California Institute of Technology

Engineering & Science

Winter 1993

In this issue

Modern Architecture?

NASA's Future

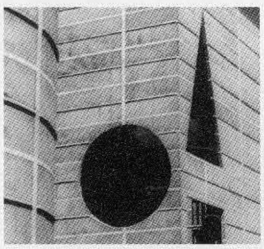
Caltech Bookworms

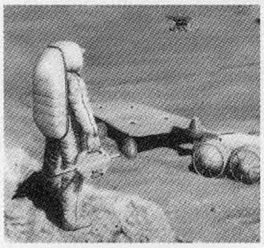
On February 7, 1984, astronaut Bruce McCandless II took a stroll around the neighborhood to get this shot of the shuttle *Challenger* from about 100 yards away. McCandless was test-flying the nitrogen-propelled Manned Maneuvering Unit, a forerunner of the "jet-packs" or "personal spacecraft" that figure largely in many space-exploration scenarios.

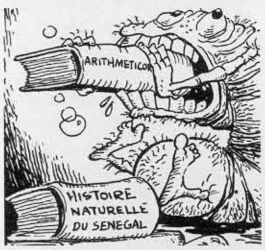
California Institute
of Technology

Engineering & Science

Winter 1993
Volume LVI, Number 2



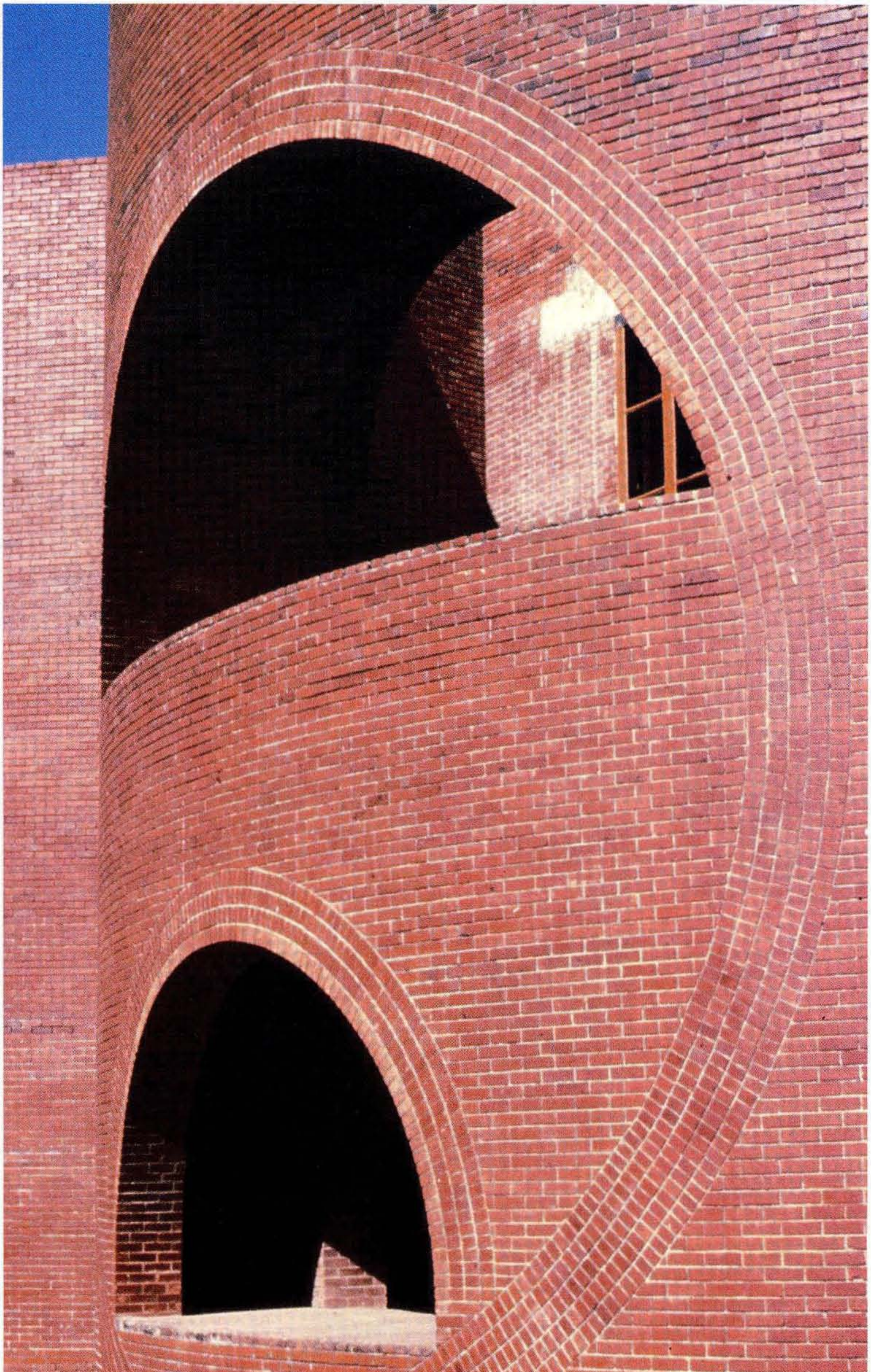




On the cover: Jonas Salk commissioned the architect Louis Kahn to build the Salk Institute for Biological Studies after hearing Kahn speak on "Order and Science in Art" in 1959. The complex in La Jolla, California (the laboratories are shown here; other photos on page 9), which was completed in 1965, represents Kahn's only building in the western United States. The architect's work and its roots in Roman ruins are discussed in an article by Vincent Scully beginning on page 2.

Engineering & Science (ISSN 0013-7812) is published quarterly, Fall, Winter, Spring, and Summer, at the California Institute of Technology, 1201 East California Boulevard, Pasadena, California 91125. Annual subscription $8.00 domestic; $20.00 foreign air mail; single copies $2.00. Third class postage paid at Pasadena, California. Published by the California Institute of Technology and the Alumni Association. Telephone: 818-356-3630. Postmaster: Send change of address to Caltech 1-71, Pasadena, CA 91125.

PICTURE CREDITS: Cover, inside back cover – Grant Mudford; 4, 5, 8, 9, 11, 13 – Yale University Slide Library; 5, 6 – Sue Ann Kahn, Jan Hochstim; 14–30 – NASA; 21, 31 – Bill Engels/NASA; 32 – Cathy Hill; 34–36 – Bob Paz; 37, 38 – FBI; 39, 40 – Pierre Baldi



Louis I. Kahn and the Ruins of Rome

Kahn wanted to deal with beginnings—with the primeval reality of architecture as a physical mass.

by Vincent Scully

Kahn's mature style, in which he succeeded in "wrapping ruins around buildings"—buildings that appear to have neither glass nor function—is best represented by his great buildings on the Indian subcontinent. This is housing for government officials at Sher-e-Bangla Nagar, Capitol of Bangladesh, (1962–83) Dhaka.

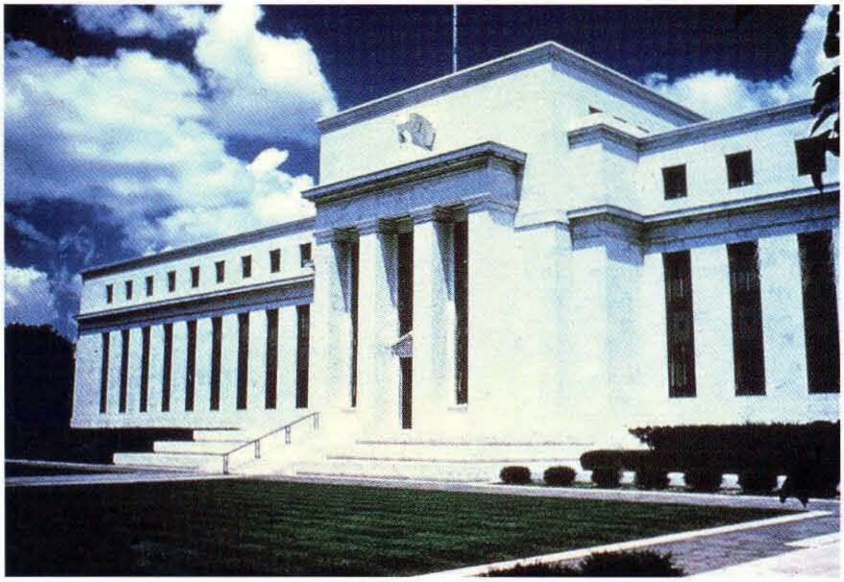
Vincent Scully gave his lecture on Louis Kahn, from which this article is adapted, on November 12, 1992, as the first James Michelin Distinguished Visitor. The Michelin Distinguished Visitor Program was established by a gift from New York designer Bonnie Cashin to foster creative interaction between the arts and the sciences by inviting annually to Caltech visitors who will stimulate thought and discussion on a wide range of topics. Cashin, an influential fashion designer, with more than 60 screen credits for costume designs and numerous national and international awards, was the principal founder of the Innovative Design Fund to encourage the development of ideas from creative designers.

Why Caltech? Cashin established the program (as well as the James Michelin Scholarship Fund in Geology and Geophysics) in memory of her uncle, a consulting geologist and longtime resident of Arcadia, California. Michelin, whose lifelong interest in mathematics inspired Cashin's own interest in the shapes, forms, and relationships of design, earned his BS in geology from UC Berkeley in 1924 and was associated with a number of oil-field ventures in southern California. But his greatest, and unfulfilled, wish was, according to his niece, to return to studying—at Caltech.

This is the first time I have been privileged to come to Caltech, and I'm very moved by the beauty of your campus. I think that it's only on the college campus, and especially on the American college campus, that architecture exists in its proper scale—not in terms of individual buildings trying to outdo others, but in terms of the creation of an environment as a whole in which buildings are designed to get along with the others to shape a space—a theater for human action. Caltech's theater seems to be one of the gentlest, most cloistered and wonderfully empty campus spaces I've ever seen. Caltech must be the most elite of institutions because all day long I haven't seen anybody. And I find that I like that very much the older I get.

Caltech also demonstrates some of the basic truths about the problems of modern architecture; that is, once, before there was modernism, Caltech had a very good plan by Bertram Goodhue. To modern historians like myself Goodhue used to be the enemy, a Beaux-Arts architect who represented the past. But Goodhue knew how to put a town together. He knew how to put a campus together, and he knew how to design buildings that got along with each other and made a place. But along about World War II something happened. Perhaps it was the Depression and then war, and, I think, also the victory of the modernist idea itself, but all of a sudden we seemed to forget what architecture was all about. We began to forget that architecture consisted of buildings that were supposed to get along with one another, and instead modern architects wanted to do things that had never been done before. Buildings began to appear as attempts at the most original, the most unusual, the most exotic, the most decorative imaginable. Caltech has its examples of these too.

Now, Louis I. Kahn was a modern architect. He wanted to invent. He wanted to seem to make it all up out of his own head. He wanted to seem to have no identifiable sources. He refused to use historical details in his buildings, and yet,



Above: Paul Cret's Federal Reserve building in Washington is an example of the "stripped classic" style popular during the New Deal. Unfortunately totalitarian governments were also fond of it. Below: George Howe's house (1924), with its primitive cylinder and suppressed glass, represents the order in which Kahn was trained and to which he ultimately returned.

by the way he built, he did in a sense end one long basic development of modern architecture and begin something very new. In the 10 years that Kahn spent with us at Yale (he joined us in 1947), we had no idea whatever that he would ever be as important as he came to be. Between about 1960 and his untimely death in 1974 he became, I think, the most important architect in the United States, whose work changed things in a fundamental way.

Starting in the early twenties, modern architects wanted to be as free as modern painters were—as free to invent as the cubist painters who had just come on the scene, and as free from the shackles of responsibility. They wanted no contextual responsibility to the traditional city; they were, in fact, contemptuous of traditional urbanism. Buildings were to have no top, no bottom, no side, no up, no down—nothing that read of construction, but rather of composition.

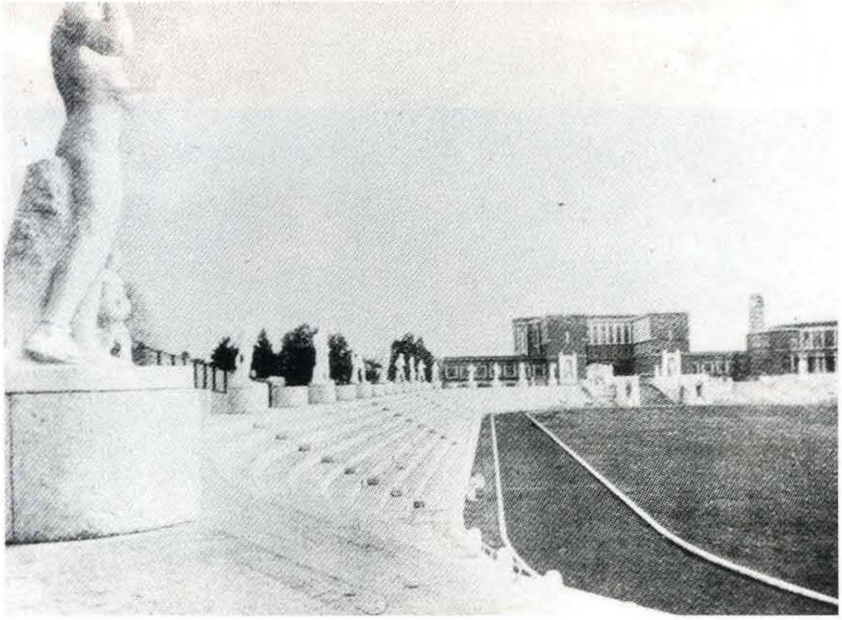
What Kahn did that was new in the high modernist period was to build buildings that were pure construction—buildings that showed nothing of the idea of composition and no trace of pictorial freedom. The connection with abstract painting, except in the abstraction of the forms that he insisted on, totally disappeared. He began to build buildings that looked like the very first kind of building that an architect might do, and he began to design only forms that were suggested to him by a structural system. His buildings had the basic architectural quality of being *constructed*. Kahn wanted to deal with beginnings—with the primeval reality of architecture as a physical mass.

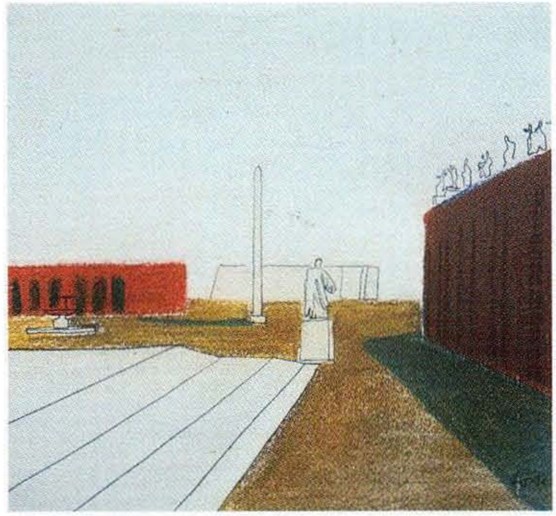
Out of that came a lot of things, for example, the revival of the vernacular and classical traditions of architecture and their reincorporation into the mainstream of modern architecture, which has, in my opinion, been the most important general development in architecture of the last generation. Along with this came a revival of traditional urbanism itself, rescued from the contempt into which the modernists had cast it. Along with that revival, too, has come the most important mass movement in architecture—indeed, the only one that has affected the course of modern architecture: the popular movement toward historic preservation. That movement is now politically so powerful that it can drive architects kicking and screaming to respect the centers of our cities, to save them from destruction at the hands of departments of transportation everywhere and to rebuild what we once had.

Now, Kahn cared not a rap for revival of vernacular and classical traditions, for urbanism and historical preservation. He wanted to be just as inventive as other modernists and just as abstract, and he was determined not to use readily identifiable historical forms in his buildings. And because of that, he has also become something of a major divinity for the current neo-modernists who would like to claim him for their own and write his history in a way that would make him the first inventor, the hero-architect, once more shaping the world anew. This is not the way it went.

Kahn was trained in a clear order, the order of the Beaux-Arts, at the University of Pennsylvania under his great teacher, Paul Cret. Then he lost that order. He lost it so completely that he forgot what it was that he'd lost. And then he had to find it again, but he had to find it on his own new terms so that he could believe, deep in his soul that he *was* inventive, that he was, in a sense, making it all up himself.

The order in which Kahn grew up can be seen in a house built in 1924 by George Howe, who later became Kahn's partner in Philadelphia. It's a masonry structure with a wonderful, primitive, cylindrical form in which glass is suppressed; he gets the glass as much out of the way as he can so he has just the quality of a cylinder with a dark void cut in it. After Kahn graduated from the University of Pennsylvania in the late twenties, he traveled to Italy, looking at precisely that kind of architecture—solid, almost primitive, masonry masses with voids in them without glass. He drew these structures with a soft, flat carpenter's pencil and also painted them in watercolor. (Watercolors were associated with the Beaux-Arts period; modernism despised the watercolor as





Mussolini's Foro Italico (top left) drew Kahn back to his modern-classic traditions when he sketched it in pastels in 1950 (top right). His drawing is reminiscent of the haunted shadows and arcades of the painter de Chirico (bottom) that evoked ancient themes antagonistic to modernism.

effete, so Kahn kept them under wraps and most of us only later learned of their existence.)

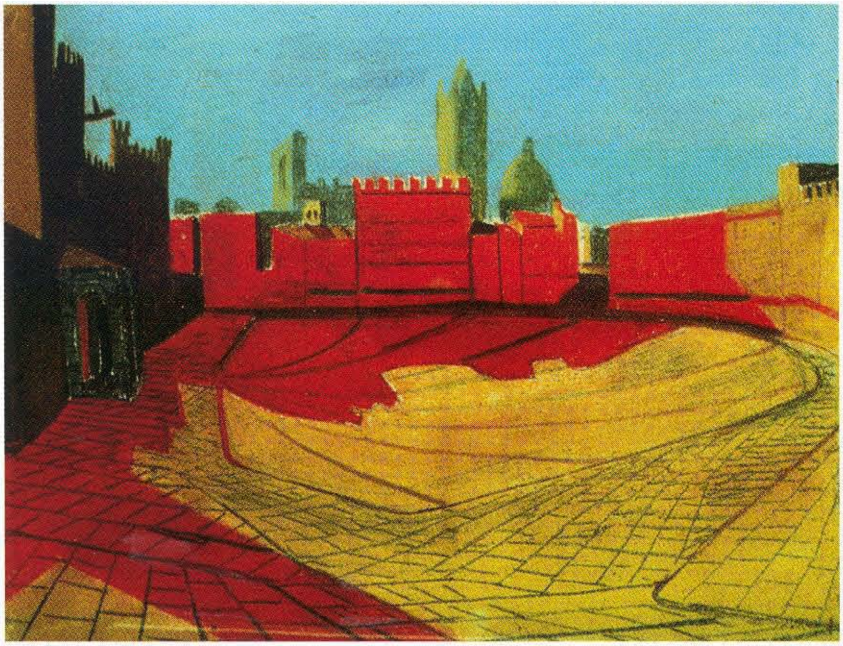
The "high style" architecture in which Kahn was trained by Cret was called "modern classic" or "stripped modern" in its time, and Cret, more than anybody else, created it. His Folger Library and Federal Reserve buildings in Washington, D.C., major commissions in Cret's office during the time Kahn worked for him in 1929–30, are good examples. They're much like the vernacular architecture that Kahn had sketched in Europe, in the sense that they're heavy, massive, and symmetrical. What you feel is the mass and the void, and glass plays very little part in the design. It's a traditional classicism simplified under the pressure of modernism, but still retaining a monumental symmetry and employing permanent materials, beautifully assembled. No sooner was Kahn trained in this approach, however, than Le Corbusier's Villa Savoye (1929–31) burst upon the architectural profession. Suddenly one could no longer look at buildings that were symmetrical, massive, heavy; one could no longer use the classical order in which Kahn had been trained, because now architecture had to be thin, taut, light, asymmetrical, stretched out to pure idea.

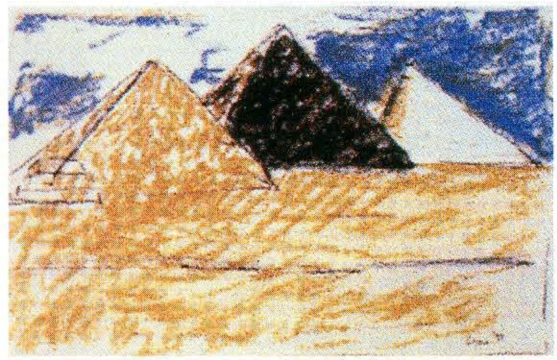
Other events also contributed to the demise of the stripped classic style. Not only did we build our best post offices and other buildings in the thirties in this style, but so did the Fascists and the Nazis. Later modernist critics, forgetting that we also had employed this style during the New Deal, used its association with totalitarianism as a club to beat classicism with. You couldn't separate it from its cultural meaning.

So Kahn did his best to do this new light architecture with thin columns and weightless walls of glass. He wasn't bad at it, but he wasn't exceptionally good at it either. And he would not have become the Kahn we know had he continued to do it. He just didn't feel it. When he came to Yale in 1947, he still had no major buildings. He was a man who clearly had lost his order. He was constantly talking about order, in particular about the order of crystals, seeming like so many other people at that time in the arts and art history to lose confidence in the arts and turn to science.

Then in 1950 Kahn went back to Italy, as a fellow at the American Academy in Rome. The very first thing he did was to go to a forum in Rome and do a pastel of it. (You weren't "allowed" to do watercolors anymore, and pastels were the closest he could get to them.) Now, it's interesting what forum he went to. He didn't go to the Forum Romanum; he didn't go to Trajan's Forum; he went to the Foro Italico, Mussolini's forum, the style that he'd been trained to see. His drawing of it, with its open arcades and ominous shadows, is reminiscent of those wonderful haunted visions of Italian urbanism painted by de Chirico during World War I. The Fascist architects themselves were, of course, very good at creating these effects to drive out modernism and use the ancient vision of haunted Italy to hold the imagination of the Italian people.

Kahn traveled to other Italian towns and drew their wonderful urban spaces—like the Piazza del Campo in Siena. In Kahn's pastel of it, he makes it curiously timeless by taking out all the





Kahn's 1951 drawing of the Piazza del Campo in Siena (above left) eliminated everything that would indicate scale or use, a style characteristic of his later architecture, particularly in India and Bangladesh. The Egyptian pyramids also had a profound influence on Kahn. The massive structures dissolve into light in his pastel of 1951 (above right).

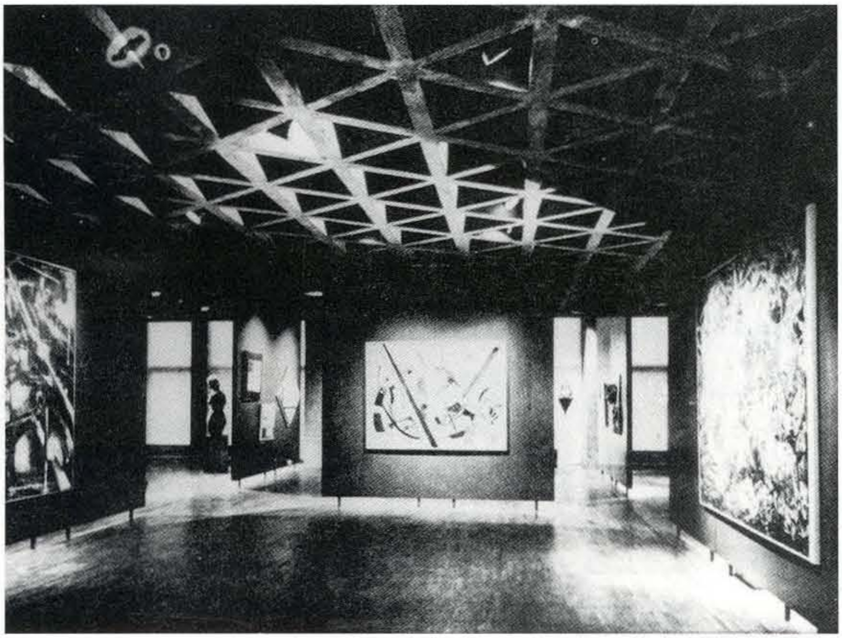
elements—windows, doors, people—that tell you scale or time or use. Everything is dissolved in one great bath of red shadow, which then floods down over the Campo. This is exactly what he'll later come to build—an architecture where all time and scale elements are eliminated.

Kahn also traveled to Greece that year, and drew in pastel the great temple of Apollo at Corinth, with its thick columns and its sense of structural power. But the white light of Greece was not what he wanted, and so he made the temple and background orange. He was looking for a hotter, heavier light, and he found it in Egypt. His great pastels of the Temple of Khons at Karnak show the swollen, compressed columns and the heavy vegetable color he wanted.

It's interesting that this trip to Egypt seemed to unlock Kahn's Jewishness, even though he had previously not had much of an interest its practice. The swollen columns of Karnak, which became for Kahn vessels of light, reappeared in Kahn's plan for the Mikveh Israel synagogue in Philadelphia. This plan, never built, also had roots in cabalistic diagrams of the order of the universe. Kahn loved pictures like an architect, and I think his Jewishness, his mysticism, would come out when he found a shape he liked. His proposal for the Mikveh Israel project would have been, I think, the most important monument of synagogue architecture in the modern day.

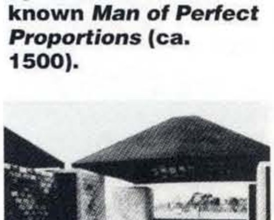
In Egypt Kahn came finally to the pyramids and did pastels of them. In 1951 he wrote a poem calling Giza "The Sanctuary of Art, of Silence and Light." Light is perhaps the most important word on the first page of Genesis, and silence in much of Jewish and Christian medieval literature has to do with the fundamental presence of God: the great silence of Jehovah is his power. In Kahn's pastels he sees the pyramids as pure light—enormous masses that dissolve, dematerialize into light. The pyramids, which were covered with blinding white limestone, served to transport the pharaoh to the sun—not with inscriptions or decorations but by pure magic. They became, massive as they are, the embodiment of pure light. As Kahn's pyramids dissolve in light, the viewer's mind does not supply the other sides; you think it might have three sides or even only one. But then, curiously enough, they always dissolve into tetrahedrons, tetrahedrons that are vehicles of light.

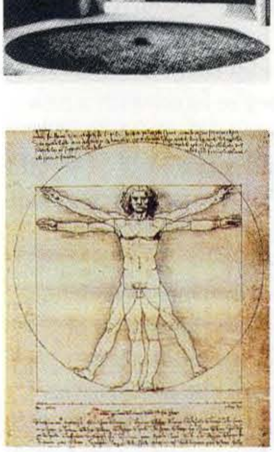
While Kahn was doing these pastels at Giza, he got word that George Howe, who by then was Yale's dean of architecture, had managed to secure him the commission for the Yale Art Gallery. It would be the first important building constructed at Yale since the war, and Kahn's first important commission. And what he built was tetrahedrons—a great ceiling slab of braced beams, creating a kind of crystalline order in the tetrahedrons that carry the lighting system. (Another influence on this building came from Kahn's partner, Ann Tyng, who was an enthusiastic admirer of Buckminster Fuller and his geodesic domes, also constructed out of tetrahedral shapes. Fuller came to Yale around that time, and talked and talked. He would utterly destroy the brains of students; if they were impressionable enough, they couldn't believe that anything else in the world was worth doing



Left: Tetrahedrons form the great ceiling slab of Kahn's Yale University Art Gallery (1951–53). Its string-courses are close to Italian palazzo design (above); the entrance is hidden at the side.

Below: In the bathhouse (1954–59) of the Trenton Jewish Community Center, Kahn employed not only his pyramids but the Neoplatonic order of the circle and the square, exemplified by Leonardo's well-known *Man of Perfect Proportions* (ca. 1500).



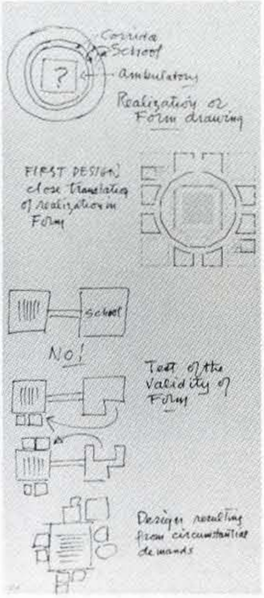


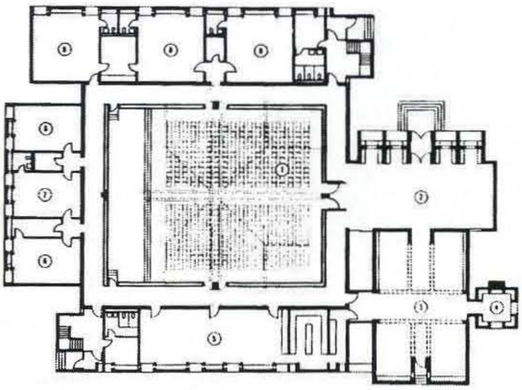
except building geodesic domes. Since the application of this one idea to the complex problems of architecture is minimal, a lot of them have had a good deal of trouble since.)

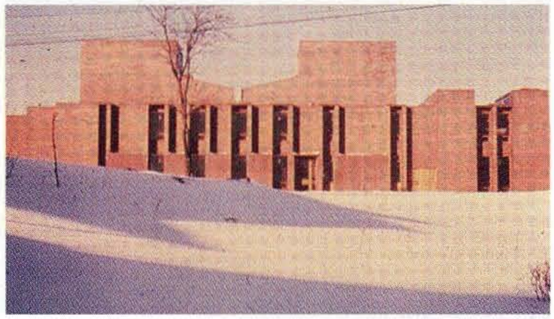
Of all the buildings built at Yale since then, it still seems to me that we have nothing to equal Kahn's art gallery. But he himself was never happy with it. Before Kahn was granted the commission, Howe and the forces at Yale had already decided that it would be a rectangular building, because it made a lot of sense on that site. Kahn then inserted into it a fundamentally triangular element, and he didn't like the disparity. The building wanted to take on a triangular shape as a whole, which, of course, it couldn't have done on its site, so he felt that it was compromised. But he was wise in the things he did *not* do. For example, he didn't try to design an entrance, because he couldn't design one not suggested by the structure. He kept the entrance back and at the same height as the base of the old building next door, so you sort of slide into the building at the side. Using the string-courses to express where the slabs were is very close to Italian palazzo design, and this enabled Kahn to pick up the movement down the street that the older building had, and then give it some velocity coming to the corner. But what Kahn really loved was inside the building—his pyramids. The staircase is especially wonderful; you look up the staircase and the black shadow of a pyramid floats there overhead, weightless, pure shadow, pure light—silence and light.

Kahn built actual pyramids in the bathhouse he designed for the Jewish Community Center in Trenton. Here he also came to other basic shapes that have pervaded Western architectural aesthetics from the time of the Roman architect Vitruvius and earlier: the square and the circle. In the Trenton bathhouse he has five squares, four of them topped by pyramids and the fifth containing a circle. Leonardo's well-known image of the *Man of Perfect Proportions* (ca. 1500) is only one of hundreds of such drawings derived from the passage in Vitruvius where he says, more or less, that it's wonderful that the human body is proportioned so that it can fit into the perfect shapes of the square and the circle. This idea, probably Pythagorean, obsessed the Middle Ages and was taken up by Neoplatonism during the Renaissance. It suggested the basic image upon which Gothic and Renaissance architecture alike are based. Implicit in it is the idea that there exists a fundamental order that you can find only in drawing; that is, in the domain of conception; if gross matter intervenes, you get further away from the idea of an underlying order of the universe as a whole. The forms, the circle and the square, thus drawn are taut as piano wire. Kahn's embrace of this idea connects him with the richest part of the classical tradition, its theoretical center, from which are derived the great architectural images of the order of the world—for example, the new France and the cosmic order as embodied in the great French classic gardens of the 17th century. This is a central theme of history that Kahn, once taught by Cret and other French Beaux-Arts architects, was now able in a sense to reclaim.

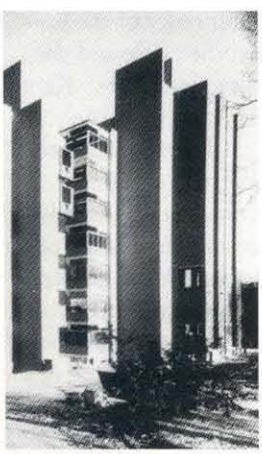
Kahn's new order, based on the circle and the







From the initial "form and design" drawing (above left) of the First Unitarian Church and School (1959–69) in Rochester, New York, the final plan (center) "deformed" and evolved, but remained based on the circle and the square and served and serving spaces. The building's windows are set back (above right), the glass suppressed. Below: The towers of the Richards Medical Research Building (1957–65), reminiscent of medieval Italian masonry towers, contain stairs and ducts and are not actually structural.

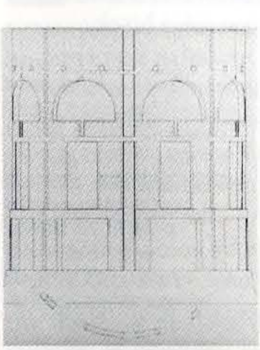


square, was also based on something else that came out of classicism and continued in the Beaux-Arts tradition—the idea of served and serving spaces, big spaces articulated and separated but connected to each other by small spaces such as corridors, bathrooms, and so on. You can see this idea in the plans of the French Gothic cathedrals that Kahn loved: square spaces capped by circular domes and articulated by groups of pillars making corridors that serve the larger spaces. Out of this influence came Kahn's great plan for the Alfred Newton Richards Medical Research Building at the University of Pennsylvania.

Although it didn't come, as modern pragmatism would have it, from pure invention, the plan was analyzed according to structure and function to produce a new unity that had never been there before. There's a central building that is basically service. The laboratories are square and are served by stairs and ducts to remove noxious air. Kahn carefully detailed the ducts and the stairs so that they don't look structural, or load-bearing, on the exterior. But while Kahn was designing the laboratory building, another deep memory intruded—his watercolor from the late twenties of the solid masonry towers of a medieval Italian town—and that's the way he finally designed the Richards Building towers. Whether they had ducts or stairways in them, they all looked like solid structural members. But he shows that they're nonstructural by stepping them in or by cutting a triangle at the bottom. There are some problems with the buildings: you *do* get confused by the towers. The major vertical structure is carried by pre-cast concrete columns that are actually smaller in scale and seem *less* structural than the towers. The pre-cast building is all laid up dry—no mortar. Kahn said he began to feel the crane as an extension of his arm and sense each one of these big heavy units as a brick, an element in the structure. In a way it's like Greek temples, which were also laid up dry without mortar; you put the parts together piece by piece, as Kahn had learned in the Beaux-Arts tradition. He was beginning to link back to the structural traditions that modernism had intended to cast aside.

It's clear from this moment in the early sixties that these memories were beginning to flood into his system, and he was beginning to use them. All of this comes together in the First Unitarian Church in Rochester, New York, which is where he proposed his theory of form and design. The "form" is the first formal idea that comes to architects' minds when they're faced with a new project. Here the project consisted of a church with a big meeting hall and also a school, which needed to be close to the hall to use it occasionally. So he draws something that looks like the circle in the square. And then he articulates it a little bit more in the next drawing, where he writes "FIRST DESIGN, close translation of realization in form." Here he bombards this perfect Neoplatonic idea with the peculiarities of the program, the demands of the structure and function of the program. When you do that, the form will deform because the rooms want to be different shapes. But if it doesn't deform too much, then you build it. And since the form

The scholars' studies at the Salk Institute for Biological Studies (1959–65) in La Jolla, California, are angled toward the sea (right). Looking toward the sea (below), only the concrete slabs are visible, and the thin stream of water running through the plaza. Kahn's design for a community center at Salk (bottom), which has never been built, shows his first breakthrough to the idea of "wrapping ruins around buildings," a style that was to culminate in his great buildings on the Indian subcontinent (next page).



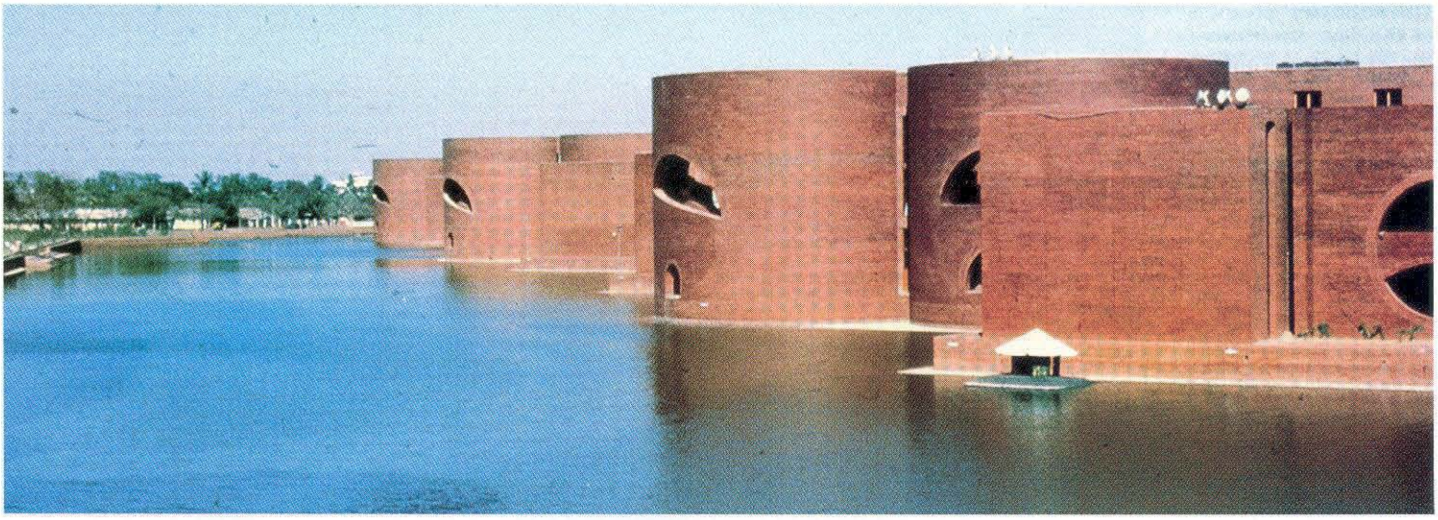
here was right, this is what he built. The client had originally had the wrong form idea, a sort of binuclear plan, but that didn't work because the school functions needed to be close to the meeting hall. It's wonderful to watch that beautiful plan evolve: the main entry hall gets larger; so does the library; the classrooms grow smaller, the kitchen longer. From that point on we can trace everything about the building through its reception of light. We can feel that Kahn has expressed function and structure like an absolute modernist, and that the plan is also wholly abstract—that he's achieved, in a sense, the modern ideal.

The windows are set back, to protect them from glare, he said, so we hardly see the glass in the exterior wall, which becomes very plastic and solid. Up above, four great monitors rise to light the central space, whose bony structure is one of Kahn's greatest. You can really feel the silence he talked about, thrumming as with the presence of divinity, when the cinder block is washed silver by the light that floods down upon it, while the heavy, heavy slab is lifted overhead. This space joins that of the Yale Art Gallery as one of Kahn's early essays in the sublime, into whose vast silences all his late work was to move.

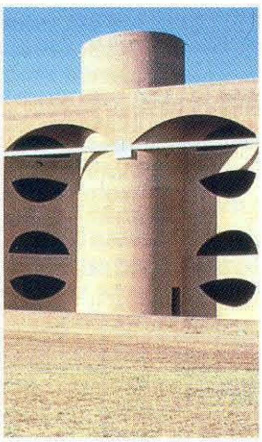
Then he built Salk—the Salk Institute for Biological Studies in La Jolla. At Salk you don't see *any* glass. There's glass set back at the entrances into the laboratories, but the general feeling is of a bony structure of concrete slabs, panels of wood, and no glass whatsoever. It was in Salk that Kahn first began to use the images that he rediscovered in the ruins of Rome in 1950 under the influence of Frank E. Brown, the great Romanist of Yale and the American Academy in Rome. Brown led us all to Rome and made us see that it wasn't just an architecture of engineers (I don't mean that the way it might sound to a Caltech audience), but also an architecture of poetry, of light and water. With Brown and alone, Kahn had visited such ancient sites as Hadrian's Villa, Trajan's Market, Ostia, and the Flavian Palace on the Palatine Hill.

In his first schemes for the scholars' studies adjoining Salk's laboratories, Kahn drew a plan consisting of a square with a fanning pattern opening outward—a pattern he had seen in the garden court of the Domus Augustana of the Flavian Palace. The fanning pattern coming out of each square bay gave the sense of forces running through matter, which had furnished baroque architecture with its life and which certainly affected Kahn. This was the first time he overtly tried to use a Roman form.

Eventually, though, Kahn discarded this plan because he wanted the scholars' studies inflected toward the sea. But the sense of forces running through matter remained. Down through the center of the empty courtyard runs a thin stream of water; instead of a normal plaza, it becomes a corridor. It's directional. You can feel the space being drawn from the continent to the sea. Many people describe the Salk Institute in terms of the Acropolis, because you can't see any glass and because the concrete is so beautifully made it looks like marble. And sometimes in that glowing space, looking toward the sea, you might happen to see Icarus gliding across the scene—



Above: Housing for officials at Sher-e-Bangla Nagar, Capital of Bangladesh (1962–83), in Dhaka, exhibits no trace of scale or function; glass is suppressed behind the voids cut in the cylindrical "ruins." Below: At the Indian Institute of Management (1962–74) in Ahmedabad, Kahn devised his new "brick order," a conscious misreading of a Roman ruin, with void, lintel, and arch.



the coast there is one of the most popular hang-gliding spots in southern California.

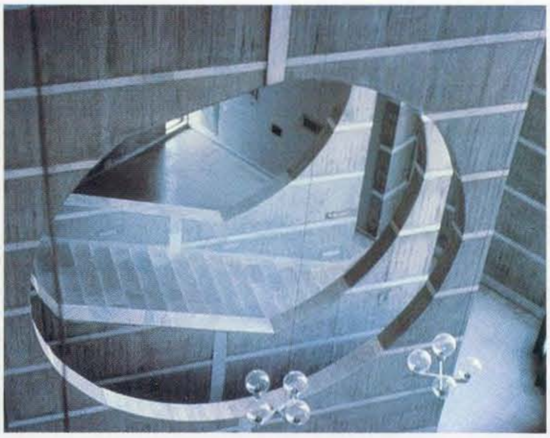
Kahn also designed a community center for the Salk Institute, and I hope someday Dr. Salk will be able to build that wonderful complex of buildings. It represents an enormous breakthrough in Kahn's design in that it wholly resembles Roman ruins. The rooms would have walls almost entirely of glass, but protected from glare by thin concrete walls that are perforated but have no glass in them. Square rooms are surrounded by cylindrical walls and circular rooms by walls at right angles. He called this "wrapping ruins around buildings" to provide a vision of a building without glass. He was encouraged in this by a paper written about that time on the forum baths at Ostia. The author, an engineer and a pupil of Brown's, showed that the orientation of these wonderful ruins, some of them rectangular, some curvilinear, was such (and the heat so efficient) that they probably were never intended to have glass, even though the Romans had plenty of glass. Kahn figured if the Romans could do it without glass, so could he. It was Kahn's beautiful drawing of this proposed building, which incorporated so many of the things he loved—the pure void in the ruin, the curved, taut, thin walls, the lintel between two levels of opening—that more than anything made me feel when I saw it in 1962 that Kahn was an architect of frighteningly awesome potential. It expressed *romanitas*—the gravity and authority of Rome. Everybody laughed at this design and called him "Loony Lou."

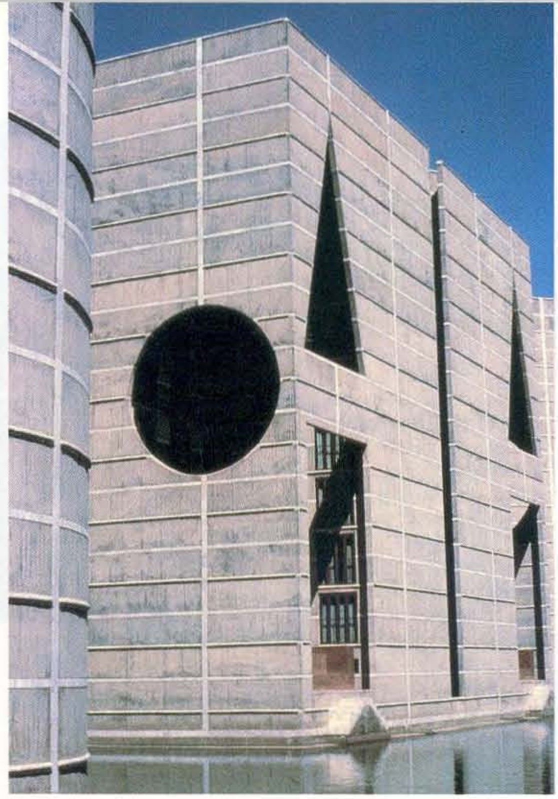
But Kahn had the last laugh; he took his glassless Roman ruins to the Indian subcontinent, and there his great primitive shapes began to appear. His brick Indian Institute of Management in Ahmedabad seems to be a conscious misreading of a Roman ruin. Romans, in Ostia for example, often built walls of two courses of brick, filled with concrete. In order to keep the fresh pour from breaking the wooden lintels over openings, they would build a relieving arch right through the two thicknesses of brick wall. So you get a void, a lintel, and an arch. In what Kahn called his "brick order" he revised this and used the lintel to hold the arch together. He splits the impost block in the middle to make you feel the tautness, the tension of the sides—as if they're trying to hold the brick back. There's so much more life in it than if it were a solid block.

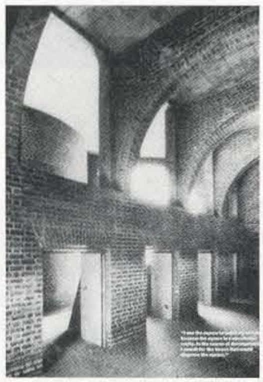
Kahn is an idealist and, indeed, a Romantic Classic architect; his models are the great architects of the 18th century—and in particular the great draftsman and etcher Piranesi, whose prints of the ruins of classical Rome inspired the Romantic Classic architects. Like them Kahn is trying to revive architecture by going back and starting with the ruins of Rome. And also like them, Kahn wants fundamentally sublime effects. The 18th-century concept of the sublime is different from that of the beautiful in that it deals with the awesome and the unfinished, the primitive and the frightening, embodied in Piranesi's fantastical prints. And this is the quality that Kahn, too, wants.

The wonderful space of the waiting room of the outpatient clinic at Sher-e-Bangla Nagar, the capitol center in Dhaka, Bangladesh, is almost an

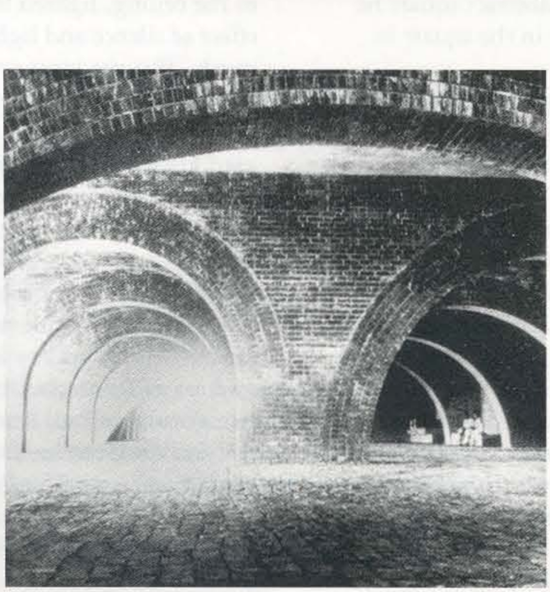
The cylindrical and block shapes of the National Assemby Building at Sher-e-Bangla Nagar, Dhaka, (far right) act as containers of light punched through with circles and triangles. Great circular holes also light the north entrance staircase (right).
Below: Kahn took the cross-vaulting in the Indian Institute of Management (right) from Trajan's Market in Rome (left)







Above: Light from both sides illuminates the Thermopolium in Ostia (left, 2nd century A.D.) as well as Kahn's waiting room of the outpatient clinic at Sher-e-Bangla Nagar.
Right: The round brick vaults under the National Assembly building at Sher-e-Bangla Nagar look self-consciously Roman, and very Piranesian.

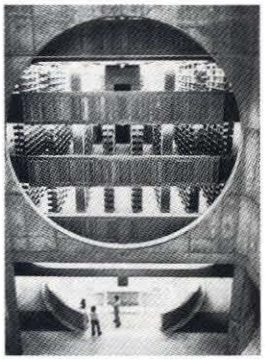


exact transcription of the Thermopolium, the famous little hot-drink stand in Ostia, where you have the light coming in from both sides. Trajan's Market is a splendid example of Roman brick and concrete structure, with a concrete barrel vault that gets light into it from penetrating cross-vaults, which make the whole thing seem to be lifted. Kahn recreated this in the Indian Institute of Management but reduced it to a simplified, clarified structure that he could build rationally. Instead of being poured concrete and cross-vaults, it uses brick arches carrying concrete slabs with steel in them. The great National Assembly building at Sher-e-Bangla Nagar has antecedents in the Temple of Jupiter Optimus Maximus at Ostia—and the shapes in the plan, some cylindrical, others square, can be found in Piranesi's fantastical reconstruction of the Roman Campus Martius that hung behind Kahn's office desk. Kahn used these shapes as he had intended to do at Mikveh Israel, as containers of light, their thin walls cut through with circles and tall pyramids, while big circles light the great council chamber.

Even though he used all these wonderful shapes from classical models, Kahn avoided tipping his hand by quoting obvious classical details like the pediment, the tondo, and so on (so now he can be deified by the modernists as inventing it all out of his head). Other architects involved in a classical revival are doing that sort of thing now but Kahn never would. He wanted to remain enigmatic, ambiguous, timeless. Any detail would give it scale.

When Kahn comes back to America in his last

The arches along one side of the Kimbell Art Museum (1966–72) in Fort Worth, Texas (right), match a sequence from Hadrian's Villa in Tivoli. Glass is again subordinated. Below: In the central Hall of the Phillips Exeter Academy library (1965–72) in New Hampshire, a circle in the concrete square illuminates the stacks.



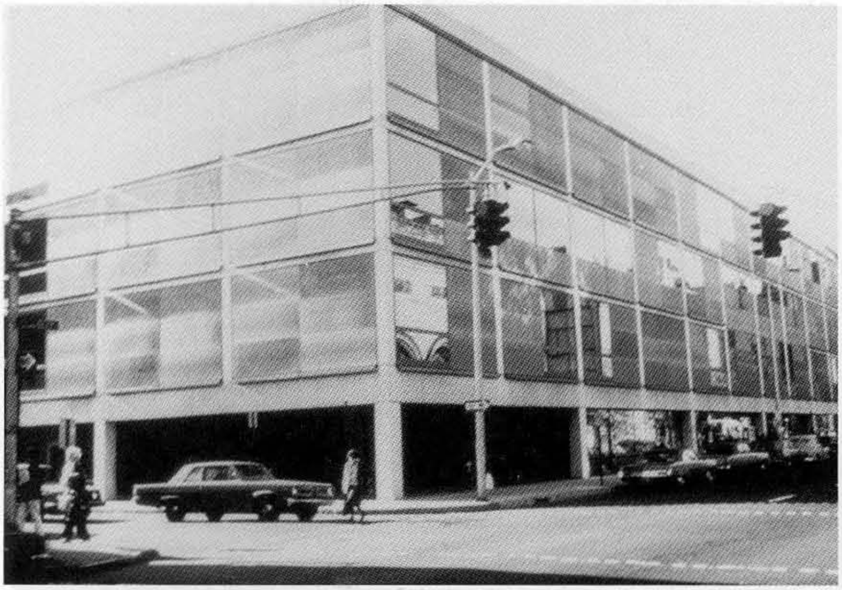
years and builds the great and much-admired Kimbell Art Museum in Fort Worth, he stays very close to the ruins and subordinates the glass. There is a wall of glass, but it's masked by trees and normally you don't see it. Inside you have Roman round-headed arches that have been deformed to distribute the indirect light better. The profile of arches along one side match very closely a sequence from Hadrian's Villa. And in his library at Phillips Exeter Academy in New Hampshire, Kahn won't even let it become a building; he wants it to remain a ruin. The walls don't connect at the corner or the top. They remain like a hollow shell into which every now and then, almost grudgingly, he will ram some glass. It's basically that hollow frame that he wants, and then inside this abstract square he puts a circle: the pure circle in the square in heavy concrete.

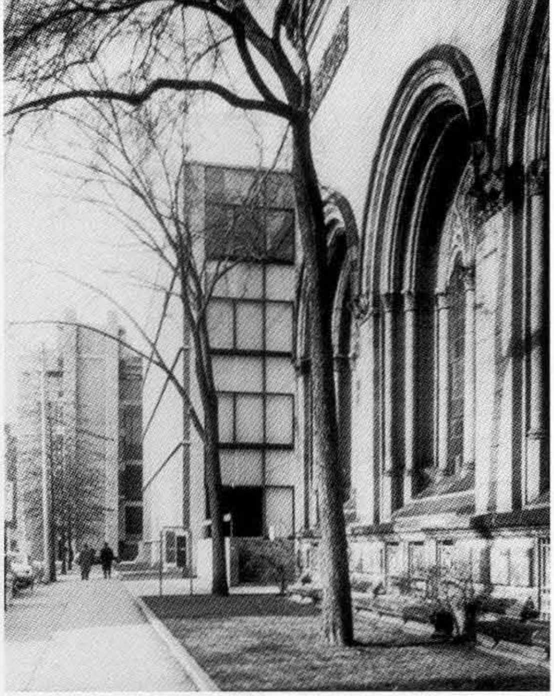
Because he stayed so close to the Romantic Classic ruins in these buildings, Kahn's last building, not completed at the time of his death, seems a miracle. With the Yale University Center for British Art he leaped forward 100 years—from the Romantic Classicism of the mid-18th century to the materialist realism of the mid-19th century. Henri Labrouste, in his Bibliothèque Sainte-Geneviève in Paris, solved the problem of building a Greek temple, which for the necessities of modern life had to be closed off from the street, by putting the columns on a base with a strong stringcourse. Nonbearing panels, some solid and some glass, fill in between the columns.

Kahn uses basically the same system in the Yale Center for British Art. A big heavy girder runs above ground level with shops underneath. Above it he builds a concrete structure holding solid panels of stainless steel and panels of glass. It's close to what Mies van der Rohe did (for example in his buildings at the Illinois Institute of Technology), and Mies got it from a similar source. But visually Kahn's building seems a more solid structure than Mies's. You feel that wonderful quality of its being "built"; it expresses weight and compression. The lintels weigh heavily on the piers; the joint is point-loaded, static, Greek, silent. And the concrete is as beautiful as marble.

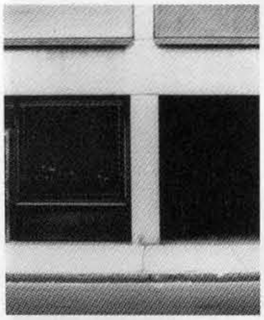
Inside, such sublime features as the great cylindrical stair tower that doesn't reach quite to the ceiling, lighted from above, create the effect of silence and light that Kahn loved so much. But the most unlikely thing for him is the use of glass, which, as we have seen, he had always avoided or tried to subordinate. And he's used glass with more light and incandescent vitality than I have ever seen in it before. Next to the surface of those matte panels, the glass simply explodes with light and reflection.

And what it's reflecting are all the buildings across the street—the wonderful old 1920s Beaux-Arts art gallery with its arches, and Kahn's own art gallery from the early 1950s with its stringcourses. Paul Rudolph's much maligned Art and Architecture Building, a villain of late modernism, stands at the end of Chapel Street, embracing and completing the movement of the buildings down the street with a wonderful open gesture. Kahn's Center for British Art seems to





The Yale Center for British Art (1969–74), Kahn's last building (above), reflects the flow of buildings across the street—the old art gallery, Kahn's own earlier building, and Rudolph's Art and Architecture Building at the end. Below: The heavy lintel point-loaded on the pier and the cylindrical stair tower give the effect of weight and silence that Kahn loved.

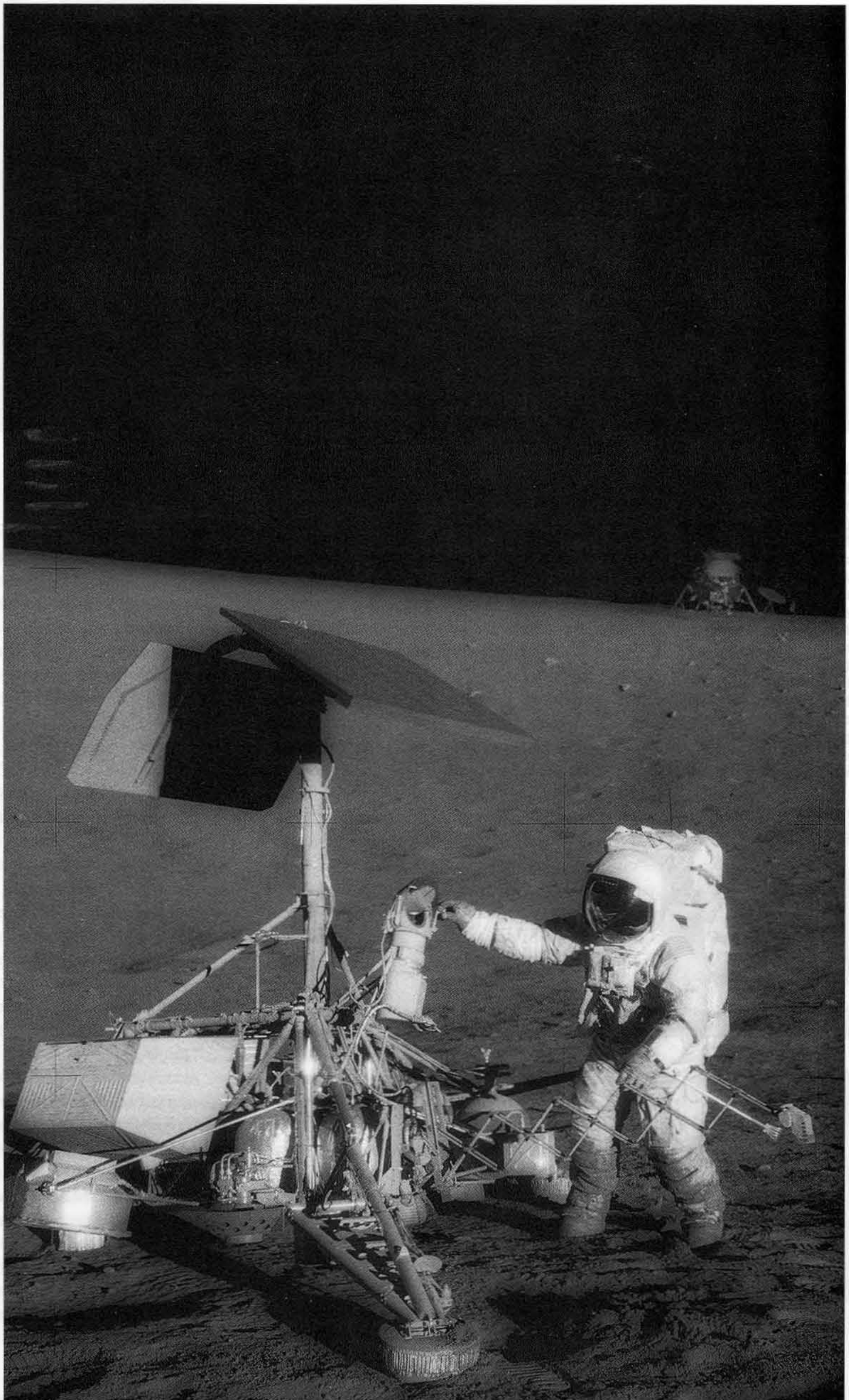


act in a community relationship with the preexisting buildings in a way that no Kahn building had ever done before. It's possible that here, in his last building, he's beginning to discover a sense of contextual responsibility—the conversation between the generations that makes civilizations, that makes towns. It's hard to say, because we don't know what he would have done afterward. But we do know that across the way, in his first great building, we can see the record of his beginnings, where he wrestled with Pharaoh and with Jehovah—or where, like Jacob, he wrestled with the angel all night through until the first great architects of western civilization reached out to him and set him on his way. □

This Vincent Scully is not, as Los Angeles Dodger fans might have presumed, the radio voice of baseball. Rather, he's widely considered to have transformed the field of architectural history and is very likely the "most influential historian of architecture ever," according to Vice Provost and Professor of Physics and Applied Physics (and Dodger fan) David Goodstein in his introduction to Scully's lecture at Caltech. When he retired in 1991 from 44 years of teaching at Yale, the final lecture of his legendary course in the history of architecture made the front page of the New York Times. *Among his students have been many of the country's leading architects and architectural critics and historians. Scully is now the Sterling Professor of History of Art, Emeritus, and the William Clyde DeVane Professor of Humanities, Emeritus, at Yale, but teaches for half the year at the University of Miami. And despite the national notice accorded his retirement, he continues to teach half the year at Yale also. His most recent book, of a total of 15,* Architecture: The Natural and the Manmade, *appeared last year.*

Scully, born and raised in New Haven, Connecticut, received both his BA and PhD from the hometown university, Yale. He met Kahn when both joined the Yale faculty in 1947, Scully as a young instructor in art history and Kahn as a visitor in the school of architecture. Although he states in his lecture that during Kahn's 10 years at Yale, "we had no idea whatever that he would ever be as important as he came to be," Scully was his ardent admirer and supporter from the beginning. It was partially due to Scully's support, in addition to that of Yale's architecture dean, George Howe, that Kahn received his first major commission for the Yale University Art Gallery, where "the first great architects of western civilization reached out to him and set him on his way" to returning classical traditions to modern architecture.

The first comprehensive retrospective of Kahn's work has been organized by the Museum of Contemporary Art, Los Angeles. After sojourns in Philadelphia, Paris, New York, and Japan, "Louis I. Kahn: In the Realm of Architecture" opened at MOCA on February 28. Scully is credited with being the "guiding spirit" and "magnificent inspiration" for the exhibit. A version of this talk has previously appeared in the MoMA Members Quarterly, *published by the Museum of Modern Art in summer 1992.*



The Future of Planetary Exploration

Goldin: It's an opportune time for change because our world is changing. The Berlin Wall came down and it changed everything.

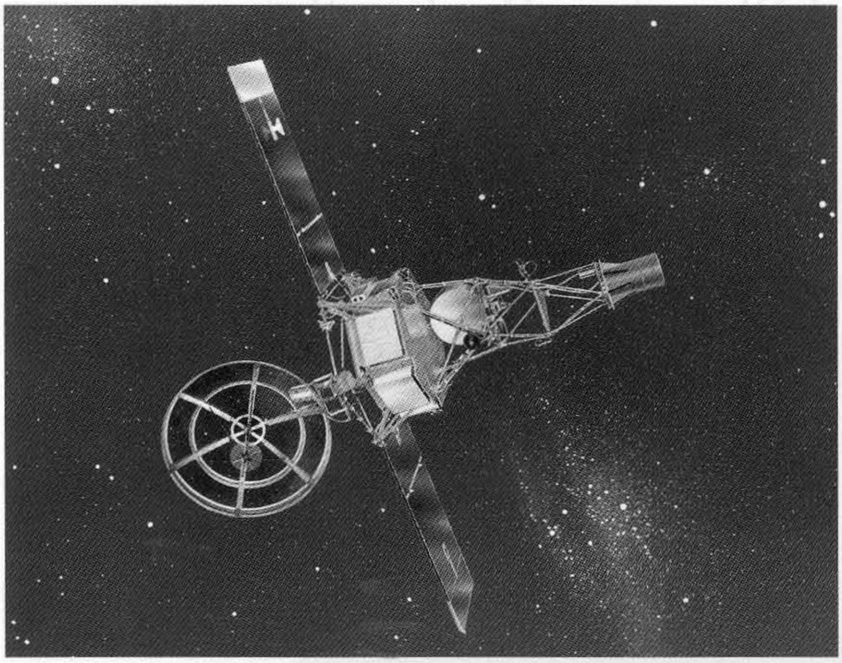
Days of future passed: Astronaut Charles Conrad, Jr., inspects the Surveyor 3 spacecraft on November 19, 1969—942 days after it soft-landed in the Ocean of Storms (Oceanus Procellarum). Apollo 12's lunar module can be seen in the background, 200 yards away. If NASA "returns to the days of Apollo," as Goldin put it, and humans follow robots to Mars, this scene may be replayed with a Viking lander.

On December 4, 1992, NASA Administrator Daniel Goldin and Planetary Society President Carl Sagan, of Cornell University, debated the future direction of America's space program before throwing the floor open to questions from the audience. The program, adapted for this article, was organized by the Pasadena-based Planetary Society, of which Sagan is a cofounder, and held at Caltech's Beckman Auditorium. The venue was particularly appropriate, as Caltech manages the Jet Propulsion Laboratory (JPL), whose bailiwick includes exploring the planets using unmanned spacecraft, for NASA.

Daniel Goldin: As I thought about what I might talk about tonight, I let my mind wander back 500 years. Columbus was having a miserable day. He was in the middle of an ocean. He knew not where the end was—maybe the edge of the world. His crew was cranky. They wanted to turn back. But he persevered and pretty soon, he made some amazing discoveries. At various times, he thought he was in India, Japan, China, and even the Garden of Eden. And what does that prove? It proves the European ignorance in the 1500s about the world, in spite of their great feats of exploration. If we extrapolate to today and look at our space program, we're in the early 1500s. Humans have been to the moon six times, but we've never returned any material from any other planetary body. We don't know if there are planets in any other solar system. We've encircled the globe with weather satellites and remote-sensing satellites, but we've yet to understand our own planet. We don't know how climate changes on other planets relate to what might happen on our own. Mars is now cold, dry, and dead, and there's a runaway greenhouse effect on Venus. We've been out to the planets, but we know so little.

Back in the days of the Mariners, we had a very robust program. I worked on Pioneers 10 and 11, which weighed 550 pounds each and were on the cutting edge of technology for their time. I think they cost $35 or $40 million each. Even converted to 1992 dollars, that's still a very modest amount of money. Since then, technology has moved at a record-breaking pace. Yet, instead of having a robust planetary program today, we have exactly one new planetary spacecraft program. Cassini is a $4 billion program. God help us if we fail. We could lose the entire planetary program. Cassini took a decade from conception to congressional approval. It'll take almost a decade to build and it will take a good fraction of a decade to get to Saturn. The participants are going to be old and gray before they get the results back. We didn't get to this point because we had bad people. We had brilliant, wonderful, enthusiastic people. But NASA only has four primary programs under development today—a shuttle, a space station, a planetary probe, and a major astronomical facility [AXAF, the Advanced X-ray Astrophysics Facility]. Something has to change.

It's an opportune time for change because our world is changing. The Berlin Wall came down and it changed everything. America for five decades was focused on the "Evil Empire." It drove our education. It drove our highway program. It drove the soul of our country. NASA is a civil space program, but our origins are in the Cold War. We had to demonstrate to the world that



JPL's Mariner 2 was launched August 27, 1962, and passed 21,648 miles from Venus on December 14, 1962.

we could throw larger things into space than they could. That isn't the case anymore. This is an opportunity that comes around once in a century. We could reach out to Russia, and instead of having two competing programs with tremendous resources going into duplicating infrastructure, we could work together. Think of the possibilities.

Instead of using 10-year-old technology because we have a multi-billion-dollar program and having to play it safe to assure success, let's get back to where we were with Pioneer, which took 11 months from inception to launch. We were inventing to schedule. We were bold. We need a complete resurgence of our space program. We have to let go of what we have in order to allow change to occur—to allow ourselves a few failures a year, instead of trying to make everything so successful that we build a bureaucracy and spend our money on paperwork instead of science and exploration. We cannot go on the way we are. We need to demonstrate again that we're not afraid to take risks.

Sagan: Mariner 2... was the first successful interplanetary mission in human history.

Carl Sagan: While I have debated all the other NASA administrators in my mind while taking a shower, and sometimes face to face, I have a very hard time arguing with Dan Goldin because I believe he is the first NASA administrator in a very long time who is willing to understand—because it takes some courage to do so—just what the problems are. In the question period, I'll try to be provocative, but I want to say here that he and I agree on many topics.

It's reasonable and appropriate to talk about anniversaries. It's also useful to remember that Columbus returned from his last voyage in chains and was thrown in jail. So there are ups and downs in exploratory programs, and it's wise to remember that, even if things seem a little gloomy on occasion, it's the long-term average that counts.

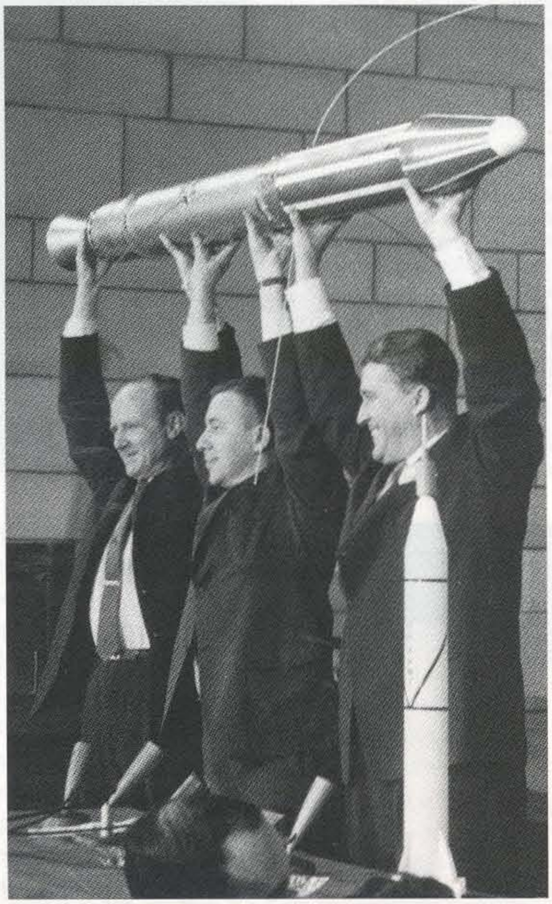
One way to look at NASA is: My goodness, we're capable of doing all these wonderful missions. Why can't Congress understand that they should give us more money? Another way to look at it is: Considering that NASA doesn't put bread on the table, it's astonishing that we've been permitted to spend so much money on what is very close to pure science.

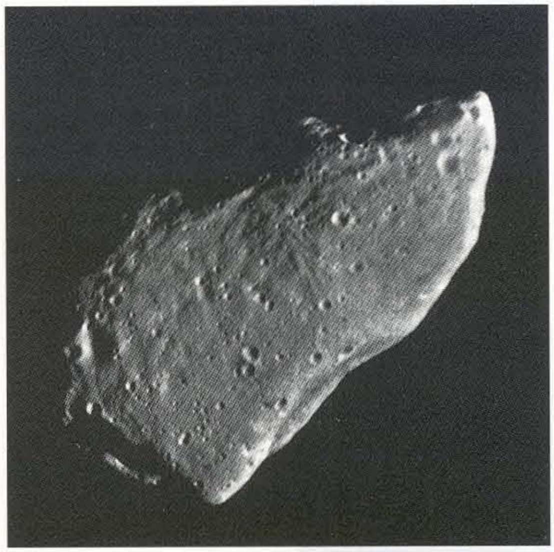
I completely agree that the space program is a creature of the Cold War. Sputnik 1—the precipitating event of the space age—was launched in the Cold War context. Mr. Khrushchev made that extremely clear. If you could launch large payloads to low Earth orbit, you could carry nuclear weapons halfway around the planet. It was a rite of national manhood, and the shape of the boosters assisted in that image. A whole generation has grown up more or less on those terms, and now that the Cold War is over, there's a loss of direction. What is the role of NASA in the post–Cold War era? What can it do that is in the national interest, in a time of pressing economic and other social problems, at a time with a painfully limited discretionary federal budget? I hope we'll get into that tonight.

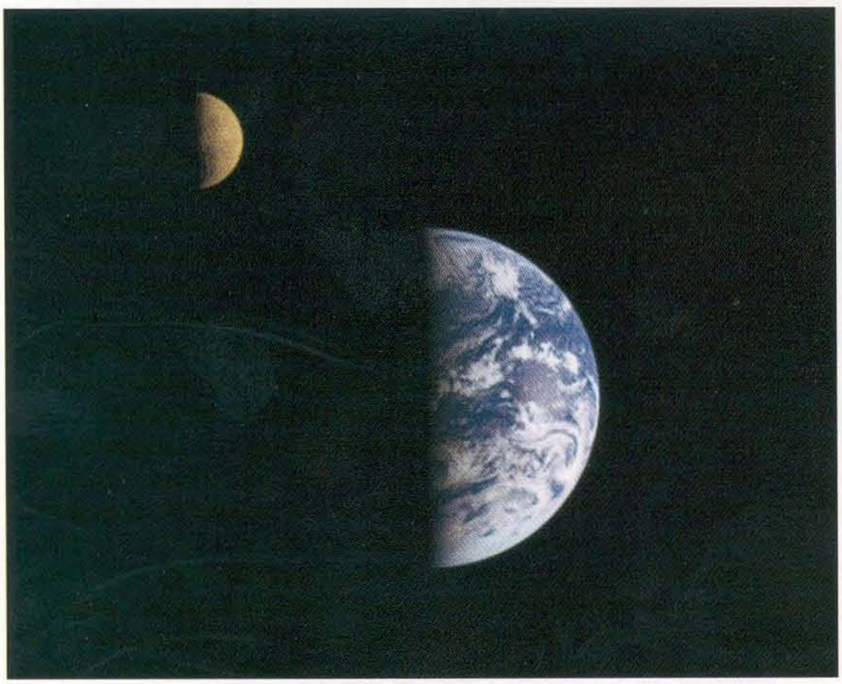
I want to add a few words about Mariner 2, in which I was involved in a peripheral way. It was the first successful interplanetary mission in human history. (As the number suggests, there was one previous failure, Mariner 1.) Mariner 2 was cheap. It was built fast. The scientists who would use the data helped build the instruments. A JPL team led by Marcia Neugebauer [and Conway Snyder, PhD '48] discovered the solar wind. There had been intimations about the solar wind from the acceleration of comet tails, but the first real measurement of it was made by Mariner 2 with an instrument that, if I remember right, was built at JPL. And Mariner 2's infrared radiometer, which gathered information about the structure of Venus's clouds, was built, at least in part, at JPL. [Caltech's Hughes Professor and Professor of Physics] Gerry Neugebauer [PhD '60] played a major role on that team. He was there only because he had been drafted, and the Army had assigned him to JPL—an event that's had momentous consequences for infrared astronomy. It's nice that there was a husband-and-wife team in those early sexist days of planetary exploration. Another instrument, the microwave radiometer, found limb-darkening—evidence

Right: (from left:) William Pickering, then director of JPL; James Van Allen, for whom the Van Allen radiation belts are named; and Wernher von Braun, the original "rocket scientist" hold aloft a model of Explorer 1, America's first successful spacecraft.

More recently, JPL's spacecraft Galileo departed on a circuitous voyage to Jupiter.
Far right: Galileo flew by the asteroid Gaspra on October 29, 1991. Taken at a range of 10,000 miles, this is the most detailed view yet of an asteroid in its native heath. Potato-shaped Gaspra is about ten miles long by six miles wide.
Below: On December 22, 1992, eight days after its second encounter with Earth, Galileo looked back over its shoulder to take this parting shot. The moon is in the foreground so we see its far side, and is moving from left to right.





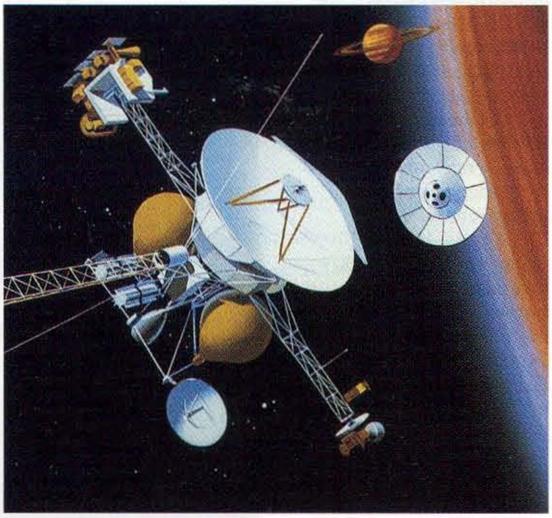


that the surface of Venus was astonishingly hot.

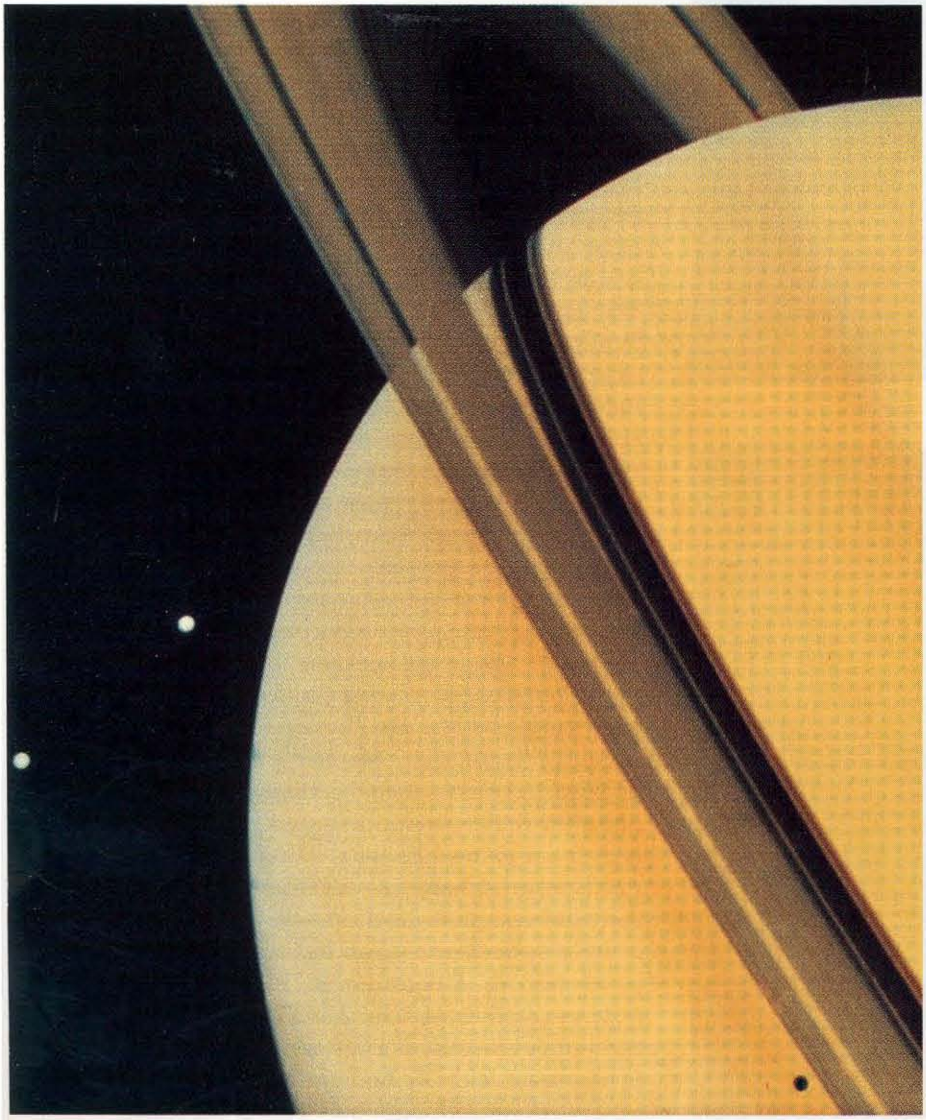
Mariner 2 didn't have a camera. I remember the debates on that. Leading figures in the scientific community said, 'It's pointless to send cameras. Cameras are unscientific. The way to do things is you pose a scientific question. Then you design an instrument to answer that question yes or no. And you proceed from that yes or no to design the next instrument for the next mission.' While that may have been a wise decision for Venus, knowing that it's covered by impenetrable clouds—although we weren't so sure of that then—the subsequent history of planetary exploration has shown that broad-gauge, multipurpose instruments that do not ask specific questions, but answer questions before we're smart enough to ask them, have been extremely productive.

Mariner 2 is still in orbit around the sun, approaching Venus's orbit once every few hundred days. Sooner or later there'll be a close encounter, like the one that Galileo has just had with Earth, and Mariner 2's trajectory will be substantially changed. Mariner 2 will make a set of such encounters, and perhaps it will be propelled to the outer solar system, as Galileo was, or out of the solar system altogether. I hope that before that happens—which will be in a few thousand years at the earliest—we go grab it and bring it to the Smithsonian Institution, or at least to von Kármán Auditorium at JPL.

If we could do Mariner 2 at a very quick pace and very low cost with a harvest of absolutely fundamental scientific findings, why is it so hard for us to do such things now? Part of the reason

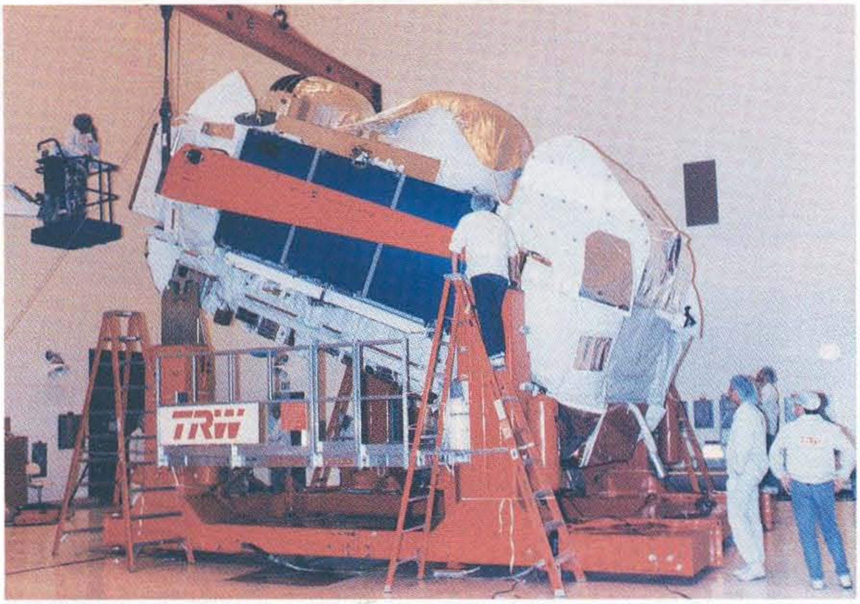


Right: Cassini, a joint JPL–European Space Agency project, will drop a probe into Titan's atmosphere to sample it. Below: Saturn and its moons Tethys and Dione at 7.8 million miles, as seen from JPL's Voyager 1. One of the moons casts its shadow on the planet just below the rings. Left: Iapetus is roughly the same size as Tethys and Dione.



is that the cream has been skimmed. Explorer 1 discovered the Van Allen radiation belts. They were waiting to be discovered—all you needed to do was fly a particle counter through them. It's inevitable that the easy discoveries are made early. Subsequent work becomes progressively harder, or you have to go farther from Earth to do it. That, in turn, means that the work becomes slower and costs more.

I pose the following question to you, Dan: You have been an eloquent proponent for what you summarized here tonight—getting cheaper missions going quickly, in order to take advantage of advances in technology and to keep pace with the human life cycle. On the other hand, there are some questions, outer-solar-system issues for example, which of necessity require larger, slower, more expensive missions. Cassini, of which you have been both an active critic and active supporter—the two are connected, of course—is a good example. You've argued that the real cost, adding in everything, is something like $4 billion. That's a heck of a lot of money. But think what it will do if it works. It will go into long-term orbit around Saturn. It will examine Saturn's rings, which are on some level a model of the solar nebula out of which the planets formed. It will make close encounters with Saturn's major moons, including Enceladus, a most peculiar object because there's no way for its surface to have melted, and yet it has been; Iapetus, which has one of the darkest materials in the solar system on one side, and one of the brightest materials on the other; and Titan, which, according to many models, has a liquid-



Workers in the Payload Hazardous Servicing Facility at Kennedy Space Center carefully position the massive Compton Gamma-Ray Observatory on a test stand. Deployed April 7, 1991 from the shuttle *Atlantis*, the 35,000-pound observatory carries four instruments to study celestial gamma-ray sources.

hydrocarbon ocean covering part of its surface. Cassini will drop a probe into Titan's atmosphere—a place where organic matter falls from the sky like manna from heaven, and is the closest model of any place in the solar system to the events that preceded the origin of life on Earth four billion years ago. That's a big return, and for a big return, it makes sense to make a big investment. Isn't there a danger that if we say small, cheap, and fast, we get small, cheap, and fast scientific results; that is, having skimmed much of the cream, we won't be able to approach the really deep issues?

Goldin: Let me take an extreme position for the sake of discussion and say that if it were up to me, I would limit spacecraft to 500 pounds. I would allow no more than four years to build them—in fact, three might be a better number. And I'd allow no more than two years for preliminary study before development, because I believe the technology is here—commercial, off-the-shelf technology. We're losing a tremendous amount of support for the current planetary program because there's not enough action for the American people. They have to wait ten years to see results. And, as a planetary scientist, if you don't get onto that one expensive spacecraft, where are you going to go? Is it right, is it fair to have such a program? There's no multiplicity or diversity.

Sometimes diversity helps bring issues into focus. I have seen a study done by a number of very bold human beings who felt that they could perform the Cassini mission much faster and just as effectively for much less money. It's still only a study, and that's symbolic of the problem. There's a very tight community that has been working together for a very long time, and they own the planetary program. They're not bad people, but they've gotten so comfortable with the program that you cannot have a divergence of opinion or you get attacked.

For example, a young man from JPL approached me about the Pluto mission. I didn't even know there *was* a Pluto mission. And he said, "Mr. Goldin, the prevailing thought says if we're going to go to Pluto, we must have the right scientific instruments. But once you put that many instruments on the spacecraft, it gets heavy." I think he said about 800 pounds. "It'll take us a decade to build. And if we put it on the biggest rocket we have, it'll take 15 years to get there. So I have a different concept—what if we make the spacecraft smaller with fewer instruments? We could get it out there in seven years. And if we do the program differently, we could build it in four or five years, so that 12 years from now, we could be at Pluto, instead of 25 years from now." I embraced the idea because I thought Pluto was such a challenging mission. If we could prove the concept of a small—he was talking about 200 pounds—spacecraft going to Pluto, we could convince everybody that there's another way to do things. A number of people attacked me in the press, "What right does the NASA administrator have to interfere with the scientific process?"

NASA's "scientific process" was pulled together because the space physicists, the astrophysicists, the planetary program, the life sciences, and the microgravity communities were arguing with each other in Congress and getting each other's programs canceled because the important thing was to get their own program going. Six years ago, they called a truce, saying, "We'll all get together at some nice place, and 500 of us space scientists will come to a consensus on America's space program." In those six years, the research and analysis money that funds university scientists has gone down 25 percent; the planetary program has dropped about 20 percent; and the physics and astronomy program has dropped 25 percent in constant fiscal 1992 dollars. The mission-operations and data-analysis budget—the money it takes to fly the spacecraft and analyze the data they send back—went up 233 percent. The space program belongs to the American people, not to the people working on the program. I submit it's not right to have the space scientists decide by consensus what the program ought to be. I'm not saying that they're bad people, but there's such a desire for survival. Why does someone have to bury a study in a

Upon settling into orbit around Jupiter, Galileo will drop a probe into the Jovian atmosphere. As the probe descends, it will analyze samples of all of the visible cloud layers, sending its findings to the orbiter for eventual transmission to Earth. The probe is expected to transmit for about an hour and a quarter before the orbiter disappears over Jupiter's horizon.

filing cabinet somewhere because it may be so controversial it'll cause a problem? We have to open up to diversity and multiplicity, and fund a technology program that makes sense.

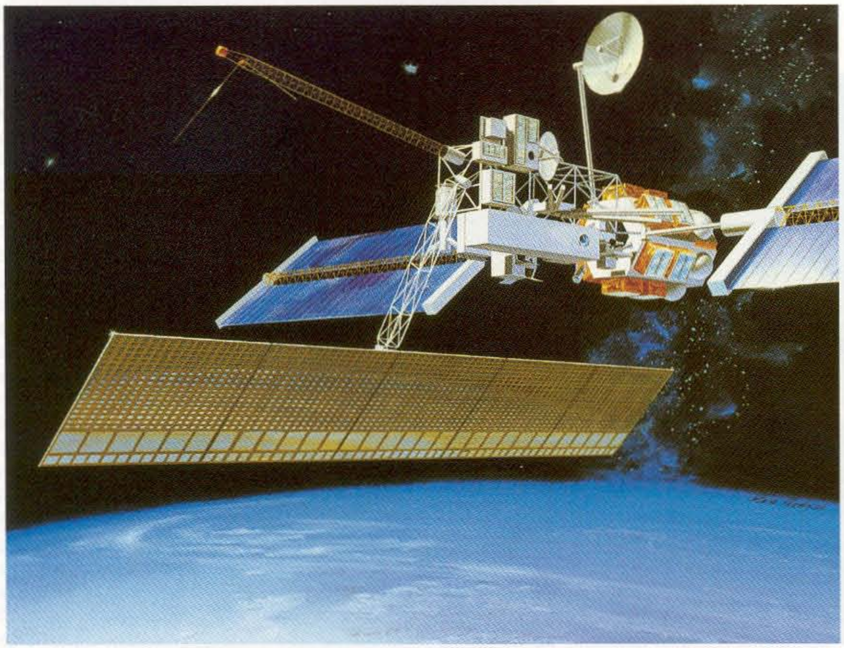
JPL's director has a discretionary budget of three-tenths of one percent. I think that's absolutely appalling. The micromanagement of NASA has gotten to the point that a fine institution has no way to use new technology. I deeply believe in my heart that my 500-pound, four-years-plus-two-years rule with robust technology funding will give us what we want. There are exceptions. Clearly if you have a large aperture requirement or need a liquid-helium dewar for cooling, like on an infrared telescope; or need bulk material for the detector, like the Compton Gamma-Ray Observatory; or have a real need for simultaneity or diversity of measurements, those conditions may dictate a large spacecraft. But just as the program has been out of balance between infrastructure and human spaceflight on the one hand, and science on the other, it's also out of balance between big and small. I know there's this desire to hold on, but I believe if we could try these things, we will have the most robust, the most wonderful science program in the world.

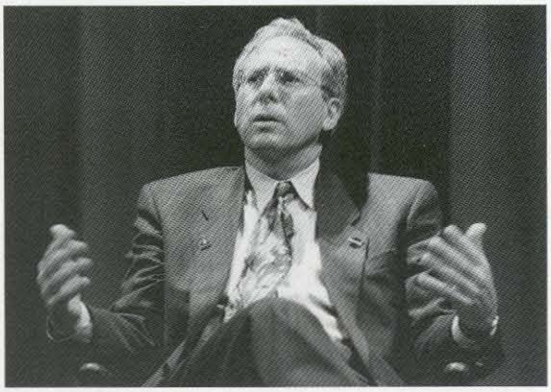
Sagan: So glad I gave you an opportunity to get that off your chest.

Goldin: I'm a little intense on the subject.

Sagan: But isn't there an excluded middle here? Surely there are many good missions that can be done by taking some risks. You can do that if you have other missions in the pipeline, so that on average you do well. In the progression of scientific exploration, there are circumstances in which the obvious next step requires something more elaborate than what preceded it. Look at the exploration of Jupiter. It starts with Pioneers 10 and 11—spacecraft like your quick Pluto mission—then Voyagers 1 and 2. And now Galileo, which is not a flyby but an orbiter. That's a logical sequence. If NASA were *really* strapped, then the conclusion would be don't go to the outer solar system. Just go nearby. You can do things quicker, for less money. And there are lots of important scientific issues to find out about near Earth. I don't consider that an absolutely hopeless position, but it loses a significant fraction of the solar system in heliocentric distance, in mass, and in many cases in scientific interest. Were you to exclude Galileo, which weighs about three tons, we'd be closing lots of options.

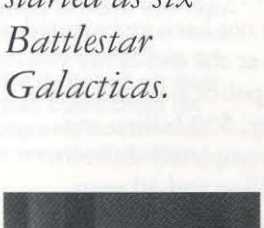
Goldin: In this course in creative thinking I teach, I ask people to put six lines on a piece of paper. Then I say, take those lines and arrange them into four equal-sized equilateral triangles. Most people will draw a square with two lines across it, but the sides of those triangles are 1:1: square root of 2. A few people will think for a few moments and realize the answer is a tetrahedron. What's the lesson? I tricked them. I asked them to think in two dimensions. Very few people, when asked to think in two dimensions, start thinking in three. There's a belief in the space community that you have to have "big" to accomplish what needs to be accomplished. I believe deeply that if we start thinking in three dimensions, we'll find that in three out of four





Dan Goldin

Goldin: Mission to Planet Earth started as six Battlestar Galacticas.



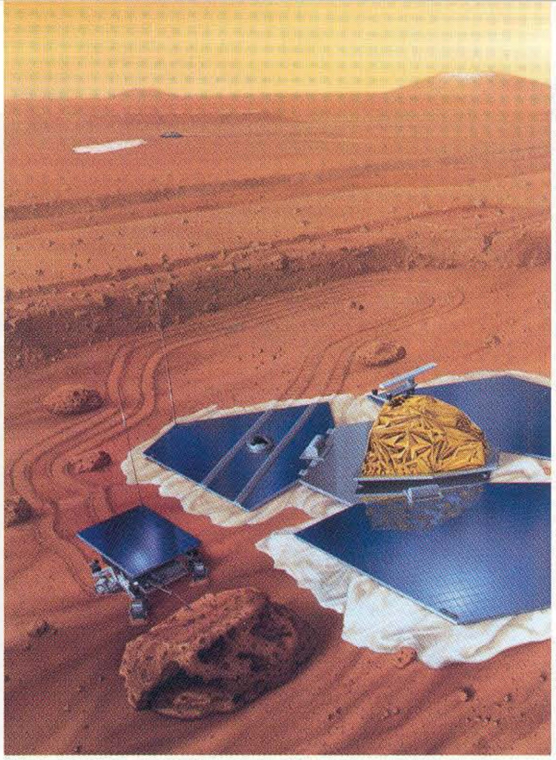
Carl Sagan

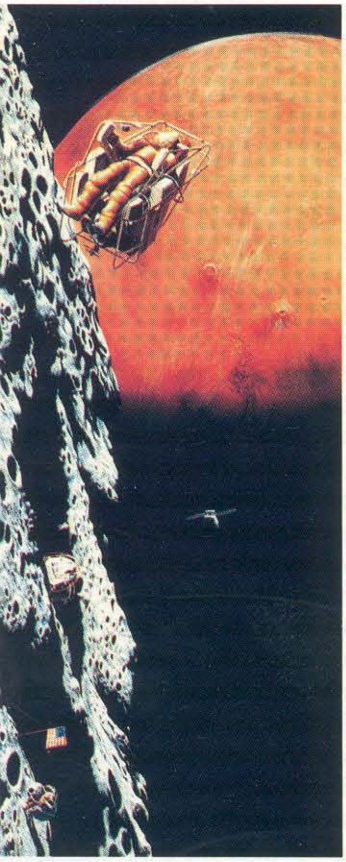
cases, we could do it small. As an example, star trackers don't have to weigh tens of pounds—they could be built for hundreds of grams. The same for inertial units. If we start using advanced technology, not even in the science, but in the bus that carries it out there, the payload mass fraction will go way up. One of the reasons I grabbed onto the Pluto mission is that I believe you should take the geniuses out here at JPL and unleash them. It's been a decade since we put technology into NASA programs. We ought to be reaching out toward technology that's two or three years away, and pulling it back so that NASA once again gets to the cutting edge. I come from a regime where we had to invent to schedule because we didn't have the luxury of debating it. I worked on a project where we designed and built dozens of integrated chips using three unique production processes in less than five years. While we reach for the planets and the stars, we will transfer technology into the American economy to create new industries and new jobs. This also meets our new president's political agenda.

Sagan: The perfect example of what you just said is in monitoring Earth with regard to global environmental issues from Earth orbit. Flying lots of small missions makes perfect sense. Then you can design each mission from what you found in the previous mission. You have quick turnaround so you can take advantage of improvements in technology. You can be responsive to presidential needs on budgets. Graduate students can work on the whole mission life cycle, from instrument construction to data analysis, before they get old and gray. But the farther away from Earth you get, it seems to me, the less true that is—after you've skimmed the cream.

Goldin: This gets back to my main message, that the space program has been run for the benefit of NASA. Mission to Planet Earth started as six Battlestar Galacticas. An enormous battle went on to try to make them smaller. The tremendous pressure not to allow them to get smaller percolated right down to where I was, in industry. Finally we went from full-blown Battlestar Galacticas to half-sized Battlestar Galacticas. That's where we are now, and God help anyone who wants to change that train as it gathers speed going down the tracks. A GAO [General Accounting Office] study says that when NASA planned this mission, most of the data-gathering requirements came from NASA researchers and not the tens of thousands of users who are going to need the data.

Let me switch the subject and say that we've now had four town-hall meetings, in general in cities where NASA does not have facilities, because we wanted to know what people thought. They've been standing-room only. In Los Angeles, at Cal State Dominguez Hills, we had an auditorium for 500 people. We had an overflow room with a video screen for 200 people. It filled up. We added a second overflow room for another 200 people, and that filled up and we had to send people away. There was a tremendous swell of opinion that we had to get back to the days of Apollo. They wanted to get humans to Mars as fast as possible. One young man spoke with such intensity that he's emblazoned in my mind.



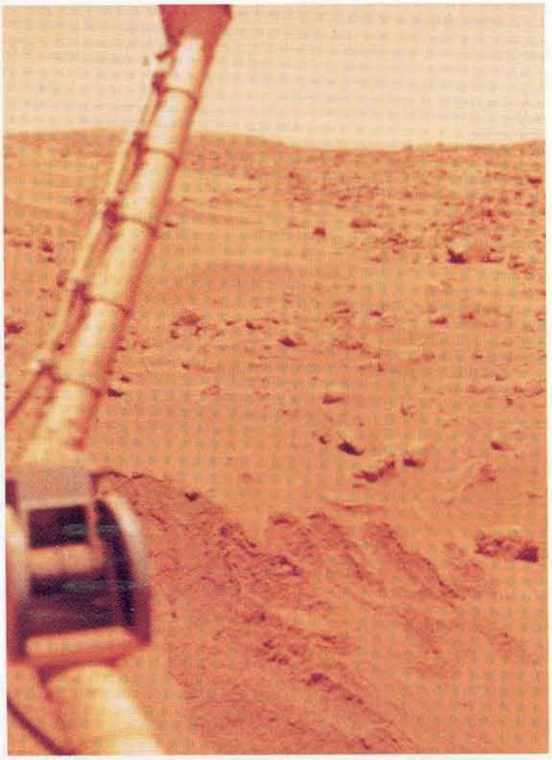


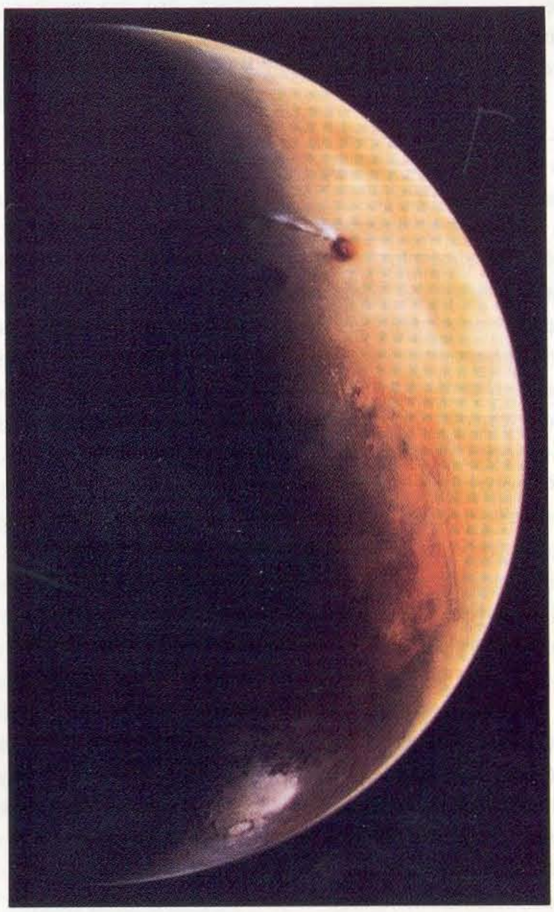
He said, "I'm 22 years old, Mr. Goldin. Tell me right now. Are we going to Mars or not? Am I going to be an old man, and gray, and walk with a cane before we get there?" He represented a lot of people. How do we get there? How do we balance economic priorities at home? How does NASA balance science versus economics, so that we don't get swallowed up in another large program? Space is more than just science. What is your sense, Carl, of how we might get to Mars and when? What ought the balance be between human and robotic space probes? And what reasons would be behind it in this new world we live in?

Sagan: That's a lot of questions. First off, we ought to acknowledge that one possible outcome of that analysis is that there isn't an economically coherent reason for sending humans to Mars, heretical as that might seem in some circles. I would say that if you cannot provide a coherent justification to the taxpayer and Congress for spending the amount of money in question, then you have no right to ask for it. Clearly, a mission that takes half a trillion dollars and 30 years to send a few people to Mars is very difficult to justify. It's as much money as the savings and loan scandal, which only benefited a small number of rich thieves. Surely going to Mars is more in the national interest. But still, the United States in its present circumstances does not have a whole lot of half-trillion-dollar checks, and 30 years is politically very difficult. We're asking a great deal of any president, no matter how farseeing, to spend a lot of political capital now for a benefit to come during some presidency two, three, four, or five presidents downstream, and—who knows?—maybe even of a different political party. John Kennedy's speech announcing the Apollo program was in 1961. Apollo 11 put humans on the moon in 1969, and had he not been assassinated, it almost would have been at the end of his second term. That makes political sense. Sending humans to Mars for, say, $50 billion and taking 10 or 12 years is a completely different kettle of fish than $500 billion and 30 years.

Arguments for going include science, although the argument that you need humans to do the science is certainly not compellingly made. If NASA were to spend anything approaching the cost of a human mission to Mars on robotic systems, artificial intelligence, and telepresence—you're wearing a virtual-reality helmet and glove and feel that you're "inside" a robot spacecraft or lander, seeing what the robot sees and using the robot's arm as if it were your own—I believe we could accomplish an enormous amount of science, including going to areas that are too dangerous to send humans, although those areas may be scientifically very exciting. Beyond that, there are arguments about education, about national prestige. But in every case, we have to ask is this the most cost-effective way to those goals? Let's say $15 billion of it is justified on the basis of education. Is that the best way to spend $15 billion on the scientific education of Americans? And it's very easy to think of activities on Earth that would earn the admiration of most nations and cost less than $15 billion. So the question is, can the sum of a fairly large number of inadequate reasons constitute

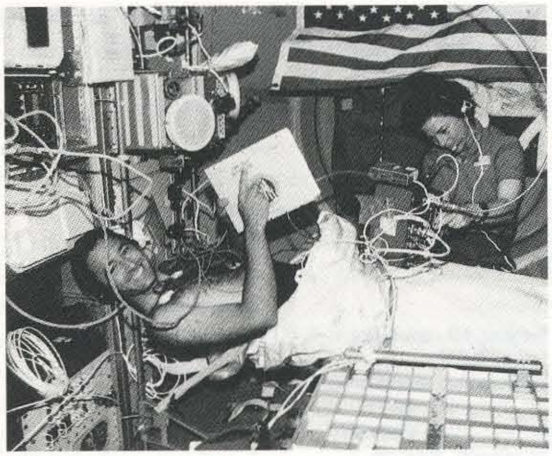
Opposite page: The possible futures of Mars exploration. Far left: An astronaut explores the surface of Phobos, Mars's larger moon, in a personal spacecraft. Top left: Rocky IV, a 16-pound microrover being developed at JPL. (The final, Mars-qualified robot explorer will be even smaller.) Rocky IV has a set of "programmed reflexes" that enable it to plot its own path through its surroundings without detailed instructions from Earth. The needle-like probe chips away weathered rock, exposing a fresh surface to the onboard spectrometer. Right: The proposed Mars Environmental Survey mission would land microrovers to emplace seismometers and collect soil samples at up to 16 sites around the Martian globe. The lander, shown sitting on the deflated air bag that cushioned its impact, doubles as a weather station.





This page: The reality of Mars, as revealed by the Viking missions. Top: The Viking 1 lander's soil scoop scrabbled at the rocky dunes of Chryse Planitia. Sadly, Viking's experiments found no signs of life. Bottom: Mars from the Viking 2 orbiter. To the north (upper right), Ascareus Mons, one of the great Martian volcanos, trails westward plumes of water-ice cloud. Valles Marineris, a canyon system almost 3,000 miles long, lies near the equator. In the south, frost dusts the lowlands of Argyre Planitia, a 480-mile-diameter impact basin, and the crater Galle in its rim.

Below: Astronaut Bonnie Dunbar monitors astronaut Lawrence DeLucas' heart in a life-science experiment aboard the shuttle *Columbia*.



an adequate reason? The answer might be yes, but how you do this arcane calculus is not clear to me.

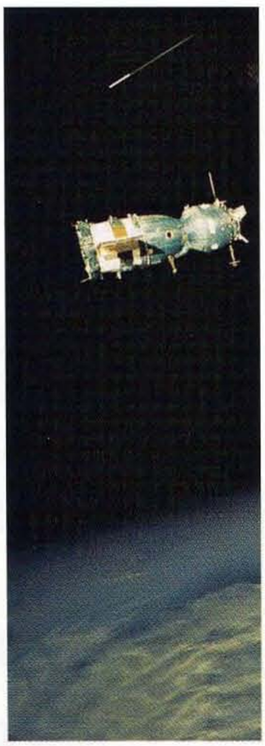
It's fantastic that you're doing these town meetings, especially away from NASA centers. Of course you get a lot of people saying, yes, I want to go to Mars. But if you tell them, "It will cost hundreds of billions of dollars. Do you know what a small fraction of that could do for your community?" the field shifts. There's also a selection effect. The people who come to your talks are, generally speaking, already supportive of NASA. It's a mistake to draw too sweeping a conclusion from what people say at these town meetings. When I talk to members of Congress, I get a very different impression.

My advice would be to vigorously pursue robotic exploration, especially of Mars. There are key questions about Mars that, for perfectly good reasons, attract public interest: the reason for its past massive climate change; the search for past, or—who knows?—present life; the question of possible future human habitability. And it would clearly be prudent to examine the safety of long-duration spaceflight, including the effects of radiation in space on humans. This seems to me to be the only conceivable justification of a space station, although it is hardly optimized for that function. All this could be done without anything like the savings and loan scandal's cost. If enthusiasm develops, if the discretionary federal budget permits, if a president wishes to make a gesture that will ensure his or her place in history, then we can well imagine that we will go to Mars. But in the present situation, it's politically unrealistic to urge endorsement, especially on a specific timetable—by the year 2019 or something like that—for sending humans to Mars.

Goldin: You're on the right track. One thing I'd like to add: 500 years ago, each individual country explored for itself, planting its flag separately for its own people. This gave rise to the most horrendous wars. We're ending a millennium just strewn with blood. Think about the possibilities of bringing nations together on a very difficult venture, under one flag planted for all humankind. I think that's a very, very positive reason for going.

Sagan: That's an argument I fervently pushed in the closing years of the Cold War. The United States and the Soviet Union working together on behalf of the human species for a change, using that same rocket technology that had put everybody on Earth at risk, was a supremely worthy goal. We found a resonant chord in some of our opposite numbers. Mr. Gorbachev was convinced and made a serious approach to Mr. Reagan, which Mr. Reagan turned down. Now, with the Soviet Union in utter collapse, the necessity seems less, although not zero. Russia, the U.S., Japan, the Europeans, and China, say, going to Mars together has a profound symbolism. Whether that's a compelling argument for people who don't have enough to eat is another question.

Soyuz 19, as seen from Apollo 18. Launched separately on July 15, 1975, astronauts Thomas Stafford, Vance Brand, and Deke Slayton and cosmonauts Alexei Leonov and Valeri Kubasov were neighbors and frequent visitors while their spacecraft flew docked for two days.



Goldin: This is a fundamental issue as NASA establishes balance in its program. Clearly I agree with your statement. You cannot send humans to Mars until you can understand how they could live and work in the hostile space environment. The interaction of cosmic rays with human tissue is yet to be resolved. We could write a book about what we don't know about humans in zero gravity. But as we perform these tasks, we can, over the next five or ten years, develop critical technologies and system designs in parallel without breaking the bank.

Sagan: [The Russian space station], Mir, is the way to do that. It's operational, although only intermittently used. Residual Cold War attitudes are decaying very slowly, and that's all that prevents us from using Mir to start to answer questions about long-duration spaceflight. A few Russian cosmonauts have already lived in Earth orbit for around a year, which is roughly the time it takes to get to Mars.

Goldin: The problem is twofold—technical and political. In the technical domain, one of the best-kept secrets has been the fact that American and Russian physicians have been working together for the last ten years, but there's a real problem with in situ measurements because of Mir's limited power and instrumentation capacity. Actually, Russia's and America's strengths are complementary. They're very sophisticated in their mechanical engineering, their propulsion, and their metallurgy. We're very sophisticated in our electronics, simulations, and computers.

Sagan: It's a marriage made in heaven, but one surprisingly difficult to consummate.

Goldin: Which gets me to the political aspect—we've only had five months to work together. There's tremendous instability in Russia, and there's a reluctance in the United States to put its program in series with the Russians. So we've decided to do some confidence-building tasks first. We'll have a cosmonaut fly in the shuttle. We'll have an astronaut fly up in the Soyuz capsule to Mir. And, finally, we'll have a shuttle rendezvous with Mir. That's a very difficult task, what with their offset centers of mass and different docking mechanisms. And we're considering changing our space station's projected orbit. Right now, it would be at 28.5°. But Mir's already up there at 51.7°. What if we put ours in the same orbit? It would be much simpler going from station to station. Think about the possibilities if our shuttle wasn't available, or vice versa. Think about lifeboats. We could build on that concept as we go along. Maybe instead of adding modules, we could start sharing them. It's not revolutionary, but it might evolve to where we could really start working together. We're going to get the best out of Mir and the best out of our space station.

Sagan: Doesn't that put off still further the day when we finish the long-term low-gravity and radiation-biology studies and so on? Does that indicate that we're not going to be sending humans to Mars in the next few decades?

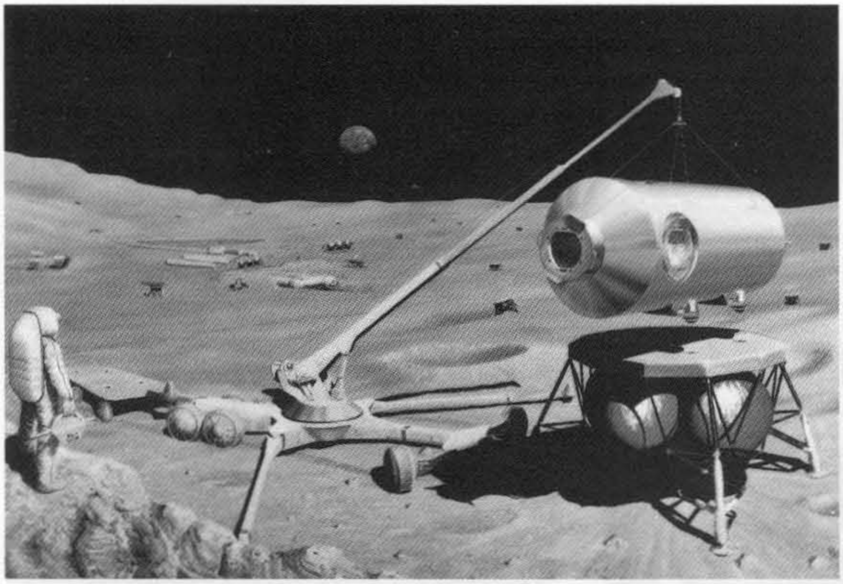
Goldin: I don't think we can in the next decade or two anyhow. For low-gravity studies, I challenge the employees at NASA Langley and NASA Johnson—and anyone in this audience—to come up with a faster, better, cheaper human centrifuge for hundreds of millions instead of billions. It can be done. I have my own design. They say I'm off base again. "Goldin, you're out of your mind."

Sagan: I like the idea of a NASA administrator designing spacecraft.

For the balance of the program, Goldin and Sagan fielded questions from the audience.

Question: Mr. Goldin, you've been to the Soviet Union three or four times in the last year and a half. Is it realistic, given what appears to be an economic black hole over there, for the United States to expect to have an equal partner in such a project?

Goldin: Is it risky? You bet. Will there be



Artist's conception of a lunar mining facility. Oxygen, silicon, iron, calcium, aluminum, and magnesium could be mined on the moon, as well as helium-3.

people who criticize it? You bet. Can we afford not to do it? We cannot. The Russians are committed to their space program. It'll be one of the last things to go. It's a matter of national pride. It does have over-capacity in overall launch capability, perhaps by a factor of three. On one trip to Russia, I visited a factory where rockets were stacked like cordwood. There are going to be terrible dislocations in their space industry, but it won't die, because the Europeans will work with them. Could there be another coup? Yes. But how can we afford not to reach out? We can't live in isolation.

Goldin: Think about the possibilities of bringing nations together on a very difficult venture, under one flag planted for all humankind.

Question: I have an article here dated December 7, 1988. It says, "a U.S. industry to build power satellites for all nations would tap a world market exceeding $250 billion." That's clean power from space. Have you considered building solar-power satellites, utilizing the moon's resources, to finance your other projects? I mean, that's a $250 billion potential every year.

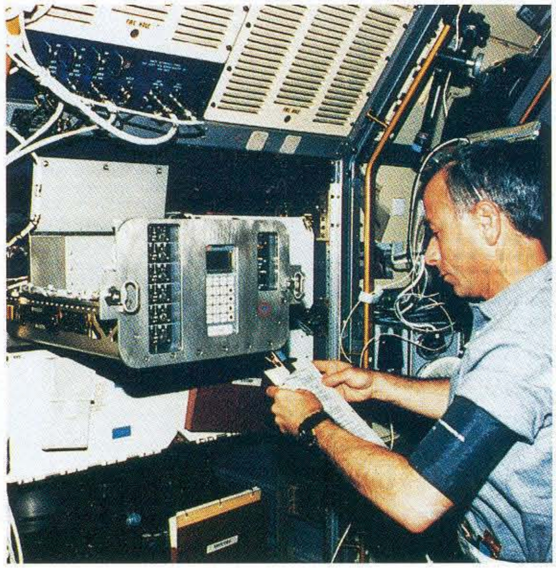
Goldin: It's clean power, with one exception—what does the microwave power that you would beam down from space do to human tissue? We don't really know. Before we start building more Battlestar Galacticas, let's understand some of the fundamentals. Once we get through that barrier, how feasible are these activities and what's the payoff? Let me give you another possibility. What if, 50 years from now, we could make a controlled thermonuclear reaction with helium-3? Helium-3 would give off almost no radioactive waste, and 20,000 pounds would power the whole United States for one year. Helium-3 comes flowing off the sun and has riddled the moon for billions of years. It shouldn't be too difficult to mine and bring back. One 20,000-pound load per year would not be very expensive, relative to what you're talking about. There's a tendency in our society to want to do everything all at once. That young man wanted to go to Mars immediately. You're proposing to rush off and get power satellites up there. Let's take our time and make the right decisions. Can we afford to spend the billions of dollars before we find out whether we're affecting human tissue? The engineers would have a jolly good time, but it gets back to the statement I made before: engineers are not the ones who should set the requirements. America should set the requirements.

Sagan: Why go into space to harvest sunlight, when you can put your sunlight-harvesting cells in the Mojave Desert at vastly less expense? It's not enough to say that it'll make $250 billion a year. You have to demonstrate that you couldn't get that $250 billion a year by making the same or lesser investment on Earth.

Question: Mr. Goldin, [at the LA town meeting] yesterday you described our space program and the aerospace contractors as having a sickness. Could you expand on that? What do you feel the cure might be? And Mr. Sagan, what is the single most important challenge to our space program, and how would you face it?

Goldin: I said that I'm terribly concerned about our credibility with the Congress. I talked about accountability and responsibility. We've built up a bureaucracy over the last 20 years. We have 24,000 NASA employees and 42,000 service-support contractors. Should we have so much help to do our job? Can't we convert NASA's bureaucratic work into science and exploration? We have a pretty full plate: Congress fully funded the space station; we have congressional approval on the Mission to Planet Earth, on Cassini, and on AXAF; and we have a number of smaller projects under way. One of Congress's biggest criticisms of NASA is that we have so much on our plate, yet we keep trying to get new things to do. So let's deliver on what we've already promised first.

Sagan: NASA does not, in my view, do a good job of explaining why it does what it does, or even what it does. The average person's sense of what NASA is about is that every few months, a few people crowd into a tin can, go up into low Earth orbit, launch a satellite that could just as well have been launched by an unmanned booster, do some experiments the significance of which we never hear about afterward—the tomatoes didn't grow, or something—and then they come



Left: Astronauts Jan Davis (left) and Mae Jemison prepare to deploy the Lower-Body Negative-Pressure apparatus aboard space shuttle *Endeavour*. The LBNP pulls blood and intercellular fluid into the legs to mimic gravity's effect on the circulatory system and, according to NASA's stock caption, should increase future astronauts' tolerance to "orthostasis"—what most folks would call standing upright—upon return to Earth. Right: Astronaut Carl Meade (MS '75) ran the Generic Bioprocessing Apparatus on Columbia. This piece of equipment can hold 132 test tubes at a time, allowing the effects of microgravity to be studied on samples ranging from molecules to small organisms.

down again. And at the same time, NASA is doing fantastic science that gets very little attention. By attention, I don't mean an occasional article in the Tuesday {Science} section of The New York Times. I mean four or five minutes—no, that's absurd—two or three minutes on the evening news, with wonderful visuals prepared by the nonexistent computer-animation laboratory devoted to public education at NASA headquarters. Orange-juice substitutes in Earth orbit we hear plenty about. But real science? Very, very little. Part of this, of course, is because of media resistance. Many people have the sense that the American public is simply too stupid to understand science. But the evidence is manifestly clear that that's not the case. I think it's important for NASA to pound on the doors of the media gatekeepers, to present the argument for science and exploration in such an appealing way that the doors are opened.

Goldin: That was one of the major comments at the town-hall meetings. The public is telling us we don't communicate, especially to schoolchildren. People talked about documents and pamphlets written in language no one understands. I agree wholeheartedly. No one's responsible for publication at NASA. It's dispersed throughout the organization, which gets back to my basic point that there must be responsibility and accountability—one task, one human being. But I do want to take issue with you relative to tomato seeds on the shuttle.

Sagan: I thought you would.

Goldin: Part of the problem is that the life sciences have been woefully underfunded relative to physics and astronomy. Yet we are doing some very sound life science and microgravity science on shuttle flights. Pharmaceutical companies are working with us as commercial participants. A shuttle is only up there for a short period of time, and life science can be performed on the space station and will be.

Sagan: If we talk about physics and astronomy, we can answer absolutely fundamental questions from space—issues like the validity of general relativity, or whether the universe will expand forever. What is fundamental to biology is the genetic code and the evolutionary process. The biology to be studied in Earth orbit is applied biology, having to do with human reactions to long-duration spaceflight, not fundamental biology. The only compelling argument, I believe, for life science in Earth orbit is to prepare for human missions to the planets. If we're not going to the planets, then there's no necessity for life science on a shuttle or space station.

Goldin: All I'm saying is that we have to have a robust life-science program to perform the basic mission of the space station. Life science, not the engineering feat, should dominate what we do on the space station, if we're to understand how humans can live and work in space.

Sagan: But no tomatoes.

Goldin: Maybe just a few.

Question: Mr. Goldin, I'm a student majoring in materials engineering. There doesn't seem to be any mechanism for NASA and JPL to handle the good ideas you get in college. What kind of proposal process would you implement for NASA to get diverse ideas for new technologies?

Goldin: Thank you for the softball. About four weeks ago, I announced a new organization at NASA—the Advanced Concepts and Technology Office. I was terribly concerned by all the people who beat a path to my door saying that NASA was resistant to new ideas, and that if someone wanted to bring a new idea, they were just sent around from organization to organization to organization. NASA had no systems-engineering team capable of analyzing, in a broad perspective, the merits of a technology. Technology by itself is not enough. It becomes a solution seeking a problem to solve. Technology applied in the broad sense of the mission is crucial. Because NASA technology gives crucial input to the American economy, we also brought in the offices where we transfer technology to industry, and commercialize activities in space. The goal is one-stop shopping. Greg Reck is the acting associate administrator. He's now traveling around the country at my request, soliciting opinions from universities and industry, professors and students, as to what's the right way to organize this. Send him a letter. He will respond.

Question: It's amazing how many Americans couldn't care less about the space program because they don't know anything about it. They don't believe that we could possibly gain anything in daily life from space exploration. They don't know about simple things, like the ball-point pen. What can NASA and The Planetary Society do to educate the American public?

Goldin: The single biggest problem may not be the lack of computer-animation capability at NASA headquarters. There's a more fundamental problem. Scientists and engineers do not write in plain English. I'm not saying that as a joke. It is a very serious problem. When I became the NASA administrator, President Bush challenged me, "On the evening news, instead of seeing a shuttle taking off or landing, can we have a minute or two of science?"

Sagan: The president said that to you?

Goldin: Yes.

Sagan: Is this the same president who boasted how he didn't understand any of his science courses at Yale?

Goldin: I will forgo discussion on that subject and answer the question. I naively set off and asked the Public Affairs Department to brief me. Now, I've spent 30 years of my career in space science and engineering. I've been involved in the AXAF program, the Gamma-Ray Observatory, and Pioneer—all cutting-edge programs. I understand the language. And I tell you, I've spent hours in meetings at NASA trying to force people to speak English. The problem has gotten so bad that we've hired science writers to sit with the engineers and scientists and translate. We cannot afford to go on like this.

Sagan: The spin-off argument seems largely spurious to me. "Spend $80 billion to send astronauts to the moon and we'll throw in a free stickless frying pan." If you want a stickless frying pan, spend money on stickless frying pans.

Sagan: I think the Planetary Society is doing a very good job. We do write in English. By the way, one of the advantages of computer animation is that it's *already* in English. You don't have to translate. It's visual. That's why no amount of talking heads would get on the evening news, but animation will. Incidentally, the ball-point pen preceded NASA. The spin-off argument seems largely spurious to me. "Spend $80 billion to send astronauts to the moon and we'll throw in a free stickless frying pan." If you want a stickless frying pan, spend money on stickless frying pans. Don't send people to the moon in order to get a stickless frying pan. You could see it in the declining days of the SDI program. "It'll be good for laser surgery." If we want laser surgery enough to make battle stations in Earth orbit, just do laser surgery. Spin-off is not a good argument. The arguments have to be fundamental to the nature of the enterprise.

Goldin: The American public is very sophisticated, in spite of what people think. They love science. They want to hear about science. We shouldn't demean them by saying they won't understand it.

Question: This idea of the evening news bringing scientific information to us is a joke. The evening news does not treat us as intelligent beings. It's a show. It's little videos that stuff us with information—not even information, just blood and guts. I don't really feel that's the avenue to be learning about what NASA and the

Goldin: I would like to see, in my lifetime, international expeditions to Mars and to nearby asteroids (an idea Carl suggested in a phone conversation a month or so ago), and an international research station on the moon—like the one at the South Pole—where we'll be able to image nearby stars and search for terrestrial-sized planets.

astronomical community are doing.

Sagan: Of course you're right. The reason is the cutthroat competition between the networks, in which a single ratings point is worth umpty-ump million dollars. What you want is specials—in fact, series. There's even empirical evidence that this works.

Question: As a consumer, I would definitely be interested in a "space channel" or something...

Goldin: Let me jump in. There is a channel, called NASA Select, that's attempting to do that. I have a vision that the American cable industry will have enough intestinal fortitude to carry NASA Select into every American home. If that happens, the second part of my vision is that NASA will rise to the occasion and communicate in plain English and visuals so that America understands the space program.

Sagan: The cable companies are talking about 200-channel technology. They're not going to fill 200 channels without NASA Select, so that time might come.

Question: Hearkening back to your Columbus analogy—aside from wiping out most of the native populations with disease, he brought on this incredible economic boom. One might expect that might happen again as a result of space exploration. For those of us interested in investing, are you considering means to fund planetary exploration such as NASA bonds, or democratized funding programs, such that we could, say, choose to finance planetary exploration versus military satellites that burn houses here on Earth?

Goldin: First, let me say that we are not involved in direct military applications. We are working to find a separation, but things don't happen overnight. We have had the last military flight on board a shuttle. I *do* believe it's necessary for NASA and the military to work together on infrastructure, because we both can't go out and build launch vehicles, and we can't have separate communications and signal-processing infrastructure. If we have a technology the military could use, we ought to give it to them, because the taxpayer paid for it. And if they have a technology NASA could use, we ought to have access to it. But mixing missions creates a problem. With regard to the other part of your question, it would be lovely if one could commercialize scientific missions. In the long run, by reaching out to the planets and the stars, there will be commercial activities in space. Let me give you an analogy. In 1915, the United States formed the National Advisory Committee on Aeronautics to help America get into the aviation business. When it first started, the Post Office was subsidizing flights, because no one could figure out what to do with the airplane. People said the airplane was useless—you can take the train and get from point to point. The government was paying for the airplane for years, trying to figure out needs for it. The government goes in for infrastructure. We have highways because the government funded them. I don't believe bonds are going to work right now because there isn't that commercial payoff in five or ten years. There are some limited commercial things happening, but it will take a long, long time before they're on their own. What we should do is transfer space technology, not as our primary mission, but as it becomes available. But that wouldn't be the driving force for why NASA exists.

Question: Mr. Goldin, what three missions would you want, if you could have them?

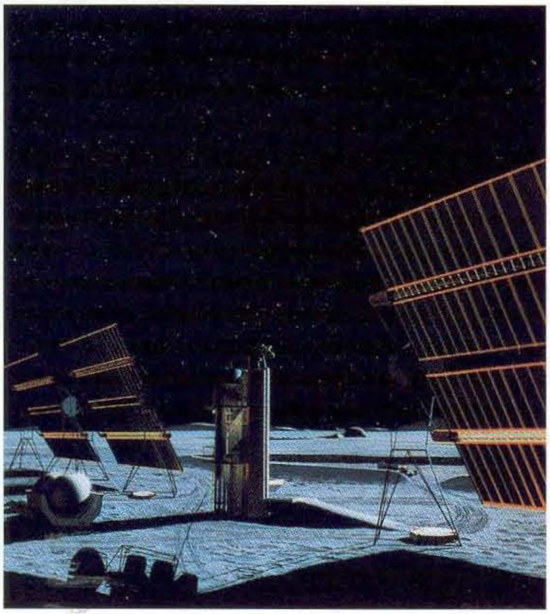
Goldin: In the planetary area, for the next 10 or 20 years, I'd like to see us darken the skies with small, low-cost, high-performance spacecraft that would be pilot pigeons if you will. I do agree with Carl that we should be sending a significant number of these spacecraft to Mars. Second, I think we ought to do all those things necessary to get us to Mars, like understanding how human beings could live and work in a hostile space environment, and getting the systems engineering right. If we devoted 10 to 20 percent of NASA's budget, we could do these things in a reasonable amount of time. Then I would like to see, in my lifetime, international expeditions to Mars and to nearby asteroids (an idea Carl suggested in a phone conversation a month or so ago), and an international research station on the moon—like the one at the South Pole—where we'll be able to image nearby stars and search for terrestrial-sized planets. That will change our view of who we are, and what we are, in the most significant manner, as would finding life, or fossilized life, on Mars.

Question: Do you want to be there?

Goldin: Of course.

Question: I'm a member of Students for the Exploration and Development of Space. What do you foresee in the way of student participation in our space program?

Goldin: Women and minorities are our future. Our engineering, scientific, and technical labor force, which was once made up exclusively of white males, must tap new pools of talent. Twenty years from now, 85 percent of those entering the national labor force are going to be females and minority Americans, and we need role models for them *now*, while they're in grades K–6. You can help them understand that they can do anything that they want to do. That could have a more profound impact on our soci-



Artist's conception of a lunar outpost.

Sagan: It's by no means clear that the only, or the best—certainly not the most cost-effective—way of finding terrestrial planets around other stars is by establishing an extremely expensive human base on the moon.

ety than any other one task you could undertake.

NASA needs a new partnership with the universities. That's very high on my priority list. We've got to involve dedicated young people, and it can't be an exclusive club. There's a crisis right now. One need only come to California to see how state funding of higher education is being reduced. And a large degree of funding for science and technology research has come from the Department of Defense. That funding is now declining very significantly. I've had professors, department heads, and even university presidents come to me and say we have a year or two before we lose a tremendous capability. We've got to transfer some of the funds we're now spending on bureaucracy to the universities. Again, you are our future. I'll be around for some years, but you'll be around for a lot more. If we don't get national attention on this issue, I worry about the future of our society.

Question: How sympathetic do you think the new administration is going to be to your projects?

Goldin: They're not my projects. They're America's projects. It's very important to understand that. I believe the new administration is very positive about the space program, because it recognizes the criticality of cutting-edge technology to America's future. Vice President Gore has been intimately involved with the space program. However, there are enormous issues facing our nation and it would be presumptive of me to say where the administration must place the space program on its priority list. I've seen a survey that shows that some 60 percent of the American people think that the NASA budget is about the size of the defense budget. It is not. We are a very small fraction of that, and I think we return a tremendous value. If you believe deeply that space exploration is important, speak out. Write letters. Pick up the phone.

Question: Earlier, you discussed the annual competition for funding among members of the planetary-science community. Has there been any thought of multi-year procurements for long-term missions? Secondly, there are similar annual competitions between advocates of the manned and the robotic programs. Has there been any thought to bringing those two communities together to stop their infighting?

Goldin: We hope to develop a shared vision with America of why NASA exists, where it's going, and how to get there. A shared vision doesn't mean 100 percent agreement. If we try to get too much of a consensus, we're going to lower the average.

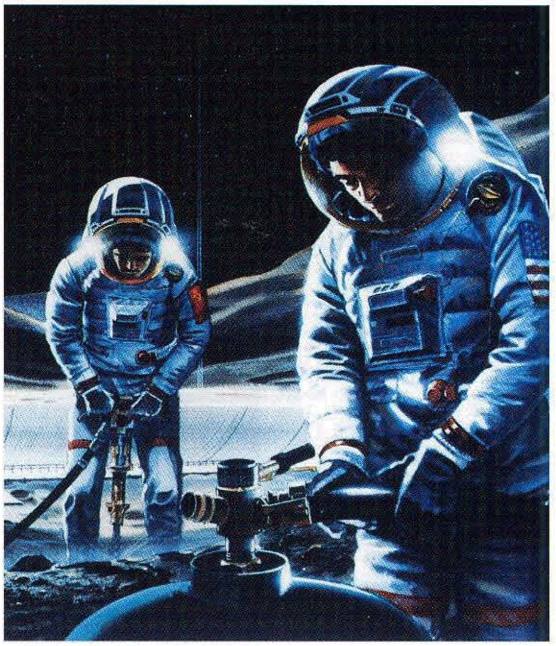
Sagan: Advocates of robotic missions and advocates of human missions should bury the hatchet and pull together. I also think that if there is not a shared, across-the-board commitment by the American people to do one or the other, then we shouldn't do it. The case for human exploration has to be made, more so than the case for robotic exploration, because human exploration is so much more expensive and also runs a risk in lives.

Question: What if a moon base is established, and you find other planets around other star systems? Isn't it disturbing to think that in order to travel to them, you would have to hand the project down several generations? The originator would never see the outcome.

Goldin: I'd love to have that frustration. To deprive ourselves of the knowledge that there might be a blue planet around another star, I think, would be the highest-level crime. Maybe we'll start working full-speed to develop warp drive. That's hokey, but...

Sagan: I agree. That's a frustration I would look forward to. But it's by no means clear that the only, or the best—certainly not the most cost-effective—way of finding terrestrial planets around other stars is by establishing an extremely expensive human base on the moon. There are other ways to do it. For example, there is a reasonably compelling case that radio astronomers have already found two planets of roughly terrestrial mass orbiting a pulsar.

Question: But is it possible to build optics strong enough to be able to see the planet's surface, or at least its color, so that you can determine what the surface might be like?



Right: In this artist's rendering, workers break ground for a lunar telescope that could look for planets in orbit around other stars.
Below: NASA's High-Resolution Microwave Survey is using this 111-foot-diameter dish at JPL's Deep Space Network facility at Goldstone, California, and a 1,000-foot-diameter dish at Arecibo, Puerto Rico, to listen for radio signals generated by other civilizations.

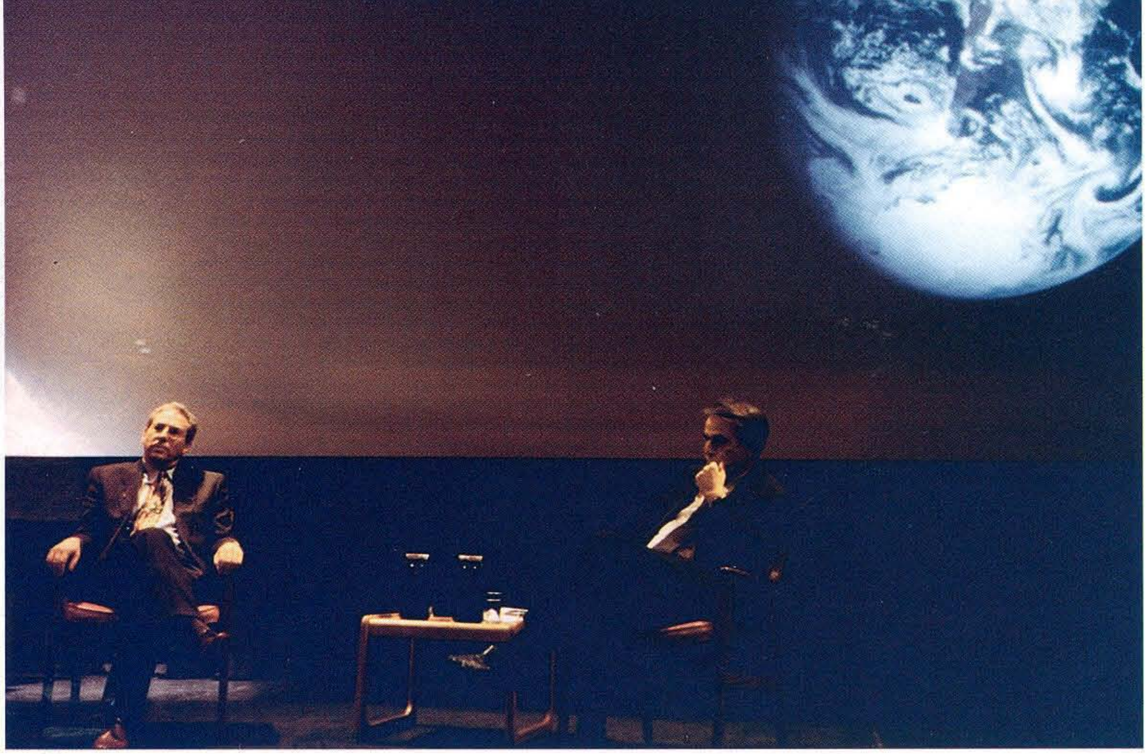
Sagan: Depends on the method. There are, for example, potentially very powerful occultation methods in which you use the limb of the moon, or an occulting disk, to momentarily block the light of the star around which the planet is going and then catch the planet's very faint light. You have to do it from space, but by no means would you have to do it from the moon. Or you might receive a message from the guys who live on that planet. Then they might tell you everything you wanted to know about it, much more than you could figure out from a mere optical interferometer on the moon. NASA, to its credit, has a very sophisticated search for extraterrestrial intelligence going on right now.

Question: I've never been able to see the importance of space exploration, as beautiful and fascinating as it is. Just as Dr. Sagan said, let's put the solar-power stations here in the Mojave Desert instead of going out there. Maybe you can leave me with something I could understand.

Goldin: Society, since the earliest time, has wrestled with the question of how much do we put into the present to survive, and what fraction do we use to plant the seeds for the future? Do we take the money from the space program to solve the homeless problem? As a society, we spend our money in three different areas. We pay for our debts of the past. We have a national debt that's beyond belief, because my generation has chosen to steal from the future to live in the present. Secondly, we have responsibilities in the present to make sure that people have proper education, nutrition, and health. And third, we have to invest in the future. I believe we have no right, as a society, to say that because we have problems in the present, we will walk away from the future. The civil space program is investing 10 years, 20 years, centuries ahead. NASA's budget is \$14 billion. Our federal budget is \$1.5 trillion. We could take the whole NASA budget and, in a feeding frenzy in the U.S. Congress, vaporize that budget in two hours. And even if we converted it into valuable things instead of pork, nine-tenths of one percent is not going to solve this nation's fundamental problems. But I would weep for our nation if we didn't have a space program.

Sagan: There's a range of justifications. People resonate differently. Let me talk a little about space in general, not just NASA programs. Communications satellites link up the planet. Meteorological satellites predict the weather, saving many billions of dollars worth of crops every year. Military-reconnaissance and treaty-verification satellites make the planet more secure. Satellites, especially those that are coming along, monitor the health of the global environment and check out the greenhouse effect, the depletion of the ozone layer, and new dangers we haven't even thought about yet. All of those are immensely practical and cost-effective.

Then there's the issue of exploration. Humans for 99 percent of our history were hunter-gatherers. We wandered. We followed the game. Exploration is built into us. And just at the moment when the planet is all explored, save perhaps for under the ocean, the planets open up as a goal for exploration. Many people feel this in a strong, emotional way—one could even call it



Sagan: The vision of the future that's offered up to young people in our society is almost universally dismal—something like guys with automatic weapons on bombed-out post-nuclear-war highways. What aspect of our society, in the natural course of doing business, offers a hopeful vision of the future? It's the space program... That's worth a whole lot.

religious in the sense that they have difficulty justifying it rationally.

And there are the deep questions that each society, one way or another, asks—the origin of life; the origin of our planet; the origin, nature, and fate of the universe. I think you'd have to be made out of wood not to wonder, at least a little, about those questions. Through folklore, religion, superstition, or science, every human culture has invested some of its resources in answering those questions. So it is reasonable for us who can, for the first time, actually find out some of the answers to make this investment as well.

If you mix those three together—the directly practical, the zest for exploration, and the answering of questions of origins—I think you'll catch a sense of what motivates a lot of people about space. And one last thing—the vision of the future that's offered up to young people in our society is almost universally dismal—something like guys with automatic weapons on bombed-out post-nuclear-war highways. What aspect of our society, in the natural course of doing business, offers a hopeful vision of the future? It's the space program. It's new worlds, new exploration. It's something that young people can be motivated by, that can help guide their lives, make them work hard and study science. That's worth a whole lot. I think NASA, despite all of its problems and its ossified bureaucracy, is a fantastic bargain. And I'd like to wrap up this evening's discussion by saying that, after listening carefully to Dan's answers to this wide variety of questions, I think that NASA headquarters finally has got a breath of fresh air. □

Ed Stone, director of JPL, introduced the speakers. "Daniel Goldin, the ninth NASA administrator, took office on April 1, 1992. Before that, he was the General Manager of TRW Space and Technology Group in Redondo Beach. He brings to NASA a long experience in developing spacecraft for NASA and for other government agencies. But even more importantly, he brings a deep conviction about the importance of the space program to both the nation and the world—a comprehensive vision and a great enthusiasm for the planetary program.

"It's hard to imagine a better-suited scientist to engage Dan Goldin in a dialogue than Carl Sagan. His career as a space scientist spans the entire 30 years of the planetary program. He was a scientific investigator on the Mariner 2 mission and has been on many planetary missions since, including Voyager's historic journey to the outer planets. He was for 12 years the editor of Icarus, the journal of the planetary science community. For the public at large, he is best known as a Pulitzer Prize-winning author, and for his masterful television series, Cosmos, *that established him as a scientific spokesman for space science."*

The Planetary Society was founded in 1980 by Sagan; Bruce Murray, professor of planetary science and geology at Caltech and then director of JPL (1976–82); and Louis Friedman, then the advanced projects manager at JPL, who had overseen Magellan, Galileo, and other spacecraft in the early stages of their development. The society was founded as a non-profit organization dedicated to the exploration of the solar system and the search for extra-terrestrial life. With approximately 100,000 members in over 100 countries, the society is the largest space-interest group in the world.


ARITHMETICOR
COPERNICUS
GALILEO
DESCARTES
ONOURABLE ROBERT BOYLE
HISTOIRE NATURELLE DU SENEGAL
KEPLER
NEWTON PRINCIPIA
C. HILL

Fear No Weevil

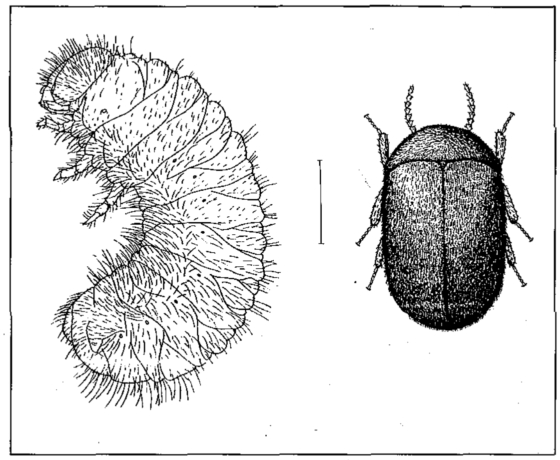
by Douglas L. Smith

But if no Scurve or Lloydie ever had a taste for Diophantus, something else did. Bookworms had burrowed through its spine.

Millikan, Hale, and Noyes kept Caltech small deliberately, in order to promote intellectual cross-pollination between disciplines, but even they probably didn't expect a hybridization of physics and library science. Yet that's what happened in the drive to eradicate bookworms from Caltech's Rare Book Collection. The collection—some 1,200 books—is, in the words of Institute Archivist Judith Goodstein, "one of Caltech's crown jewels. It has the books written by the people who made the first scientific revolution, starting with Copernicus, going through Kepler and Galileo, and ending with Newton. All original editions. The collection also includes all of their important contemporaries, Descartes and others, who wrote pro-Copernicus or anti-Copernicus; pro-Galileo or anti-Galileo; pro-Newton or anti-Newton. It's a rich cultural history of science. Remember that Newton said, 'If I have seen farther... it is by standing upon the shoulders of giants.' Here are the giants' shoulders—the literary shoulders." The collection's heart is some 200 books bought in 1955 from Count Giampaolo Rocco of Bologna, Italy, an avid collector of early astronomical works. The purchase was arranged by then-dean Earnest C. Watson, of Watson Lecture Series fame, using money provided by Caltech Trustee Harry Bauer. To this were added hundreds of books from Watson's own collection, and others that the library already owned.

Believe it or not, until recently the latter had been sitting out on the open shelves, with call numbers tattooed on their spines, just like ordinary library books. Such rarities as the *Arithmeticorum* of Diophantus of Alexandria, printed in 1621 in Greek with a Latin translation in parallel columns, were available for any undergraduate so inclined to check out. (A cursory glance at the blank "Date Due" slip glued inside the front cover showed that none had.) "Millikan bought that one in the twenties, when Throop became Caltech," Goodstein explains. "They had to build up a library, and it says something about the people that they bought deeply. They didn't just buy the standard texts; they obviously felt it was important to buy this too." *Arithmeticorum* is the work from which Kepler learned the theory of conic sections that enabled him to deduce the true orbits of the planets—and his three laws of planetary motion—from the observations of Tycho Brahe. And although no earnest Darb ever took advantage of the opportunity to read Diophantus in the original Greek, or even the Latin translation, the point is that one could have. (The late Nobel laureate Max Delbrück *did* check it out twice, after it was moved to the Rare Books Collection.)

But if no Scurve or Lloydie ever had a taste for Diophantus, something else did. Bookworms had burrowed through its spine, a fact discovered last May when the collection was finally put in call-number order in the Archives' new home in the subbasement of the Beckman Institute. Since every volume was being picked up and handled individually anyway, it was an ideal time to take stock of the stock, as it were, and see which books needed pages repaired, or spines rebound, or other attention. One of the things that turned out to need attention was insect damage.



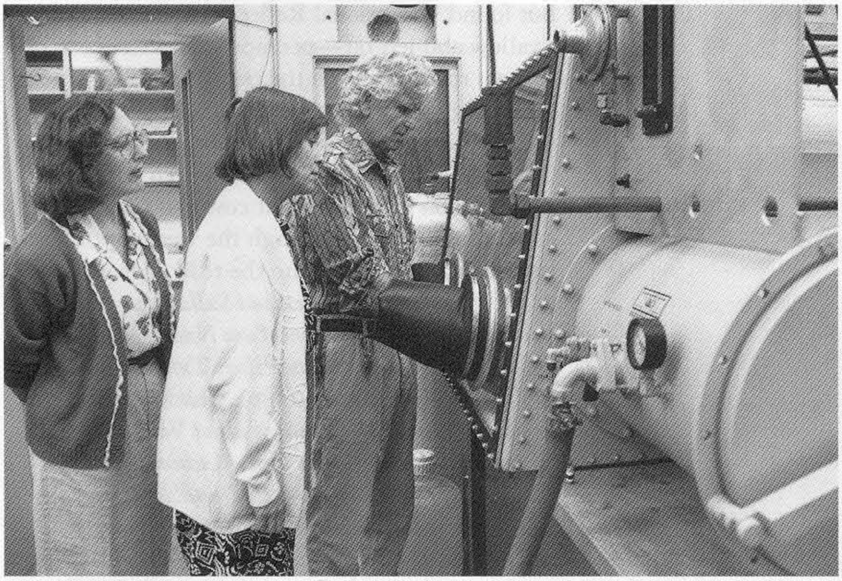
The perp: *Lasioderma serricorne*, a.k.a. the cigarette beetle. The larva is on the left side; the adult is on the right. The bar between them is one millimeter long. The larvae are white; the adults, reddish brown. Both are covered with fine hairs.

Like any good university, these hallowed hardbacks provide room and board, as well as a sheltered environment in which the larvae may develop their full potential. The ancient glue, a collagenous distillate of horses' hides, pig snouts, and other dainties, is their staple diet, while the rice paper used to repair torn pages makes a tempting dessert.

Caltech has its share of bipedal bookworms, to be sure, but the ones that haunt the Rare Book Room are even more secretive than the most reclusive Mole. "You won't see bugs running around on the shelves," says Associate Archivist Shelley Erwin. "They're way too clever for that." The bookworms, which are actually the larvae of any number of species of beetles and moths, live unseen in the binding. Like any good university, these hallowed hardbacks provide room and board, as well as a sheltered environment in which the larvae may develop their full potential. The ancient glue, a collagenous distillate of horses' hides, pig snouts, and other dainties, is their staple diet, while the rice paper used to repair torn pages makes a tempting dessert. And in the fullness of time—a month or two—they pupate. The adults, an inerudite lot, have no interest in books and fly off to parts unknown, returning only to lay their eggs. But like bored students carving their initials in the desks of lecture halls, these boring bugs leave their own signature. An exit hole in the binding marks where a graduating beetle forsook academia for the Real World. Often the only sign of their passage is a pinch of cinnamon-hued dust that trickles out of the binding the first time the book is opened. And occasionally one finds their homework assignments on interior pages: some species are dilettantes, randomly chewing crescent moons the size of rice grains, while others are serious scholars, leaving tunnels that may penetrate the volume from flyleaf to appendix.

"We saw evidence of these two kinds of eating in a number of books," Erwin recalls. "Enough that we decided to call in an expert." James Harmon, R.P.E. (Registered Professional Entomologist), came highly recommended by the rare-book people at UCLA. "He looked at the books that we thought had bugs in them, and got very excited and oohed and ahhed over these wonderful carcasses that he was able to find. He didn't find anything alive." What Harmon found were tawny, slightly fuzzy husks, about an eighth of an inch long—the mortal remains of both larval and adult cigarette beetles, *Lasioderma serricorne*. Says Harmon, "These guys are a very common household pest, first identified in cigarettes and loose tobacco. They're kissing cousins to the carpet beetle. I looked at about 20 books, all of which had some type of damage, but only a couple of them had any signs of recent infestation." All the recent damage was attributable to cigarette-beetle larvae, based on the nature of the damage as well as the corpses of the perpetrators. (The damage to all the other books Harmon inspected was older, accumulated under previous owners.)

What to do? A few years ago, the li'l vandals would have been dispatched with methyl bromide, a fumigant. But that's expensive nowadays, and only one company in southern California still has a fumigation chamber. Alternatively, says Harmon, "You could leave the books in a house that's to be tented for termites and kill two bugs with one stone, but I wouldn't recommend it, and archivists tend to be reluctant to do this." And in any case, methyl bromide damages leather and rubber. Deep freezing, often done with newer, less valuable books, was out, too. "It's quite



Another book checks in to the roach motel. Asplund (right) makes the guest comfy inside the glove box as Goodstein (center) and Erwin (left) look on with proprietary interest.

"Dry nitrogen generally killed everything in about two and a half hours. Actually, a roach lasts longer than anything, but they don't attack books."

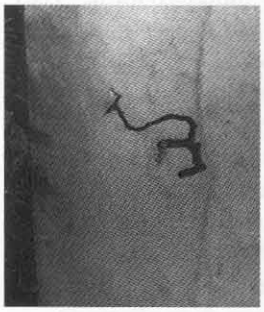
tricky. Unless you're an expert, it's very easy to damage the books." Any moisture in the book becomes ice crystals that can ruin the binding. Clearly, a kinder, gentler killing method was needed. Harmon recommended asphyxiation, specifically via liquid nitrogen, which would instantly evaporate and eventually suffocate the bugs.

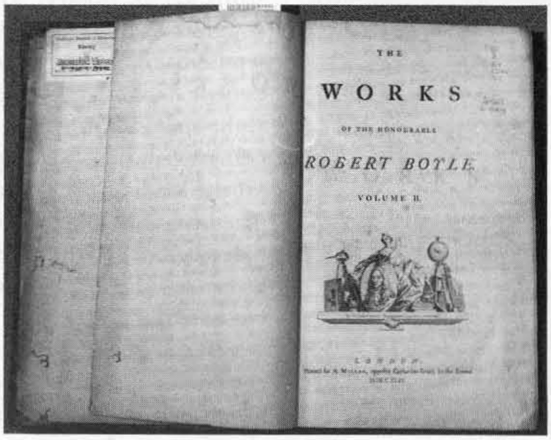
"He told us to seal the books in a plastic bag with masking tape, and then fill it with liquid nitrogen through a straw. This is not trivial for twelve hundred books," says Goodstein. Fortunately, when the idea of freezing books came up, she had immediately thought to enlist the aid of her husband, David, professor of physics and applied physics, on the grounds that his academic specialty—a field formerly known as low-temperature physics—amply qualified him to freeze books. "I said to David, 'Could we do this in our own freezer at home?' and he just looked at me." But he knew who to turn to: Nils Asplund, research engineer for condensed-matter physics—the expert on vacuum systems who builds experimental apparatus for Goodstein's, Assistant Professor of Physics Nai-Chang Yeh's, and Associate Professor of Physics Michael Roukes's research groups. Although Goodstein didn't know it, Asplund is rather an amateur entomologist himself, a hobby he picked up through fishing, by tying flies.

"David called me into his office and said, 'Boy, have I got a job for you,'" Asplund remembers. "'Kill bugs.' And I said, 'Yeah, I can do that, probably, without destroying the book, I hope.' Not being a chemist, I would have just used a hammer on them, but this wouldn't have been good for the book. You can beat hell out of the book and never dislodge the bugs. I once killed a bunch of bugs in feathers by putting them in a Ziploc bag with some crushed mothballs. I could have done that here, but it would have stunk up the library. They didn't go for it. They suggested liquid nitrogen, but I was afraid it would break down the paper fibers." As it happened, Asplund had a spare glove box—an airtight chamber in which oxygen-sensitive chemicals are handled—sitting around in his workshop off the loading dock behind Sloan Laboratory. The box, which he purged with nitrogen for half a day before getting started, was big enough to accommodate one folio-sized book or two quartos. He built a stand of heavy-duty plastic on which the books could be propped open, placed the books in the box, and pumped it down to a 25-micron vacuum before refilling the box with the nitrogen that came conveniently to hand out of the pressure-relief vent line from the LN_2 tank next to the dock. However, nitrogen straight from the tank contains traces of water vapor. "I wanted to dry the nitrogen, so I ran it through a desiccant—phosphorus pentoxide, which is a very good drying agent. I'd leave the books in there four to six hours to make sure, and every so often, I'd turn the pages. I was thinking about hanging the books open, but I was afraid of ripping the glue. Some of them are quite fragile." Some insects can survive in an oxygen-free environment for quite a while, so before starting on the books, Asplund did some endurance tests. "I grabbed as many different sample bugs as I could. Dry nitrogen generally killed everything in about two and a half hours. Actually, a roach lasts longer than anything, but they don't attack books."

For the most part, Asplund was hunting an unseen enemy. But *Arithmeticorum* (the oldest book treated) yielded up a live one. "I did see a weevil come out of the binding. And no, he wasn't clutching his throat and gasping."

Rather than attempting to treat the entire 1,200-book collection, Goodstein and Erwin decided to just treat the 15 or so books with visible damage. These included volumes two and four of *The Works of the Honourable Robert Boyle in Five Volumes, to Which is Prefixed the Life of the Author* (1744)—Boyle being a countryman and contemporary of Newton and the father of modern chemistry. Volume four had only suffered a spinal injury, but volume two had been devoured from the front endpaper and flyleaf straight on through the "Experimental History of Colours," and "Some Considerations Touching





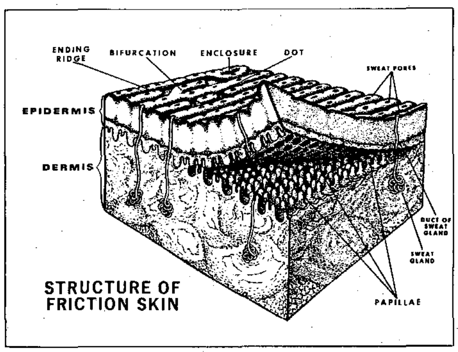
Upper right: Boyle's *Works*, Volume II. Note the call number penciled on the title page, and the Engineering Library sticker on the inside front cover, mementos of life on the open shelves. The filigree on the lower left corner of the cover, the endpaper and, less visibly, on the lower right corner of the title page, is the worm's work. Above: A closer look at the damage. Right: Looks like this one's a real page-turner! The swiss-cheesy item in the lower left-hand corner is the book stand Asplund made.

the Style of the Holy Scriptures"; the worm then ruminated on "Occasional Meditations" but found "Occasional Reflections" too much to swallow and left off—perhaps with a foretaste of its own mortality—on the essay entitled, "Upon the Being in Danger of Death." Other courses included *Histoire Naturelle du Senegal* (1757, by Claude-Jean-Baptiste Bauche), which had been munched on its inside front cover and ornately marbled endpaper, although the worm apparently lost interest after perusing the title page; and *Saggio di Naturali Osservazioni Sulla Elettricità Voltiana, Colla Descrizione d'une Nuova Macchina a Corona di Persone e di un Piliere Tutto Vegetabile* (1806, by Giuseppe Baronio), which translates as *Essay on Natural Observations about Voltaic Electricity, with a Description of a New Machine with a Crown of People and of an All-Vegetable Battery.* The "new machine with a crown of people" recalls that at that time, electricity's primary use was as a parlor trick wherein a ring of partygoers would hold hands with a static-electricity generator and watch one another's hair stand on end, while the "all-vegetable battery" is just what it says—a recipe for a voltaic pile made entirely of veggies. Besides being the ideal crudités to serve at a static-electricity party, this recipe must have whetted the worm's appetite—the inside cover, spine, front flyleaf, and endpapers had all been savored. A dozen less-thoroughly digested volumes were treated as well.

For the short term, at least, the problem appears to have been solved. But preservation is a constant struggle. Who knows what lurks in the books that haven't yet betrayed obvious signs of life? And even in the treated ones, whether the eggs have been killed is anybody's guess. Goodstein and Erwin will now inspect each book annually, and Asplund stands ready with his glove box any time more chewed classics are found. "It really doesn't take any of my time," he says. "I just put the book in the box." Says Goodstein, "We couldn't have asked for a better synergism between our needs, his expertise, and his own interests. We did it without any bureaucracy. The absence of paperwork was impressive. We offered to reimburse him, but he said no. If he'd done the entire collection, that would have been different. But the goodwill, the genuine interest, and the crossing of disciplinary lines really happens a lot at Caltech. People say it a lot, but it's really true. And we have a wonderful staff whose members are as creative as the professors." □

This article originally appeared in the December, 1992, issue of On Campus.

Every fingerprint has 100 or more minutiae. As a rule of thumb, the positive matching of a dozen or so minutiae is sufficient to establish identity in American courts.



A cross section of fingertip skin. The epidermis (outer skin) is anchored to the dermis (inner skin) by a double row of peglike papillae that determine how the fingerprint's ridges run. Thus superficial injuries to the epidermis and the normal sloughing of skin cells do not change a person's fingerprints.

Digital Computing

Watch practically any science-fiction movie, and there will be a scene where some high-security area—the master computer room, or the vault where the viruses are kept—is protected by a palm lock. Someone walks up to the door, raises a hand, and presses the palm against a plate set in the wall. The device recognizes the palm print and opens the door—or refuses to, once the bad guys have seized control.

This stock feature of 21st-century technology is taking form today, and here it is only 1993. Pierre Baldi (PhD '86), a member of the technical staff at JPL and visiting associate in biology at Caltech, and Yves Chauvin, a visiting research associate at Stanford University's psychology department, have developed a system that scans a fingerprint, compares it against a set of stored fingerprints, and decides whether it matches one of the stored ones. In addition to keeping bad guys (or good guys) out of supersecret labs, the technology could be applied to door locks of all sorts, and expanded to such other workaday applications as credit-card, check, or passport verification.

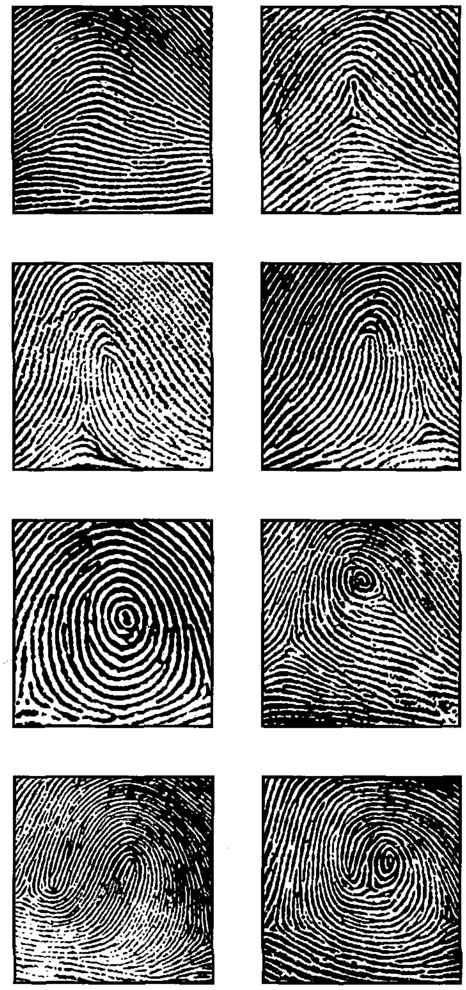
Fingerprint matching for identity verification dates back to at least 1901, when Sir Edward Henry introduced his system of fingerprint classification at Scotland Yard. (Today, variants of Henry's system are used by many agencies, including the FBI.) Now, as then, fingerprints were taken by pressing an inked finger against a white index card. After sorting the fingerprints into such classes as loops, arches, and whorls, final matches are made by comparing minutiae—quirks of individual lines in the print, such as bifurcations, trifurcations, line endings, and islands. Every fingerprint has 100 or more minutiae. As a rule of thumb, the positive matching of a dozen or so minutiae is sufficient to establish identity in American courts. But for your average computer to make those dozen matches entails locating every minutia in both prints—a complex task in its own right—and comparing all ten-thousand-plus possible pairings of those minutiae. To further confound J. Edgar Computer, ink impressions are usually blurry, dirty, and replete with gratuitous ink spots. And minutiae are unreliable—a quick

The computational problems are horrendous, and minutiae-based matching programs haven't fared too well.

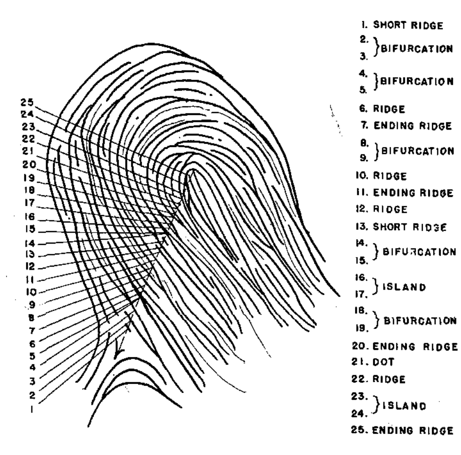
twitch can create a bifurcation on the index card where none existed on the finger. The computational problems are horrendous, and minutiae-based matching programs haven't fared too well.

Baldi and Chauvin use a piece of software, called a neural network, that recognizes the gestalt of a fingerprint rather than picking it apart. Neural nets, which are loosely modeled on protoplasmic brains, have proven quite adept at rapid pattern recognition—a function basic to survival. Instead of having a few very complex processing units performing sequential calculations in isolation, a neural net has many simple, interconnected processors. Like relatives at a family reunion, the neurons all talk at once, and feedback between them pushes the network into a steady state—the "answer"—almost as fast as the news of Cousin Debbie's engagement travels round the dinner table. The network's programs and memories are encoded in the connections between its neurons. Learning a new task, or creating new memories, involves adjusting the connections' strengths.

The network learns to match fingerprints by trial and error—it is given pairs of images and asked whether they are the same or not. Its connections are tweaked a bit after each guess until it picks the right answer every time. To do this, of course, you need lots of fingerprints. "We phoned the FBI, and that didn't work, for obvious reasons," Baldi recalled dryly. "They wanted to investigate us. 'Who are you? What do you want it for? What is your telephone number?' Plus, some of their prints are of very poor quality, because they're taken from people who don't want to be fingerprinted. We ended up constructing our own data base." The FBI's fingerprint files wouldn't have helped much, anyhow—in order to teach print matching, you need multiple prints from the same finger, taken at different times under different conditions, so that the network learns how much a print can vary and still constitute a match. So Baldi and Chauvin rounded up twenty of the usual suspects—colleagues—taking one index-finger print from each person on each of five different days. From this pool of 4,950 possible pairs of



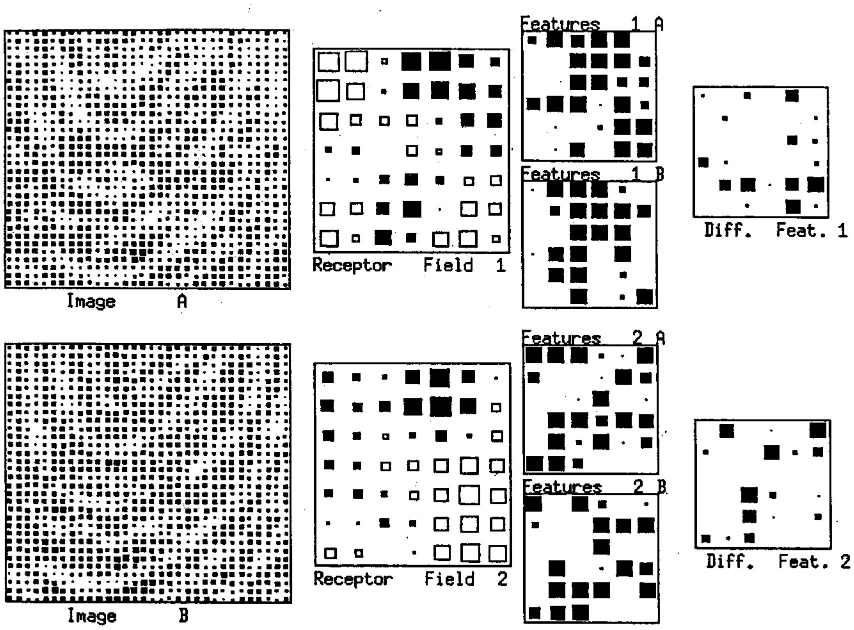
Fingerprint classes and subclasses, according to the FBI's system. Top row: The arch (left), and tented arch. About five percent of all fingerprints fall in this class. Second row: Loops come in two varieties. Radial loops open toward the thumb, while ulnar loops open toward the pinkie. Loops account for roughly 65 percent of all prints, with the ulnar loop being the single most common print. Third row: The whorl (left), and the central pocket loop, a subclass of whorls. Whorls make up some 30 percent of all prints. Bottom row: Double loops (left) are also a whorl subclass. Accidentals (right) include whatever doesn't fit elsewhere in the system.



Final classifications are made by counting the number of ridges that intersect a very precisely defined line. From here, the only thing needed to establish identity is the minutiae match. This sketch shows a 25-ridge print. Its numbered ridges contain several minutiae—two short ridges, five bifurcations, four line endings, two islands, and a dot.

Right: The frame grabber creates a 512 × 464 pixel image of the fingerprint to be matched. The computer draws a rectangle around what it thinks are the print's edges. It then draws a 105 × 105 pixel square (black), the midpoint of whose top line is the rectangle's center. This square is slid over a 65 × 65 pixel square (white) of the reference image until they line up. Below, from left: The computer compresses each 65 × 65 image to 32 × 32—Images A and B. Two filters—Receptor Field 1 and 2—scan each image. The squares symbolize the filters' internal connections. Black is positive, white is negative, and a square's size reflects the connection's strength. The more black in the Features column, the more that filter recognizes what it sees. Upon subtraction (Diff. Feat.), the more white, the better the match. The last column comes up black for a match, white for a mismatch.

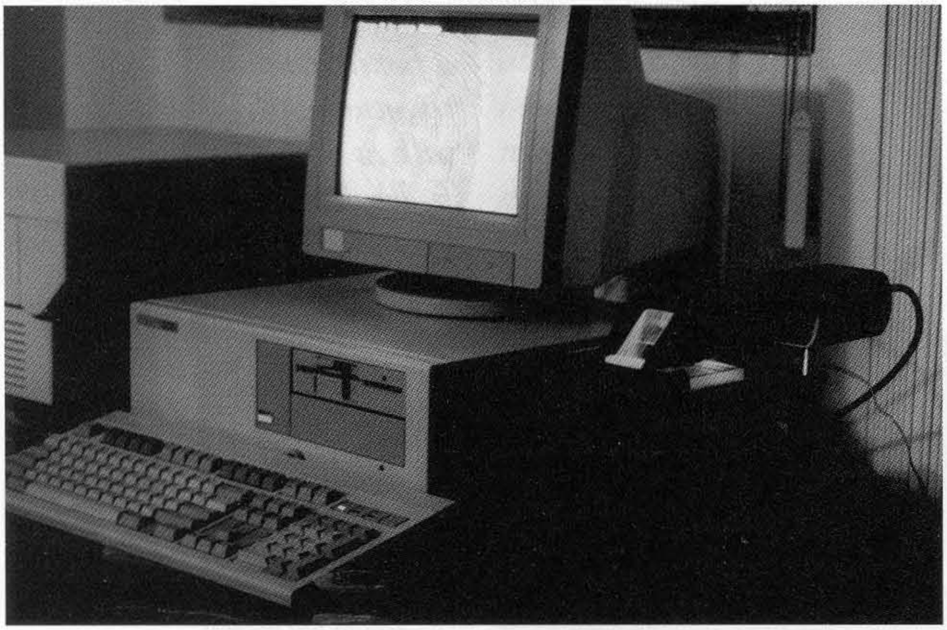
Like relatives at a family reunion, the neurons all talk at once, and feedback between them pushes the network into a steady state—the "answer"—almost as fast as the news of Cousin Debbie's engagement travels round the dinner table.



prints, they used 300 pairs for training, saving the remaining 4,650 to verify that the network had mastered the task.

To input a print, the subject presses his or her finger against a prism. (Nobody wipes the prism off between takes, adding some real-world noise to the data.) The prism reflects a beam of light into a CCD camera—essentially a video camera. Wherever the fingerprint's ridges touch the glass, however, there is no reflection. The resulting pattern of bright and dark lines seen by the CCD camera is converted to a still picture in digital format by a frame grabber. This digital image contains nearly two million bits of data—rather a lot—so the computer locates the center of the fingerprint and then discards everything but a patch about ten ridge widths square, just below the center of the image.

The computer then slides this square patch over an even smaller square of the reference image in its memory until the two images line up—even if the fingerprints are different, you can still shove them around until they are more or less aligned. The computer discards the part of the test image that sticks out beyond the reference square, and compresses the two overlaid squares into squares one-quarter their size. The compressed squares are scanned by a set of "filters"—



The neural net running on a personal computer. To the right of the computer, the prism glows brightly; the CCD camera lurks behind it in the shadows.

"For the lock on your car, a 25-second wait is annoying, and could be dangerous if you're parked in a bad neighborhood. But for checking passports at the border, it's reasonable."

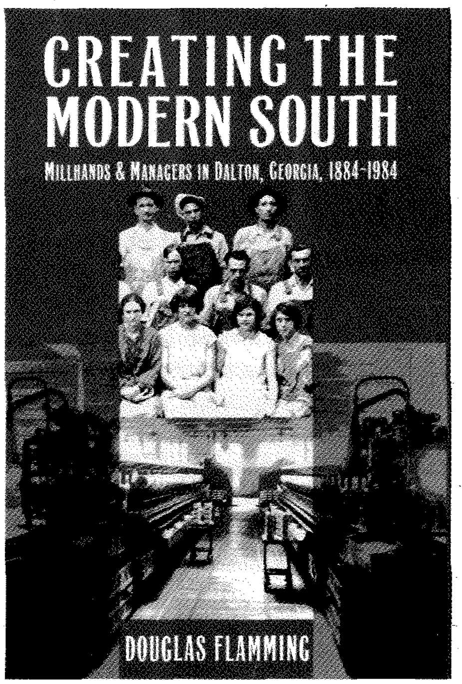
specialized groups of neurons—that look for specific features. (At least two different filters are needed to make reliable matches.) "The network learns what kinds of filters to use as it goes through the training," Baldi noted. "We don't tell it, 'Oh, you should use an averaging filter, or you should use a low-pass filter.' We tell it, 'Use whatever you think is necessary for this task.' That's the essence of neural networks. We don't even know what the filters are looking for. One of them seems to detect lines at a specific orientation, say 45 degrees. It's tempting to say the others are looking for minutiae, but very difficult to prove it." Each filter summarizes its findings as a 6×6 matrix, each element of which ranges from 0 ("I don't see anything remotely resembling what I'm looking for") to 1 ("Ooh, here's a beauty!").

The network compares the filtered images by subtracting one matrix from the other, with the differences squared to ensure that all the results are positive numbers. A zero difference between two matrix elements means a perfect match in that piece of the image, while a difference of one means not even close. The more zeros (or very small numbers) that come out of this subtraction, the better the two prints match, in that filter's view. The neural net then tots up all the filters' comparisons and decides whether the prints match. The net's final output is a number between one (dead certainty) and zero (no way) that represents the computer's level of confidence that the prints came from the same finger. Not that the system hedges its guesses, mind you—it generally gives its confirmed matches ratings of 0.8 or higher, while the pairs it says are mismatches it rates as less than 0.2. It has good reason to be cocky. In the verification set of 4,650 pairs, it was wrong only 0.5 percent of the time, with the errors about evenly split between false matches and false mismatches. Since letting the wrong person in is usually more catastrophic than keeping the right person out, the system can be adjusted to give no false matches at a penalty of increasing the rate of false mismatches to four percent.

Baldi and Chauvin created the neural net on a midsized computer. The training program took all night to run, but now that the machine is a certified dactyloscopist, it only takes ten seconds to make up its mind. The same net running on a personal computer takes 20 to 25 seconds to decide whether the owner of a finger is who he claims to be. "If that's for the lock on your car, a 25-second wait is annoying, and could be dangerous if you're parked in a bad neighborhood. But for checking passports at the border, it's reasonable. If we ran the same software on a parallel machine, or built a special-purpose chip to run it, we could make matches in milliseconds."

Matching the owner of a fingerprint (or a palm print) against a short list of people authorized to enter a virus vault is a much simpler proposition than identifying an airplane-crash victim by matching a fingerprint in the FBI's files. "If you're working with a small data base, say the five people in your family that drive the car, you can do five matches in quick succession." But the FBI has roughly two billion fingerprints on file, and, even at a millisecond per print, it would take more than three weeks of machine time to try them all. "But most of the interesting commercial applications, like credit cards and passports, are simple validation problems. And yes, there is commercial interest in this process." □ —*DS*

Books



The University of North Carolina Press, 1992
$42.50
433 pages

A century before there was the New South of Bill Clinton and Jesse Helms, of Nissan and BMW plants, of interstate highways and Wal-Marts, there was the New South of textile mills. A generation after the Civil War, southern boosterism merged cheap southern white labor with northern machinery and management expertise, promising regional salvation through the obliteration of regional distinctiveness (and, incidentally, generous profits for the millowners). High technology and low wages, owner-dominated governments and weak or nonexistent unions, overblown propaganda and strenuous efforts to create contented, controlled workers—every New South is the same.

Much of the scholarship on the New South is similarly stereotyped and mechanistic. While some scholars romanticize millowners, picturing them as selfless, patriotic paternalists, others demonize the same capitalists as brutal, hypocritical, heartless profiteers and glorify workers as heroic victims, sorely oppressed but inexorably doomed to defeat. In these portraits, figures on both sides are flat, one-dimensional, and dehumanized.

This well-written, thoroughly researched, and beautifully produced new book by Doug Flamming, assistant professor of history at Caltech, avoids such clichés through an extensive and intensive look at 80 years' experience in the Crown Cotton Mills of Dalton, Georgia, a small town in the hills south of Atlanta. Combining oral histories and traditional research in manuscripts, newspapers, and company and union records with revealing statistical analyses, especially of workers' behavior during the pivotal 1939 strike at Crown, Flamming gives new depth and breadth to our image of both millhands and their bosses. Joining the concerns of the "New Labor History" with the quantitative techniques of the "New Social History," Flamming has produced a major work in what is in many senses a "New Southern History."

The symbolic heart of the southern textile industry was the mill village, a separate town where the company owned not only the houses, but also the schools, churches, playing fields, stores, and, largely, the government. The mill village lies at the center of Flamming's book, as well. Why did companies go to the trouble and expense of building mill villages, why did workers agree to live in them, and what were the consequences, unintended as well as intended, of the existence of these socioeconomic arrangements? Did these towns represent for the owners a continuation of the paternalistic tradition of social control that some historians believe characterized slavery and, for the workers, a continuation of a tightly knit preindustrial farming community? Were mill towns full of contented ex-peasants or seething, oppositional proto-unionists? Was the mill village imposed on the workers or chosen by them?

Pointing out that at Crown and elsewhere, the mills operated for a generation before building a mill village, Flamming sees the construction of the village and the provision of a whole range of company-sponsored services, from sewers and running water to semiprofessional baseball teams, as a response to labor turnover rates that often exceeded 90 percent a year before World War I. The women and children who made up the bulk of the labor force at the turn of the century were cheap and often efficient workers, but they did not stay long. The mill village, which attracted whole families, who subsequently provided a stable and flexible work force, was much less a charitable act by the company than a business proposition.

Nonetheless, to attract workers, the mill village had to be attractive to them. Only someone who has never lived an isolated rural existence, and who has always enjoyed piped water and indoor plumbing, can romanticize places without those "conveniences." For some upcountry poor whites (Crown never hired a single African American), the mill village was such a change for the better that the company won their loyalty almost without reservation. However, at the same time that it bound workers to the company, the mill village also linked them to one another. Ironically, it was company paternalism that created a community of workers and the potential for unionization. For once the company formed expectations among workers about the "benevolent" way it would behave, it could violate that implicit contract only at the risk of outraging many of them.

The Great Depression of the 1930s brought the crisis. When profits plunged, Crown cut wages, laid off workers, and speeded up the work process. Workers, feeling betrayed, joined the textile workers union and eventually struck. Although the strike failed and World War II brought a dramatic increase in profits and wages, the old feelings between workers and owners never returned, and the mill village crumbled as a social institution. Autos gave the workers mobility, McCarthyism and prosperity sapped the union, textiles eventually resumed their southward migration, this time moving to Mexico, the Phillipines, Malaysia, and elsewhere, and Dalton became a bedspread- and carpet-making center. Crown finally closed its doors in 1969, symbolizing the end of one "New South," of one stage of modernization.

What a short and necessarily skeletal review cannot convey is the way Flamming makes the people of Dalton and Crown come alive. If you want to make the acquaintance of owners like George Hamilton and Frank Hardwick, of workers like Lillie Ann Hill and Sibyl Queen, of union leaders like Tom Crow and Don West, you will just have to read the book. At once deeply humane and informed by social scientific thought and methods, Doug Flamming's book is an appropriate product for a member of Caltech's Division of the Humanities and Social Sciences.

J. Morgan Kousser
Professor of History and Social Science

Honors and Awards

Arnold Beckman, chairman emeritus of Caltech's Board of Trustees, has received the Bower Award for Business Leadership from the Franklin Institute in Philadelphia. He was honored for his inventiveness and philanthropic activities in the areas of research and development.

Chris Brennen, professor of mechanical engineering, was awarded the Fluids Engineering Award of the American Society of Mechanical Engineers "for exceptional contributions to fluids engineering through outstanding research, teaching, and service to ASME."

Peter Dervan, the Bren Professor of Chemistry, will receive the $75,000 Arthur C. Cope Award at the 1993 meeting of the American Chemical Society for his work in DNA site recognition. Dervan has also won the Gibbs Medal of the Chicago Section of the ACS for his "creative ability" in the field of chemistry.

Samuel Epstein, the Leonhard Professor of Geology, Emeritus, has won the Wollaston Prize of the Geological Society. This prize was established in Great Britain in 1831 to "promote researches concerning the mineral structure of the Earth."

Peter Goldreich, the DuBridge Professor of Astrophysics and Planetary Physics, has been awarded the gold medal of the Royal Astronomical Society, its highest award, to recognize "his outstanding achievements, especially in planetary science."

Harry Gray, the Arnold O. Beckman

Professor of Chemistry and director of the Beckman Institute, received the $6,000 Kaj Linderstrøm-Lang Prize in Copenhagen, for his "pioneering contributions to the study of the electron transport mechanism in proteins."

Philip Hoffman, associate professor of history and social science, has won the Arthur H. Cole Prize for his article "Land Rents and Agricultural Productivity: The Paris Basin, 1450-1789." The prize recognizes the outstanding article published in *The Journal of Economic History* in 1992.

Barbara Imperiali, assistant professor of chemistry, and Tomasz Mrowka, associate professor of mathematics, have been named Alfred P. Sloan Research Fellows.

Hiroo Kanamori, the Smits Professor of Geophysics and Director of the Seismological Laboratory, was awarded the $20,000 Arthur L. Day Prize and Lectureship, presented every three years by the National Academy of Sciences to "a distinguished scientist and renowned lecturer on the physics of the earth."

Mark Konishi, the Bing Professor of Behavioral Biology, will share the $50,000 Charles A. Dana Award for Pioneering Achievement in Health for his studies of nerve-cell death in songbird development.

Manfred Morari, the McCollum-Corcoran Professor of Chemical Engineering, and Fredric Raichlen, professor of civil engineering, have been elected to the National Academy of Engineering. Caltech faculty members in the NAE now number 28.

Ares Rosakis, associate professor of aeronautics and applied mechanics, has received the Hetényi Award from the Society for Experimental Mechanics for the best paper in its field in 1991. Rosakis coauthored the paper, entitled "Quasi-static and Dynamic Crack Growth Along Bimaterial Interfaces: A Note on Crack-tip Field Measurements Using Coherent Gradient Sensing."

David Rutledge, professor of electrical engineering, earned the $1,000 IEEE Microwave Prize for his paper "A 100-MESFET Planar Grid Oscillator," judged to be "the most significant contribution" to that field published in an IEEE journal.

Thayer Scudder, professor of anthropology, whose work concerns the social consequences of forced resettlement, has won the American Anthropological Association's Edward J. Lehman Award for his "creative and valuable application of anthropology in the public sector."

Paul Sternberg, associate professor of biology and assistant investigator at the Howard Hughes Medical Institute, and Rochus Vogt, the Avery Distinguished Service Professor and Professor of Physics and Director of LIGO, have been elected fellows of the American Association for the Advancement of Science.

Nai-Chang Yeh, assistant professor of physics, has received a five-year Packard Fellowship in Science and Engineering to further her research in high-temperature superconducting materials. The award, which provides $100,000 per year, recognizes the most promising young scientists in the nation.

Ahmed Zewail, the Linus Pauling Professor of Chemical Physics, has won the Wolf Prize in Chemistry for 1993 for his pioneering work in the new field of laser femtochemistry. The $100,000 prize is awarded by the Jerusalem-based Wolf Foundation. Zewail has also been awarded the Earle K. Plyler Prize of the American Physical Society.

Check Your Local Listings

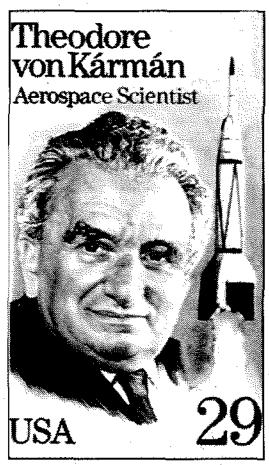
Laszlo Keszthelyi, a graduate student in geology and planetary sciences, is coming soon to a TV set near you. He joins Jaime Escalante, America's best-known math teacher; Kathy Bates, winner of an Academy Award for *Misery*; Pat Morita, of *Karate Kid* fame; professional-wrestler-turned-actor Jesse "The Body" Ventura; rock 'n' roll parodist "Weird Al" Yankovic, and a cast of dozens of celebrities, scientists, and engineers in *Living and Working in Space: The Countdown Has Begun*, an hour-long special airing Wednesday, March 31, at 8:00 p.m. on PBS.

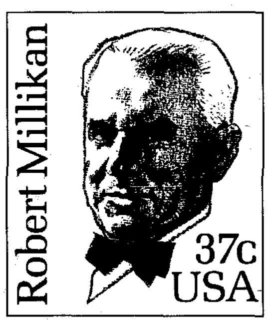
The program, set about 25 years in the future, revolves around Escalante's reading a letter from a former student (Raymond Cruz), now a mining engineer en route to the moon for his first job. Intercut with the letter are interviews with space professionals on subjects ranging from space medicine to microgravity agriculture.

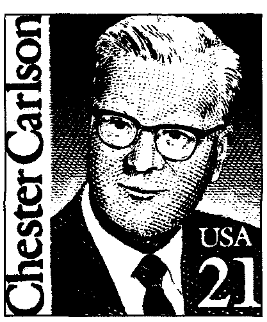
Keszthelyi has been helping to test Russia's Mars Rover, part of their Mars '96 mission, here in the United States. He got involved in the Rover project through his advisor, Professor of Planetary Science and Geology Bruce Murray, and the Planetary Society. "As a geologist and planetary scientist, my primary mission was to locate test sites in the Mojave Desert that are both Mars-like and logistically accessible. And, as with any major field test, there was a lot of grunt work involved, for which grad students seem to be uniquely qualified."

The message is twofold: humanity will be living and working in space sooner than most people realize; and that just as dexterity with a rope and a gun was essential in the old west, facility with math and science will be the survival skills of the new frontier. And space is not just for astronauts—the celebrities appear in vignettes depicting such down-to-Earth careers as raising children, playing baseball, and working for the Department of Moon Vehicles.

The program was produced by the Foundation for Advancements in Science and Education, with support from ARCO and the Department of Energy. NASA underwrote the package of educational materials that accompany it.







Postage Due

Victor Wouk, MS '40, PhD '42, of New York City, who has previously appeared in these pages promoting hybrid and electric vehicles (*E&S*, May–June 1980) now offers a contribution wearing a different hat—that of "Ardent Advanced Amateur Philatelist." He figures stamps are a legitimate subject for *E&S* ever since, as he puts it, "Richard Feynman came out of the closet with respect to Tannu-Tuva" (Summer 1991).

The recent issue of a 29-cent stamp in honor of Theodore von Kármán inspired Wouk's recent letter in which he states his belief that there have been "more stamps issued featuring scientists and engineers closely affiliated or associated with Caltech than with any other institute of learning in the USA." He hastens to add that he doesn't mean "just people; Harvard probably wins this hands down, with US presidents."

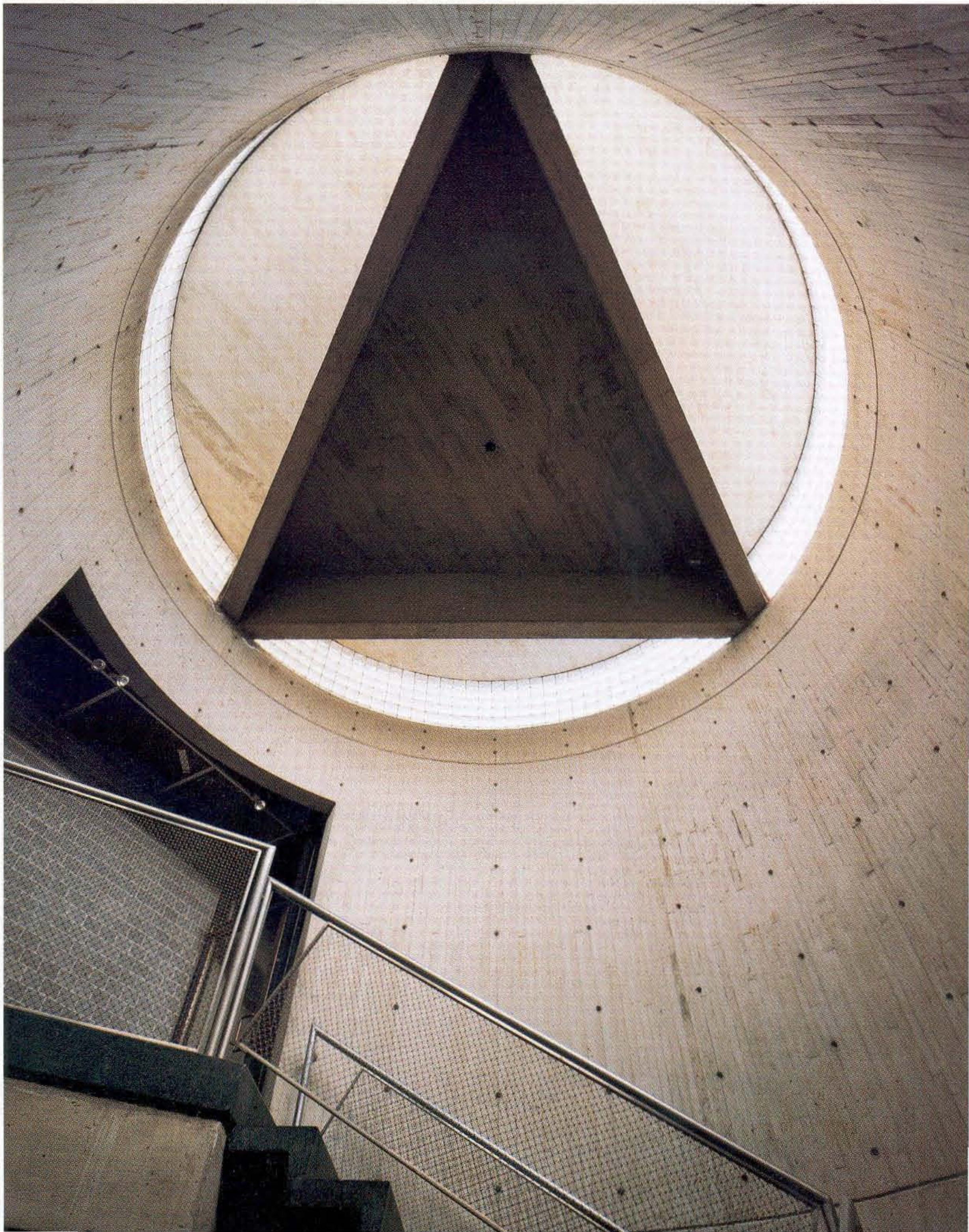
Besides von Kármán, Wouk notes stamps honoring Caltech's former leader Robert A. Millikan (37 cents) and Chester Carlson (21 cents), BS '30, inventor of the photocopying machine. He's even willing to stretch a bit to include Einstein ("he did spend some time at Tech") and other "Caltech-related items" such as Palomar Observatory and an assortment of spacecraft, including Pioneers I and II, Mariner, and Viking, in his campaign to carve a philatelic niche for Caltech.

Wouk adds: "I think that someday, if the US Postal Service continues to issue commemoratives at the rate associated with former colonies of Britain that use stamps as a major source of revenue, Richard Feynman will be so honored. However, it cannot be done until after the year 2000. Why? Because a person must be dead for at least 10 years before a commemorative can be issued, presidents excepted."

Perhaps alumni and members of the Caltech community will get to vote on whether to depict a young Richard Feynman or an old Richard Feynman.

So Much for Linear Equations

Hockey archrivals Caltech and MIT did battle in Beaver Cup VII on February 14. The Cup is named for the mascot of both teams (and of practically every other engineering school in the country, for that matter), and orginally pitted Caltech's club team—which consists of graduate students, faculty, staff, and JPL employees as well as undergrads—against the MIT varsity. Caltech lost the first Cup, 3-11, and the second, 0-13, due in part to a ten-to-one advantage in student-body size at That Other Technical Institute, and to a scarcity of sub-zero days in Pasadena that limits the opportunities to practice. At that point, Caltech redefined its goal to beating a team of MIT alumni. Since then, the scores have been 0-2, 1-6, 0-2, and 1-2. The trend is intuitively obvious, and this was the year the lines should cross. Caltech lost, 0-4.



A pyramid seems to float above a staircase in the Yale University Art Gallery, evoking the silence and mystery that moved the architect Louis Kahn on seeing the pyramids in Egypt. The art gallery was his first important commission (1951) and the first design in which he reached back to an ancient model.

Engineering & Science

California Institute of Technology
Pasadena, California 91125

ADDRESS CORRECTION REQUESTED