California Institute
of Technology

Engineering & Science

Volume LIX, Number 2
1996

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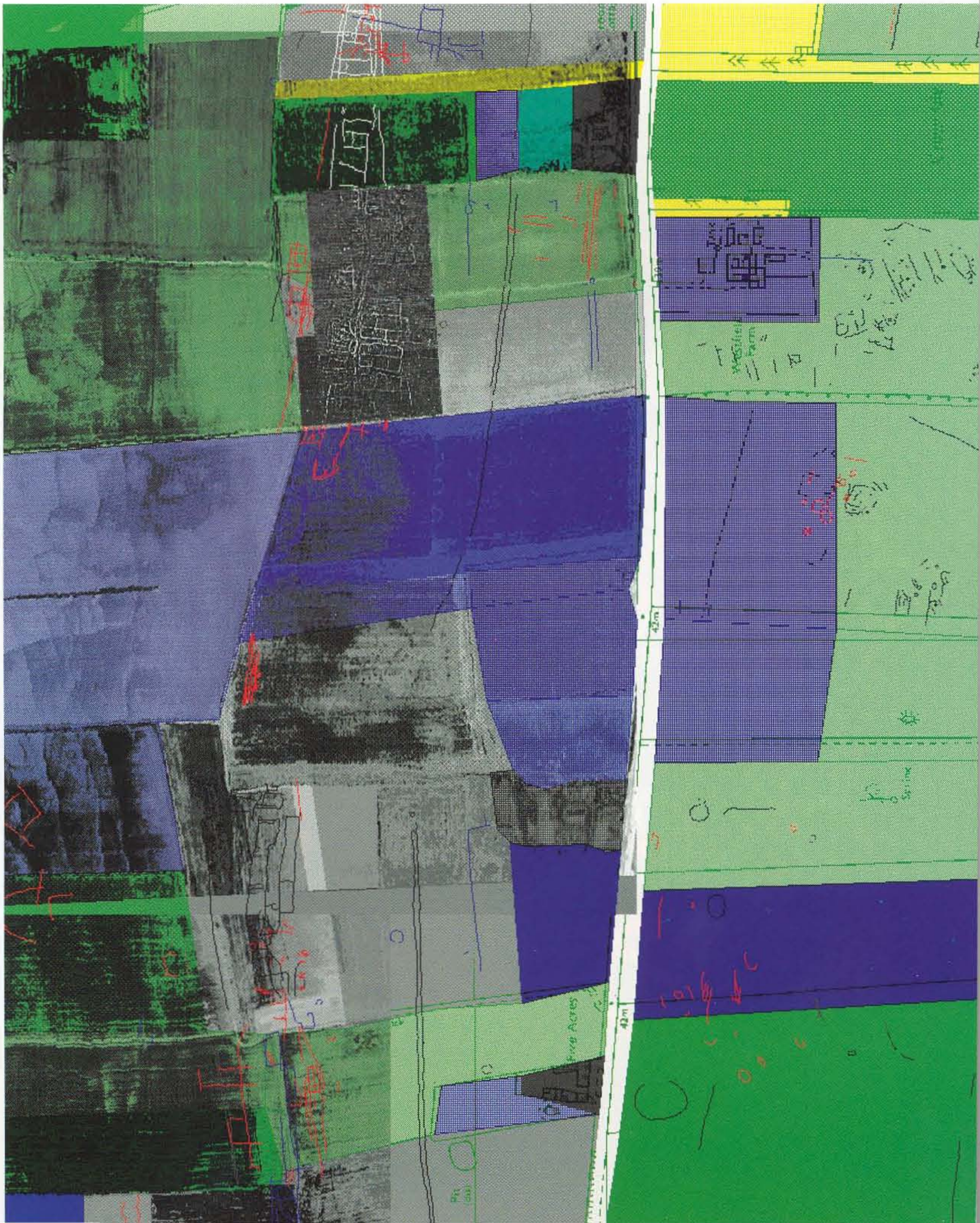

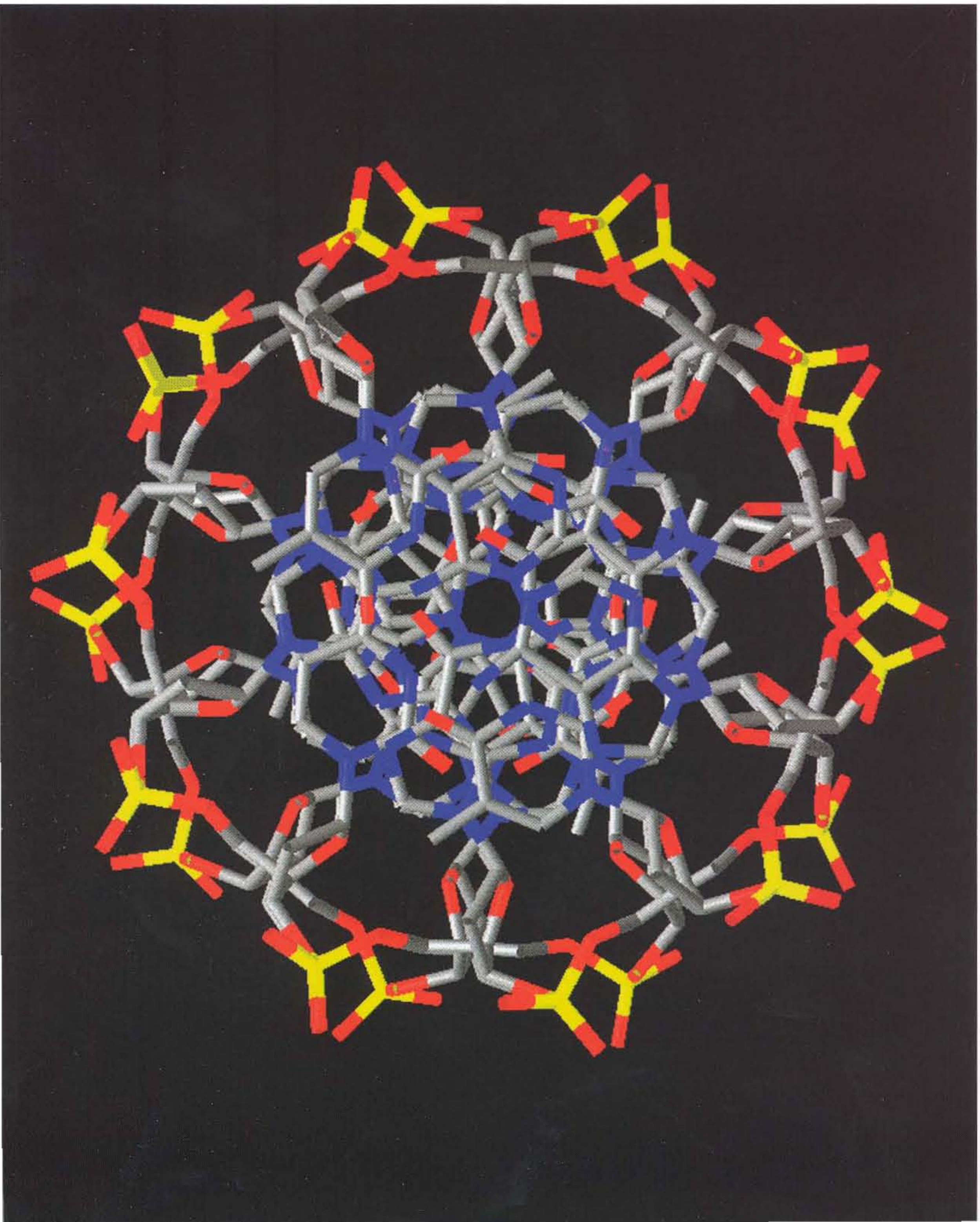

This lovely, symmetrical design is not a rose window from a Gothic cathedral, nor even a Hindu mandala, but the religious overtones are not inappropriate—it's the molecular structure of double-helical DNA, the molecule of life, as seen along the long axis. In this rendering, carbon atoms are shown in gray, phosphorus in yellow, oxygen in red, and nitrogen in blue. The hydrogen atoms aren't shown, for clarity. To find out how this view of DNA could be the basis for a new method of diagnosing diseases with a genetic component, see page 22.

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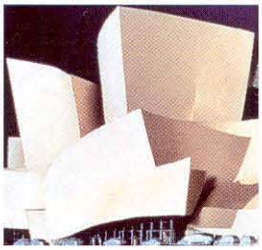
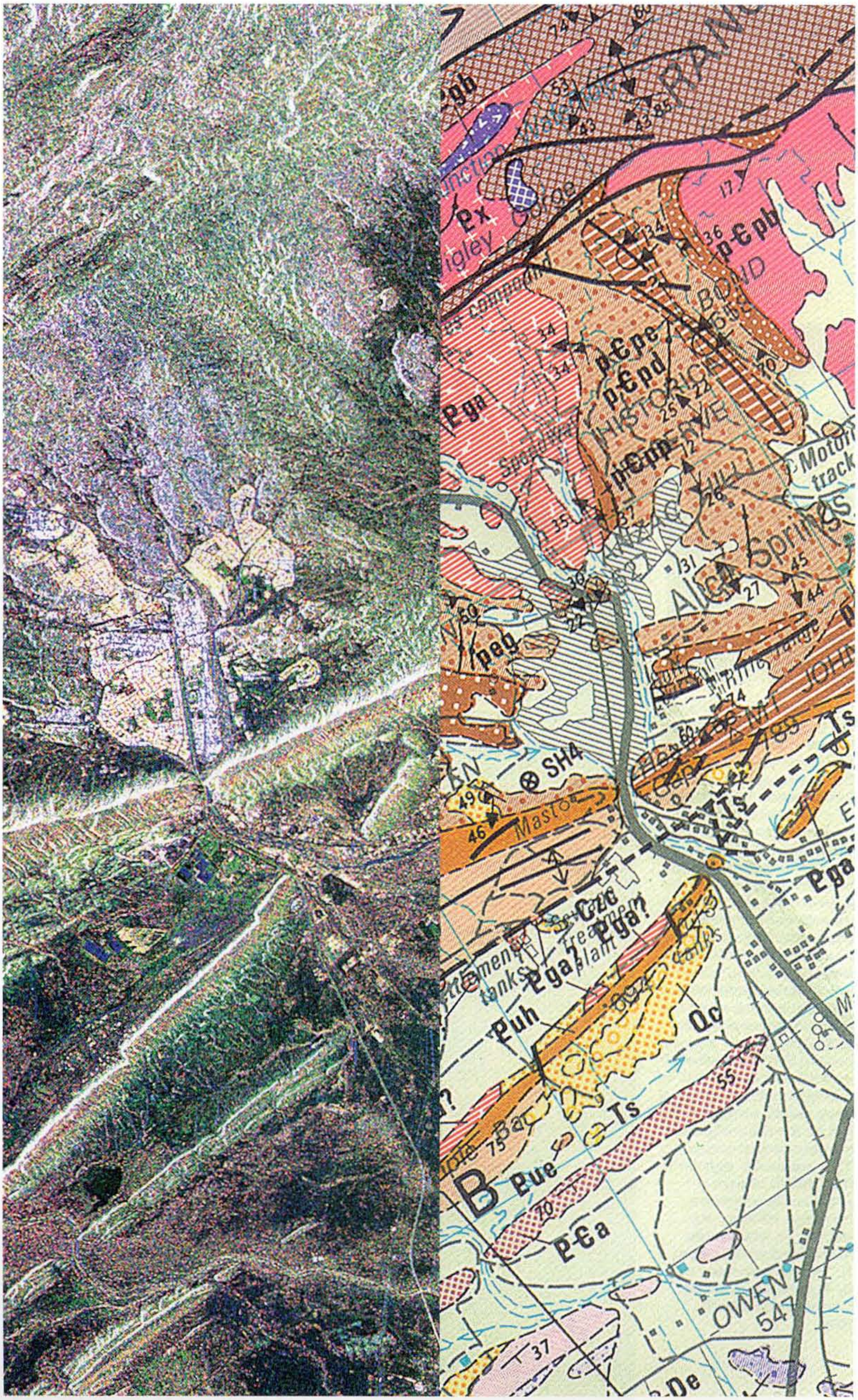


On the cover: Remote sensing and noninvasive field work reveal the archaeological landscape. This shot of a 5- x 3-km bit of England fuses five data sets: the colored blocks show crop cover; the green markings are from a digital map; the dark gray thermal-imaging data show medieval field boundaries and modern plowing patterns; the red, black, and white lines are prehistoric trackways and recent drainage ditches from an aerial survey; and the small gray patch at upper left is from a magnetic survey on the ground. The magnetic data's fine detail shows a previously unknown iron-age village. An article on electronic maps begins on page 2. Image courtesy of D. Powlesland, Getty Conservation Institute.

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1201 East California Boulevard, Pasadena, California 91125. Annual subscription $10.00 domestic; $20.00 foreign air mail; single copies $3.00. Third class postage paid at Pasadena, California. Published by the California Institute of Technology and the Alumni Association. Telephone: 818-395-3630. Postmaster: Send change of address to Caltech 1-71, Pasadena, CA 91125.

PICTURE CREDITS: Inside front cover, 22, 24, 26–28, 31, 33 — Tom Meade; 2, 4 — Wayne Waller; 5 — Peggy Li; 6 — William Jepson; 10 – 21, inside back cover — Frank O. Gehry & Assoc., Inc.; 21 — Erich Ansel Koyama; 25 — David Laidlaw; 29 – 30 — Russ Jacobs and Scott Fraser; 34 – 36, 39, 40, 42 — Bob Paz; 36 — Margaret Burbidge; 37 – 38 — Martha Schoenemann; 42 — David Arnett



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Dreaming of Hypermaps

I have dreamed for years of an electronic alternative: owning a map whose center, scale, and content are determined by me, not by the maker of the map.

by Roy D. Williams

The vicinity of Alice Springs, Northern Territory, Australia, as seen by the space shuttle's Synthetic Aperture Radar, or SAR, (left) and the Australian Bureau of Mineral Resources, Geology, and Geophysics (right). The colors in the radar image are keyed to the region's mineralogy. The map helps us make sense of what we see in the radar view by marking faults (thick black lines), labeling rock types, and naming features, both natural and man-made. But maps don't always get things quite right, as you can see in the curve of the railroad in the bottom right corner.

I'm writing this on a laptop on an airplane, watching the Oklahoma landscape roll smoothly by. There's a lot to see, in my opinion, from airplane windows—geological faults and rock unconformities; the way water erodes rock, and how roads, farms, and cities form themselves around the resulting watercourses. Sometimes, with raking sunlight and a dusting of snow, you can see ancient villages or medieval agriculture (though not in Oklahoma). I love the nonstop from Los Angeles to London, looking over endless, endless Arctic Canada and the mountains, like broken bottles, that cut through the Greenland ice sheet.

With a little imagination, such a landscape springs forth from a paper map, especially a finely detailed, large-scale one. For this reason I have always enjoyed armchair traveling with the aid of a map; this is especially fun before a trip, and occasionally more fun than the actual trip. Thus, the favorite maps in my own collection are those that represent lands far from my own experience. I like to say the names to myself, to wonder what happens when that tiny road simply ends in the middle of a jungle, to speculate about who uses the quay that gives access to a tiny, Atlantic-battered island. There are others who share this passion: in the meat-market district of Manhattan there's a café whose walls are covered in old street plans of cities from around the world, stuck up with thumb tacks. (The time I was there I walked from map to map, peering at them over the heads of other customers, who had to lean aside to get out of my way.) A map can add color to a book or newspaper story by showing where a battle was fought, or a train derailed; where the world's rice is grown, or the territory of a vanished empire stretched.

Old maps can be a lot of fun too. A few years ago, I was living in Oxford, quite close to Holywell Church, which is on Holywell Street. After a few exploratory sessions, I could find no evidence of a well, holy or otherwise. This seemed like a challenge, since it must have existed at some time, so I decided to try to nail it down. I wheedled my way into the Map Room of Oxford University's Geography Department and dug up some town-planning maps from 1862. These maps were at the scale of 1:1250—in other words, an inch on the map equaled roughly a hundred feet on the ground. At this scale you could see everything! Next to the church, at a distance equivalent to perhaps 20 feet, the map was annotated "Ancient Well" in gothic characters. I rushed back to the church to check it out. The ground showed no evidence of anything ancient, just a compost heap. But the churchyard wall contained some extra angles, implying that the builders had been making space for something—presumably the well. It was quite satisfying to feel that a tiny scrap of very unobvious history had been unveiled.

Maps as objects are fun to collect and pore over, but maps as information providers sometimes leave something to be desired. The area one really wants to see so often seems to be near a corner of the map, or the journey one imagines continues off the edge; besides, paper maps are really very awkward to file and store.

I have dreamed for years of an electronic

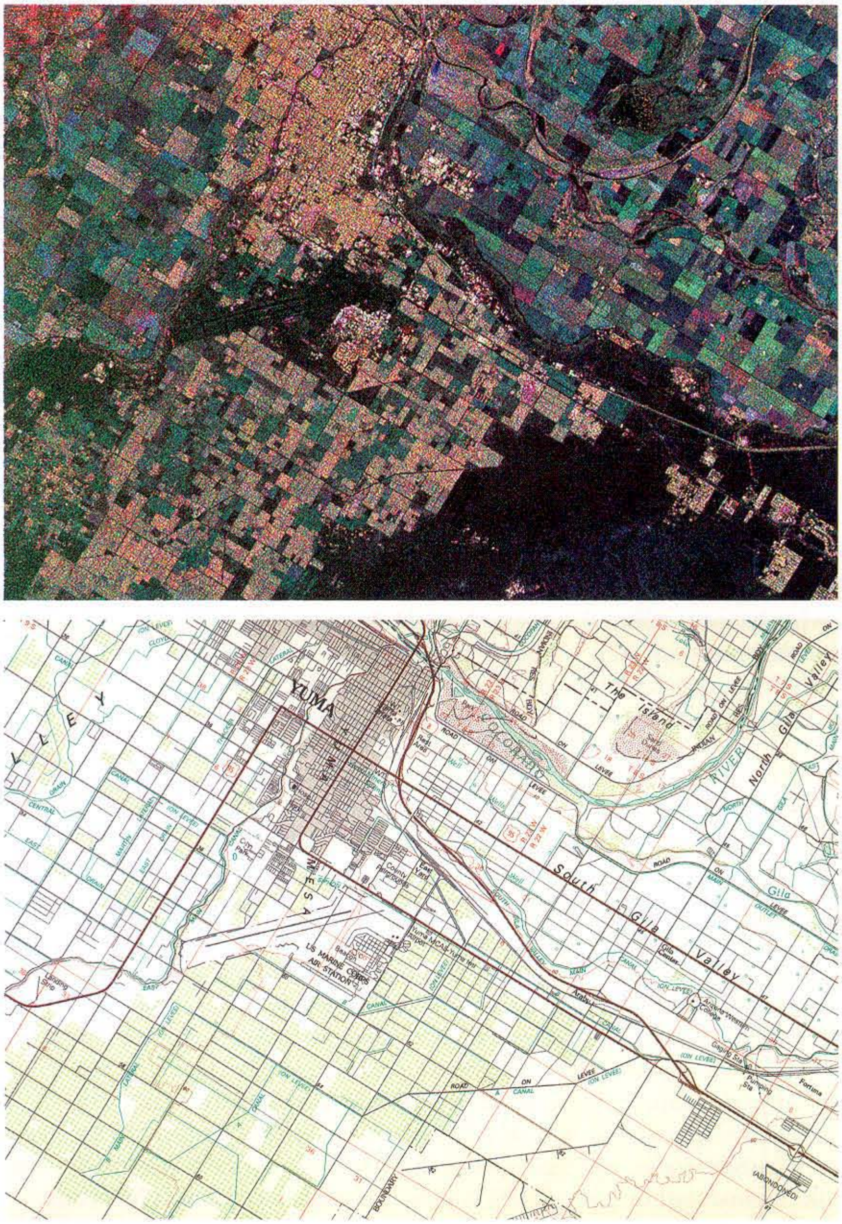
The map showing the entire Earth would be stored within the display itself and instantly accessible, but to plan a hike in the Macdonnell Ranges deep in the Australian outback, the hypermap would need to use the Internet to get the data from a machine in, say, Alice Springs.

alternative: owning a map whose center, scale, and content are determined by me, not by the maker of the map. I envision a high-resolution display that can show custom maps, not just the ones that I happen to have bought for earlier expeditions, or the ones that someone else has decided would be useful enough to have printed. Such a display is generally called a Geographic Information System, or GIS, and is already in use in specialized forms in urban planning, epidemiology, seismology, and many other fields. I would like to develop something rather more general, however, that I call a hypermap. A hypermap would integrate data from many different sources, making the information available to professionals and amateurs alike.

My personal hypermap would be wall-mounted and backlit for armchair use; I'd also like a handheld version, the size of a legal pad, to look at while lying in bed. I would enter the map by selecting a point and having the scale double. After ten iterations, my point of view will have been reduced from a flyover of the globe to a ramble in the countryside. Naturally, things would slow down as the scale increases; the map showing the entire Earth would be stored within the display itself and instantly accessible, but to plan a hike in the Macdonnell Ranges deep in the Australian outback, the hypermap would need to use the Internet to get the data from a machine in, say, Alice Springs. As I looked at the map, its software wouldn't simply sit waiting for my next command, but would instead prefetch data on the surrounding areas, filling its memory in a spiral pattern, on the assumption that I would soon want to look at the land just beyond the frame of my display. Also, perhaps, software agents would be scouring the Net for other maps covering the same area, but containing different information.

For each map I called up, especially if I had set the prefetching at a voracious level, there would be a disbursal of micro-cyber-cash from my credit-card account to various data purveyors, some in Australia. Inevitably, my Net provider would sell this information to a database company specializing in travel-related matters. Over the next few days, junk mail (both electronic and paper) would arrive, advertising the joys of an adventure vacation in Australia. Through automated database correlation, yet another company would have narrowcast to me with piercing accuracy, simultaneously helpful and eerie.

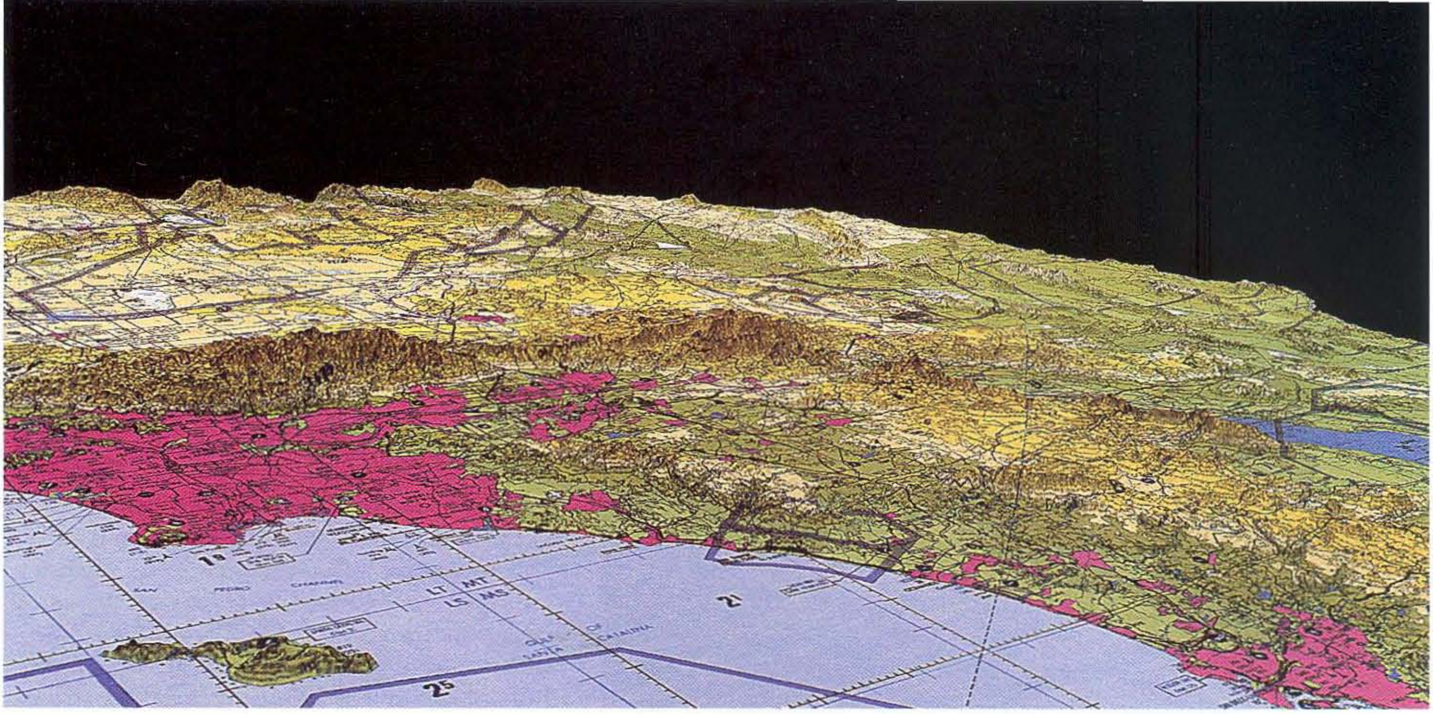
The hypermap would be ideally suited to do what is known in the data trade as fusion: taking different data sets and combining them to produce something new and, one would hope, more informative. Fusion is the essence of mapmaking. A cartographer creates a paper map from survey data and aerial photographs. Information is added from other maps—the cartographer uses a pen or a mouse to draw in roads and county boundaries, and writes or types names such as "Wyre Piddle" next to a beautiful English village that sits next to a small stream. Information is cross-checked (the cartographer compares the scattered height data from the survey with the contour lines drawn from stereoscopic pairs of aerial photographs) and updated (a reservoir's shoreline is redrawn because the dam is now higher than it was). The hypermap should do all this as well, while combining a high-resolution photograph's intense feeling of reality with a cartographer's knowledge of the geographical significance of the landscape. Some maps already approach this—on my office wall hangs an image of Los Angeles as seen from space. The green, forested mountains, the gray-brown urban area, the brilliant white dry lake beds in the red-brown Mojave desert, the San Andreas fault, and a lot of other physical features are shown in absorbing detail. But major roads and place names are also marked, allowing us to get our bearings. We can relate what we see anew to what we already know, and thereby create knowledge from data.



Yuma, Arizona, as seen by SAR (top) and on a U.S. Geological Survey map (bottom). Note how the course of the Colorado River has changed since the map was drawn.

The personal GIS already exists, but without the use of remote servers and the possibility of junk mail: there's a CD-ROM called *Street Atlas*, which gets the most use of the dozen or so CD-ROMs that my wife and I have bought since getting a CD-capable machine. (*Street Atlas* even has the scale-doubling feature, though I would like to point out that I thought of it before I got the CD!) In one sense, these little plastic disks hold a great deal of data: one of today's CDs can hold enough novels to read one a week for ten years, and soon it will be possible to pack a lifetime's supply into an alluring plastic rainbow. But for storing images or geographic data the CD-ROM seems much smaller—more like a single drawer than a library—simply because a page of image takes up a lot more bits of data than a page of text. Consequently, *Street Atlas*'s maps do indeed cover the whole United States, but the streets are really just named geometric lines, all the same width. And there's no indication of any texture to the landscape: no forests, ruins, salt marshes, glaciers, battlegrounds, or wind farms.

There's another, more compelling reason why a physical data repository—even a roomful of CDs!—cannot be adequate for the full efflorescence of the hypermap. The problem is that a single physical object is tangibly limited; no matter how much data it holds, it is obviously finite in extent. In contrast, a networked hypermap can explore a potential infinity of data and can go anywhere in the world to get it. True, the amount of digital geographic data in the world is also finite, but the difference is that it is growing. The hypermap concept carries with it the idea that as data is newly minted from cartographers and orbiting satellites, then all the world's hypermaps immediately gain the new depth. Thanks to airplanes and satellites, the quantity of geographic data is increasing even faster than the violent increase in computer speed that's changing society so quickly. When up-to-date maps of essentially infinite detail are combined with



The view out the right-hand cockpit window of a virtual space shuttle descending toward Los Angeles International Airport. We're about 62 miles high and 138 miles southwest of the airport. Catalina Island is in the foreground, LAX is at the very left, and San Diego can be seen at the far right. This relief map combines an air-traffic control chart issued by the Federal Aviation Administration with digital elevation data from the USGS. The vertical relief has been exaggerated by a factor of 3.5.

cellular phones and high-accuracy geographic positioning systems, can the concept of an expedition into the wilderness survive?

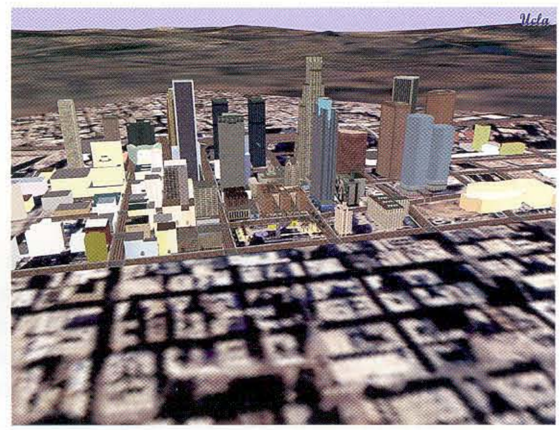
So we zoom in closer and closer and the map's scale gets larger and larger—what happens when we let our imaginations play with this system? Suppose the map becomes three-dimensional, like those plastic maps that you can run your fingers over to feel the mountains. Perhaps the viewer will use a virtual-reality helmet to land an airliner at LAX, or loop-the-loop in Arches National Monument, or fly through the glacial canyons of Antarctica and over Everest.

An existing system of some interest here is the "Virtual Los Angeles" project—created by William Jepson and the rest of the Urban Simulation Team from UCLA's Department of Architecture—a virtual model of large tracts of the city, complete with trees and graffiti. Graduate students shoot video footage of the streetscape, which is fused with satellite and mapping data into a seamless, realistic, textured urban landscape. The user can then "walk" around within the model by means of a mouse, a joystick, or a virtual-reality helmet. The city is intensely real, yet eerily deserted—the streets and sidewalks are practically empty because vehicles and pedestrians still take too much computing power at this point to be included profligately.

The Internet is providing this kind of three-dimensional experience today, meaning that all you need is a fancy computer, rather than having to know the right people in addition to having a fancy computer. At the moment, one can tour, among other places, an Italian castle, Jerusalem's city hall, and the city of Berlin. The new protocol that enables this to occur is called Virtual Reality Modeling Language, or VRML; when you download a VRML document, your computer opens a 3-D "browser" that reads the file and allows you to explore the space encoded within it—turning, twisting, accelerating, panning, and zooming at your whim. You might even meet representations of other people, known in the trade as avatars. (If I am ever virtually represented in a 3-D space, I would like my avatar to be the boot token from the Monopoly game.) And VRML isn't just for architectural touring or city planning; it's a method of transmitting any kind of three-dimensional data for interactive exploration. Other Net sites allow the user to wander about within molecular structures, the fruit fly's nervous system, and galaxies, to name a few.

So how can we get closer to the hypermap? Where will all the data come from, and who will pay for it? If the science budget can survive congressional attack, the Earth Observing System (EOS) will be operational in the next few years. EOS is part of NASA's "Mission to Planet Earth"; even if it gets cut, as seems likely, I hope it will just be delayed for a year or two until the next Congress reinstates it. One rationale for EOS is to provide the data needed to predict the effects of global warming in specific, quantitative, local detail for long-range planning purposes. The current climate models, even those that run on the fastest supercomputers, have as inputs scattered observations supplemented by sharp guesses, and give vague, global predictions as outputs. When the EOS data start coming, there

A flight into Jepson's Virtual L.A. model, starting over Catalina Island and then hooking around to land at the intersection of 5th and Hill from the east. From here, one could stroll around downtown. In this version of the model, every building and streetscape in a one-square-mile area is modeled in three-dimensional detail; the surrounding city is roughed in from LANDSAT photos. Detailed models of several other parts of the city, including the Pico-Union district, Playa Vista, and part of South-Central L.A., have also been created, primarily for urban-planning studies. Jepson also models streetscapes that don't exist any more—another project shows the Forum in Rome; by pushing a time control back and forth, one can watch the landscape evolve over the centuries.



will be much more sharply detailed predictions based on a much firmer footing. EOS will bring in satellite-based remote-sensing data about Earth's land, oceans, and atmosphere at a vast number of gigabytes per day. Supercomputer centers and data-handling warehouses are already deciding how to process and store the data: silos of tapes and disks will be needed, and the task of keeping it organized, catalogued, and accessible will be Herculean.

And the data aren't just digital photographs, but the outputs of other sensors that have nothing to do with visible light and work instead in infrared or microwave frequencies. There's a strong analogy here to astronomy, which was confined to optical observations until the arrival of radio telescopes. Today, a burgeoning family of telescopes observes the entire electromagnetic spectrum, neutrinos, and soon even gravity waves. The invisible emissions captured by these instruments have provided a new view of the universe, revealing it to be a violent and capricious place, in sharp contrast to the quintessentially perfect "music of the spheres" of the medieval imagination. In the same way, the wide availability of high-resolution geographic data will change our view of Earth, making it at the same time more familiar, more mundane, more complex, and more precious.

One source of such high-volume data is Synthetic Aperture Radar (SAR). Parts of Earth that had previously been difficult to see with visible light because of almost continuous cloud cover, can now be seen clearly by radar. SAR can see through clouds, vegetation, and sometimes even

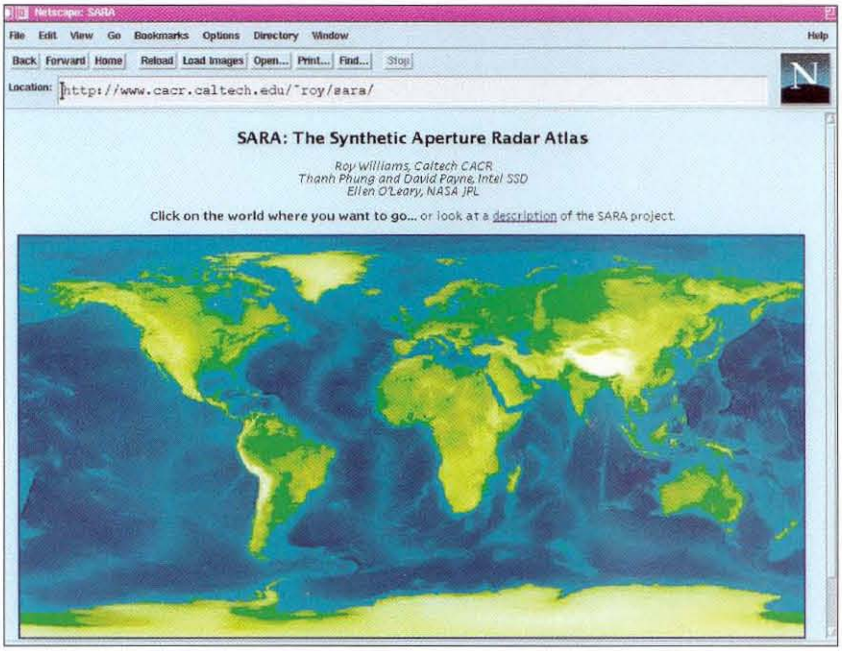
SAR can see deep enough into sandy desert to discover an ancient ghost city on the Silk Road, and can espy eco-friendly farming taking place beneath the canopy of the Amazon rain forest. SAR can measure the moisture content of Kansas cornfields, and differentiate spruce from birch in the Russian taiga.

a few meters of sand. In the Andes, volcanoes have been discovered that were previously unknown, due to their inaccessibility at ground level and to being shrouded in clouds and fog when looked at from above. SAR can see deep enough into sandy desert to discover an ancient ghost city on the Silk Road, and can espy eco-friendly farming taking place beneath the canopy of the Amazon rain forest. SAR can measure the moisture content of Kansas cornfields, and differentiate spruce from birch in the Russian taiga. SAR can trace the movement of Chilean glaciers, document the destruction of African gorilla habitat, probe the geology of Hawaiian volcanoes, determine the vintage of Antarctic sea-ice, and monitor the recovery of Yellowstone from forest fires.

In order to see so much so clearly, there is of course a price to pay—the raw data from the satellite are not directly visible, but need to be processed by a supercomputer before becoming intelligible. Such a project has been under way at Caltech and JPL for two years now, and it's a massive endeavor involving many people. We feed Intel and Cray parallel supercomputers with tapes of raw data and receive multichannel color images in exchange. Every pixel in a color image conventionally represents three data channels, encoded in the colors red, green, and blue, which correspond to the three kinds of receptors in the human eye. But SAR takes data at eight or more channels, leaving a choice of how to throttle the flow down to only three. Such filtering choices can be made to emphasize different aspects of the terrain; for example, to identify types of trees or the composition of volcanic lava, or to gauge the quality of potential ski slopes.

For the armchair explorer, part of the exhilaration of this remote-sensing data is that it has not been processed and digested by a human, only by a computer. There may be the ruins of a hidden city, barely visible without contrast enhancement, or a lake forming where none was known before. "Traveling" by means of SAR data carries the possibility of discovery, much like that offered the patient comet-watchers, roving the sky with binoculars. By comparison, making the trip by paper map will feel like looking at a star atlas instead of looking at the sky. SAR data are not simple pictures to be examined, but can be reprocessed in many ways—just as statistical data can be massaged and processed to highlight, emphasize, and maybe even cheat. When we combine SAR data with conventional maps, we can see correlations and associations that were previously hidden, thereby creating knowledge, and—who knows?—perhaps a scrap of what we all crave: insight.

With my colleagues Thanh Phung and David Payne of Intel Corporation and Ellen O'Leary of JPL, I am developing a pilot version of a World Wide Web–based hypermap, called SARA, for Synthetic Aperture Radar Atlas. SARA actually lives on a supercomputer here at Caltech, but you can get to SARA's Web site via an ordinary Web browser, such as Netscape. SARA welcomes you with a map of the world, on which you click in the general area you wish to visit. This in turn brings up a closer view of that region, in which the available SAR data sets are highlighted in red. Clicking on a red zone brings up a "thumbnail" black-and-white SAR image. These images are compressed eightfold from the actual SAR data, meaning that the smallest details one can see in the thumbnail image are eight times bigger than the smallest details one can see in the actual data; similarly, the color channels of SAR data are replaced by one channel rendered in shades of gray. Thus the volume of data to be transferred to your computer is a mere 1/512th of the actual SAR data set—a necessary concession to the speed of the average modem. If you're directly connected to the high-speed part of the Internet, you can then call up the real SAR images, set the three color channels to show you what you want to see, and zoom in to bring up the spatial data that got compressed out of the thumbnail version. This is currently unrealistic for home or high-school use, but soon, we netmongers hope, higher-speed networking and even-faster cheap computing will make its way to the domestic hearth. SARA was demonstrated



Click anywhere in this map of the world on SARA's home page, and you get a map of SAR data sets available in that region.

The taxpayers have already paid for the raw material, but not for the mining and processing that is necessary to understand it.

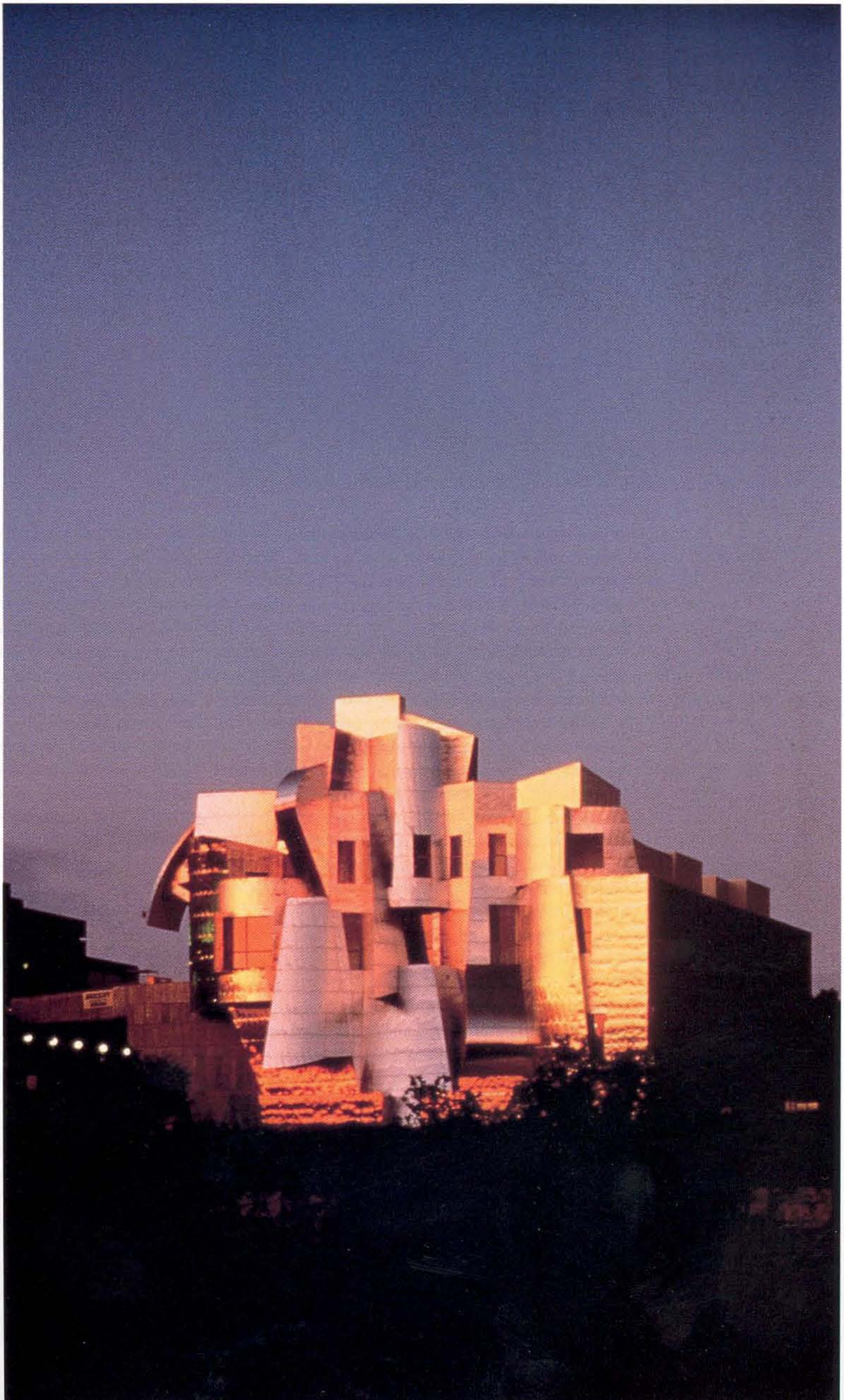
at the Supercomputing '95 conference in San Diego last December, running on an Intel Paragon machine, and, I think, was received with some interest—we had people standing in line to see our show.

The technical path to the hypermap is fairly well marked at this point. There are enormous challenges awaiting in database management, and in designing means of exploiting and presenting the data that will be useful to the expert and novice alike, but the routes to solving these problems look reasonably clear. More difficult are the political issues inherent in making available remote-sensing data owned by the government. Part of the difficulty springs from copyright issues; the laws governing the ownership of electronic documents are being written and rewritten even as this article is. But the most daunting issue is cost: the taxpayers have already paid for the raw material, but not for the mining and processing that is necessary to understand it. Geographic data produced at the public's expense has traditionally been made available for the cost of the duplication. In the old days, this meant that you wrote a check to cover the cost of the clerk photocopying the information and mailing it to you, or in the case of a U.S. Geological Survey map, the cost of printing the map. But now, the cost of duplication includes the cost of the electronic pipeline that brings the data to you—the networks, the disk farms and tape robots, the software to run them, and the people to keep it all going. They all cost money, and who will be paying how much for this service is probably the thorniest question of all. Significantly, the U.S. government has already decided that EOS data will be available not only to the priesthood of scientific digerati, but also to colleges, high schools, and individuals.

I hope that these issues can be resolved, and the hypermap brought to fruition, because it will deliver information that is not only useful but inspiring, enabling individuals to see the world through their own uniquely personal maps. In earlier times the translation of the Latin Bible into the languages of the common folk allowed fresh views on Christianity; now hypermaps will allow people to choose how raw data are to be processed and delivered to them, thereby minimizing the distorting lenses of those who would "interpret" the data for us. □

Roy Williams, a senior staff scientist at Caltech's Center for Advanced Computing Research, earned his bachelor's degree in mathematics at Trinity College, Cambridge, in 1979, and his PhD in physics at Caltech in 1983. After postdoctoral stints in England, he returned to Caltech in 1986. His non-map-related research interests include fluid-flow algorithms, differential equations, parallel software, and high-speed networking.

This is his second article for E&S.



Current Work

The questions I get asked most often are: How do I concoct these crazy things? How do I talk clients into them?

by Frank O. Gehry

The University of Minnesota in Minneapolis wanted an art museum not made out of brick like the rest of the campus. In a land of mostly gray skies Gehry's shiny stainless steel facade picks up the evening light.

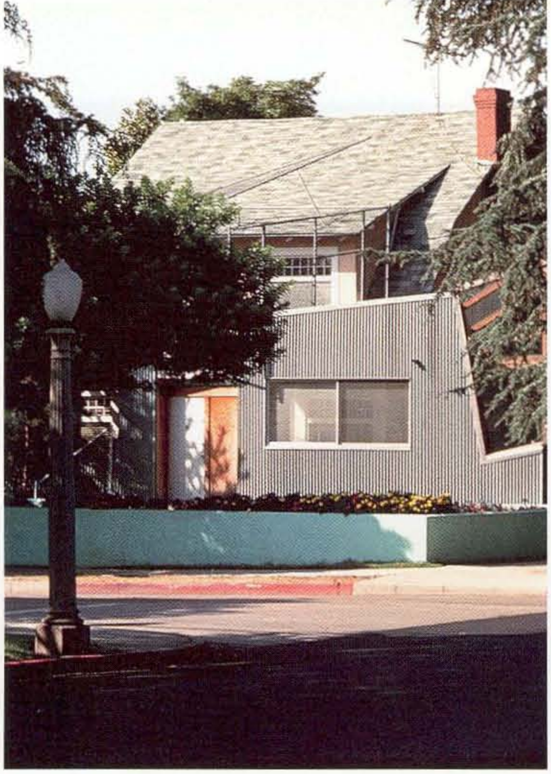
The fourth annual James Michelin Distinguished Visitor's Lecture took place on November 8, and was introduced, as has now become the tradition, by Vice Provost and physicist David Goodstein, who claimed that he teaches philosophy at Caltech and does research in condensed metaphysics. As usual, Goodstein thanked Bonnie Cashin, the distinguished fashion designer, who donated funds to support the series to foster creative interaction between the arts and the sciences. The series is named for Cashin's uncle, James Michelin, "a petroleum geologist whose ambition it was to attend Caltech. Although he was a brilliant geologist, enormously successful in his career, he never achieved his ambition to attend the Institute, and that's why he never lost his affection for us," said Goodstein, as he says every year.

But an opportunity for a new joke came when Goodstein noted that the evening's speaker, distinguished architect Frank O. Gehry, had won the Pritzker Architecture Prize, which he hastened to explain is like the Nobel Prize in architecture and not to be confused with the Pritikin diet, for which you only get the No-Belly prize. When the groans from the audience subsided, Goodstein went on to describe the significance of the fish motif in Gehry's work, tracing it to his Toronto boyhood, when he was allowed to play in the bathtub with the weekly live carp before it was turned into gefilte fish.

In addition to the Pritzker Prize, which he won in 1989, for his "significant contributions to humanity and the built environment through the art of architecture," Gehry won the Wolf Prize in Art (Architecture) in 1992, the Imperiale Award in Architecture from the Japan Art Association in 1994, and was the first recipient of the Dorothy and Lillian Gish Award for lifetime contribution to the arts. He has received six honorary degrees and has held named chairs at Yale and Harvard. The New York Times *has called his buildings "among the most profound and brilliant works of architecture of our time."*

When I got out of school, city planning was what I really wanted to do. But it has always been very difficult to be an effective designer in the modern American city because of the complexities of our cities—and because of the dollar-driven priorities where visual quality is low on the wish list going in, but much pined for after the fact. Democracy creates cities in which there are so many constituencies pulling in so many different directions that it's very difficult to give a form to the city other than the chaos that we seem to have. Since I like democracy, and I don't want to change the government that we have, I'm optimistic that we can find a way of making better cities within these constraints, rather than looking backwards to, say, Europe in the 19th century, where a different political system enforced the form of the city. We have to try to work with what we've got.

The questions I get asked most often are: How do I concoct these crazy things? How do I talk clients into them? How do I do it? What I do has grown out of years of evolution of a way of thinking. It seems very ordinary and logical to me, but I know that isn't the way others see it. So I'd like to try to explain how my buildings evolve.

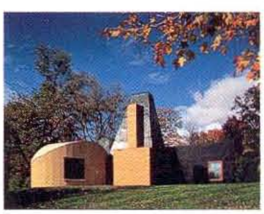


Left: Gehry's own residence in Santa Monica typifies his work in the 1960s and 1970s—buildings that used rough, raw materials.
Far left: Furniture made of laminated cardboard was so popular that Gehry had to stop making it for fear he would end up designing furniture for a living.
Below: The Loyola Law School in Los Angeles was conceived as a kind of urban village with relation to the surrounding buildings.

I started my architectural practice in 1962, and in those early days I couldn't get good craftsmen for the kind of budgets I was working with. The craft was starting to disappear, and I couldn't get the kind of perfection that I'd been trained by my Viennese teacher to try to achieve. At that time, my artist friends were making sculptures and paintings out of trash: Jasper Johns used coathangers and plumbing devices; Rauschenberg used old tires; Donald Judd was working with galvanized metal. The kind of raw beauty of this art, as well as the small budgets that I had to deal with, encouraged me to think that way about building and architecture, and I started optimistically working with what was available. I used rough materials such as the raw framing and lumber as it came straight from the lumber yard, one example being this house in Santa Monica, which I built for myself in 1978.

I also explored materials for furniture, such as corrugated paper or cardboard; I was interested in the strength of the material, and I was also interested in the finish. I wanted to make furniture that constituted one idea—that the structure and the finish were the same. Using the edge of the paper and laminating pieces together, I ended up with a soft corduroy-like surface that was pleasing to touch and still allowed all kinds of structural hi-jinks like double and triple cantilevers, which you can actually stand on and bounce. When this furniture found its way to Bloomingdale's in 1972 and was rather successful, it scared me because I was starting to find myself in a career in furniture design before I had become known as an architect. So I stopped the

Right: Collaboration between architect and artist produced the Chiat/Day headquarters in Venice, California, better known as the "binocular building" for Claes Oldenburg's sculpture at the entrance. Below, top: Thinking of a house itself as a sculpture in the garden was the idea behind this guest house next to a Philip Johnson house in Minneapolis. Bottom: This furniture factory in Sacramento of galvanized iron and copper is an "urban idea" in the middle of an industrial park.



whole thing and took the stuff out of Bloomingdale's. I told them I didn't want to do that and got everybody mad at me. Then I made some furniture for myself that nobody would like.

My first large local commission (not that large—about $4–5 million) was the Loyola Law School in 1978. I liked the idea of making the building itself a kind of urban village, and I was also interested in including the neighborhood; all of the surrounding buildings became part of the composition. Students and faculty had asked that it look like a place to study law, so I used minimal decorative elements such as columns, to evoke this.

Another local building, the Chiat/Day headquarters in Venice, California, is also an urban idea. I believe that eventually our cities have to be some kind of collaboration between different thoughts, different ideas, and different constituencies. And here I collaborated with the artist Claes Oldenburg and his wife, Coosje Van Bruggen. Before this project, artists were usually given a plaza in front of a building and told to make a little mud pie of their own there; this has become affectionately known as "plop art." I thought it would be a great experiment not only to bring the artist into the building as a major part of it, but to put him front and center—give him the entrance. After I started down this path and Claes and his wife made the first gesture, I realized how good it was going to be. Then I became a little worried that some magazine would cut my parts out and just show the Oldenburg entrance, which actually did happen: two architectural books came out with just that on the cover. But by that time I was so identified with the project (I think of it as the "binocular building" project) that I was able to survive the ego problem. I really think architects have to be able to play together—maybe not always in a small building like this one, but I think that doing a Rockefeller-Center-scale project single-handedly is antithetical to today's culture.

It has been noted that I'm interested in fish. Years ago, Norton Simon had a Shiva figure from India on loan for awhile. When he showed me this figure, he commented, "frozen motion." I remember looking at it and looking away, and I was sure that it had moved. So I tried to design a trellis for his house using that idea of frozen motion, which confused the hell out of him, and he, being a prudent businessman, stopped me. My "unfinished symphony," he called it. But I continued to pursue it in other work, because the idea of inert materials having a sense of motion appealed to me. In the end it becomes another kind of decoration. Buildings need *something*, and whether movement is important or not, time will tell. But the idea seems to have some logic in our fast-moving society.

I started with the fish because my colleagues were starting to regurgitate the past. A few years ago modern architecture was abandoned in favor of a rebirth of Greek temples with pediments and so on. I didn't like this trend and thought, "Well, if we're going to go back in time, why don't we go back further—to fish, which existed 300 million years before man?" So I started drawing these fish as a symbol of my anger.

Above and right: One of Gehry's first attempts to use curvy shapes (before computers) was in this furniture museum in Weil am Rhein, Germany.
Below: Gehry's first fish was a lamp that emerged from broken pieces of another lamp—and from his anger at architectural retrogression.

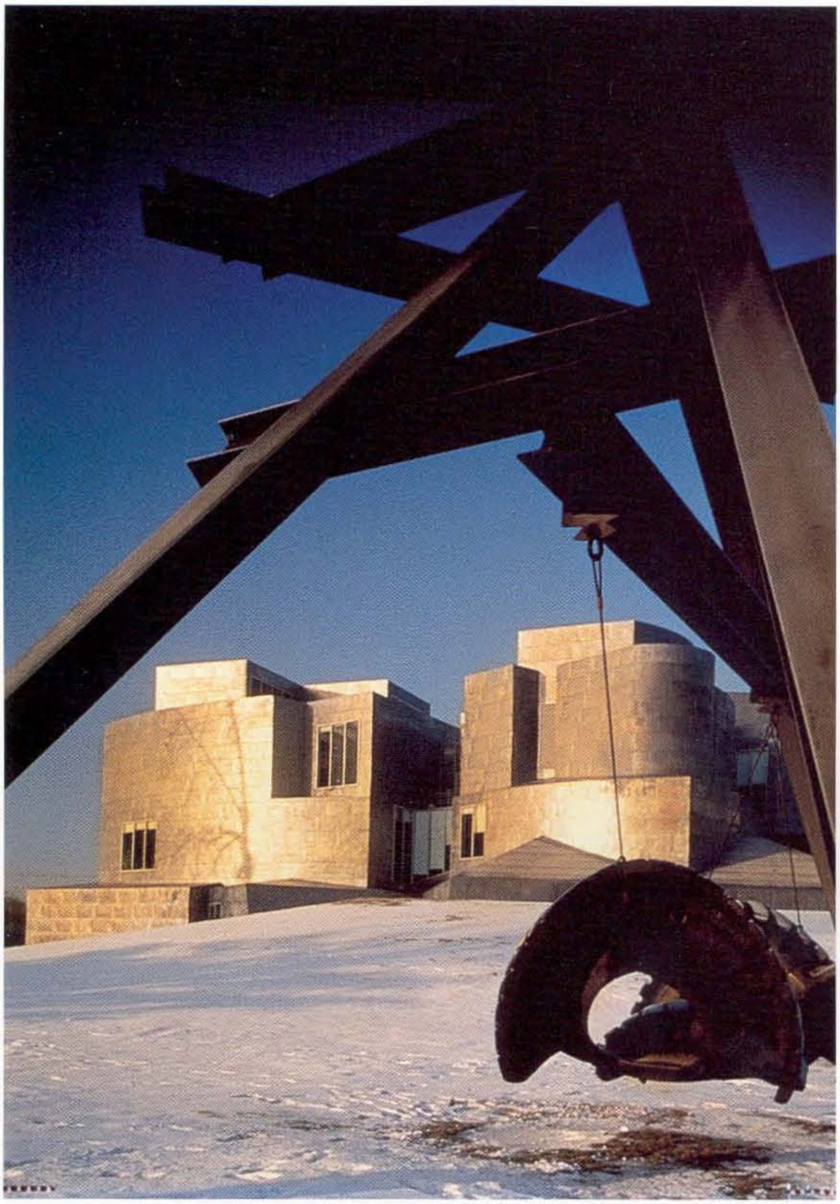
Then somebody asked me to make something with Colorcore formica. Because this material is translucent, I made a lamp with it. But when I didn't like the way it turned out, I threw it down; it broke into a bunch of pieces and I made a fish.

This led to many other fish stories. I made one that was 25 feet long, in wood, for an exhibit in Florence, and when I stood beside it, it had the same effect that the Shiva had had, and I thought, "Eureka, I've found it!" So I started to make forms of buildings by cutting off the tail and head, because they're kind of funny to make buildings out of, and then started to see how minimal the abstraction could be, while still keeping the form. Out of this came a lot of study and work, which led to the realization of some double-curve forms. These curves seemed almost impossible to build (or at least very expensive), and I spent the next years learning how to do it. The furniture museum in Switzerland shown above is an example of one of my first attempts to use these curvy shapes. You can see how awkward it was—not because of the workmanship but because of the primitive descriptive geometry techniques for drawing such things before computers offered us better tools. Oldenburg was already there, so I didn't have to bring him; I just nuzzled up beside him.

Sometimes it's more difficult to nuzzle up to what's already there—for example the art school that we were commissioned to build next to the Toledo Art Museum. How do you make a building that attaches itself to something that's so strong and classical, with its light marble, and colonnades and columns? Most architects with commissions like this try to copy it and usually fail. As in the Salk Institute in La Jolla, the new addition can't *really* be like what Louis Kahn did, so everything that mimics Kahn's work trivializes it. We didn't do that in Toledo. Since the museum is an expansive long building, we decided to make the opposite—a compressed building. I wanted it to look like compressing a piece of coal into a diamond, pushing it together as tightly as I could, so that it looks as if it would just spring apart if you pulled the plug.

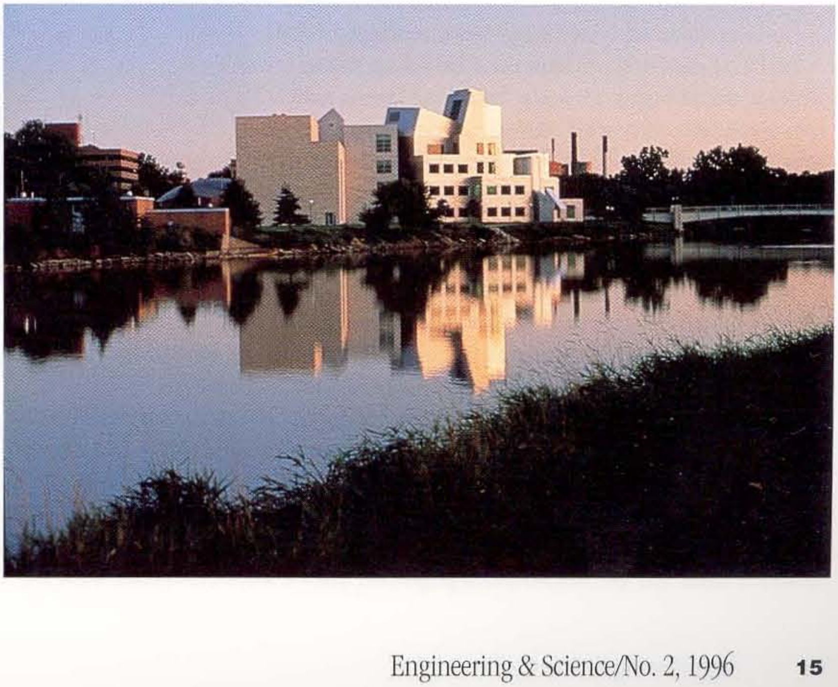
We also did an art museum at the University of Minnesota. Since the campus is all brick, the president of the university asked me not to make another brick "lump." He wanted the building to attract attention, because until this point the art facilities at the University of Minnesota were not in anybody's consciousness. So we used stainless steel. I agonized about using this shiny stainless. But I spent a lot of time there looking at the site, watching the light. The winter Minnesota skies are pretty gray, so we angled the facade to the west, where it picks up the sunset—or whatever light remains. Inside, the galleries are very simple, with skylights above eye level.

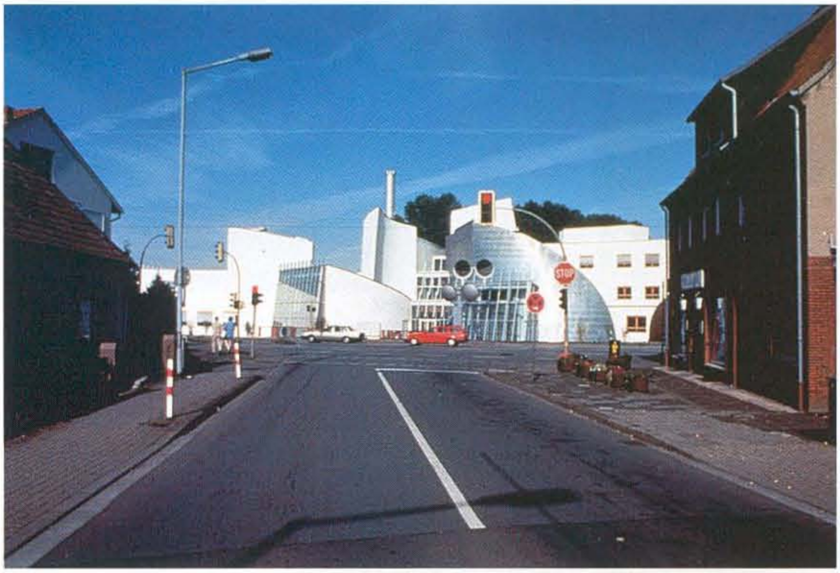
In Basel, Switzerland, we were hired to build an office building, a headquarters for a furniture manufacturer next to a factory of theirs. (This was the same client for whom we did the furniture museum.) We kept the main offices simple and rather stodgy, because this place sells furniture. We were afraid that if we made a wiggly-wobbly building the customers would say, "Well, your furniture looks good in this building but we

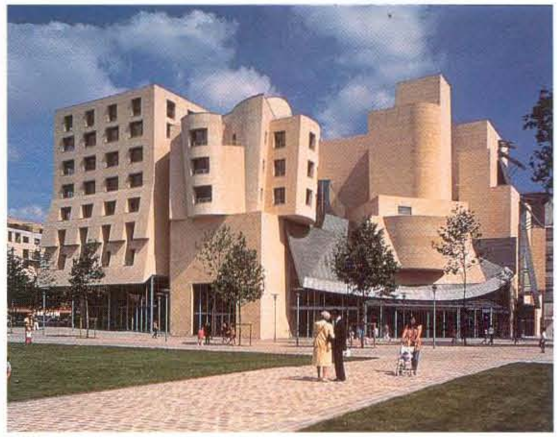


Left: For the art school, the Center for the Visual Arts, attached to the Toledo Art Museum, Gehry built a tightly compressed building, in contrast to the long, classical colonnades of the museum. The exterior of the building is lead-coated copper.
Below: The headquarters of a furniture manufacturer in Basel, Switzerland, has a fairly straightforward building for the offices and a "wiggly, wobbly" conference center.

Right: The offices of the laser laboratory at the University of Iowa are intended to be somewhat "crystalline," while the support facilities, which are mostly pipes and require no windows, allowed Gehry to design the sculptural shape below.







Right: In the American Center in Paris, Gehry wanted to embody the different parts of the center's programs in the sculptural energy of the building.
Left: Not just metaphorical energy but *real* energy here—a local energy company in Bad Oeynhausen, Germany. The scale of the building was carefully planned to fit into the neighborhood—even the heavily trafficked street.

don't have a building like this." So we made a very simple backdrop and put all the sculptural qualities in the conference center. Bridges lead from the conference center back across into the offices. In the future, other wings will be added to the office building. The building works contextually—the shapes are different from the nearby office building and housing, but the scale of the pieces is designed to fit into the neighborhood. Quite often when I do things like that, by the time the building's built, all the other buildings have been torn down and my building is standing there alone.

I built the American Center out of my love for Paris, where I lived for a year in 1960. I loved the limestone of the city and what I call the "cleavage" of the 19th-century Parisian buildings—the rooftops. I had the opportunity here to make a building along a street and then opening the building into a park. The Center contains housing, a theater, and a language school, so the building has many parts to it. I wanted to give it a sculptural energy to represent the different parts of its synergistic program. But on the back, it's very simple to match the surrounding buildings. When I started, all of these surrounding buildings looked Parisian, and when I finished, the new buildings around me looked like social housing in Copenhagen.

In Bad Oeynhausen, Germany, we designed a building for a local energy company. The client, the head of this company, told me when he met me that energy was not just what people thought it was; it was also musical energy, art energy, and so on. He got off onto a wonderful toot with me on this building. Again, there's a contextual quality in the relationship of the pieces to the neighborhood, even though the building looks a little strange in comparison. The pieces have been carefully planned to be in the same scale with the houses nearby. The most exciting thing about this context is that about a hundred huge trucks go by this site every minute. When you sit in the little cafe across the street, the trucks blend in with the architecture.

Inside, there's an exhibit, designed by Craig Hodgetts and Ming Fung, on energy and saving energy. It has lots of gadgets in it, including a device that brings sunlight into the room, which then goes through a kind of Rube Goldberg contraption before coming down to a tiny, one-inch magnifying glass. This burns a hole in a turning piece of wood, so that at the end of a day you can see how many times the sun came out.

The fish kept getting bigger and bigger, and the one shown on the opposite page, in Barcelona near the Olympic Village, nearly got away. It's made of stainless steel, and we ran into great difficulty trying to describe the curved structure that had to be built underneath. By some miracle someone in our office discovered a program called CATIA used by the French firm Dassault Systemes. They make the Mirage fighter plane. To avant-garde scientists this program is probably old-hat, but it's a pretty good system for us—to allow us to take some of these curved shapes, demystify them, and explain them to real builders who build real buildings. We were able to use the computer to make the shop drawings, actually cut the steel, make the

Below: Difficulties describing the curved structure that supports the metal mesh of this fish—the biggest one of all—in Barcelona led to use of a computer program for designing aircraft that henceforth enabled Gehry to incorporate wavy shapes into his buildings relatively easily and economically.

Left: This bus stop in Hannover, Germany, was designed and built quickly and on a low budget with the help of computers.

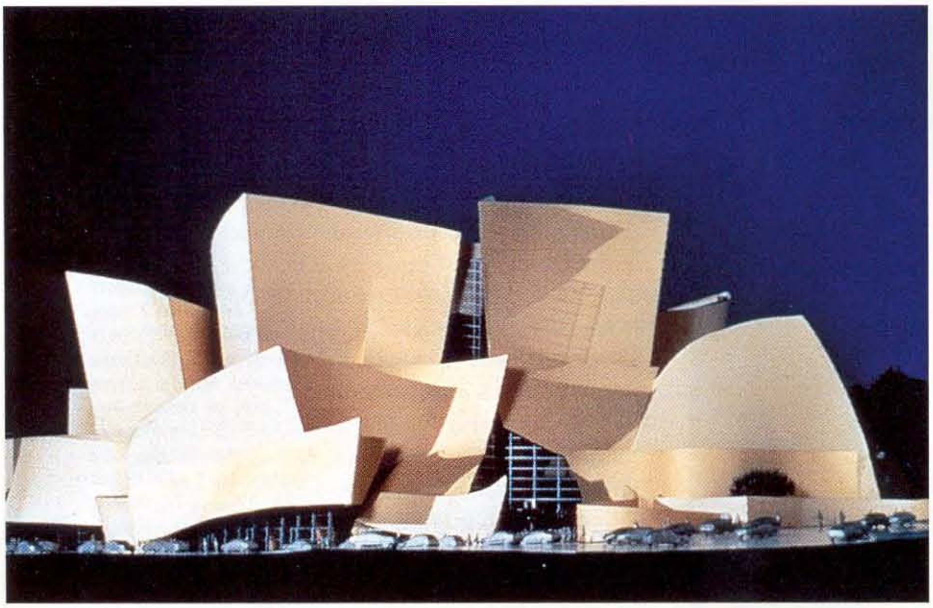
shapes, and put in the bolt holes. It was wonderful to see it being put together and the holes actually lining up. When I say "we," I mean the colleagues in my office. I still do not even know how to turn a computer on. (Later I did play with the computer a bit and actually used it to design some of the shapes for the residence in Cleveland shown on page 20). Artists and people like me who worry about how things look hate computer imagery. I can't stand looking at the screen; the images drain all the juice out of your ideas. But I tried it. It was like putting my hand in the fire to see how long I could stay on the screen. I logged about three and a half minutes before I had to run out of the room. But it's promising, and I'll be able to do it some day.

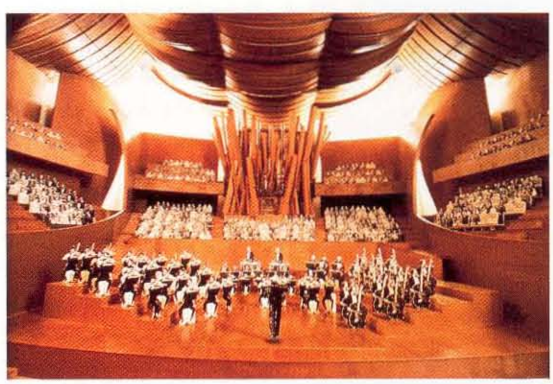
But regardless of my own problems with it, the computer has been very helpful to us. We built a little bus stop in Hannover, Germany, that was all done very quickly on the computer. All the pieces and shapes were cut and made within a very tight budget—I think it was $120,000. Without the computer program I would have just squared it, but the computer allowed us to be daring and still stay within the parameters of a reasonable budget.

One thing that has not stayed within the parameters of a reasonable budget is the Walt Disney Concert Hall for Los Angeles. I talk about it reluctantly because I want it built; but it's not all up to me. The clients asked us for a surround hall like the Berlin Philharmonie, but they wanted to have the sound of the Boston Symphony Hall, which is a shoebox. We met with the selected acoustician, Dr. Nagata from Japan, who told us that the hall should be narrow at the stage end and widen as it went out to the audience. When we went to Berlin to look at that hall and we met the Berlin acoustician, he said that the ideal hall should be *wider* at the stage end. This left us a bit confused, so I had the great idea to get the two acousticians together over dinner and listen to how they discussed this disparity with each other. The German guy was really cranky; Dr. Nagata was very polite, and I'm afraid in the end he won just by being extra polite. We then settled for a wood box that was wider than Boston. The people of the Los Angeles Philharmonic also wanted a hall with no balconies, because they thought balconies created second-class citizens—even though everybody knows that in every great hall in the world the best sound is in the balconies.

In the end, to get the number of seats, we had to put in some very shallow balconies. Dr. Nagata and his crew came and tested every seat. They had comparative data, by the same method of testing, from all the great halls, and after they were finished, told us that this hall would sound better than any of them. They even played a Mozart sonata for me, which they digitized into what it would sound like in the hall. It was quite extraordinary, although I don't believe it. In working with musicians, I have learned a lot of things about sound. One of them is that people like to be in a wooden room to listen to music. Also musicians can come into a space and understand it acoustically. Sometimes they move the orchestra seats around and can, I think, modify the sound as much as 30 percent.

Then, of course, the orchestra has to be good, the music has to be good, and *The Los Angeles Times* critic has to have a good seat. The orchestra has to practice and learn to use the hall for a year or so, and the audience has to be understanding and compassionate. And then after 30 years, when the hall has become older, and the great musicians of the world have conducted there, and great recordings have been made there, nobody will dispute that it's the greatest hall in the world. When you go to Boston Symphony Hall today, and the brass section is a little louder than it should be, and you sit in the orchestra and get blasted, you don't mind because you've been told that it's the greatest hall. So you believe it. It's precarious to do one of these things, but I'm hopeful.

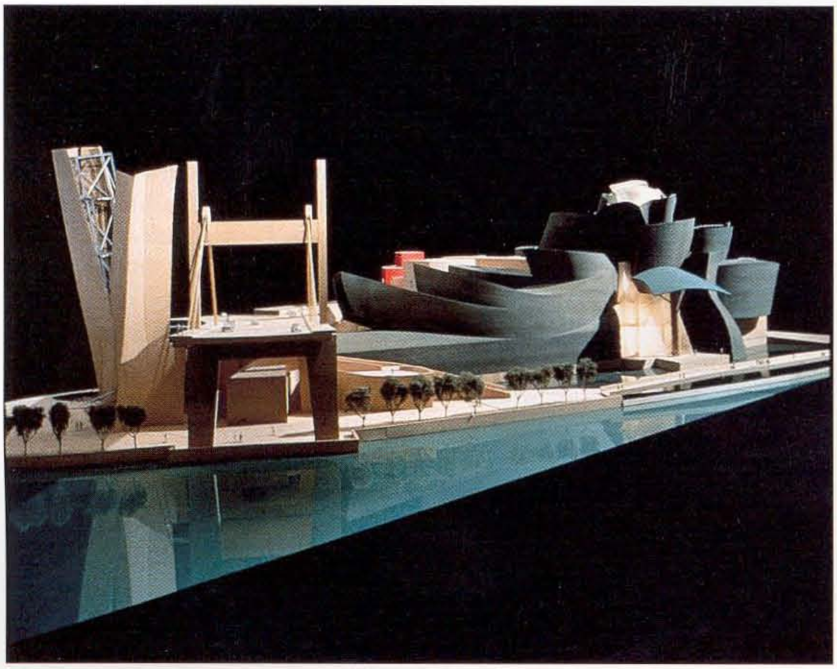




The exterior of the Walt Disney Concert Hall, which has yet to begin construction in downtown Los Angeles, is made of an Italian limestone, cut by computer into sweeping, curved components. The interior finally ended up a wide, wood box with shallow balconies.

Disney Hall's exterior, on the other hand, has been relatively easy. All of the part that looks as if it would have been way out of our reach was within budget. We had been told that the building had to be stone, and we selected a beautiful limestone from Vicenza. When we finished the design and turned it over three years ago to other executive architects to do the drawings, we were told that it was all on budget. Our office maintained control of the exterior, because it was wiggling and wobbling, and we didn't think anybody would know how to do it. A year or so ago, when the project collapsed, this was the only part that was still on budget, because of the computer work. The gadget for digitizing the shapes allows us to take the shape of a particular piece right off the model. Each piece of stone is analyzed; the computer pretends to cut it and makes a program; then that program is given to the stonecutter in Vicenza, who, with no hands, makes that piece of stone. On Disney Hall the most complicated piece of stone is fairly flat. The larger shapes come out of the subtlety of the cutting. When you look at the building you don't understand it as a bunch of rather flat blocks—it just aggregates into those shapes. All the stone for Disney Hall was quarried and ready

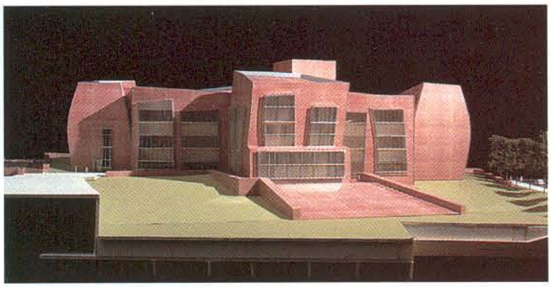
"Fred and Ginger," as this building was dubbed by the Czechs, was made to fit in with the buildings along the Prague riverfront (right) but not copy them. What Gehry calls "implied towers" pick up the look of the 19th-century neighborhood, and floor-to-ceiling windows correspond to the busier texture and higher ceilings of the older buildings. "Ginger" sticks out from "Fred" so that the street will curve into the bridge, a feature requested by the city.
Below: The Guggenheim Museum in Bilbao, Spain, was done, like Disney Hall in Los Angeles, on a fast track, using computer technology. Computer fabrication of the steel shapes came in under bid. This model was also milled out by a computer with special tools.



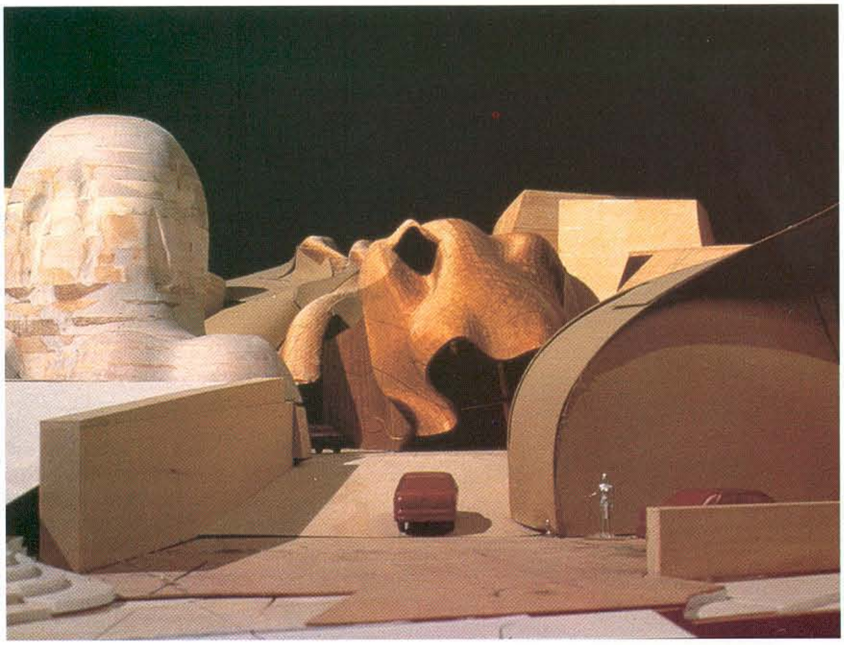
to cut when we stopped.

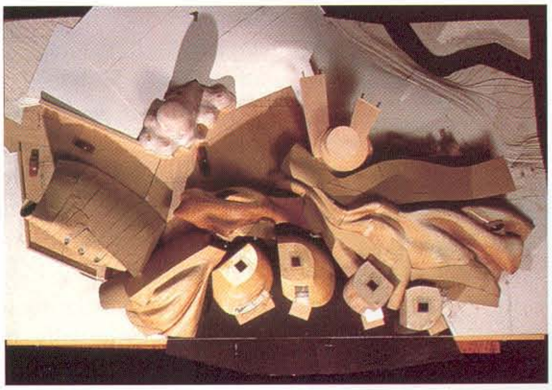
One building that wasn't stopped is the office building in Prague, shown above. President Havel lives here, next door to our building; his grandfather designed it a long time ago and liked it so well he even built two identical buildings. In 1945 an American bomber accidentally dropped a bomb on this site, and Mr. Havel, when he became president, asked that it be fixed. I was recommended through a Dutch company, and when I met with Mr. Havel, he asked me to make a building that fit into the site with its 19th-century neighbors but that didn't copy them. Unfortunately, Mr. Havel's wife was a friend of Prince Charles, and she was horrified that I was chosen. When the Czechs saw the models in the earlier stages, they named the building "Fred and Ginger." Articles appeared in the press about "Fred and Ginger," blaming me for bringing Hollywood kitsch to Prague, even though *they* had invented the names. This created such a fuss that the building was actually put to a public referendum. We got 68 percent of the vote. It should be finished this month.

In Bilbao, Spain, we're building the Guggenheim Museum. Bilbao, cradled in a lovely green valley, is a beautiful town with a character like a section of Paris. The main city, sort of blocky with a "tough" aesthetic, was mostly built in the 19th century. The industrial development along the river is now being converted into cultural facilities. Originally, the museum site had been designated in town, but that didn't work. This was a competition that we had won, and when we were taken on a tour of the city and asked where



Left: The molecular biology laboratory at the University of Cincinnati Medical School is made of brick to match the campus and for reasons of cost, but Gehry selected the particular brick for its warm glow in the Cincinnati light. The building is in the shape of a simple cross, with offices in the center and the labs pulled out to the sides.



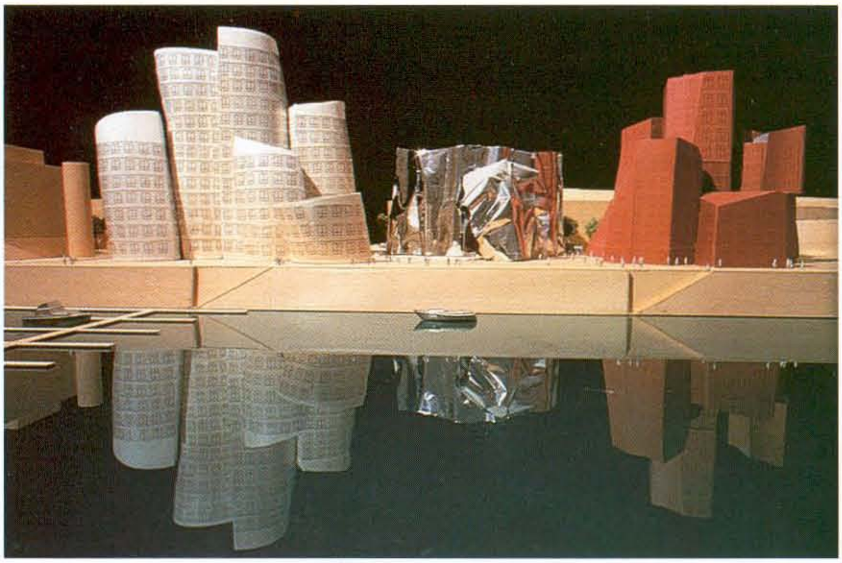


This residence in Cleveland was an experimental project, from which many ideas emerged, but it will never be built. Gehry actually interacted with the computer himself to design some of the shapes.

we wanted to build, I picked out this site. The site also includes a piece that stretches under and past a large bridge. We threaded the building through the bridge tower to the other side, making a relationship with the heart of the city down river.

When I saw the site for the first time, I made a sketch that looks a lot like the finished building. Whenever I do that, it makes me wonder why I have to work so hard. Why can't I just *do* it? But it took two years to go from the initial sketch through rough models and various computer-generated models to the finished design. We work in several model scales at the same time in order to insure that we don't get fixated on the particular scale that we're working on. You can become enamored of your drawings and your models as you're working, and lose sight of what you're doing in a scale sense. Shifting back and forth between several different scales forces you to think of the real building. This building was done in the same way as Disney Hall—on a fast track, using computer technology. In this case our office was able to do *all* the drawings, but since it's thousands of miles away in a country with a different language, it was still a complex project. There aren't many straight lines in it. It's just as complicated as Disney Hall, but it's all being built right on budget. By using the computer, the steel fabrication came in 18 percent under the budget as bid. So it *can* be done.

When I started this project, I was reacting to the space created by Frank Lloyd Wright in the Guggenheim Museum in New York. Over the years I had witnessed the trouble people had



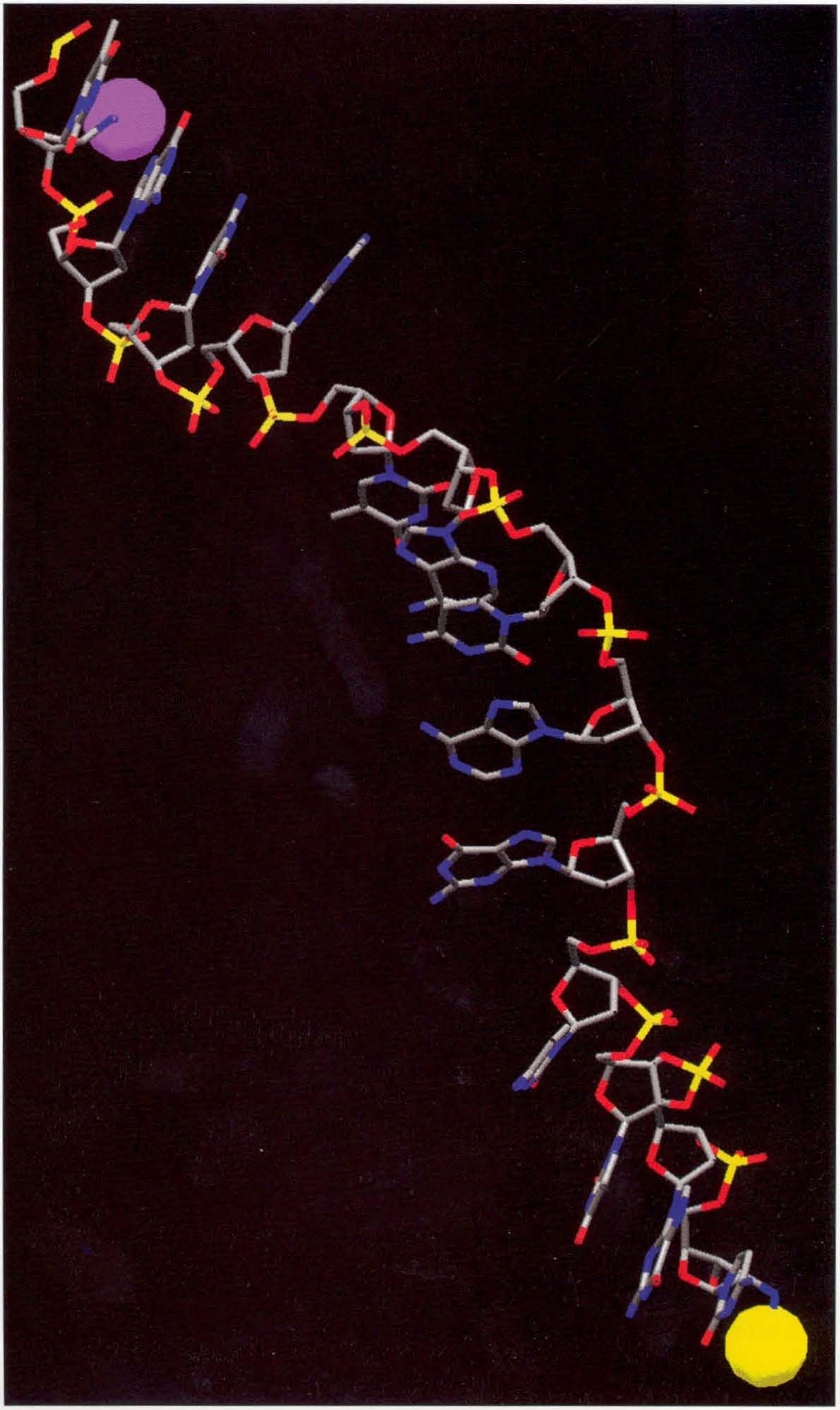
Above: Gehry decided to make this office building in Düsseldorf, Germany, three buildings instead of one, in order to fit in with the street pattern and break down the scale. The three are sculpturally related yet have separate identities. This model was also developed with the use of computers.
Below: The practice rink for the Mighty Ducks hockey team was commissioned by Disney and struck a particular chord for hockey-fan Gehry. (Photo courtey of Erich Ansel Koyama)

hanging shows in that space, and so I was trying to be "polite" on the inside and make it easier on the artists. But my client, Tom Krens, director of the Guggenheim Museum, told me, "Now, I want you to be more cantankerous than Mr. Wright; I want you to outstrip him, take him on." He said that some of the best shows they've had in New York were shows in which the artists were reacting to or interacting with Wright's space. So my atrium is twice the height of the one in New York. And the artists, at least the living ones, can interact with three shaped galleries. The dead artists, who can't defend themselves, will get the stodgy galleries plus the rectilinear galleries that can be sliced out of the long, straight exhibition hall if needed.

The piece of the building that's along the river was envisioned as evocative of the river and the boats, and the back side, facing the city, would develop a relationship with the city. The entrance to the museum is down a ramp into a glass enclosure; the ramp lines up with the city street, and as you come from town you're sort of swept into the entrance. I'm hoping to put a hologram of Frank Lloyd Wright standing there in the entrance sneering at us. The building's exterior skin will be titanium, a metal mined in Russia and Australia that has only recently become available for building use. We've spent a year studying the materials for this building and working with the factory to get the right finish on the titanium. The nice thing about the material is that in the rain it doesn't look metallic; it has a warm glow. In Bilbao, which gets a lot of rain and cloudy days, it will be a very friendly facade.

We've been asked to do another museum in Seoul, Korea. Because it's on a very complicated urban site next to office buildings, our first ideas related to the office buildings, and the shapes became part of those buildings. Then we realized that this wasn't appropriate; a museum should have its own language. There are some palaces and small-scale buildings near it, and we decided to relate to those in scale, but I still needed to find myself in Korea and find a language that has some relationship to the place. We started with blocks and sketches, and found inspiration in the beautiful Korean landscape paintings and screens that we looked at. Unfortunately, Seoul has a lot of bad copies of American and European buildings. The city has been built fast, and what's left that is beautiful is the landscape. With this building I'm trying to make a relationship with that landscape. The design isn't finished yet; we are still in the early struggles of getting ideas and figuring out how to start.

I'll close with a hockey rink in Anaheim. Three years ago, when I turned 63, I decided to start playing ice hockey. My kids had been playing hockey, and these rinks are cold at 5 a.m. when you go to practice. So when Michael Eisner asked us to do the Mighty Ducks practice rink, I loved getting involved with it. I wanted to use a lot of wood, because I knew how cold it could get. Disney (not the Ducks) challenged us to a hockey game. We beat them 11-5. □



Heart Attack or Heartburn: New Chemical Diagnostics That Make the Call

If the creators of Star Trek *can build a medical tricorder capable of instantaneous diagnosis, why can't we?*

by Thomas J. Meade

Two-stranded DNA likes to coil up into the double helix whose shape has become emblematic of the Age of Biotechnology. But a single strand of DNA, like the one shown on the opposite page, flops about loosely like an overstretched telephone cord that's lost its curl. This lackadaisical behavior has pronounced effects on DNA's ability to conduct electricity, as Meade's lab has discovered. The researchers timed the flight of electrons from a ruthenium atom (yellow) at one end of the strand to a second ruthenium atom (purple) at the other end. A device that recognizes DNA strands by the way they conduct electricity could be developed for medical diagnoses.

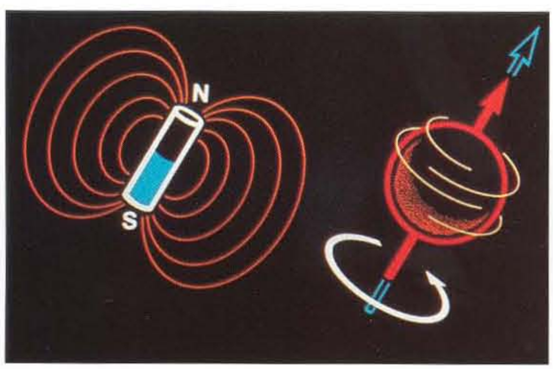
An accurate diagnostic tool should, ideally, make the correct decision the first time every time. Consider a baseball game, where every call the umpire makes is a diagnosis. He has to make a rapid, accurate judgment based on limited information, and sometimes he's wrong. Do these diagnoses really matter? Apparently so. On August 10, 1995, the St. Louis Cardinals came to town to play the Dodgers. Moments after batter Raoul Mondesi and manager Tommy Lasorda got sent to the showers for arguing a called strike, about 4,000 fans who agreed that the ump had erred began throwing their souvenir baseballs (it was Ball Night at Dodger Stadium) onto the field. Los Angeles wound up forfeiting the game. While this type of diagnosis may ruffle the feathers of a few fans, medical diagnoses have a more far-reaching impact—a mistaken diagnosis can lead to something far worse than an early shower.

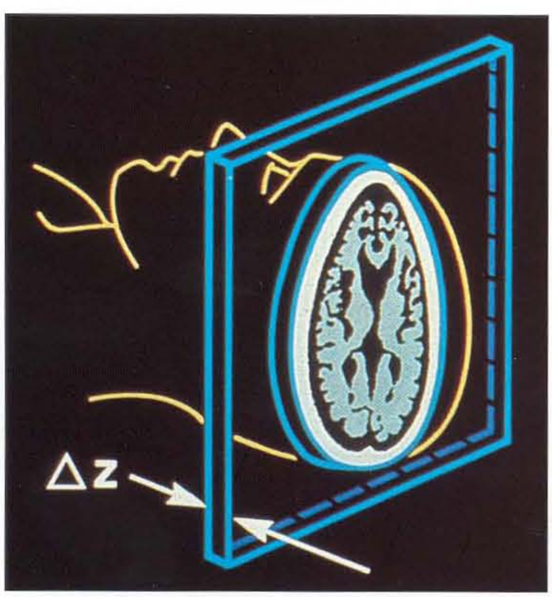
In my research group, basic science is being harnessed to develop the chemical reagents needed to create the next generation of vastly more sensitive and discriminating diagnostic tools—tools that will give us a lot of detailed information about a patient in a cost-effective manner. Ideally, we'd like to make these tools portable, so that instead of you having to visit a huge, expensive machine in some clinic somewhere, the machine would come to you. Hollywood, of course, has gotten there before us, but if the creators of *Star Trek* can build a medical tricorder capable of instantaneous diagnosis, why can't we?

This work is a direct consequence of the collision of disciplines that the Beckman Institute, where I work, was designed to foster. The Beckman Institute houses people from diverse fields—cell biologists, developmental biologists, chemists, physicists, and engineers—all contained in one building, so that we're constantly tripping over one another. For example, my group, which is part of the Beckman Institute's Biological Imaging Center, consists of nine people. No two of them have degrees in the same field. I was born and raised in a large chemistry department, where the inorganic chemists didn't talk to the organic chemists, let alone the biologists. But this is a special place. It's a very active, exciting environment, where research projects cut across disciplinary lines. Our work is emblematic of the kind of research that results when you're forced to speak lots of different scientific languages simultaneously.

I'll focus on two types of new diagnostic tools that are emerging as a result of the interdisciplinary work that is taking place here. The first consists of a new variation on Magnetic Resonance Imaging, or MRI, which is a technique that's widely used to take three-dimensional pictures of the inside of a specimen (and sometimes that specimen is you). While traditional MRI provides millimeter-scale anatomical information, our new chemical tools allow the same instrument to provide equally detailed information about the physiological and metabolic functioning of a specimen as well. The second new diagnostic technique is an entirely new way of analyzing DNA that exploits some fundamental properties of electron-transfer reactions. The method is designed to be rapid, require no

Medical X rays are the diagnostic equivalent of stone knives and bearskins—I can imagine a time when we won't have to bombard somebody with high-energy particles just to take a picture, even for dentistry.





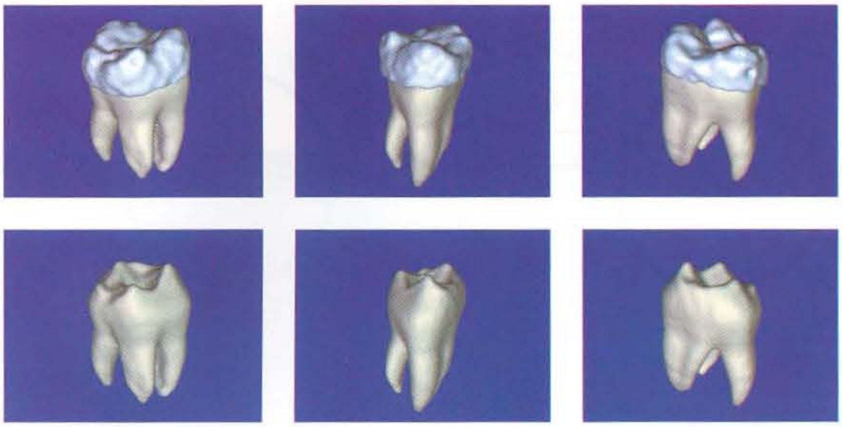
Top: A charged, spinning sphere (in this case, a proton) generates its own tiny magnetic field, as indicated by the north-pointing arrow. Bottom: So if you stick something containing a lot of protons (in this case, your head) into a larger magnetic field, they will tend to line up with that field. A radio-frequency pulse will then excite all the protons, but computer manipulation of the resulting signals allows the protons in a particular slice (Δz) of the brain to be singled out, and an image of them to be constructed.

sample purification or amplification, and is virtually automatic, unlike current methods of DNA testing.

I will begin with the MRI method. In recent years, MRI has emerged as a powerful clinical tool because it is noninvasive and nondestructive and renders visible the entire three-dimensional volume of the subject. MRI measures the differences in the local environments of all the water molecules in your body. This is an excellent way to examine the human body, which is mostly water.

MRI works because the hydrogen atom's nucleus is a single proton, whose charge and spin cause it to behave like a tiny magnet. So if the doctor sticks the patient in a large magnet, those protons will tend to align themselves with the magnetic field. An image is created by imposing one or more magnetic fields upon the specimen, while exciting the protons with radio-frequency pulses. Each pulse flips the protons' spin axes, briefly inverting them before they "relax," or flip back into their original alignment, emitting another radio signal. The rate at which the protons relax is very sensitive to their local environment in several ways. Thus, the signal intensity from a given unit of volume in the specimen is a function of the local water concentration and of two relaxation-time parameters called T_1 and T_2. Local variations in these three properties provide the vivid contrast seen in magnetic-resonance images. For example, the low water content of bone makes it appear dark, while the short T_2 of clotted blood affords it a higher signal intensity than nonclotted blood—

Your nose will tell you there's a leak, but not where it is, and the plumber doesn't want to dig up your entire yard to find it. So he brings a can of dye with him, flushes it down the toilet, and looks out in the yard—wherever the dye comes up is where the leak is. In other words, the dye says "Dig here." Standard MRI contrast agents work in a similar way—they go where the pipes go. A tumor generally has thin-walled, leaky blood vessels, so the contrast agent leaks out and pools there. Contrast agents are good for determining the type and scope of any injury in which the circulatory system is damaged—brain trauma suffered in a car accident, for example.



Above: Six computer renderings based on an MRI scan of an adult human molar. The top frames show the tooth's exterior: enamel (white) extends down to just below the gum line, while dentine (beige) lies beneath. The enamel has been "peeled" away in the bottom views, revealing the growth points at the dentine-enamel interface—the cusps from which new tooth tissue springs. It's normally difficult to get good magnetic-resonance images of teeth, because enamel and dentine contain very little water, but research fellow Pratik Ghosh and Member of the Beckman Institute Russell Jacobs have developed a method for taking MRIs of dry solids. Postdoc David Laidlaw, grad student Kurt Fleischer, and Associate Professor of Computer Science Alan Barr developed the image-processing software that distinguishes the rock-hard enamel from the slightly softer dentine and generates three-dimensional images of them both.

thus blood clots appear bright. Moreover, the image may be acquired in a variety of different ways that emphasize the variation in one or more of those three properties. In any case, we collect intensity data as the specimen is exposed to a variety of fields, and then a mathematical technique called deconvolution yields a one-, two-, or three-dimensional image of the specimen.

MRI scans have already replaced X-ray photos in many ways. Magnetic resonance images are much more detailed, and, unlike an X ray, you can have an MRI taken of you every day. Medical X rays are the diagnostic equivalent of stone knives and bearskins—I can imagine a time when we won't have to bombard somebody with high-energy particles just to take a picture, even for dentistry. We can take an MRI of a tooth, for example, and pictorially peel off the enamel and look directly inside.

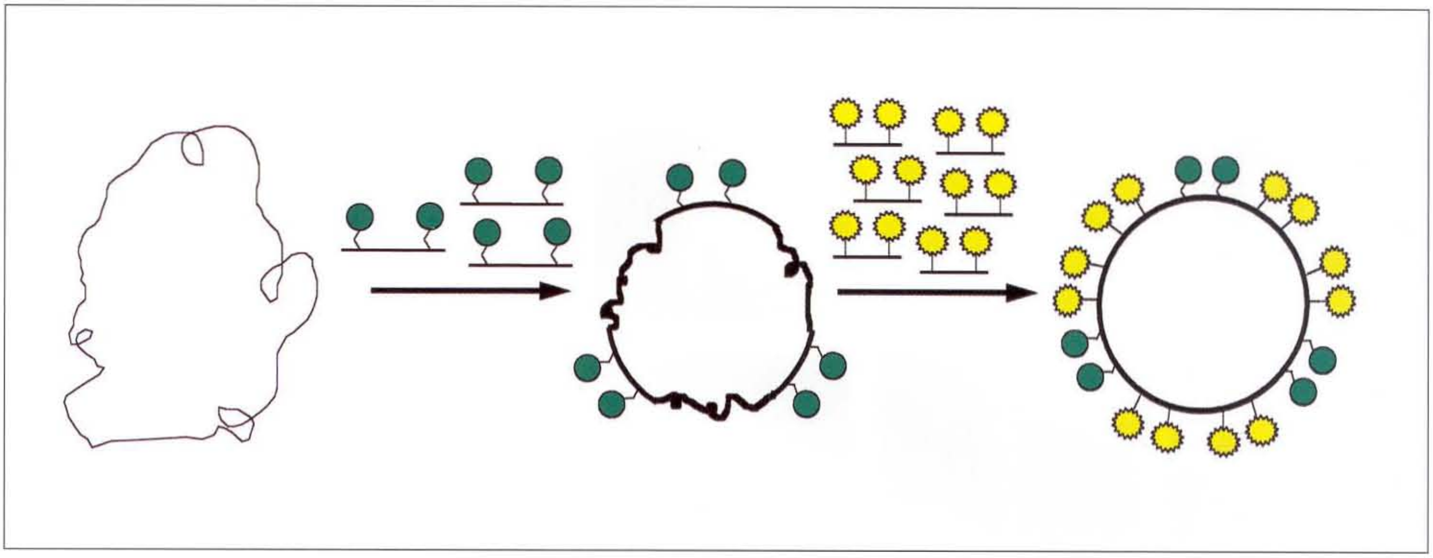
But, as some doctors know, we can make better images for better diagnoses through chemistry. Consider a patient with a brain tumor, for example. An ordinary magnetic resonance image gives the surgeon a lot of vital information—where the tumor is, how big it is, and what brain functions might be affected by it or by its removal. However, by injecting an MRI contrast agent—basically a magnetic-resonance dye—into the patient, the surgeon can delineate that same tumor in much more detail. In the brain, where every millimeter matters, I'd certainly prefer my surgeons to have the highest-resolution images possible.

The principle behind a contrast agent is the same as that of tracing a leak in your sewer line.

The area where the contrast agent congregates appears brighter than the surrounding tissue, because the contrast agent allows the protons in the neighboring water molecules to flip back into alignment with the magnetic field faster. Thus, each succeeding pulse will find those protons back in alignment, and can tip them against the field again, while the protons elsewhere may still be tipped against the field from the previous pulse. Unlike a radioactive tracer, such as a barium milk shake, you don't see an MRI contrast agent directly, but rather its effect on its neighboring molecules.

The best contrast agents contain large numbers of unpaired electrons, which cause the protons to relax by essentially siphoning off their extra energy magnetically. (T_1 becomes much shorter, in other words.) Most researchers, including us, use gadolinium ions (Gd^{+3}), which have seven unpaired electrons each—the highest number in the entire periodic table. Unfortunately, gadolinium is also very toxic—if it's not chelated, or caged, you might get a great picture, but you'd end up killing the subject. Several ways to cage gadolinium safely have been developed. These cages also limit the number of water molecules that can snuggle in the gadolinium ion's relaxing embrace at any given time, but the water molecules exchange in and out so fast that it doesn't really matter.

We have been working on "smart" MRI contrast agents that don't simply go where the pipes go and that don't simply report their anatomical location. These new agents report on the metabolic state of cells and organs in a way that shows up under MRI. This provides, for the first time, a means to obtain high-resolution, three-dimensional magnetic resonance images based on the metabolic and physiological function of living systems. We've developed two ways to make a contrast agent smarter. The simpler one, which we developed last summer, is a cell-specific reporter that's designed to seek out a specific type



A schematic representation of the contrast-agent-delivery vehicle assembly line. The DNA backbone of the plasmid (the tangled loop at left) contains numerous negative charges, so the transferrin (teal spheres) is chemically bound to a molecule called polylysine (the short, straight line segments), whose backbone has many positive charges. A molecular version of static cling causes the polylysines and the plasmid to stick together when mixed. Not enough polylysine is used to neutralize all of the DNA's negative charges, so the gadolinium cages (gold stars) are bound to other polylysine molecules that, when added to the mixture, also cling to the DNA and soak up the rest of the charge.

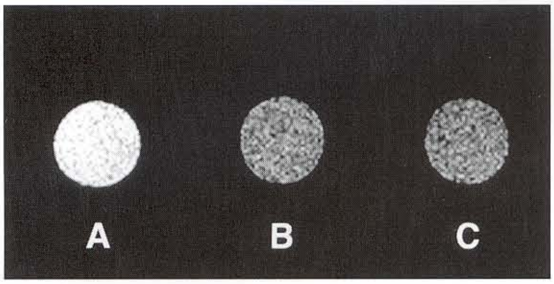
of cell. Those cells, and only those cells, will light up wherever they are in the body. The second type, the functional reporter, is even smarter. It stays dark—or off—to the MRI until some metabolic or physiological event of our choosing turns it on, that is, lights it up.

Let's begin with the agent that's smart enough to find a specific cell type. In order to deliver our contrast agent reliably to a specific cellular address, we've borrowed a technique from gene therapy. Gene therapy is getting a lot of press nowadays, and the basic idea is this: Say you're missing an enzyme because your body's copy of the gene that makes that enzyme is defective. If a doctor could insert a working copy of the gene into your cells, your body would start making the enzyme, and you'd be cured. This technique has only very recently been attempted in humans, and one major technical hurdle is quantifying how much of the gene is actually getting into the target cells.

The "truck" that gets the gene into the cell is called a plasmid, which is a little ring of DNA containing the gene, and the truck's "driver" is a protein attached to the plasmid that recognizes a receptor on the cell's surface. When the protein docks with its receptor, a sequence of events is triggered that causes the plasmid to tumble into the cell like a truck into an opening sinkhole. The cell surface dimples underneath the plasmid, folds over it, envelops it, and pulls it in. So if the plasmids are loaded up with large numbers of our contrast agents before being injected into the subject, we can collect magnetic resonance images to see where the plasmids go. It's akin to having a radio-equipped moving van. We've been using an iron-containing protein called transferrin as our truck driver because it was one of the first recognition proteins used in gene therapy, but there are many other kinds of receptors that work in a similar way, and potentially we could use any one of them.

To verify that our contrast agent is going where we want it to, we did an experiment whose results are shown at the top of the opposite page. We loaded three capillary tubes with K562 leukemia cells, which have transferrin receptors. Tube A also contains the plasmid-transferrin-gadolinium particle, and the cells light up. To prove that they didn't light up for some other reason, tube B holds the plasmid-transferrin particle without the gadolinium. And, finally, to show that it's the transferrin that's actually responsible for getting the contrast agent in, tube C gets a large excess of free transferrin molecules—enough to monopolize all the transferrin receptors on the cell surface. You can see that tubes B and C remain dark in the MRI image. (The contrast agent doesn't light up outside the cells in tube C because we rinse them off before we do the MRI.)

But confirming that the gene was delivered to the right address doesn't necessarily mean we've fixed the cell. Simply because the cell swallowed the gene doesn't guarantee that it will be taken to the nucleus, where the cell's own DNA is kept, or that if it gets to the nucleus that it will work correctly in its new environment. Currently, gene therapists just dispatch the plasmid trucks and wait to see if appreciable amounts of the gene's

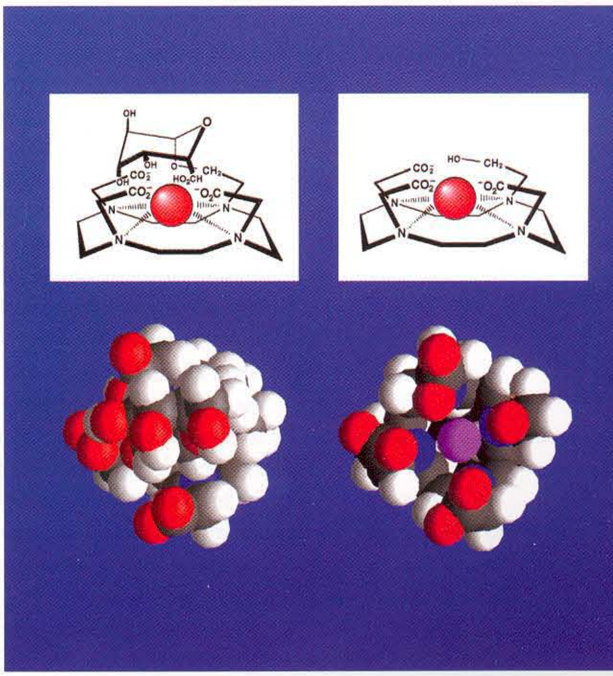


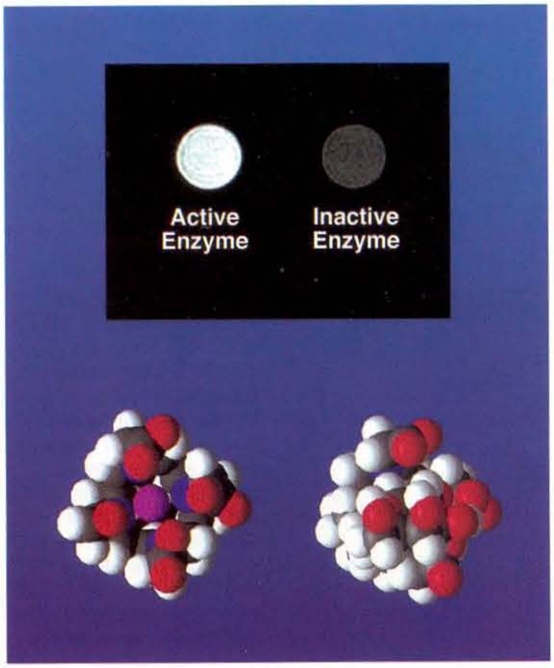
Above: The bright spots in tube A are MRI return receipts from aggregates of cells that have absorbed the smart contrast agent. Tube B has cells and plasmids but no gadolinium, and remains dark. Tube C's darkness says, "Return to sender/ Address unknown"—the tube contains the same ingredients as tube A, plus enough extra transferrin to block all the binding sites on the cells' surface and prevent the delivery from being made.

product begin to appear. It often takes weeks, or even months, to know whether the procedure has succeeded. (We knew immediately when our gene had arrived in the nucleus, because we were using the luciferase gene that puts the fire in fireflies. Our cells glowed in the dark the moment the gene started working. However, this gene is of no therapeutic value in people.)

This brings us to the functional reporters—agents smart enough to be turned on only by a physiological or metabolic event of our choosing. Such an agent would give us two pieces of information—the agent's location and the fact that the desired event has taken place there. How does this work? Remember that our magnetic dye, our gadolinium ion, makes water molecules light up, but that only a few water molecules can get to it at a time because it's in a cage. The gadolinium ion is big enough that nine water molecules could bind with it if it were uncaged, so we started with a cage design that blocked eight of the nine sites. (This cage, called 1,4,7,10-tetraazacyclododecane-N,N',N'',N'''-tetraacetic acid, or DOTA for short, is approved in France for human use, but has not yet been approved here by the FDA.) DOTA looks like a picnic basket, with the gadolinium ion inside. So postdocs Rex Moats and Andrea Staubli put a lid on the basket that blocks the water molecules from getting to the last available site. The lid's hinge is a sugar called galactopyranose, which is digested by an enzyme called β-galactosidase. Our hope was that the enzyme would still recognize the galactopyranose lid, even though it's been built into the picnic basket, and break it

Below: The cage's chemical structure, with the lid (left column) and without it (right).
In the diagrams in the top row, a carbon atom sits wherever two line segments meet. The heavy segments represent parts of the molecule that stick out in front of the page; light segments lie behind the page. The sphere in the middle is the gadolinium, which lies in the plane of the page.
In the 3-D models in the bottom row, the cage has been rotated 90° toward you to show what a water molecule sitting above it would see. White spheres are hydrogen atoms, red are oxygen, gray are carbon, blue are nitrogen, and the purple one is the gadolinium.





In an MRI experiment similar to the one on the preceding page, the left tube contains the active enzyme and the contrast agent; the enzyme breaks the lid off and the tube lights up. The right tube has an inactive form of the enzyme; the lid stays attached and the tube remains dark.

down. If the hinge did break, the lid would fall off, the gadolinium would be exposed to water, and the area would light up.

Above is an experiment that verified that this is what actually happened. The right tube contains our contrast agent, plus a chemically inactivated form of the enzyme that can't break the hinge; the left tube has the normal enzyme. Only the left tube lit up.

In principle, this idea could be adapted to almost any enzyme, by incorporating whatever the enzyme feeds on into the basket's hinge. We could track the progress of gene therapy in real time by injecting the patient with a contrast agent whose hinge is the target of the enzyme we're trying to impart. More broadly, we could map the pattern of activity of any enzyme throughout an organism, and follow how that activity changes over time.

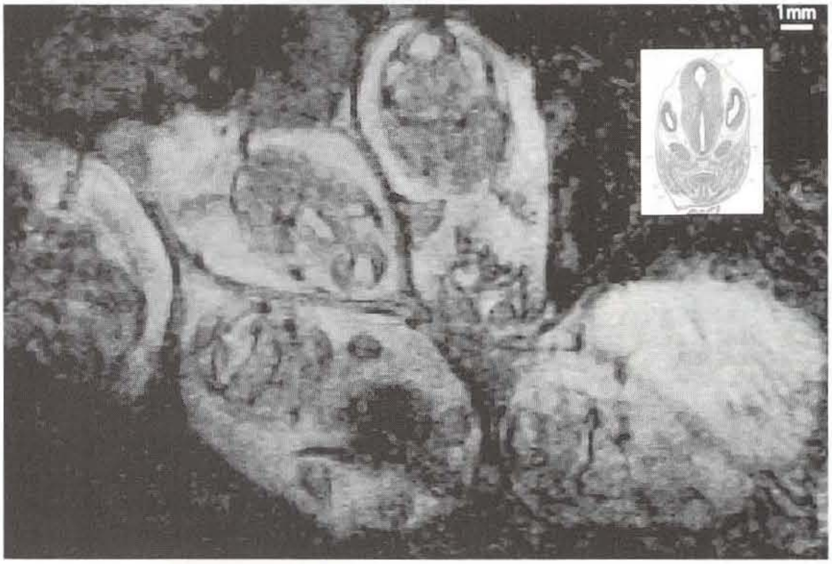
The important uses of these agents in clinical and laboratory settings are several. We could diagnose many classes of brain disease, and I'll come back to this shortly. We could tell the difference between myocardial infarction (a heart attack caused by the complete blockage of a coronary artery) and ischemia (a partial blockage of an artery) in real time. This is important, because infarcted tissue is dead and gone beyond any hope of revival, but ischemic tissue can be saved by prompt action. We could identify and locate the binding sites of drugs and toxins anywhere in the body. And we could rapidly screen physiological responses to drug therapy. These agents are an enormously powerful addition to the established diagnostic technique of MRI.

We could use functional contrast agents to diagnose any organ, not just the brain and heart. As I said before, one limitation to MRI diagnoses is that ordinary, dumb contrast agents only go where the pipes go. If the patient is suffering from liver disease, for example, you can send an ordinary contrast agent to the liver to see if it's swollen, or shriveled, or otherwise abnormal looking. But you can't see how well the cells are functioning. However, a smart contrast agent that's keyed to an important liver enzyme could easily tell the quick from the dead. Healthy cells will light up, dead tissue will be black, and diseased cells will be shades of gray depending on how sick they are. You could locate the worst damage quickly and easily, without having to do biopsies or exploratory surgery.

But the biggest clinical application could be in brain diseases. We've recently modified our contrast agent to detect, not enzyme activity, but the presence of calcium—a so-called secondary messenger that transmits chemical signals between nerve cells. So by mapping calcium levels, we're mapping brain function. In this variation, the basket has a floppy lid that can grab hold of a calcium ion. When there aren't any calcium ions around, the lid dangles down on top of the gadolinium ion, keeping the water molecules away. But if a stream of calcium ions passes by, the lid swings up to grab one, exposing the gadolinium ion and lighting up the water molecules. This technique can in principle be expanded to include a variety of other secondary messengers.

Ultimately, these new MRI agents used in a traditional MRI machine may replace Positron Emission Tomography, or PET, which is how brain activity is currently mapped. PET uses a radioactive tracer, which MRI does not, and has a lower spatial and temporal resolution. (PET scans also cost several thousand dollars a pop.) Furthermore, PET needs to be done in conjunction with MRI anyway, because PET doesn't give much anatomical detail. One of the trickiest things in PET imaging is making sure that the PET and MRI images are precisely in register—otherwise you can't be sure what anatomical structure is responsible for the brain activity you see. But if all you need is the MRI scan, this problem disappears.

Our agents may have potential in the early and accurate clinical diagnosis of Alzheimer's disease, by differentiating Alzheimer's sufferers from manic-depressive individuals. The psychological manifestations of the early stages of Alzheimer's are very similar to those exhibited by manic-depressives, and it's hard to tell one disorder

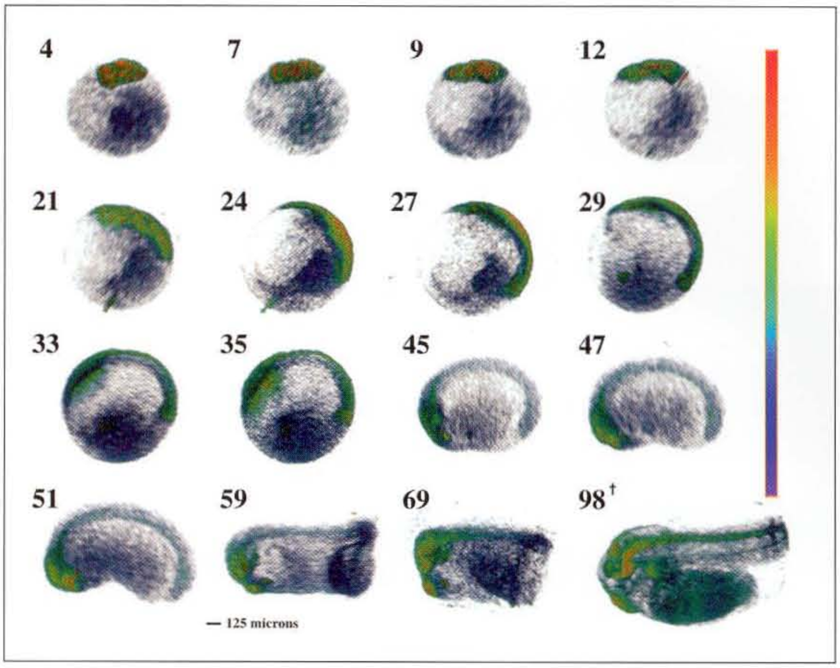


Above: The five pups in utero, as seen by MRI. Some parts of the pups are behind the image plane (the paws and belly of the pup at bottom center, for example, and the head of the one above it), while the parts in the plane show up in cross section (such as the head of the pup at top center). The inset is an anatomical map of the mouse brain, for comparison. Right: The mouse mom and the radio-frequency coil she was in, half an hour after the MRI scan was made.

from the other in a clinical interview. (The physiological changes don't become apparent until much later.) The pathology of the brains of those suffering from these diseases are quite different, however. If we were to map the calcium distributions in the brains of several known Alzheimer's patients and an equal number of manic-depressives, we might find enough differences between the two groups to form the basis for a diagnostic method. And, of course, researchers who study brain function to figure out how we perceive the world around us, how we learn, and so forth, would benefit greatly as well.

While my lab has been working with MRI contrast agents to bring out anatomical and functional details, another lab in the Biological Imaging Center has been working to push the level of detail we can see. Clinical MRI systems can see structures as small as a few millimeters, but Scott Fraser, the Rosen Professor of Biology, and Russell Jacobs, member of the Beckman Institute, have built a system that can see detail as fine as 10–15 microns—roughly the size of an individual cell. The system is purely experimental, because the magnet is too small to fit a person into. An MRI system's resolution is proportional to the strength of the magnetic field(s) used to generate the image data, and building a people-sized magnet this powerful is beyond the capabilities of current technology. But whole-body systems have recently been built that can get about 100 microns' resolution—10 times better than the clinical instruments and only 10 times worse than Scott and Russ's. (In fact, the above experiments were done using their MRI system—the capillary tubes in the pictures are a mere two millimeters in diameter.) At left is another example of their work—it's an MRI slice through the abdomen of a pregnant mouse, revealing five pups each no more than three or four millimeters long. You can see a wealth of anatomical detail in the pups' brains. And I want to emphasize that months after this MRI was taken, mom is still alive and perfectly happy, and her offspring are too.

The same advantages that have made MRI the technique of choice in medical imaging make it an ideal tool for biological experiments, so Scott, Russ, and I are using MRI to take moving pictures of embryos as they develop. We're looking at a range of organisms, from African tadpoles to small primates. This effort will open up whole new vistas in developmental biology. For example, many researchers focus on a single cell in an embryo and say, "Cell, what do you want to be when you grow up? When was that decision made, and who made it?" Up to now,



This series of images shows a *Xenopus laevis* embryo as it develops. The number next to each image denotes the elapsed time in hours since the egg was fertilized. When the egg had divided to the point where the embryo contained 32 cells (about two hours after fertilization), one cell was injected with an MRI contrast agent. By F+4 hours, that cell had become eight cells. In later frames, these descendants marched off two or three abreast to become the spinal cord until, at F+33 hours, one end of the spinal cord begins thickening to become the brain. A small platoon of progeny, visible at F+29 hours as a green spot near the center of the embryo's lower left quadrant, became the heart. The color bar along the right side of the panel is keyed to the contrast agent's concentration, with red being the highest and purple the lowest.

the way to find out was to inject a contrast agent into that cell and follow its descendants as the animal developed. But now, we can not only watch the migrations of a certain family of nerve cells, say, as the embryo's brain wires itself up, but we can also see when those cells decided to become nerve cells in the first place. We could inject the original cell with our really smart contrast agent, which we had programmed to light up when some enzyme specific to the nerve cell becomes active. Or, we could add our moderately smart agent to the solution in which the embryo is swimming, and wait for the cells to sprout nerve-cell-type receptors.

But what really makes our contrast agents so powerful is that MRI data are three-dimensional. We can build a 3-D model of our organism and rotate, tilt, and slice through it any way we please. We can extract innumerable images from a single 3-D scan without ever pulling a scalpel out of the drawer. And when we make a succession of 3-D scans over time, to follow an organism's growth or a disease's spread, it gives us amazing flexibility in the questions we can ask of the data. Here's a vivid example—the pictures above are frames from a video by Russ Jacobs' group. They have labeled one of the 32 cells in a frog embryo with an MRI contrast agent. That cell is going to split many times as the embryo grows, and we can track the great-great-great-great-granddaughter cells in 3-D. Some of the offspring will form what will become the spinal cord, others will become the heart, and most of them will eventually wind up in the brain. (Had we started with another cell, we might have gotten the intestinal tract.) So we can cut an embryo in slices any way we please while it's still growing, and we can make out changes in very fine three-dimensional detail in a single animal over a long period of time.

We'll never make a handheld diagnostic MRI system, because the magnet still has to be big enough to fit a person into, but we could perhaps make a system that would fit into an ambulance or minivan. (Today's "mobile" systems only qualify in the broadest sense of the world—they live in those semitrailers you sometimes see parked behind medical centers. You have to hitch them up to a diesel cab to take them anywhere.) In contrast, our system for DNA analysis truly is portable—a simple one could be built into a device the size of a garage-door opener.

DNA is our genetic material—and not just human genetic material, but that of every living thing. Knowing what kind of DNA one has in a sample and who that DNA belongs to, whether searching for a disease or a hardier strain of vegetable, requires a lot of technology and is rather cumbersome. You have to collect a sample, extract the DNA, and then purify it. There are all sorts of ways that contamination can creep in, and innumerable opportunities for mistakes to be made. The procedures require a lot of complicated equipment and all sorts of chemicals, so you can't take the lab to the samples; you have to bring the samples to the lab. The current methods are very powerful, but they're also labor intensive, time consuming, and extremely expensive.

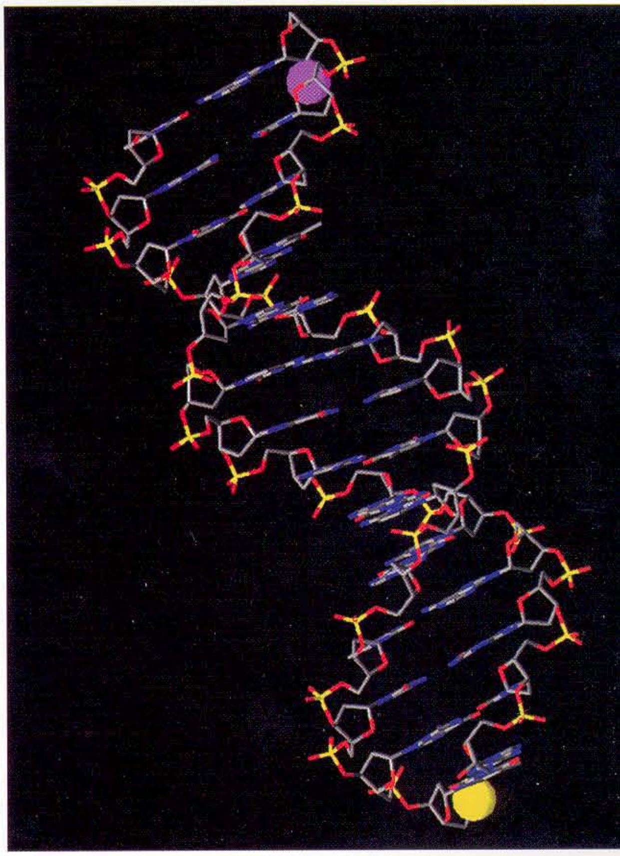
If, however, there existed a handheld tricorder that could run a whole bunch of DNA tests simultaneously, a lot of applications would open up that are impractical today. We could, for example, rapidly check the entire U.S. blood supply for contamination by all known strains of the AIDS virus. We could monitor our air and water supplies for infectious agents. This could be anything from tracing the progress of a particularly virulent strain of the flu, to dealing with a situation like in the movie *Outbreak*, where an airborne Ebola-like virus got loose in the United States. More prosaically, the food industry is very concerned about bacterial contamination, especially by *E. coli*, which can cause food poisoning. (You may remember the fast-food scare of a couple of years ago.) There are forensic applications—finding out who the murderer is from bloodstains left behind. In addition, there's agricultural monitoring. Disease-resistant genes can be inserted into plants to improve crop yields, but, again, there's currently no way to tell if the gene has "taken," short of waiting for the seedlings to sprout and then screening them for whatever resistance the gene was supposed to impart. Being able to test the DNA of the seed itself, before it ever leaves the lab, would assure that only the disease-resistant seeds get planted.

We can extract innumerable images from a single 3-D scan without ever pulling a scalpel out of the drawer.

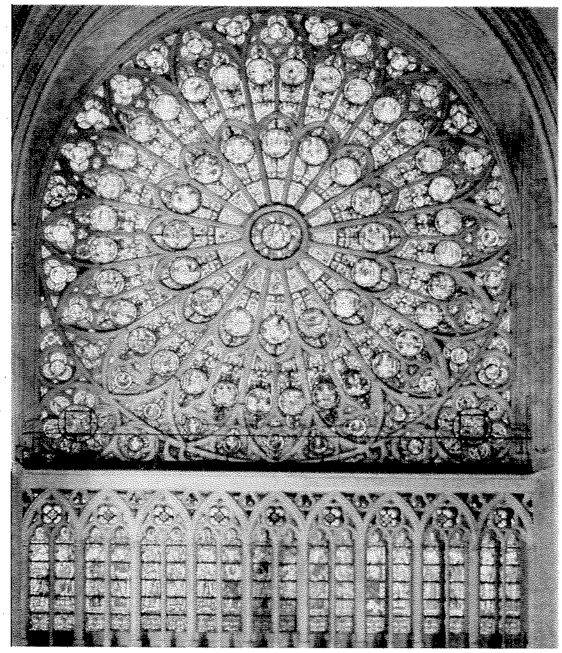
Our method uses electron-transfer reactions to analyze DNA. Electron-transfer mechanisms have been a popular subject here at Caltech for many years—Rudy Marcus, the Noyes Professor of Chemistry, won the Nobel Prize in 1992 for electron-transfer work. And Harry Gray, the Beckman Professor of Chemistry, has been studying electron transfer in proteins for more than a decade. His group discovered that electrons could travel across large distances in complex biological molecules such as electron-transfer proteins. Such processes are not unique to proteins; for example, Professor of Chemistry Jackie Barton's group has data indicating that electrons can go through DNA very rapidly. In a nutshell, you do these experiments by putting an electron donor on one end of a piece of DNA, and an electron acceptor on the other end. Then you launch an electron from the donor and measure how long it takes to arrive at the acceptor.

It would seem reasonable to assume that how fast the electron goes might depend on the exact nature of the DNA it's traveling along, which led us to wonder if we could use electron-transfer rates to identify a DNA molecule—specifically to tell us whether it matches a reference piece of DNA whose identity is already known. DNA is a long, linear molecule, and normally two strands of it interlock like the two halves of a zipped zipper. It's the way that the four chemical "letters"

In a piece of double-stranded DNA, the chemical "letters" (seen here edge-on), which carry the genetic information, recognize one another and pair up like rungs on a ladder. The surrounding tracery of yellow and red is the phosphate backbone on which the letters are strung,and whose natural twist imparts to the molecule its classic shape. The magenta and yellow spheres are the electron donor and acceptor added for electron-transfer experiments.



I've often wondered if perhaps the monks stumbled onto the structure of DNA 700 years ago, and the cathedral was the only journal they could find to publish it in.

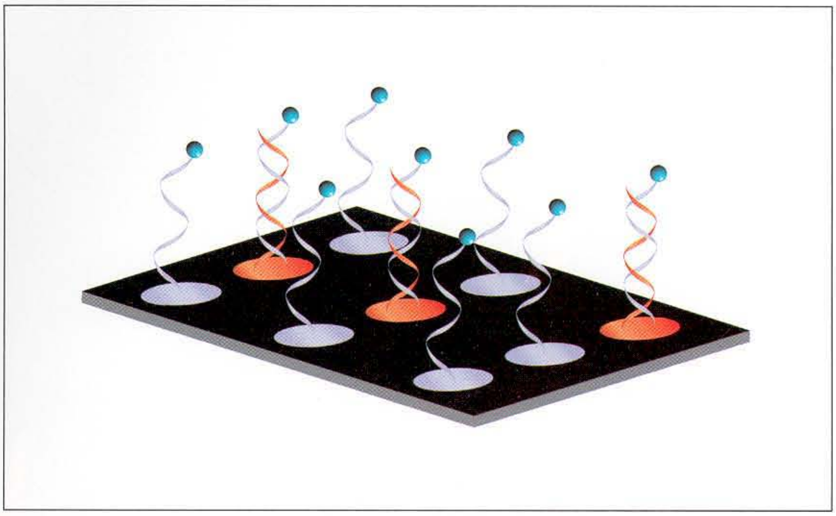


(A, C, G, and T) in the DNA code recognize each other that makes the zipper zip. The code follows two simple rules: an A on one strand only binds to a T on another strand, and a C on one strand only binds with a G on the other. So if you know the sequence of one strand of DNA, you also know the sequence of its complementary strand—the strand that will zip up with it. For every A on one strand, there's a T in that spot on the other, and vice versa; as is the case for C and G. Thus, if we know the sequence of a strand of DNA that's unique to a defective gene, for example, we can make a probe—a single strand of DNA with the complementary sequence—and if that defective gene is present in our sample, the probe will find it and zip it up into a double strand.

This leads to the key question: is the electron-transfer rate along a double strand sufficiently different from the rate along a single strand that we could reliably tell double from single? To find out, we made short pieces of DNA that had an electron donor attached to the terminal letter on one end and an electron acceptor attached to the terminal letter on the other end, taking pains that the donor and acceptor didn't perturb the DNA structure in any way. We synthesized some pieces with the donor and acceptor on the same strand, and some with them on opposite strands. That way we could not only do the single-strand versus double-strand experiment, but we could also find out whether it made a difference whether the electron had to transfer from one strand to the other. Finally, we wanted to be able to track the electron unambiguously, so we gave the donor and acceptor different spectroscopic fingerprints. In fact, we actually had four distinct spectroscopic signals—one from the donor with the traveling electron ready for launch, one from the donor after the electron left, one from the acceptor before the electron arrived, and one from the acceptor after the electron had landed.

It turns out that the electron goes from one end to the other end of a double-stranded piece of DNA very rapidly, much faster than would be predicted from the rate of electron transfer through a single strand. In a single strand, the only way the electron can get from donor to acceptor is by tunneling down the phosphate backbone on which the DNA's letters are strung. But when two strands zip up, the electron can scoot along the letters themselves, which now line up like the steps in a spiral staircase. You can see this alignment better on the inside front cover of this magazine, where there's a nontraditional view of DNA that rather resembles the rose window at Notre Dame shown above. I've often wondered if perhaps the monks stumbled onto the structure of DNA 700 years ago, and the cathedral was the only journal they could find to publish it in.

This rate difference is being exploited by building a microelectronic chip, or biosensor, that has the single-strand probe DNA attached to it. The chip would send electrons through the probe and measure its resistance, which is very easy to do. If the probe recognizes its target sequence—say, a viral gene—the resistance would suddenly drop, because electrons would



The conceptual basis for a tricorder on a chip. Anchored to the chip is an array of single strands of DNA whose sequences are complementary to, say, an assortment of disease-susceptibility genes. When a piece of the suspect gene drifts by, it binds to its opposite number on the chip, and the decreased resistance through the double-stranded DNA indicates a match.

travel faster through the double-stranded DNA than the single strand. Ultimately, we could put an array of thousands of different probes for all sorts of things on a single chip.

In principle, anything that has DNA in it could be reliably detected on such a chip. We already know the sequences of many pieces of DNA—including the *p53* gene, which has been linked to colon cancer, and all the mutants of the HIV virus, which causes AIDS—and laboratories are working out more sequences all the time. The laws of statistics say that using a 17-letter probe for a sequence that is found only in the piece of DNA we're looking for will virtually guarantee that only that single-stranded piece will match. To further reduce the possibility of false-positive results, a number of different probes for each gene can be placed on a single chip. A collective pattern of decreased resistance from those probes would indicate that a match had been detected.

Today, several companies are integrating DNA into chips with individually addressable circuits. Jon Faiz Kayyem (PhD '92), formerly a postdoc in my group, has cofounded a local company (in cooperation with Caltech's newly formed Office of Technology Transfer) to explore ways of combining this chip-making technology with our rapid-electron-transfer diagnostic methods.

In the next generation, a five-year-old might go to the doctor's office, and the doctor might draw a blood sample, stick it in the tricorder, and say, "Aha. We have decreased resistance through this probe, and this one, and that probe over there, and those two probes there." This pattern might reveal that the child has a mutant *p53* gene and might be at risk, some day, of developing colon cancer. Then the doctor could say to the child, "You need to come back in 45 years, because we'll want to start screening you for colon cancer on a regular basis then." Now, that's what I call early detection—45 years in advance of the potential onset of something is a pretty big lead time.

This brings us full circle to the notion of a diagnostic tool that we began with—a device that's fast, accurate, and makes the right call the first time every time. If Hollywood's vision of the medical technology of the future has any basis in reality, then today we may be laying the groundwork needed to put a tricorder in Dr. McCoy's hands tomorrow. □

Thomas J. Meade earned his undergraduate degree in chemistry from Arizona State in 1980, and proceeded to Ohio State, where he got his master's degree in biochemistry in 1982 and his PhD in inorganic chemistry in 1985. He next worked on magnetic resonance imaging as an NIH postdoctoral fellow at Harvard Medical School, before his first sojourn at Caltech as a research fellow (1987–89), when he studied electron transfer in metalloenzymes with Harry Gray. He joined the Division of Biology and the Beckman Institute in 1991. This article is adapted from a recent Watson lecture.


CALTECH

A Celebration of Willy Fowler

"Some people are ageless and Willy was one of them. His creative mind, wit, and exuberant personality never dimmed or clouded."

At the December "Celebration," Robert Christy (left), a long-time colleague of Fowler's, likened him to a locomotive. Some of Fowler's collection of model locomotives adorned the stage in Beckman Auditorium (below).

The late William A. Fowler, Nobel laureate and Institute Professor of Physics, Emeritus, had participated in more than half of Caltech's history. He arrived on campus in 1933 as a graduate student under Charles Lauritsen in Kellogg Radiation Laboratory, earned his PhD in 1936, stayed on as a faculty member, and essentially never left. He won the Nobel Prize in 1983 for describing the succession of complex nuclear reaction processes by which elements are synthesized during the evolution of stars.

When Fowler died on March 14, 1995, at the age of 83, his colleagues and friends decided that no ordinary memorial would suffice. So, for three days in December, a symposium on nuclear astrophysics (subtitled "A Celebration of Willy Fowler") was held on the Caltech campus. "The idea was to have a celebration for what has been contributed," said G. J. Wasserburg, Crafoord laureate and the John D. MacArthur Professor of Geology and Geophysics, who chaired the program committee. "The celebration was to exhibit the vitality of the field, which is the real inheritance of Willy Fowler." The symposium included sessions on the early universe, experimental nuclear astrophysics, the neutrino, stellar nucleosynthesis, chemical evolution of the galaxy, formation of stars from the interstellar medium, presolar stellar dust grains in meteorites, and gamma ray astronomy.

Also part of the celebration was a more customary memorial observance, which attracted a large audience of Fowler's friends and admirers to Beckman Auditorium on the afternoon of December 14. Before introducing the other speakers, Wasserburg read a poem by John Donne, "The Will," which included the lines:

To him for whom the passing bell next tolls,
I give my physick bookes; my writen rowles
Of Morall counsels, I to Bedlam give;
My brazen medals, unto them which live
In want of bread; To them which passe among
  All forrainers, mine English tongue.

. . . .

Therefore I'll give no more; But I'll undoe
The world by dying; because love dies too.
Then all your beauties will be no more worth
Than gold in Mines, which none doth draw it forth;
And all your graces no more use shall have
  Than a Sun dyall in a grave.

"Willy was a big fan of the English," Wasserburg explained. "It was even rumored that Willy liked English food. And he loved Cambridge and Oxford. Donne was at Oxford in the 1580s and reportedly went from Oxford to Cambridge to improve his character. Willy did this also, but I don't think much improvement was either necessary or possible at that time."

Wasserburg also read parts of letters from John H. Gibbons and Fred Hoyle, who were unable to attend the memorial. Gibbons, science adviser to President Clinton, wrote that, "some people are ageless and Willy was one of them. His creative mind, wit, and exuberant personality never dimmed or clouded." Gibbons noted the seminal 1957 paper by Burbidge, Burbidge, Fowler, and Hoyle (whichWasserburg always called "Burble, Burble, Toil, and Trouble") and the influence it had on his own work at Oak

Left: B²FH (in order, left to right) at the Institute of Theoretical Astronomy in Cambridge, England, on the occasion of Fowler's 60th birthday in 1971. The locomotive (also seen on the previous page) was a present from his Cambridge friends on this occasion.

Ridge National Laboratory. "Willy was himself a kind of bright star, a supernova in my book," wrote Gibbons. "He was particularly pleased when we included a quote from Walt Whitman in one of our papers: 'I believe that a leaf of grass is no less than the churning work of the stars.' Now Willy belongs to the stars."

In his letter Fred Hoyle evoked the many memories that had come crowding in when he started to write—the high points of his scientific work with Fowler, "events one would greatly wish to relive if that were possible." One event in particular that he remembered well was the Moscow International Atomic Union in 1958, in which "protocol in 1958, as you can jolly well imagine, was very difficult. There was a long lunch with lots of vodka, and the person who carried the ball that day was Willy, who could belt vodka down and keep up the good humor with our Soviet compatriots."

Wasserburg then introduced the speakers who were there in person.

Margaret Burbidge wearing a "gorgeous shiner" ("Willy would have loved it") with G. J. Wasserburg at the memorial observance.

Margaret Burbidge
Professor of Physics
University of California at San Diego

{Burbidge, who appeared wearing a black eye and a head scarf where her scalp had been stitched up, explained that she had hit the edge of a door while running to pick up a computer printout. "Willy would have loved it," she said. "He'd have been sorry for me and sympathized with all his heart, but he would have made a joke of it and so I make a joke of it." She then read from an excerpt of an autobiographical article entitled "Watcher of the Skies," which she had written for the 1994 volume of the Annual Reviews of Astronomy and Astrophysics.*}*

"It was in the autumn of 1954 that Geoff and I made the acquaintance of Willy Fowler and his family. He was spending a sabbatical year at the Cavendish, where he had hoped to do some experimental nuclear physics but had found that none of the equipment he needed was available or working. At this time element abundances were emerging from our curve of growth analysis of [a particular star with a strong magnetic field], and the heavy element anomalies were beginning to suggest that somehow neutrons were involved, an idea whose germ had been planted by work which we had heard two years earlier in a talk given by Maria Mayer and a talk given a year later by Gamow about primordial nucleosynthesis. But we believed the processes must take place in stars. While we were well educated in atomic physics, we knew much less about nuclear physics. Geoff attended a meeting of a scientific society in Cambridge, England, and listened to a lecture given by Willy Fowler, and after the lecture, Geoff asked him if we could talk to him about processes involving neutrons in stars.

"Fowler, a leader in the experimental nuclear physics program at Kellogg on the light elements, had recently worked with Salpeter and Hoyle while they were visiting Caltech. He was excited by the prospect of adding neutron processes towards a theory to build all the elements

Right: Spruce Schoenemann (age 7) and his grandfather rest atop Haystack Mountain in Vermont after a hike in June 1988.

in their cosmic abundances through generations of stars, which through evolution, finally produced [the elements around iron in the periodic table of elements], and then supernovae exploding and enriching the interstellar medium with heavy elements made from the initial ingredient, hydrogen. Fred Hoyle was in Cambridge, and we four worked together during that exciting 1954–55 year, adding together one piece after another of the puzzle. Willy's wife, Ardy Fowler, in her wonderful hospitable way made available their rented home in Cambridge, and we four divided time between there, the Cavendish Laboratory, and Botolph Lane, which was where Geoff and I had a flat, until the time came when Geoff and I had to think about jobs for next year. . . . We set off for Pasadena while the work on B^2FH was only partly completed, the primary goal to spend most of the next two years on that major project."

"B^2FH brought me some of the happiest and most productive times in my scientific life. It was such fun working with you and Geoff and Fred that I really do not know what brought the tears."

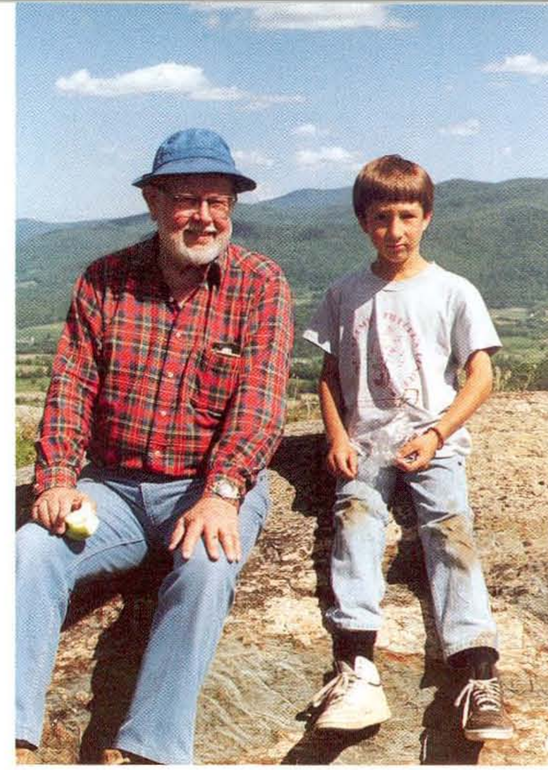
{Skipping to another passage in her article, Burbidge described the experimental work that Fowler and the Lauritsens organized at Kellogg Lab, which was crucial to the calculation of the synthesis of the light elements.}

When I sent Willy a reprint of this article, he wrote me a wonderful letter in November 1994, which must have been among the last letters that he wrote:

"Dear Margaret,

Nothing in recent years has given me such pleasure as reading 'Watcher of the Skies.' Actually, at some times tears came to my eyes. B^2FH brought me some of the happiest and most productive times in my scientific life. It was such fun working with you and Geoff and Fred that I really do not know what brought the tears. Thank you for bringing back those wonderful times."

Being here brings back all the memories of the two years we spent at Caltech and the summers that we spent subsequent to that. During those two years we lived in a house on South Chester, and I think that, from Beckman Auditorium I can see one or two of the trees that used to grow in our backyard.



Spruce William Schoenemann
Pawlet, Vermont

My grandfather spent a lot of time with me when I was a child, even though we lived far apart. Up until the last two or three years, Willy and I shared many physical activities. On my numerous visits to California, we kicked the soccer ball around or tossed the football at the Caltech soccer field. As a family we took hikes in the Angeles Crest, which I enjoyed immensely. I know Willy enjoyed those excursions too. On Willy's visits to Vermont we would sometimes go on hikes up Haystack Mountain, take walks through the beautiful Vermont countryside or pick apples. In the summer of 1988 my grandfather helped build a treehouse for me. I think what he enjoyed most about it was the supervising part. He told my father how things should be done or he would tell me to hand him a tool, depending on what he was doing.

Willy loved telling people things, especially the plentiful stories of his experiences. Many evenings were spent listening to his adventures in the South Pacific, his work in Los Alamos, or his train trips through Russia. He delighted in telling people of his reminiscences. Willy was quite a talker.

One of Willy's fond memories was working at Caltech throughout most of his life. He told me about the work he was doing at the Institute and once in a while he would bring me to his office or lab. I could tell by his exuberance when he spoke of Caltech that he loved the school greatly. He enjoyed his work, his colleagues, and his students. I am sure all of you can remember Willy's extreme fondness for Caltech and the joy he got from telling his stories and jokes.

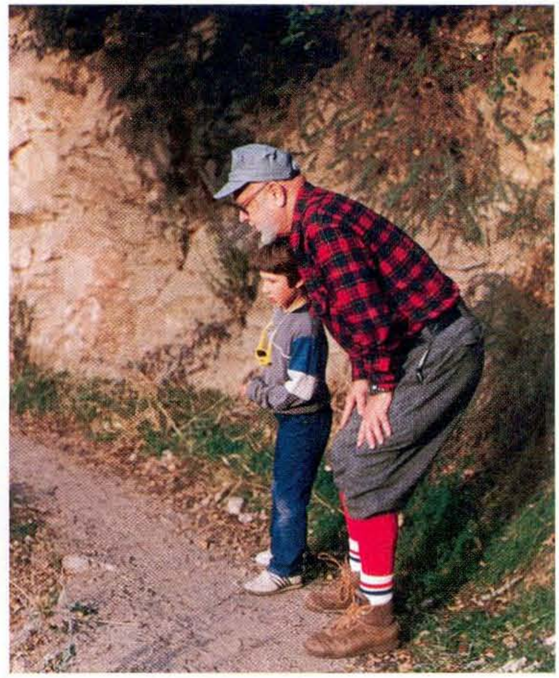
One story that Willy told me about was his disregard for the label "expert." He was very skeptical of experts, especially self-appointed ones, as he said. He once sprained his wrist while traveling on the East Coast. He went to a doctor recommended by a friend, and found through x-rays that the wrist was not broken. When Willy walked out of the doctor's office, the doctor directed him to bathe the wrist in hot water three times a day. Willy explained, "Doctor, what do you mean? My mother always told me to bathe a sprain in ice water." "Well, your mother was wrong," the doctor replied. "*My* mother told me to use hot water." So much for titles and degrees.

However, Willy did become an expert in his own field, and it is interesting to me that even as a teenager he recognized some importance of his being here in this world. I know this because Mary Dutcher Fowler found a short autobiography Willy had written as a senior at Lima Center High School. She unearthed it this past summer from the piles of papers and books on the floor of Willy's study.

In the first chapter he relates a strange event that occurred on the day he was born. A lone owl, perched in an oak tree outside the room in which he and his mother slept, shrieked in a weird and terrifying way all through the night. In the following words Willy questions the significance of this event: "All of us have a touch of the superstitious in us. I would not be human if I did not think deep in my mind that the cry of the screech owl meant something. But what that something was has never occurred to me—whether the owl was prophesying, warning, or neither. Nevertheless, I feel at least my birth transcended the commonplace." While Willy was unable or unwilling to identify this herald, to me the owl's screech and its presence meant one thing: owls are known for being wise and retaining immense amounts of knowledge. I think the owl's screech was symbolic of Willy's gift of wisdom and knowledge.

{Spruce read a few more excerpts from Fowler's teenage autobiography—about his "golden childhood" as a typical American boy who liked to play baseball and who was looking forward eagerly to the rest of his education. The essay concluded: "I sincerely want to live a life that shall not have been in vain."}

How prophetic his autobiography seems. Although the young Willy could not know it, his life certainly became extraordinary.



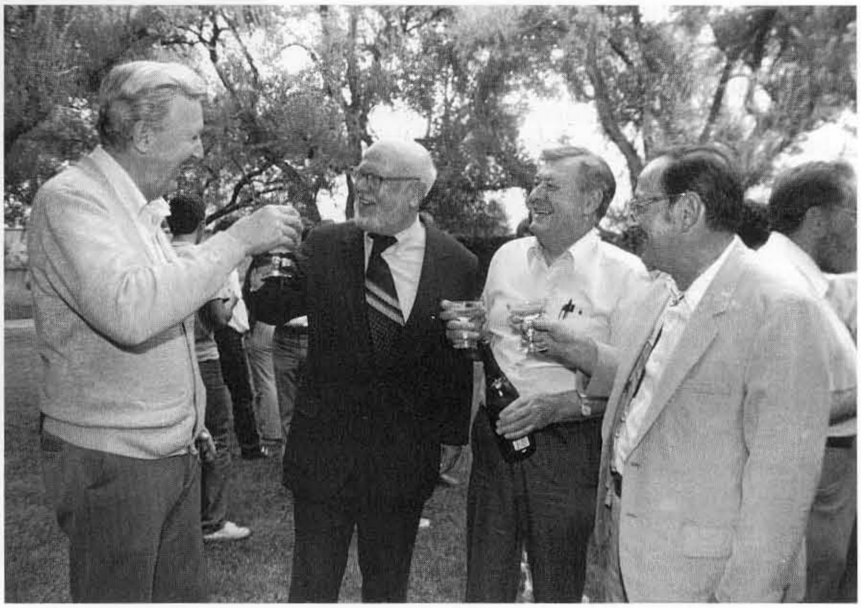
Willy and Spruce (age 6) in the San Gabriel Mountains above Pasadena on another hike (right), and in Vermont for Fowler's 83rd birthday in August 1994 (below). It was Fowler's last visit to Vermont before becoming bedridden in November.

In a talk prepared for the 1988 Caltech graduation exercises, Willy noted his dissatisfaction with the term "commencement." He preferred to call it "completion." Today we celebrate his life and recognize the completion of his physical life. But my grandfather will live on in my mind, my heart, and my fond memories, as well as yours, and in his contributions to the world of science. In spirit Willy and I will be sharing many more hikes, side by side.

Robert Christy
Institute Professor of Theoretical Physics, Emeritus
Caltech

I have many fond memories of Willy, and I would like to share some of them with you. He was a real leader, which I assume came naturally to him; in any case, he did it well. In 1951 Caltech was asked to run a study project, Project Vista, on the defense of Western Europe. Many of us contributed in our areas of expertise, but Willy was chosen to be the director. He ran it and he ran it well. Also, as many of you know, Willy ran a considerable research group and ran it well for many years. It is fitting that he had a passion for steam locomotives. In a way, he himself was a locomotive, a prime mover. Now, although Willy was the powerful force pulling in front in many cases, Charlie Lauritsen was sometimes the one with his hand on the throttle.

Willy helped the careers of his students, postdocs, and colleagues. He recommended them for positions, for promotions, and for honors. I



Above: At Tommy Lauritsen's house in the 1950s, a then-beardless Fowler (center) joins the chorus with Volney Rasmussen (left) and Lauritsen, while Victor Weisskopf accompanies. Right: Long-term Kellogg collaborators Ralph Kavanagh (left) and Charles Barnes (second from right) toast Fowler's Nobel Prize in October 1983, along with G. J. Wasserburg (right), whose work was strongly identified with the Kellogg group.

expect that many of you, like myself, are indebted to Willy. I came to Caltech as a result of a phone call from him, and such honors as I have received I suspect were helped by a good word from Willy.

I remember the strong sense of fun that marked him. He was in the best sense of the word the life of the party, and I remember well his leading the singing at the Kellogg parties. I also remember the hat and mirror trick he liked to do, in which he wore a hat next to a mirror and someone in front would blow at a glancing angle, and Willy's hat would hover a few inches above his head and then settle down. He also loved to dance, and I'm told he was very good.

He was a strong supporter of his favorite teams—the Pittsburgh Pirates and, in football, Ohio State, which he had attended as an undergraduate. He and Bob Bacher, who was a Michigan alumnus, always had a bet on the Ohio State-Michigan game, and I can imagine Willy turning over in his grave at the result of that game this fall.

Having known Willy, and having worked and played with him, will always mean a lot to me. He was a major force in my own life, and, like most of you, I miss him.

Charles Barnes
Professor of Physics, Emeritus
Caltech

I can't imagine any group of young physicists who had a better time in their careers than those who were fortunate enough to have worked with Willy Fowler. He, and Charlie and Tommy Lauritsen, worked hard themselves and inspired everyone around them to do the same. The excitement of the search for new understanding made it all something that we loved to do. After their pioneering nuclear physics work with an old and primitive accelerator through the 1930s, the Kellogg Lab physicists were fascinated by Hans Bethe's and Carl von Weizsäcker's proposals for two alternative ways that four hydrogen nuclei might fuse together to make a helium nucleus and, at the same time, produce the prodigious energy output of a star for millions, or even billions, of years, depending on the mass of the star. Willy and his colleagues proceeded to build a new and much improved accelerator to study the feasibility of these theoretical proposals, but their efforts were interrupted in 1940 by urgent national defense work.

After the war, Willy and his students resumed their study, and by 1954 they had shown that both mechanisms were indeed feasible processes for fusing hydrogen to helium in stars and, surprisingly, that our sun functioned on the chain of reactions that had been considered as the less favorable one in the theoretical work. After this work on the hydrogen-burning reactions, another equally exciting period began with critically important ideas from Ed Salpeter and Fred Hoyle that led to the study of the reactions building carbon and oxygen from the helium nuclei that had, in turn, been produced earlier by the fusion of hydrogen. In this way Willy and his team proceeded step by step to study the nuclear reactions that would occur deep within a star at later, *He was a rare individual, a man who will be remembered as much for his wonderful personality as for his many contributions to the world of science.*

Below: Fowler and Barnes with Kellogg's new (in 1982) accelerator, known as the "Yellow Submarine." Barnes is explaining how the focal properties of the beam change as it turns a corner.

higher-temperature stages of the life of the star, leading to its final explosive demise as a supernova—if the star were massive enough—or to its protracted quiescent decline into oblivion.

After the helium-burning program was well established, Willy elected to take a sabbatical year, 1954–55, in Cambridge to work with Hoyle. He met Margaret and Geoffrey Burbidge, and the four of them formed a highly fruitful collaboration that continued at Caltech, resulting in the publication in 1957 of their seminal work showing that all of the chemical elements could be produced in the cores of stars. This work, still referred to as B^2FH from the names of the authors, remains largely intact 40 years later. (Many of the same conclusions were reached independently by A.G.W. Cameron, also in 1957.)

{Barnes then recalled other milestones of Fowler's scientific career, including his farsighted work suggesting the detection of neutrinos from the nuclear reactions in the sun's core; his work with Hoyle on producing a more reliable way to gauge the age of our galaxy (and his delight in coining the term "nucleocosmochronology" to describe the field); his joint work with Hoyle and Bob Wagoner on the simultaneous dynamical evolution of and nucleosynthesis in the big bang; and the enduring legacy of his critical reviews of the huge body of experimental reaction data that led to his recommended values for astrophysics calculations.}

Willy loved finding felicitous epigraphs for his papers, from Samuel Pepys to Isaac Newton. A quote from the latter (1704) reads: "The changing of bodies into light, and light into bodies, is very conformable with the course of Nature, which seems delighted with transformations." I can still see, in my mind's eye, Willy's satisfied smile as he finds yet another apt quotation for one of his papers.

As Fred Hoyle said last March about Willy, "The technical description of a man's career says little of what he was like." Willy was above all a great person to meet and to get to know. Working with him was an ongoing exciting experience. His dedication, his irrepressible optimism, and his unquenchable energy made him an inspiration both here at the Institute and in his many other undertakings, the host of academic and scientific organizations he served, science-policy circles in Washington, and committees on national defense policy. Because of his remarkable virtuosity, it is not surprising that Willy was a much sought-after speaker. He was a rare individual, a man who will be remembered as much for his wonderful personality as for his many contributions to the world of science.

Steven Koonin
Vice President and Provost; Professor of Theoretical Physics; BS '72
Caltech

Our memories of people are a collage of the experiences that we have with them, and I had more than 25 years to build up my mental image of Willy—as his student, his colleague, and his collaborator. My mental image of Professor Fowler is quite dissonant with the decorum that's

Left: Provost Steve Koonin hails a couple of well-known Caltech nonadministrators, and (right) Fowler gets a laugh out of the queen of Sweden.

traditional for occasions like this, and so, rather than the usual solemn recitation of fine qualities and noble achievements, I thought I'd tell you a few of my favorite stories by and about Willy that for me at least capture the essence of the man.

Willy loved to party, and one of my recollections stems from a party. It dates not from when I first met him but rather from when my wife, Laurie, did. In June of 1972, Borje Persson, a physics professor in West Bridge for whom I had worked, threw me a graduation party. Since I had also spent a good deal of time in Kellogg, many Kellogg folks were there as well, and, as might be expected, much alcohol was consumed. At some point during the evening Willy sneaked off alone to a bedroom. Laurie's introduction to the great man occurred when a co-conspirator summoned her to the bedroom, from which she burst giggling hysterically five minutes later. She never told me what went on in there with Willy, but I want to talk to Bob Christie about that mirror and hat.

Willy did great things, he had fun while he did them, and he enjoyed involving others in the doing.

That Willy could instantly put anyone at ease is shown by the picture above. The real reason why these people are laughing is perhaps less well known. It seems that in the course of the Nobel preparations, Willy had been shown a picture of the royal family. During the dinner conversation our hero remarked to the queen that, since he had had the chance to admire her children, it was only fair that she have a look at his grandchild, and he promptly pulled out a picture of Spruce. As he did so, he asked whether Her Majesty knew the difference between a grandfather and a grandson. She replied, "Yes, Willy, I think I do." (He'd already taught her to call him Willy.) "But I'm not certain it's what you're thinking of." Willy then answered his own question: "A grandfather always carries a picture of his grandson, but a grandson never carries a picture of his grandfather," prompting the hilarity caught by the photographer.

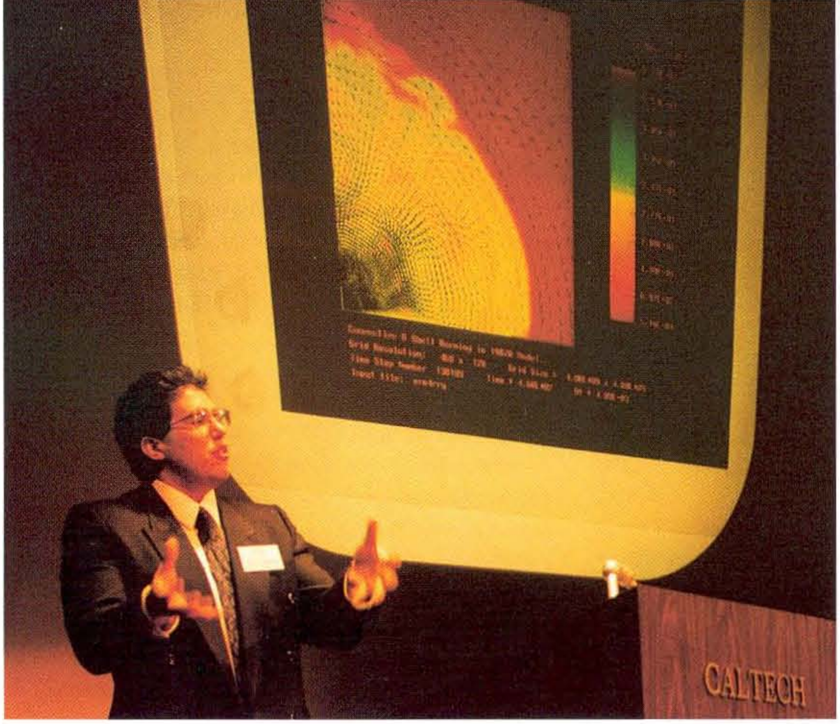
Willy seemed to have a story for every occasion. You've already heard from Spruce the one about experts, and there's another one about lawyers. But one whose recollection helps keep me humble in my present position is the one about administrators. Willy had a standard response to the question of why he never became an administrator. It seems that when Professor Fowler was visiting a small college to deliver a lecture, he stopped in to use the men's room. As he turned to use the electric hand dryer on the wall, he noticed a graffito scrawled next to it: "Push here to hear the dean speak." That was enough to cure him of administration.

I have many more Willy stories, as I'm sure everyone does, but I think the common threads of all of them are that Willy did great things, he had fun while he did them, and he enjoyed involving others in the doing. That combination of qualities is something that we should cherish and aspire to.

Grant Bazan
Research Associate, Steward Observatory
University of Arizona

Like many of you here, I owe a great debt of gratitude to Willy Fowler for what he has done for stellar nucleosynthesis. His direct contributions to the field obviously include his seminal paper, Burbidge, Burbidge, Fowler and Hoyle, and many other papers on nuclear reactions that either laid the foundation for nucleosynthesis or clarified any lingering doubts that we might have had about a certain reaction chain. I was asked today to comment on my impressions of Willy's contributions to the current state of stellar nucleosynthesis and to prognosticate about the future of it. Even though I met him only a few times and don't have a rich history of interaction with him, I do still feel that Willy is a part of me, because I am a product of the people with whom he has populated the field. So the field of nucleosynthesis rests in good hands because a piece of Willy lives on in all of us who continue to do this work.

In the current state of nucleosynthesis, the extent to which we can explain what we see in



Grant Bazan describes the stellar evolution models now possible with current computer power, in particular those that include convection in the latter stages of a star as it becomes a supernova.

I think that within the next 10 years we might actually be able to explain maybe one iota more than what Willy has already taught us.

the universe is the result of the contributions of Willy Fowler. Just from simple assumptions about how a star evolves, from compilations of nuclear reaction rates, we can estimate the chemical abundances in individual stars (very different from the abundances on Earth) and come remarkably close to what is observed, even though just a small error in these rates can make a huge difference. I think Willy would be very proud of how the field looks now, especially when you consider that these complex processes work as well as they do theoretically.

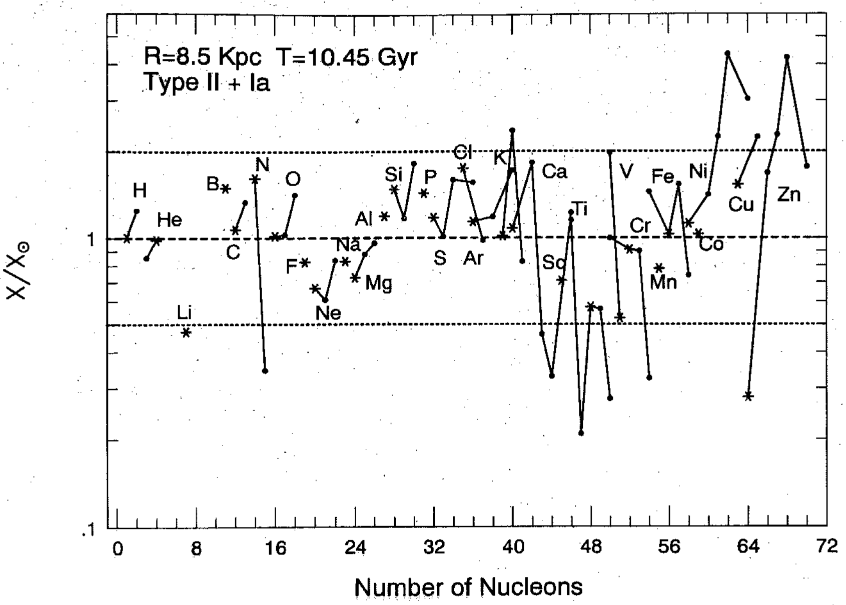
We can actually plug the sum of all the stars—the output, the chemical yields that we calculate—into an even simpler model of chemical evolution and come out with individual isotopic abundances that match those on Earth within a factor of unity. I find this simply amazing. This is probably the greatest testament to Willy's life. This is what he set out to do, and in a way he is doing it still.

What is there, then, left to do in stellar nucleosynthesis? There are still lingering questions concerning individual isotopic reactions, things in meteorites that we can't explain using the simple assumptions of stellar evolution. We are now at the point where computer power allows us to employ real hydrodynamics, real assessments of nuclear reactions, and put these into real stellar evolution models. One example of such a model is our attempt to put convection into the latter stages of a star as it goes into a supernova. The computer power necessary to do this was not available even three to five years ago. With this better technology, combined with the knowledge that has been accrued since Willy Fowler began it, the field of stellar nucleosynthesis rests on very firm ground. I think that within the next 10 years we might actually be able to explain maybe one iota more than what Willy has already taught us.

Frank Timmes
Compton Gamma Ray Observatory Postdoctoral Fellow
Clemson University

Within the notion that there are scientific families that parallel personal families, this photograph always puts a smile on my face. For then this picture shows my great-grandfather, my grandfather, and my father, along with several uncles: Uncle Ray, Uncle Mike, and Uncle Syd. I take some of my fashion tips from Grandpa there, and Pop is looking pretty cool in his black Levis.

I wasn't one of William Fowler's graduate



Recent models of the chemical evolution of stars have calculated the abundances of stable isotopes from hydrogen to zinc, trying to show that, after many rounds of star formation, this process will eventually reproduce the sun's known composition. The y-axis here gives the calculated abundance divided by the measured solar abundance. The most abundant isotope is marked by an asterisk, and isotopes of the same element are connected by solid lines. If this calculated stellar composition were the same as the sun's, the isotopes would all lie on the horizontal dashed line. They do, however, replicate solar composition within a factor of two, represented by the horizontal dashed lines.

students or postdocs, and yet I consider Dr. Fowler to be one of the most important influences upon my scientific life. For without the sustained advice, unwavering support, and friendship of his students and collaborators, much, if not all, of the nuclear astrophysics that I am involved in would simply not exist as it does in its present form. I am highly appreciative, and greatly indebted.

Since my principal connection with Willy is through his science, I would like to spend a few moments on one aspect of that relationship.

Burbidge, Burbidge, Fowler, and Hoyle composed a broad and compelling paradigm of how the elements are synthesized in stars. They identified the various processes that operate in stellar interiors, and predicted the chief nucleosynthetic products from the major nuclear burning stages. Some of the details have changed, especially in the light of new physics that was unknown in the late 1950s. For example, scattering by intermediate vector bosons gives rise to neutral currents, which add a source of neutrino cooling. This cooling affects the core structure of a massive star, which in turn determines, to some extent, the detailed nucleosynthesis. Burbidge et al. and Cameron posed the following very important question: can the nucleosynthesis that takes place in stars and is forcefully ejected, eventually, after many rounds of star formation, reproduce the measured solar composition? I wish to briefly address this question.

By the mid 1980s various groups had run detailed nuclear reaction networks on specific stages of stellar evolution: core silicon burning, shell oxygen burning, and neutron capture reaction sites to name just a few. These specific studies suggested that a sizable portion of the solar composition could be synthesized. Supernova 1987A arrived and offered several observational tests of stellar evolution and nucleosynthesis, along with providing a few unexpected features. In the early 1990s the index n in Moore's Law (computer speed doubles and price halves every 18 months) had become significant enough to allow the routine use of detailed nuclear reaction networks in very finely gridded stellar evolution models. Coupled with an increase in our knowledge of the physical and evolutionary properties of our galaxy, the question posed by Burbidge et al. began receiving fresh attention.

The graph at left shows an example from the results of these recent stellar-chemical evolution studies. In terms of absolute solar abundances, the stable isotopes from hydrogen to zinc range over some 10 orders of magnitude. There are many uncertainties that affect the spread and pattern in the figure, for example: the treatment of convection, residual disagreement on key nuclear reaction rates, functional form of the star formation rate, and even the measured abundances themselves. Certainly this graph does not represent the final answer, nor the first, but it is very encouraging that the isotopic solar composition from hydrogen to zinc is replicated to within a factor of two.

Willy played a central role in this calculation— directly, by his compilations of the necessary nuclear reaction rates, and indirectly by training and motivating his students, grandstudents, and great-grand-students. I think a reasonably correct calculation of the isotopic solar composition is a beautiful example of the adventure associated with connecting nuclear physics to astronomy. It is very exciting, and an honor, to assist in propelling the science which Willy had such a profound influence on into the next millenia. □

{The "family" photograph on the opposite page was taken by David Arnett in front of The Green Man pub in Grantchester, England, at lunchtime, ca. 1971. From left to right: Syd Falk, Kem Hainebach, Mike Howard, Stan Woosley (identified as Pop in the text), Ray Talbot, F. C. Michel (Caltech BS '55, PhD '62), Cliff Morris, Don Clayton (MS '59, PhD '62; identified as Grandpa in the text), and Willy Fowler.}

Honors and Awards

Four faculty members have received Sloan Research Fellowships for 1996. Assistant Professor of Chemistry Erick Carreira, Associate Professor of Mathematics Matthias Flach, Assistant Professor of Computer Science Peter Schröder, and Assistant Professor of Chemical Engineering Zhen-Gang Wang join 96 other exceptional scientists nationwide who were named Sloan Fellows this year.

John Abelson, the Beadle Professor of Biology, has received the Alumni Achievement Award from Washington State University, his undergraduate alma mater, in honor of his contributions "to the understanding of protein biosynthesis."

Thomas Ahrens (MS '58), professor of geophysics, has been awarded the Harry E. Hess Medal of the American Geophysical Union for "outstanding achievements in research in the constitution and evolution of Earth and sister planets."

William Bridges, the Braun Professor of Engineering, has received a Distinguished Engineering Alumnus Award from UC Berkeley's Engineering Alumni Society. Bridges's three-time alma mater cited his leadership role at Hughes Aircraft Company in the 1960s in the discovery of a series of noble gas ion lasers, still used extensively in airborne systems.

Peter Dervan, the Bren Professor of Chemistry, is a corecipient (with Claude Hèlène of France's National Museum of Natural History) of the Grand Prix, awarded annually by France's Fondation de la Maison de la Chimie.

Matthias Flach, associate professor of mathematics, was awarded the Heinz-Maier-Leibnitz Prize by the German Ministry for Development, Science, Research, and Technology for "A Finiteness Theorem for the Symmetric Square of an Elliptic Curve."

Caroline Fohlin, assistant professor of economics, has been awarded the inaugural Gino Luzzato Prize for her dissertation "Financial Intermediation, Investment, and Industrial Development: Universal Banking in Germany and Italy from Unification to World War I." The award is given by the European Association of Historical Economics for "the best PhD dissertation in European economic history."

Kevin Gilmartin, associate professor of literature, has been awarded the Arnold L. and Lois P. Graves Award, which seeks to encourage innovative scholarship in the humanities by young professors at liberal arts institutions on the West Coast.

Harry Gray, the Beckman Professor of Chemistry and director of the Beckman Institute, has been inducted into Western Kentucky University's Hall of Distinguished Alumni. Gray received his bachelor's degree from Western Kentucky in 1957.

Michael Hoffmann, professor of environmental chemistry, has been named the E. Gordon Young Distinguished Lecturer at three Canadian universities—Alberta, Calgary, and Regina.

Wolfgang Knauss (BS '58, MS '59, PhD '63), professor of aeronautics and applied mechanics, has been named a Fellow of the American Society of Mechanical Engineers.

Julia Kornfield (BS '83, MS '84), associate professor of chemical engineering, has been awarded the American Physical Society's John N. Dillon Medal for Research in Polymer Physics.

Gordon Moore (PhD '54), chair of the Caltech Board of Trustees and chairman of the board of the Intel Corp., is one of 10 distinguished Americans to receive the Horatio Alger Award. The award honors individuals who have triumphed over great adversity in their lives to achieve remarkable success.

Gerry Neugebauer (PhD '60), Millikan Professor of Physics, has been given the American Astronomical Society's Henry Norris Russell Lectureship.

Ares Rosakis, professor of aeronautics and applied mechanics, has been awarded the Society for Experimental Mechanics' B. J. Lazan Award. The award is given to "individuals who have made outstanding original technical contributions to experimenal mechanics."

Kip Thorne (BS '62), the Feynman Professor of Theoretical Physics, will be awarded the Julius Edgar Lilienfeld Prize by the American Physical Society at the APS spring meeting on May 4. (Valentine Telegdi, a longtime Caltech visiting associate in physics and presently a faculty associate, won last year's prize.) Thorne was cited for "contributing significantly to the theoretical understanding of such topics as black holes, gravitational radiation and quantum nondemolition measurements... and for conveying lucidly the excitement of these topics to professional and lay audiences alike."

The American Center in Paris was designed by Frank O. Gehry to house a variety of programs, including a language school and a theater. The curved forms that have become identified with Gehry's recent work are evident here —and continued to grow curvier and curvier—a process made easier and more economical with computers. As Caltech's James Michelin Distinguished Visitor last November, Gehry lectured on his current work—how it's conceived and how it's made. An article adapted from that talk begins on page 10.

Engineering & Science

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