MO,DA:"; MO,DA: IF MO < 3 THEN MO = MO + 12
20 DA = DA + INT (30.6 * MO - 32.4): Z = 279.5 + DA * 360/
     365.25 : M = 357 + .9856 * DA
25 LO = Z + 1.915 * SIN (M * RPD) + .02 * SIN (2 * M * RPD)
30 X = SIN (LO * RPD) * .398 : D = ATN( X/ SQR(1 -X*X) ) :
     DECL = D / RPD : PRINT "DECL ="; DECL
35 Y = COS (LO * RPD) / COS (D) : RA = ATN (SQR (1- Y*Y) /
     Y) : IF RA < 0 THEN RA = RA + 3.14159
40 IF X < 0 THEN RA = -RA
45 ET = RA - Z * RPD : ET = ET * 4 /RPD
50 IF ET < -720 THEN ET = ET + 1440: GO TO 50
55 ET = ET/4
85 T = -5
90 FOR K = -10 TO 10 : C = (K * 7.5 - DL - ET) * RPD:
     B = TAN (C)
```

Charles Kluepfel's modifications of the computer program for the analemmic sundial

I kept closed. The field consisted of petals in brilliant reds and yellows. Then I suddenly exposed both closed eyes. The center was again bright and the petals were still brilliant, but soon the display formed into checkerboards of red, yellow and blue. The sight was unnerving. It actually made me dizzy; I had to hold on to the chair to steady myself. The displays formed, dissolved, expanded and shrank, all in full color.

When I tilted my head forward, the structures seemed to broaden. With my head tilted upward a white horizon appeared across the bottom of my field of view. Presumably it was caused by a leakage of light between my closed eyelids. Above the white band were the colored designs.

At higher frequencies the field became progressively less interesting until at about 40 hertz I saw only a bright, featureless background. At one point I faced away from the stroboscope, waited for a few minutes and then opened my eyes so that I could see my desk. White sheets of paper and Styrofoam cups were illuminated by the flashing light. On these objects I saw swirling designs similar to the ones I had seen while I was facing the stroboscope, but they now lacked color.

When I faced the flashing light, any sensations of ordered arrays of polygons were certainly more noticeable with both of my closed eyes illuminated. Occasionally, however, the petals or tortoiseshell features could be seen when only one eye was exposed or when one eye was exposed and then suddenly covered. The tortoiseshell pattern, sometimes with a swirling visible in each of its cells, does not seem to require flickering light, just bright light. I can occasionally see the pattern when I face (with closed eyes) a bright incandescent lamp. I have also seen it in my dentist's bright working light. (I will do anything to take my mind off what she is doing.)

Much more could be done to classify phosphenes and track down their causes. You can watch for the displays when you are under physical strain. You might also want to try some of the experiments with pressure and flashing lights. If you do so, remember that if any of the maneuvers start to hurt your eyes, you should stop them immediately.

Many people have written to me about two errors I made last December in my description of the analemmic sundial designed by C. K. Sloan. In explaining how to lay out the degree marks on the equinoctial line I incorrectly implied that the separation between the marks was a constant along the line. The illustrations were correct but I erred in the text.

To find where the marks should be made, calculate the distance of a mark from the noon radial line. That distance is equal to the height of the gnomon multiplied by the secant of the dial's latitude and the tangent of the mark's hour angle. Suppose you want to place the mark for one degree past 1:00. Each passage of an hour represents 15 degrees. The mark is therefore 16 degrees past the noon radial line. Change this number to radians and then plug it into the tangent in the foregoing formula. You now have the distance between the noon radial line and the mark to be made on the equinoctial line.

I also erred in explaining how the corrections for the longitude and for the equation of time are taken into account. I stated that once you have calculated the uncorrected position of the shadow point all you have to do is rotate the position either left or right around the ecliptic point to get the number of degrees for the correction. What I forgot is that you must also adjust the length of the shadow. For example, if you calculate the position of the shadow point for 3:00 and then rotate it a few degrees to the left for the correction, you also must make the shadow somewhat shorter.

One easy way to make the correction is to calculate the uncorrected positions of the shadow point for each hour of the day. Lightly draw a curved line through the positions. Now make your corrections. Take the shadow position for, say, 3:00 and correct it for the longitude and the equation of time by sliding it the proper number of degrees along the lightly drawn line. If you are supposed to move it two degrees to the left, go to the left by two of the degree marks you have made on the equinoctial line and mark the shadow point on the lightly drawn curved line.

Charles Kluepfel of New York sent plans by which the correction can be done with the computer program I presented in December. He also sent additional program lines by which the computer automatically calculates the equation of time and the declination for any day of the year. These lines, which are shown in the top illustration on this page, are intended for Level II Basic for a Radio Shack TRS-80, but probably only slight changes are needed for other versions of the Basic language. Add these lines to my program. (Some of them replace lines in my program.) Also remove from the end of line 70 of my original program *,A$*.

When you run the program now, it will ask you for the date in which you are interested. For June 1 you would enter *6,1*. The program then computes the equation of time, the declination and the distance (from the equinoctial line) for the shadow point after it has been corrected for the longitude and the equation of time. All you have left to do is make the angular correction for the longitude and the equation of time.

```
10 CLS : RPD = .01745 : L = 35.0 * RPD : DL = 1.8 : H = 1.0
15 INPUT "MO,DA:"; MO,DA: IF MO < 3 THEN MO = MO + 12
20 DA = DA + INT (30.6 * MO - 32.4): Z = 279.5 + DA * 360/
     365.25 : M = 357 + .9856 * DA
25 LO = Z + 1.915 * SIN (M * RPD) + .02 * SIN (2 * M * RPD)
30 X = SIN (LO * RPD) * .398 : D = ATN(X/ SQR(1 - X*X) ) :
     DECL = D / RPD : PRINT "DECL ="; DECL
35 Y = COS (LO * RPD) / COS (D) : RA = ATN (SQR (1-Y*Y) /
     Y) : IF RA < 0 THEN RA = RA + 3.14159
40 IF X < 0 THEN RA = -RA
45 ET = RA - Z * RPD : ET = ET * 4/RPD
50 IF ET < -720 THEN ET = ET + 1440: GO TO 50
55 ET = ET/4
60 PRINT "DL="; DL, "EQ TIME ="; ET, "TOTAL ANGLE ="; DL + ET
70 PRINT " ": PRINT "TIME(HRS)", "DIST(METERS)"
80 X = TAN (L) : F = 1 / COS (L) : G = X + 1 / X : W = 1 / SIN (L)
85 T = -5
90 FOR K = -10 TO 10 : C = (K * 7.5 - DL - ET) * RPD : B = TAN (C)
100 E = SQR ( (B * F) ↑ 2 + G ↑ 2) / G : J = 1/ (E * X)
110 A = ATN ( (G * E - J) / SQR (W ↑ 2 - J ↑ 2) )
120 Z = TAN (A - D) / TAN (A) : DIST = H * (Z - 1) * (G * E - J)
130 PRINT T, DIST : T = T + .5 : NEXT K : END
```

The entire program with Kluepfel's revisions

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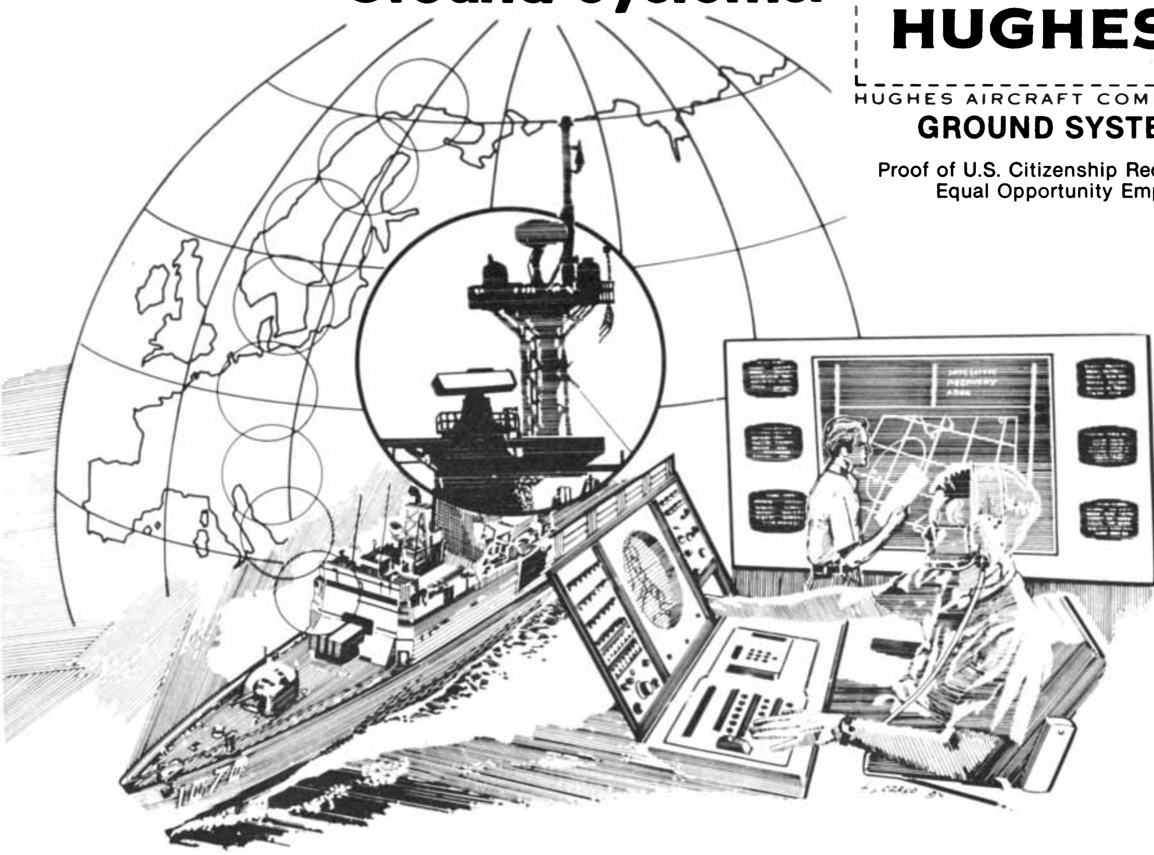

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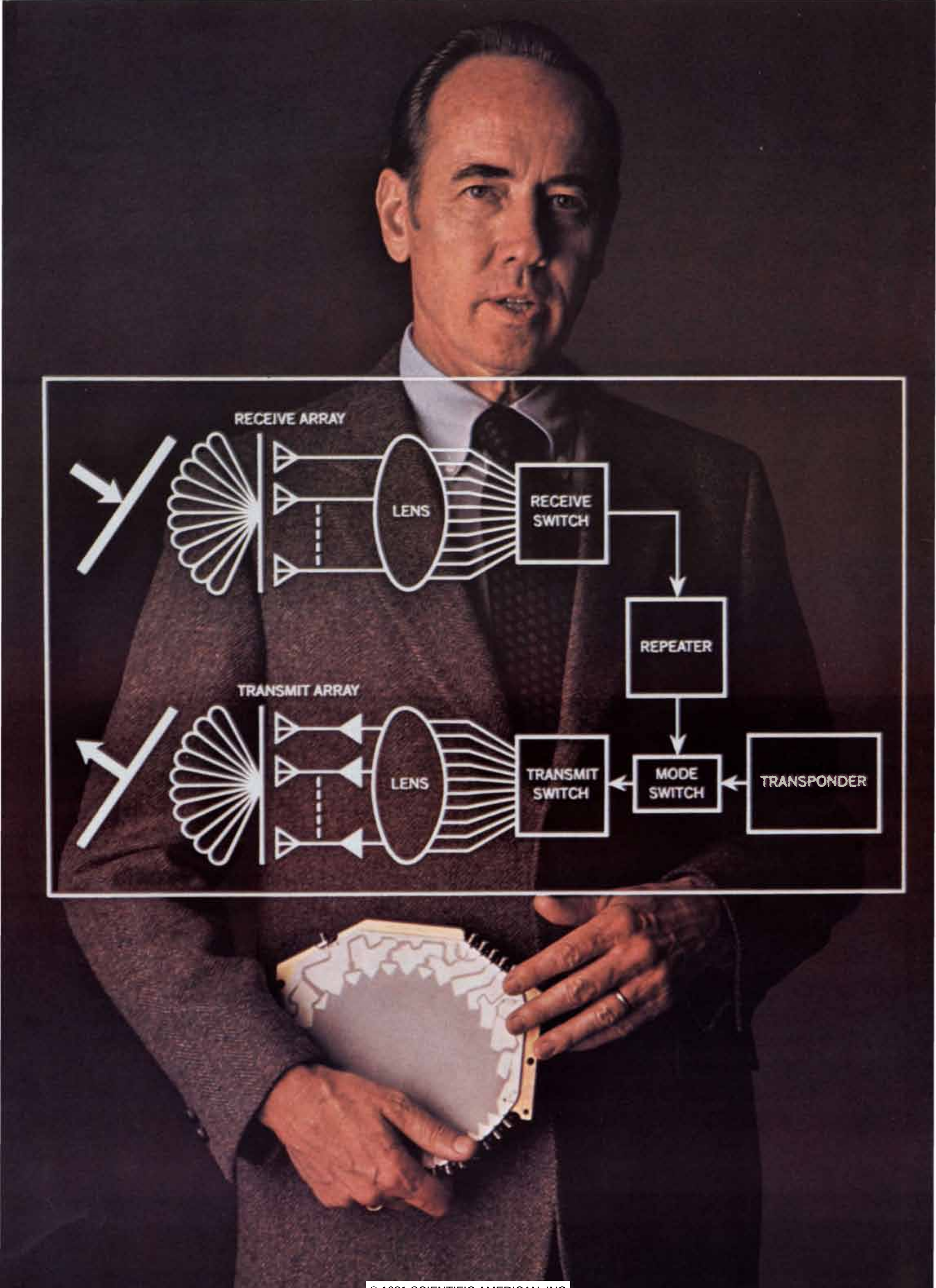
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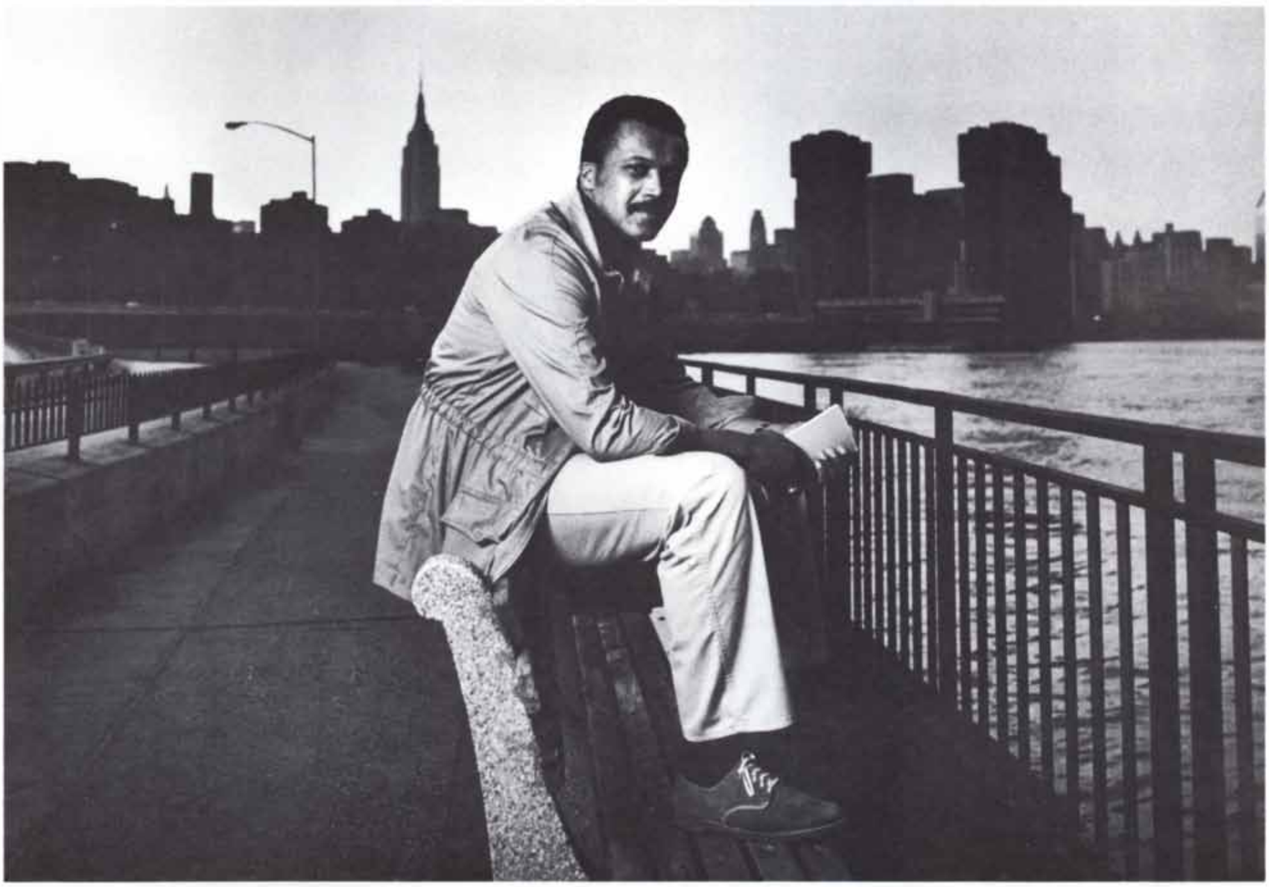

DAVID HARDY

BORN: Plainfield, New Jersey, 1942
HOME: West New York, New Jersey
PROFESSION: Investigative/political reporter, *New York Daily News.*
RESPONSIBILITY: "To share reality with others, even though I'm mindful that reality is not always an inspiring spectacle."
STORY: "Be it a homicide, a zoning fight, a political scandal, or simply a tale of a compassionate Jersey City hot dog vendor, my job is sometimes thrilling, often onerous, occasionally perilous, but always interesting."
QUOTE: "Every human being should possess a sense of morality about society and accept personal responsibility for his or her role."
SCOTCH: Dewar's "White Label."® "On the rocks with a splash, when relaxing with my chess computer."

David W. Hardy