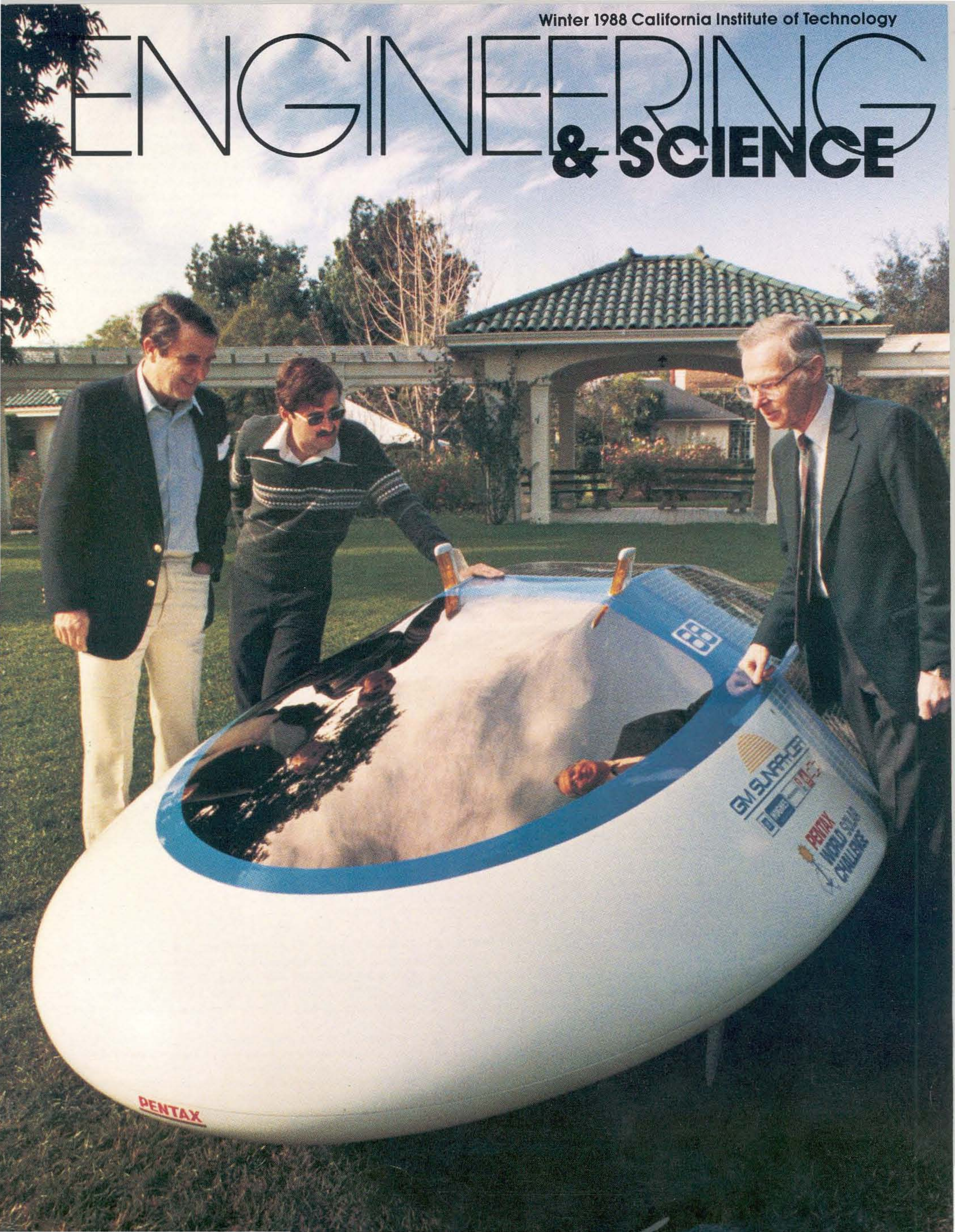
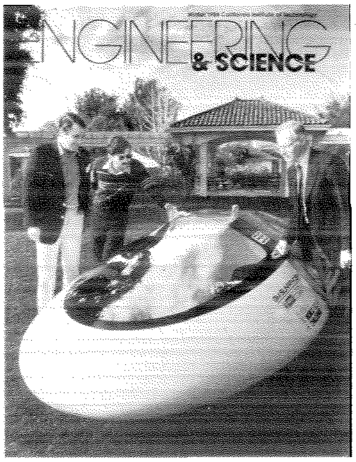
Winter 1988 California Institute of Technology

ENGINEERING & SCIENCE



In This Issue



Sun Run

On the cover—the solar-powered GM Sunraycer, which outdistanced all competition in a recent race across Australia, rests on the grounds of Pasadena's Tournament House before undertaking the less strenuous chore of leading the 1988 Rose Parade as the "pace car of the future." With Sunraycer are (from left) Peter Lissaman, Alec Brooks, and Paul MacCready, who played leading roles in the vehicle's development; all hold PhDs in aeronautics from Caltech. In addition to these three, there was a strong Caltech component in the whole project—with alumni at GM and Hughes, as well as at AeroVironment and among its consultants.

MacCready (MS 1948, PhD 1952) is president of AeroVironment, Inc., a firm whose staff specializes in environmental and alternative energy projects but is perhaps best known for creating unusual aeronautical vehicles powered by muscle, batteries, or solar cells. So the small Monrovia, California, company was a natural place for GM to turn to for meeting the Pentax World Solar Challenge.

MacCready's story of how the car was conceived, designed, and built (beginning last March) in time for the November 1 race appears on page 2. "Sunraycer Odyssey" also gives an overview of some of the vehicle's advanced technology as well as an account of the race itself and the strategy that contributed to the victory.

Light Fantastic

A little over three years ago the American Physical Society appointed a study group of scientists to look into the technological aspects (not the ethical or philosophical ones) of the Strategic Defense Initiative and to present a report to the society's membership. That report was released last April. One of the 17 members of the study group was Caltech's Amnon Yariv, the Thomas G. Myers Professor of Electrical Engineering and professor of applied physics. In "Star Wars Technology: Will It Work?" beginning on page 29, Yariv describes some basics of lasers and missiles and then sums up the study group's conclusions. The article was adapted from a Watson Lecture.

Yariv came to Caltech as associate professor of electrical engineering in 1964. His BS (1954), MS (1956), and PhD (1958) are all from Berkeley. He has been a pioneer in integrated optoelectronics—marrying lasers and electronic circuits on a single semiconductor chip—and in phase conjugate optics—a technique for correcting atmospheric distortion, which could provide a solution for one of the problems of beaming lasers over great distances.

But Not Escher or Bach

Olga Taussky-Todd met Kurt Gödel in 1925 at the University of Vienna where they were both students. Gödel went on to prove the existence of undecidable mathematical statements and to become one of the giants of 20th-century mathematics.

Although she hasn't starred in any bestsellers, Taussky-Todd also went on to become a famous mathematician (algebraic number theory, topological algebra, matrix theory). After earning her doctorate in 1930, she taught at Bryn Mawr College, and Girton College, Cambridge, and worked for the English Ministry of Aircraft Production during the war. She and her husband Jack then worked at the National Bureau of Standards in Washington, D.C. for 10 years (with a year off at the Institute for Advanced Study) before coming to Caltech in 1957. Taussky-Todd has been professor emeritus (a term she doesn't care for) since 1977. In 1980 she was awarded a Golden Doctorate from the University of Vienna—50 years after the original. Taussky-Todd recalls the earlier times in "Remembrances of Kurt Gödel," beginning on page 24. The article was adapted from a talk given in Salzburg in July 1983.

David Harper — *President of the Alumni Association*
Theodore P. Hurwitz — *Vice President for Institute Relations*
Robert L. O'Rourke — *Director of Public Relations*

STAFF: *Editor* — Jane Dietrich
Writer — Douglas Smith
Production Artist — Barbara Wirick
Business Manager — Marilee Wood
Circulation Manager — Susan Lee
Photographer — Robert Paz

PICTURE CREDITS: Cover, 7, 43 — Robert Paz; 2, 10, 12, 13, back cover — Paul MacCready; 7 — Alec Brooks; 4, 5, 7, 10, 12 — GM; 13 — Martyn Cowley; 13 — DuPont; 14-21 — Photo CERN; 23 — R. Zhu; 25 — Caltech Archives; 25-27 — Olga Taussky-Todd; 29, 30, 34 — Physics Today; 32, 33 — Scientific American; back cover — Walt Mancini/Pasadena Star News

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.


GM SUNRAYCER
HUGHES

ENGINEERING & SCIENCE

CALIFORNIA INSTITUTE OF TECHNOLOGY | WINTER 1988 — VOLUME LI, NUMBER 2

Sunraycer Odyssey — *by Paul B. MacCready* *Page 2*
An innovative solar-powered car was created and built in just eight months; one of Sunraycer's creators describes its genesis and its victory in a race across Australia.

Quark Quest *Page 14*
Scientists may find the top quark at LEP, an accelerator under construction at CERN.

Remembrances of Kurt Gödel — *by Olga Taussky-Todd* *Page 24*
A Caltech mathematician recalls the late 1920s and early 1930s at the University of Vienna, when her friend and fellow student proved undecidability.

Star Wars Technology: Will It Work? — *by Amnon Yariv* *Page 29*
Conclusions of the American Physical Society's study group on directed-energy weapons are explained by a member of that committee.

Departments

Research in Progress *Page 37*
Photographic Memory
Computer's-Eye View

Books *Page 41*

Random Walk *Page 42*

Sunraycer Odyssey

Winning the Solar-Powered Car Race Across Australia

by Paul B. MacCready

For days we had been traveling south on Australia's deserted Stuart Highway, but now crowds of spectators lined the road for the final few kilometers to watch the GM Sunraycer, powered by sunbeams, win the 3,005-kilometer (1,867-mile) race from Darwin to Adelaide. Sunraycer completed the Pentax World Solar Challenge course across the continent in 44.9 hours of running time during $5\frac{1}{4}$ days; the car's speed averaged 66.9 kilometers per hour (41.6 mph), 50 percent faster than the runner-up; the average electric power to the motor was just a bit over 1,000 watts ($1\frac{1}{3}$ horsepower). Of the 24 solar-powered vehicles that started out from Darwin on November 1, 1987 (nine from Australia, four from Japan, four from the United States, three from Germany, two from Switzerland, and one each from Denmark and Pakistan), 13 completed the course. The runner-up from Ford of Australia finished 23 hours behind Sunraycer, and only six had arrived by the time of the banquet and prize ceremony November 13. The last one finally reached Adelaide December 2.

The story of the race began in 1982 when the Australian visionary and adventurer Hans Tholstrup drove a pioneering solar-powered car slowly from Perth to Sydney. Soon afterward he had the idea that a dramatic competition would stimulate global interest in this inexhaustible and nonpolluting energy resource, and he acted on the idea. In 1986 he sent out invitations to the 1987 World Solar Challenge. One of these invitations reached the desk of General Motors Chairman Roger Smith. Smith found the concept intriguing and sent the invitation on to GM's subsidiary, Hughes Aircraft, for consideration of the project's feasibility. From GM's standpoint, developing and racing such a vehicle would serve to focus technological developments within the whole company, would make GM's technological capabilities more evident to the public, would fit GM's racing philosophy, and would attract students to engineering as an exciting and rewarding career.

This article gives an overview of the GM-Sunraycer story and my personal view of some of the main issues. More detailed treatments of the technology and of the race are available elsewhere. Many people contributed significantly to the success of Sunraycer, although space allows me to cite only a few of them here.

My company's involvement began last February when Edmund Ellion of Hughes (whom I knew 35 years ago at Caltech) contacted me to explore whether AeroVironment (AV), with its reputation for developing unusual low-powered vehicles, could help. In early March Hughes and AV began an intense three-week program-planning effort.

The basic overall design had to be established during this three-week phase. Engineers always wish for adequate time to deliberate and explore alternatives before irrevocable decisions must be made, but the real world rarely grants that wish. We quickly considered the trade-offs involved in a dozen

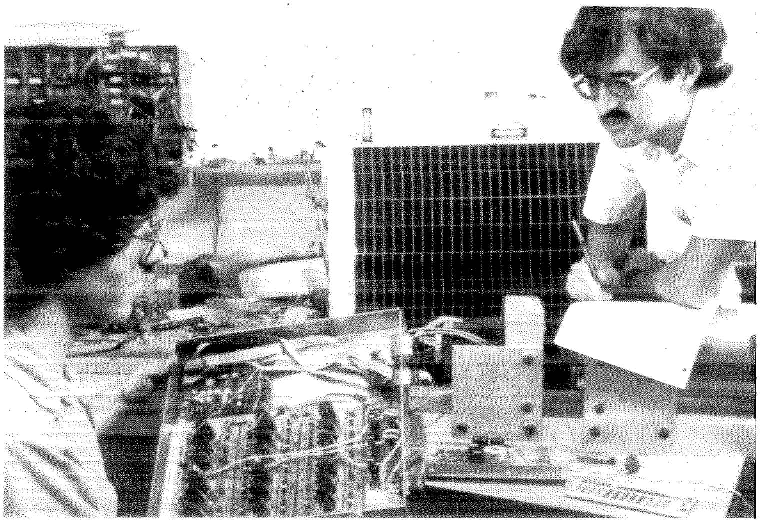
Besides creating interesting photographic opportunities, the gold plating on Sunraycer's canopy (left) keeps out 98 percent of the infrared and 90 percent of the visible radiation. As a result of this shielding, plus a bit of ventilation, the driver remains comfortable even on the hottest days. From inside, the visibility is surprisingly good; sometimes a driver would even wear dark glasses. Such a windscreen wouldn't be suitable for night driving, but that's of small concern for a solar-powered car.

different configurations: different shapes and orientations of solar panels, various body shapes, and the location and structural support of the wheels (and whether to have three or four of them). We explored virtually every vehicle configuration that finally showed up at Darwin. Our study supported the advantages of what was to become the Sunraycer concept, which emphasizes low aerodynamic drag and invulnerability to crosswinds even at the sacrifice of some solar power from additional or tilting panels. Almost all the other cars in the race had solar panels distinct from the car bodies. Although their frontal areas could be small, the vehicles suffered from the drag associated with large wetted areas, as well as the interference drag of separate wheels and connecting structures exposed to the wind. Such vehicles also had to cope with some structural complexities. Fortunately, our concept happened to result in a design that was not only efficient but also looked dramatically super-streamlined—like something James Bond might drive.

Essential to our design was the peak power tracker, a prototype of which was designed, built, and demonstrated during that three-week stage by AV's electronics consultant, Alan Cocconi. The peak power tracker continually adjusts the voltage of an array of solar cells so that the maximum power is extracted, and then it delivers this power with 98.5 percent efficiency to the battery or motor at the appropriate voltage. This prototype demonstrated the feasibility of the key concept of splitting the whole solar array into a dozen subarrays, each oriented differently on the vehicle's body and each operated optimally with its own peak power tracker despite exposure to different amounts of solar radiation. This made Sunraycer's curved panels practicable.

On March 26 we presented our plan in Detroit to Robert Stempel, soon to become GM's president, and Don Atwood, GM vice chairman. The presenters were Howard Wilson, the Hughes vice president who serves as the primary link between Hughes and GM; Bruce McCristal, whose public relations role for GM is also a part of the Hughes-GM link; and Alec Brooks and myself from AV. On April 1 GM accepted the plan and the project commenced officially with Howard Wilson in charge.

Although the basic Sunraycer shape was created in those first three weeks, now it had to be quantified by theory, validated and



Alan Cocconi (left) and Alec Brooks check a power-electronics module prototype.

THE CALTECH CONNECTION

More than a dozen Caltech graduates participated in the Sunraycer programs. Four are full-time employees of AeroVironment: Paul MacCready (MS '48, PhD '52) was program director; Peter Lissaman (MS '55, PhD '66), who heads AV's Aerosciences Division, which handled the project, participated actively in the aerodynamic phases; Alec Brooks (MS '77, PhD '81) was Sunraycer project manager and also one of the six drivers in the race; and Bart Hibbs (BS '77) served as lead aerodynamicist.

Six Caltech alumni were consultants to AV. The most deeply involved was Alan Cocconi (BS '80), who was responsible for the power electronics system interconnecting the solar array, battery, and motor, plus the associated controls and instrumentation. John Gord (BS '75) built the telemetry system that continually conveyed Sunraycer's condition to the observer vehicle during the race; John Letcher, Jr. (BS '63, PhD '66) aided with the utilization of the VSAERO computer program used to refine the Sunraycer shape; Wally Rippel (BS '68) advised on electric drive systems; and Taras Kicenuik, Jr. (BS '78) contributed to the final stages of design and construction.

At Hughes Edmund Ellion (PhD '53), who initiated the Hughes/GM contact with AV, subsequently made sure the project stayed on course; Ervin Adler (BS '74) was responsible for the day-to-day participation of Hughes, particularly with regard to the solar array and battery; Max Schenkel (MS '71), an aerodynamicist at GM, helped with the Sunraycer wind-tunnel tests at Caltech.

Tests of various aerodynamic designs were performed over a two-week period at the GALCIT 10-foot wind tunnel, resulting in the selection of the final Sunraycer configuration.

refined by wind-tunnel tests—and then built. The crosswind safety problem loomed large during the configuration-planning stage and subsequently during the refinement of the shape by computer, wind tunnel, and field tests. For a lightweight vehicle operating occasionally in the 70- to 100-km/h regime and encountering real-world winds, our preliminary calculations indicated that a tilted flat solar panel would be out of the question. A number of vehicles of such configuration did finish the Australian race without mishap, but they were slower and mostly heavier—and sometimes frightening to watch as they jittered along in a crosswind. Even a non-tilted flat panel above the body was considered dangerous because of the lift that could be generated at high speeds from momentary gusts (especially the up-gusts from the vortices in the wakes of the enormous trucks that ply Australia's outback region). Sunraycer's basic body shape is relatively impervious to crosswinds; but the four wheels, especially if covered with steamlined pants, tend to straighten the crossflow under the vehicle, creating a side force and also disturbing the balance between the vertical force on the upper and lower rear half.

The side force is associated with some beneficial thrust, as with a sailboat, but for the wind speeds expected in Australia and the anticipated vehicle speeds the net speed benefit would be insignificant. And there are drawbacks to consider. A side force adds a bit to tire drag and wear. Much more troublesome is the possibility that the side force will be enough to destabilize the vehicle and even blow it off the road.

Also, at high vehicle speeds the vertical force from strong crosswinds could lighten the load on the rear tires enough to make the vehicle yaw. The two strakes, or fins, on Sunraycer's top are there to help solve this problem. They serve somewhat as flow straighteners for the top to balance partially the flow straightening produced by the wheels on the underside. They may also serve as vortex generators to modify boundary-layer separation. Tests in Caltech's 10-foot wind tunnel showed that the strakes yielded the desired result, while the many other configurations of add-on devices we tried—fins and spoilers that seemed more logical—did not do as well. There was no time to explore the matter more deeply; the empirical solution was adopted. Of course, like all engineers, we hope someday to be able to

SOLAR CHALLENGE RULES

The vehicle can be as much as 6 m long, 2 m wide, and 2 m high, but the solar array panel cannot extend beyond an imaginary box 4 m by 2 m by 2 m (with the exception that the arrays can be hinged to exceed this height when the vehicle is charging while stopped). The vehicle must demonstrate adequate brakes, brake lights, and turn signals; it must show that it is stable when passed by large, fast trucks and that the driver can see surrounding traffic.

A battery may be used but can be charged only from the solar panel. A replacement battery may be installed but at the cost of such a severe time penalty that no serious contender would use one. Between 7:00 p.m. and 5:00 a.m. the panel is to be covered to preclude any charging from artificial light.

The race winner is the vehicle with the minimum running time to Gepps Cross at the edge of Adelaide, 3,005 kilometers from the start at Darwin. (The official, but not timed, end is at Seppeltsfield after a drive through Adelaide.) The daily running time lasts from 8:00 a.m. until 5:00 p.m. This may be extended as much as 10 minutes beyond 5:00 to facilitate camping-site selection, but the vehicle is then held an equivalent length of time beyond 8:00 the next morning. There are seven 10-minute media stops at specified locations, during which drivers can be changed but no maintenance work done.

This quarter-scale model of Sunraycer scored the lowest drag coefficient ever recorded for a land vehicle in Caltech's 10-foot wind tunnel. From left to right Bart Hibbs, Max Schenkel, and Kent Kelly view the tests.

treat the subject in a more fundamental way.

These strakes also offered several benefits beyond extending the envelope of safe speed in crosswinds. They added height, which allowed Sunraycer to meet the one-meter minimum height requirement while maintaining a slender silhouette for low drag and a low center of gravity for stability. They provided a convenient place for turn signals. And they helped solve the problem of giving the driver a rear view without the drag of an exterior rear-view mirror. Hughes concocted a fiber optics remote-viewing system whereby the driver could see on a tiny screen what was observed through a lens pointed rearward from the top of the right strake. And finally, we think the strakes look rather jazzy, and we would not be surprised to see their descendants sprouting on cars (and caps), whose owners appreciate Sunraycer's style.

Because of the tight schedule, many interrelated aspects of the design had to be pursued in parallel. While the shape was being refined, the chassis and suspension were under development, the electronic system was being designed, new tires were being researched, wheels and axles were being built, the solar cells were being ordered, and an expedition was mounted to Australia to gather meteorological data and to survey the entire Stuart Highway for road hazards and road-surface details.

A prototype vehicle was built containing 7,200 single-crystal silicon 6- by 1.8-cm cells. Manufactured by Hughes' subsidiary Spectrolab (the same brand that six years earlier powered our Solar Challenger on its 163-mile flight from Paris to England), these cells convert approximately 16.5 percent of the incident radiation to electricity. The final race vehicle had 20 percent of its panel area covered with these silicon cells, but the remaining 80 percent held 4- by 2-cm gallium arsenide cells. Half of these were obtained from Applied Solar Energy Corporation and the other half from Mitsubishi International Corporation. Use of these space-quality gallium arsenide cells resulted in a solar array having about 25 percent more power than the prototype array. In the best steady-sun conditions in Australia this 8-meter^2 array would deliver more than 1,550 watts. In comparison to silicon the gallium arsenide cells have higher output and a lower negative temperature coefficient of power, but they cost more, are smaller, more delicate, and heavier, and require more diodes to provide protection against back voltage when a portion of the array is shadowed. Both solar arrays were designed and built by Hughes.

The battery, also designed by Hughes, is silver zinc, has 68 cells, can store three kilowatt hours and weighs 27 kilograms (60 lbs). It is the electrical equivalent of a lead-acid battery weighing four times as much. A silver zinc battery tires rapidly as it is cycled a number of times, however, which lowers its capacity, but the effect was small for the few cycles of the Australian race.

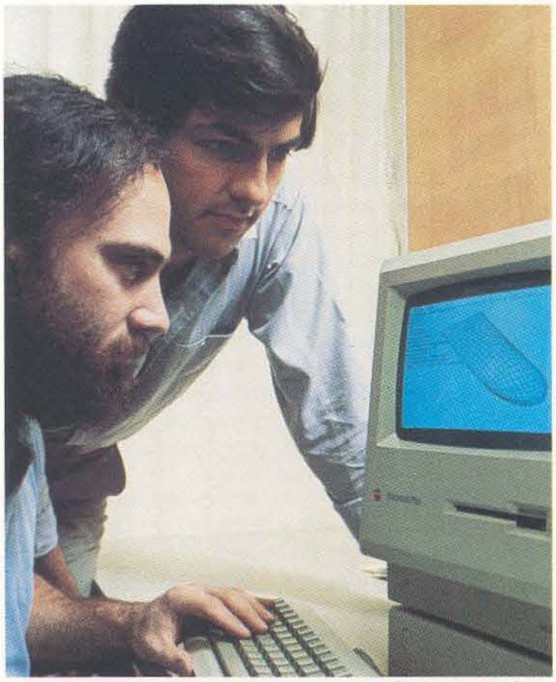
The motor, developed by GM's Research Laboratories, uses Magnequench magnets from GM's Delco Remy Division. It weighs 5 kg (11 lbs), reaches an efficiency of 92 percent, and can deliver 4 horsepower continuously and more than 10 horsepower briefly. A cogged belt conveys its output to the left rear wheel.

Twelve separate solar panel arrays are connected to the battery by peak power trackers. The battery drives the motor with a motor drive inverter that generates three-phase AC power. The drive inverter includes control based on constant current, constant speed (rpm), or constant torque; its efficiency is greater than 97 percent.

The human driver has instruments to monitor the operating conditions and temperatures of all the electronic devices, and there is a 90-channel telemetry system delivering all the information to the nearby observer vehicle.

Sunraycer weighs 175 kg and carries a driver ballasted up to 85 kg for a gross weight of 260 kg (573 lbs). The space-frame chassis, which weighs less than 7 kg, is constructed of aluminum tubing. The body's exterior is made of a Kevlar-Nomex-Kevlar sandwich. The portion supporting the solar cells is built with high-temperature epoxy to maintain structural integrity when heated strongly by the sun. To keep the driver cool, the canopy is gold plated. While every aspect of the Sunraycer development had its pressures, construction of the body was especially trying because of the need to let panel layers cure, sometimes for several days, before the next step could be undertaken.

The technological phase of the Sunraycer program was essentially finished by mid-August—all the major engineering challenges were solved just four and a half months after the April 1 start. In the remaining two and a half months we placed a strong emphasis on reliability testing, somewhat to the neglect of



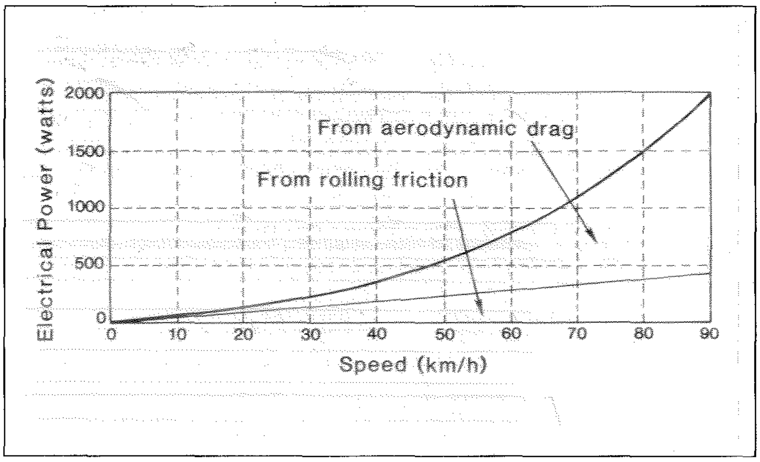
Bart Hibbs (left) and Graham Gyatt check the input data to the VSAERO program using a graphic depiction of the body shape.

Above: Alec Brooks, who was one of the six drivers in the race, observes Paul MacCready through a fiber optics remote viewing system connected to the top of the strake at left. This served as Sunraycer's rear-view "mirror."

Above: Nomex honeycomb, the sandwich filling, is laid onto the Kevlar skin in the mold for the solar-array panel.

Left: the lightness of the chassis and emptiness of the interior are apparent when the canopy is removed and the solar-array panel tilted up.

An AeroVironment crew checks out the Sunraycer prototype during tests in the GM wind tunnel. There were no surprises, but the tests quantified the effects of many small cleanups, making it possible to decide which ones justified being incorporated into the race vehicle.



In constructing Sunraycer's idealized performance curve, the rolling-friction drag (tires, bearings) portion is assumed constant and so consumes power directly proportional to speed; the aerodynamic drag is proportional to speed squared and so consumes power proportional to speed cubed; and the conversion of electrical power to mechanical power of the drive wheel is taken as 88 percent efficient. For a smooth road surface and no wind or hills at the temperature and altitude typical of the Australia race course, the curve was consistent with observations in the 50-80 km/h range. Note that the graph can also be interpreted as energy (in watt hours) versus distance (in kilometers) for one hour of running.

some obvious improvements in aerodynamic details. We put the prototype vehicle through a rigorous 3,000-km field-test program while the actual race vehicle was built. Also time was spent planning the logistics of the race and developing race strategy. Then the race vehicle also received extensive field testing, much of it in Australia under the guidance of Ray Borrett (of GM's Holden subsidiary in Australia), who put the team through its practice for every conceivable contingency.

Race strategy would be simple if we didn't have batteries to store energy: except for speed limits imposed by safety or traffic laws, always go as fast as you can. The course is prescribed; you just follow the Stuart Highway (and drive on the left side). But a battery complicates the situation. It serves as a bank in which you can store your charge of energy "money" in sunny times for withdrawal at a time when you can make better use of it. This is a great convenience, but one for which you pay the price of having to use your brains without certain necessary inputs.

On a windless day in nonhilly terrain, a reasonable initial strategy is to maintain constant speed independent of the sun situation —the speed that just consumes the total energy available from sun and/or battery in the available time. Referring to the performance curve above, if in one hour you go 70 km/h you will "spend" 1,080 watt hours. If instead you drive a half hour at 50 km/h and a half hour at 90 km/h, your 70-km journey in one hour will "cost" more, namely 1,250 watt hours, because of the nonlinearity of the performance curve.

Selection of the proper constant speed requires that you assume how much energy will be available for the time interval in question. Unfortunately, this assumption depends on future events that can't be forecast with certainty. If the last day of the race is going to be cloudy instead of sunny, you should go more slowly during the early days so as to have more energy in the bank to spend on maintaining speed at the end. If all forecasts through the end of the race could be counted on to be perfect, there would be a specific optimal speed for any moment, and it can be calculated. The complete calculations depend on many factors besides the amount of cloudiness. For example, a headwind or a rougher road surface in the future will then affect the Sunraycer performance curve (watts vs. speed), and this affects the present optimal speed. The solar array power depends on Sunraycer's heading relative to the sun's position, a function of the highway orientation where the vehicle will be at a particular time. Motor efficiency varies with both the power and the rpm (vehicle speed). Battery

SOLAR CELLS AND YOUR BATTERY "BANK"

Solar cells (photovoltaic cells) generate power when the sun shines on them. If the energy is not consumed immediately, it can be stored in a battery "bank account" for later withdrawal. If you think of energy as dollars (not an unreasonable concept nowadays), the strategy for managing the energy is analogous to the way you budget your money. You know how much energy you are starting with in the battery (your bank balance), how much you want to finish the period with so as to be prepared for the future, and, if the weather forecast is accurate, you know the rate at which energy will be provided to you by radiation during the day (your salary).

Your race strategy is to spend your energy in a way that avoids overdrawing your energy account while achieving the maximum distance by day's end, just as you budget spending to maximize life's rewards without causing distress to your bank.

The analogy holds if you explore some aspects more deeply. The energy available from solar cells or battery has a "sales tax," say 15 percent, by motor and transmission inefficiency before the power is converted to driving power (the product of your speed and the force pushing you along the road). The energy from the sun is taxed heavily, some 80 percent, before the solar cell electrical output is available for your use. And the battery bank charges a service charge of 20 percent on each withdrawal. These inefficiencies may seem large in comparison to real taxes and service charges, but at least the sun's radiation is free.

efficiency, the charge you get out compared to what you put in, varies with the charge/discharge rate, the total charge in the battery, and the battery's prior history of charge/discharge cycles. Because of the motor and battery inefficiencies, you don't save as much energy going down 100 m of altitude as you spend going up.

A further complication is that the battery storage is not infinite. The charge is just three kilowatt hours at most, and only the region between 20 percent and 80 percent of full charge should be used for best efficiency and cell longevity. This 1.8 kilowatt hours of preferred battery range is only about a fifth of the total energy available to Sunraycer on a sunny day. The right speed at one moment depends on events throughout subsequent days, but only insofar as these narrow battery limits are not exceeded each day. In practice, the battery operating limits for race strategy solution are even more restrictive. The target discharge condition for the end of a day had to be pre-selected within a narrow range of only 0.5 kilowatt hours, a conservative target for preserving "fuel" to get through a cloud cover the next morning. The target would be revised as the end of the day neared, and the forecast of evening and morning radiation became more certain.

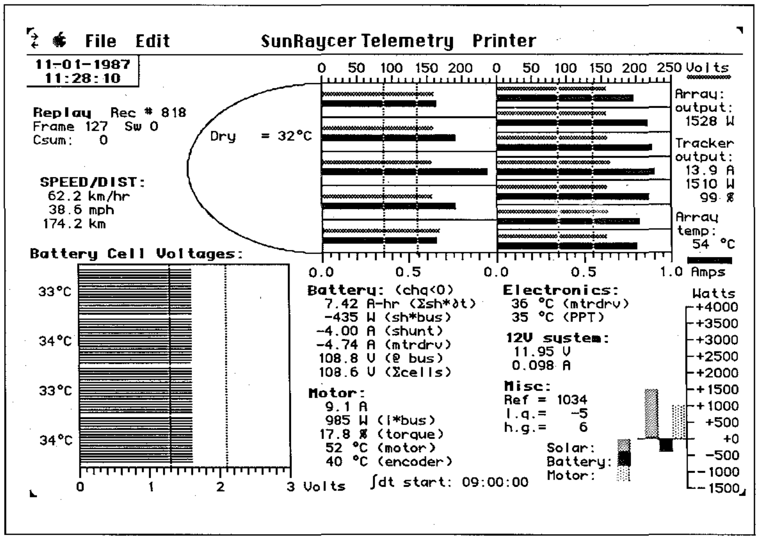
The complete race strategy was modeled by Mike Cassidy and Joe Gurley of Hughes Aircraft Co. Their program was used to explore various scenarios and thereby develop guidelines or rules-of-thumb to guide decisions during the race. For the race itself the program was exercised before each day began, using the weather forecast, to yield optimal speeds and battery charge conditions throughout that day. As the day progressed, if forecast conditions changed significantly, new speed and charge scenarios would be prepared for the remainder of the day.

Graham Gyatt at AV had also modeled strategy factors and worked on rules-of-thumb with the Hughes group. One rule was to avoid mechanical braking at all costs consistent with safety; such braking represents an unproductive withdrawal from your energy bank. Regenerative braking is more desirable. It converts your kinetic or potential energy into battery energy for subsequent withdrawal, but because of various losses you can recover only about half. So, until your speed is considerably greater than the average speed for the day, it's best to avoid regenerative braking while descending a hill.

Another rule-of-thumb was to maintain constant speed during cumulus cloud conditions when small cloud shadows alternated with sunny spots. But when cloud shadow areas were large (say, five kilometers or more), the driver should speed up when in shadow. It may seem counterintuitive to go faster when nature is giving you less power, but since you get through the shadow more quickly you actually benefit. In a headwind (or tailwind), you should slow down (or speed up) from the zero-wind optimum by an amount of about half of the wind speed. A constant battery current mode is convenient for handling varying winds as long as the terrain is rather flat.

Fortunately, operating a bit off optimum does not hurt much. If you operate 10 percent faster or slower than the optimum speed for 100 seconds, you lose only about 1 second; for a 20-percent difference the net loss is under 4 seconds. Going too slowly costs you distance in a given time but consumes less energy, and so the battery ends up containing more energy. This excess can then be spent efficiently over a long period of time to increase your subsequent speed. The net consequence on time lost is surprisingly small.

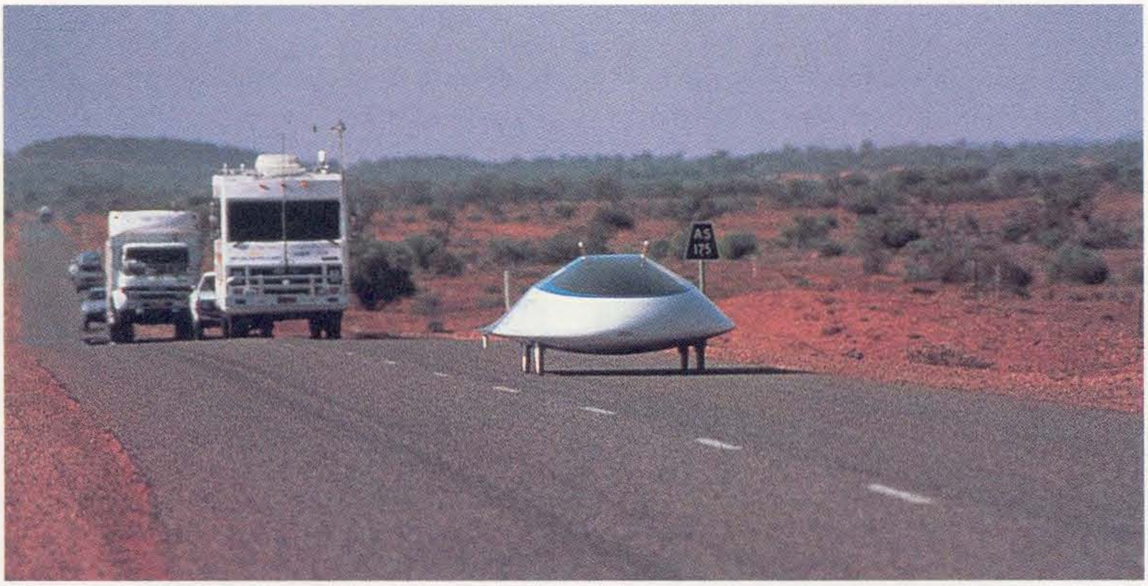
Sunraycer managed to maintain a rather steady average pace from Darwin to Adelaide.



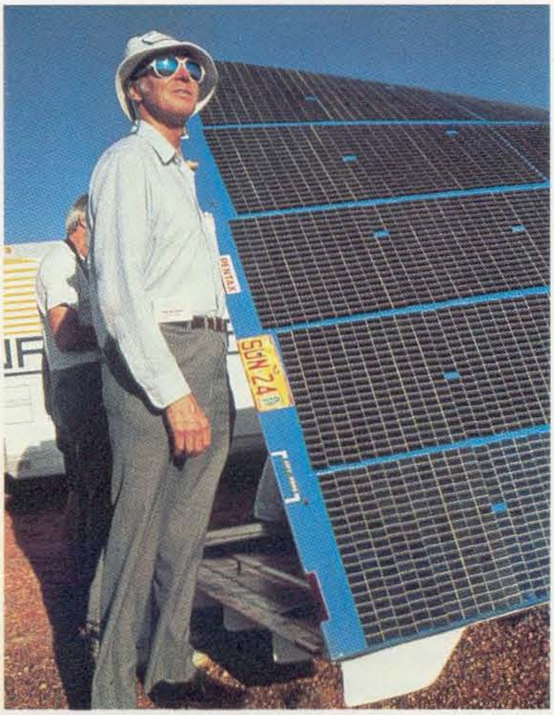
```
11-01-1987
 11:28:10

Replay  Rec # 818
Frame 127  Sw 0
Csum:   0

Dry   = 32°C

SPEED/DIST:
 62.2 km/hr
 38.6 mph
174.2 km

Battery Cell Voltages:
33°C
34°C
33°C
34°C

Array:
output:
 1528 W
Tracker
output:
 13.9 A
 1510 W
   99 %
Array
temp:
 54 °C

Battery: (chg<0)
  7.42 A-hr (Σsh*∂t)
  -435 W (sh*bus)
 -4.00 A (shunt)
 -4.74 A (mtrdrv)
 108.8 V (@ bus)
 108.6 V (Σcells)
Motor:
   9.1 A
   985 W (I*bus)
  17.8 % (torque)
  52 °C (motor)
  40 °C (encoder)
∫dt start: 09:00:00

Electronics:
 36 °C (mtrdrv)
 35 °C (PPT)
12V system:
 11.95 V
 0.098 A
Misc:
Ref =  1034
I.q.=    -5
h.g.=     6

Solar:
Battery:
Motor:
```

The telemetry display above shows Sunraycer's health. Graham Gyatt developed the display that updates 90 items of Sunraycer's condition every six seconds. On this first day of the race the battery cell temperatures in the lower left are a comfortable 33- 34°C, and voltages are 1.60, well within the 1.25 and 2.05 volt limits. The top of the screen depicts Sunraycer from above, with bars showing the output of each of the dozen subpanels that make up the solar array. The total array output is a healthy 1,528 watts (upper right). The bar graph in the lower right shows at a glance that the motor is drawing only about 1 kilowatt, and the rest of the power is going into the battery. The surrounding numerical information quantifies the situation.

Sunraycer leads its entourage of observer vehicle (the motor home immediately behind), supply truck, and various cars containing helpers and media. The entourage also included a lead car 100 meters ahead, a scout car that roved sometimes many miles ahead, a communications car, a satellite-system vehicle, trucks carrying the camping gear, and a media bus. Sunraycer may save global fuel in the long run but definitely did not do so during the race.



The crew changes one of three flat tires during the race. Stopping, changing the wheel, and reaccelerating took only about two minutes.



Paul MacCready checks out sky conditions as Mother Nature recharges the battery.

Sunraycer's solar panel is tilted for recharging at 5 p.m.

At 7 p.m. of the third day Sunraycer is snuggled under its blanket for the night.

For the first five days the daily average speeds ranged from 62.8 to 69.5 km/h. The difference arose mostly from headwinds and tailwinds and only secondarily from altitude changes, sections of unpaved road, or the amount of battery charge consumed or replaced. We traveled 521 km on the shorter (8-hour) initial day and on the subsequent four days, 605, 564, 563, and 600 km. For the last 152 km on the sixth day, since there was no need to preserve battery charge for later, Sunraycer's average speed increased dramatically but was held down to 77.1 km/h by the heavier traffic.

It was not as easy as it may have looked. The steady pace belies the stress on the weather forecasters and strategists for the first several days, until improving weather and the lack of any close competition took some of the pressure off. At the very start of the race we wanted to drive fast and escape the traffic problems associated with all the other solar vehicles and their large entourages. This required borrowing heavily from the battery bank to cope with low sun angle, clouds, and hills. Operating Sunraycer in a constant-speed mode was appropriate for the hilly topography and cumulus-cloud weather, but this mode makes the prediction of battery charge difficult. Our anxiety was compounded by the fact that we were unsure of the battery charge condition; this could only be determined from an amp-hour meter, and the accuracy of ours was uncertain. Only when the battery was recharged back up to the effective top at the official end of the race at Seppeltsfield were we able to ascertain that the amp-hour meter had been right all along.

The strategy discussions continued throughout the first day, as we watched the battery condition and modified our view of the weather forecast. Watching the weather unfold in our region seduced us into upgrading the forecast that had been provided by the Australian Meteorological Service (and interpreted for our purposes by AV's George Ettenheim). When we saw that the clouds were developing unexpectedly slowly, we could not help but presume that radiation would be better than predicted for late in the day. But Nature disdained our revised expectations. As the 5:00 p.m. stopping time neared that first day, the radiation was weak because of cloud shadows, and the forecasts of the charging potential for the evening and morning grew pessimistic. We drove slowly to conserve battery charge and leave enough in the bank to handle possible poor sunlight conditions in the evening and next morning. The evening charging period indeed yielded almost no charge, but on the morning of November 2 the sun filled the battery even above the top of its efficient range.

On the second day I decided to maintain speed late in the afternoon because I was optimistic about the upcoming evening-morning radiation situation. But Nature was again uncooperative during the final running period of the day (perversely agreeing well with the official forecast). The battery was reduced to 25 percent of full charge by the 5:00 p.m. stopping time, and large storms made the evening charge negligible. If the next morning were overcast, we might have a serious problem. I spent a sleepless night, promising Nature I would be more respectful in the future if she would just give us a fair shake. Nature didn't listen. It rained that night, and clouds kept the morning charge small. At 8:00 a.m. the battery was recharged to only 30 percent, but we started out courageously and spent charge rapidly to maintain a fair speed under the overcast to try to reach the sunny area far to the south. We did reach sunshine as planned, and hindsight showed that we had used almost exactly the proper strategy for the previous 24 hours. It is sometimes better to be lucky (or to have a special relationship with Nature) than to be skillful.

On subsequent days we were usually a bit more cautious, but the weather was improving and the last half of the course proved to be almost a slam dunk, with only a bit of high cloud. Still, every day the strategy decision process was dicey after 4:00 p.m., as solar radiation diminished and Sunraycer

TIRES

The race did demonstrate one system design "flaw" in Sunraycer. We had only three flat tires during the race; we should have had more. If we had used tires with thinner tread, the lessened rolling friction would have saved a good hour over the 45-hour race, more than compensating for the extra 15 minutes or so that would have been lost handling another dozen flats. Stopping, changing a wheel, and reaccelerating took about two minutes (after many practice sessions), while the extra charge accumulating from the sun during the interval could later be used to make up some of the time lost.

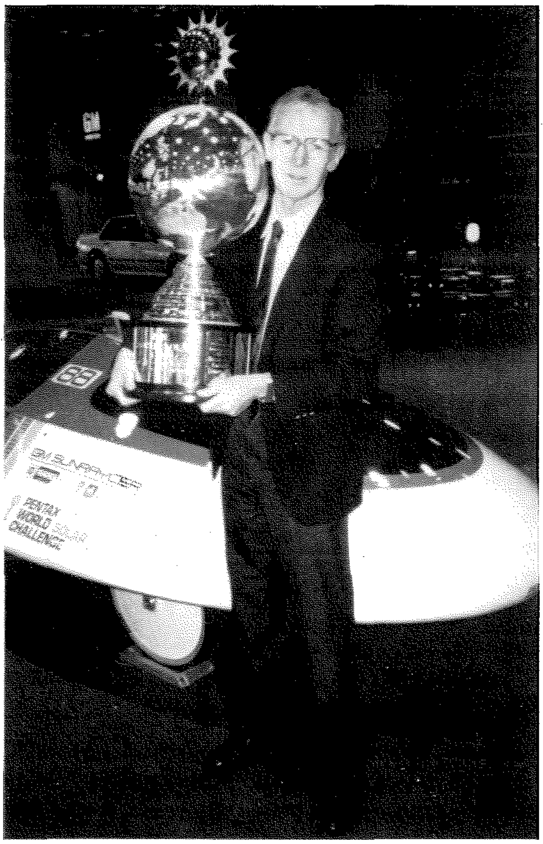
began feeding hungrily on an emptying battery, while we hunted for a stopping location in the 5:00-5:10 p.m. time slot that would afford both a comfortable camping spot and a chance for a good evening charge unhindered by shadows of trees or clouds. The scout vehicle would be probing ahead for likely spots, and we would be coordinating by radio and trying to locate ourselves on featureless terrain while using uncoordinated odometers. The scout car always requested that we use constant speed the last half hour so as to make the coordinated selection of a roosting location somewhat easier. We always agreed, but then worries about the battery would cause us to change speed anyway. After making bum decisions about our stopping point for several days, I was delighted to leave it to others thereafter.

Sunraycer cruised to the finish line on the sixth day with a huge margin of victory. Most of this was due to Sunraycer's basic speed, but other factors helped. There were some jokes about GM's influence extending to very high levels, and we did indeed have some luck with the weather. Our early speed helped us escape the meteorological misery that moved in on those farther back in the race, including gully-washing precipitation that flooded roads and a storm with 1-inch hailstones in a spot where reportedly no rain had been recorded in three years.

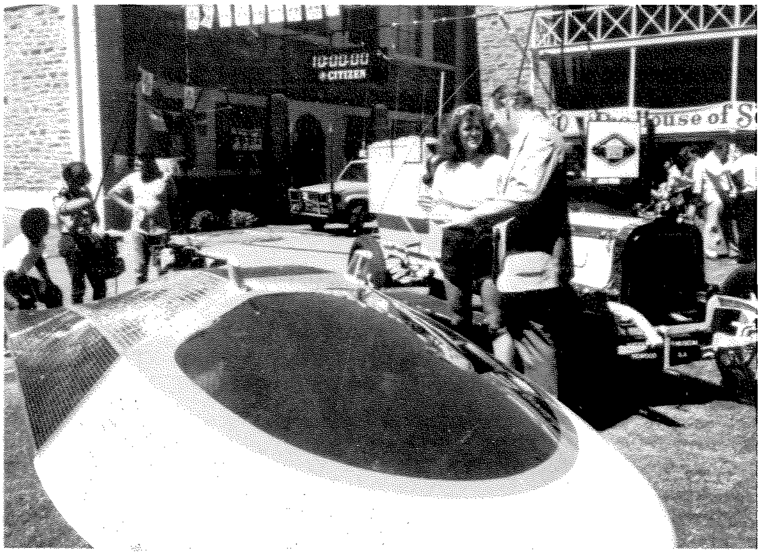
Was Sunraycer's edge due to the solar array, power electronics, motor, battery, aerodynamics, tires, race strategy, reliability, or luck? Every factor helped, with the effectiveness of the total power system from the solar cells to the motor output representing a substantial advantage. Sunraycer was 50 percent faster than the runner-up and would probably still have been 30 percent faster if the runner-up had had our weather. Comparisons become less clear as we explore "ifs" further. The 30-percent figure would probably have been below 20 percent if we had used the all-silicon solar array and the prototype Sunraycer, but we would have won even with a total power system equivalent to those of the next two finishers. But if we had opted for a less advanced power system, we would have saved development time, which could have been invested in aerodynamic cleanup. And with a slower vehicle we would have been less concerned with vehicle dynamics and could have used our alternate tires, which featured substantially lower drag but less comfortable stability and control. Sunraycer's superiority and value lay not in one single advantage but in pushing the frontiers in all the technological areas encountered. The race was the design focus; technological advancement on a broad front was the goal.

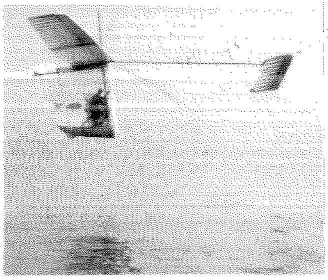
This success and the fact that the whole project was conceived and accomplished in so short a time were partly the result of a remarkably effective organizational setup, which harnessed diverse talents. General Motors had the resources— GM's Magnequench motor and car-suspension design;

At right Paul MacCready holds the World Solar Challenge Perpetual Trophy, which was donated by Broken Hill Associated Smelters Pty. Ltd. It will reside in Detroit until (and after?) the next race in 1990.

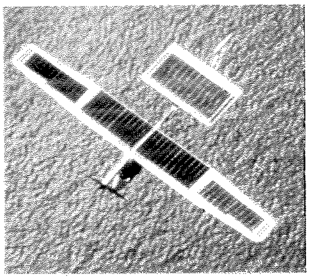


Below: GM's President Bob Stempel talks design with Sunraycer driver Molly Brennan (also from GM) at Seppeltsfield, the ultimate finish of the race. The car behind was the first to cross Australia from south to north, a feat it accomplished in 1908.

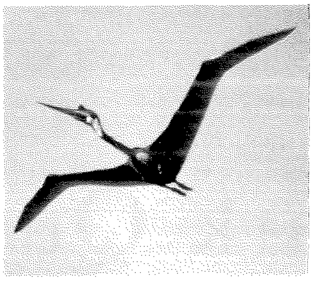




Gossamer Albatross



Solar Challenger



Quetzalcoatlus northropi

Flying Fish hydrofoil

Some of the previous projects of AeroVironment's staff are shown above.

Hughes' unique abilities in solar arrays, silver zinc batteries, electromechanical testing, and strategy theory; the GM-Holden strengths in race management in Australia; and the abilities of another 10 GM groups that were involved more peripherally. GM also had the vision and daring to enter the competition and, with priority commitment from the top levels, to take it seriously.

AeroVironment, which was given the charter to play a substantial role in both program management and technological areas, had resources of another sort to contribute. The company's background has included a number of vehicle developments featuring the emphasis on low power and efficiency that is the essence of a solar-powered race car. Members of AV's staff or teams at the company itself had created human-powered aircraft (the Gossamer Condor and Gossamer Albatross, and the battery-assisted Bionic Bat), the solar-powered Gossamer Penguin and Solar Challenger, a flying replica of a giant pterodactyl (*E&S*, November 1985), and various human-powered land and water vehicles, such as the Flying Fish hydrofoil. All of these projects had to operate with power in the 0.25- to 2-horsepower range. These projects, in addition to a number of specialized aircraft developments AV has conducted for government customers, made it uniquely qualified to take on Sunraycer. Also, AV, 10^{-4} the size of GM, with its short chain of command and versatile staff, has the capacity for quick response to a problem and rapid development of solutions. Together—the huge company and the tiny one—we formed a team of unusual strength—one especially appropriate for this challenge.

Can this sort of organizational system and the excitement of a race situation (which demands absolute deadlines and produces an unequivocal winner) be applied to handle other developments as quickly and effectively? The answer is probably "yes" in principle, but perhaps only in rather special circumstances. One should recognize the uniqueness of the confluence of challenge, interest, resources, and capability that this project represented.

The second most frequently asked question (after "How much did it cost?") has been, "What good is it?" or, phrased differently, "Will solar-powered cars ever be practical?" The answer seems clear. Cars powered solely by sunlight are unlikely to be practical enough to justify wide usage. The maximum solar power intercepted by a car-sized object is small in comparison to the power required by our present safe and comfortable automobiles, and, in any case, sunlight is not always available. But Sunraycer and the World Solar Challenge are valuable when viewed more broadly. The attention that a solar car race focuses on doing big jobs with little power expands our insights into, expectations of, and demands for getting better fuel economy with gasoline and edging battery-powered and hybrid cars toward practicality. The project moves us toward handling the transportation needs of the future while making fewer demands on the earth's resources and environment. And, as a special bonus, as Sunraycer goes on an extended tour, it can serve as a stimulus to students to appreciate that engineering is fun and that nonpolluting transportation is achievable. □

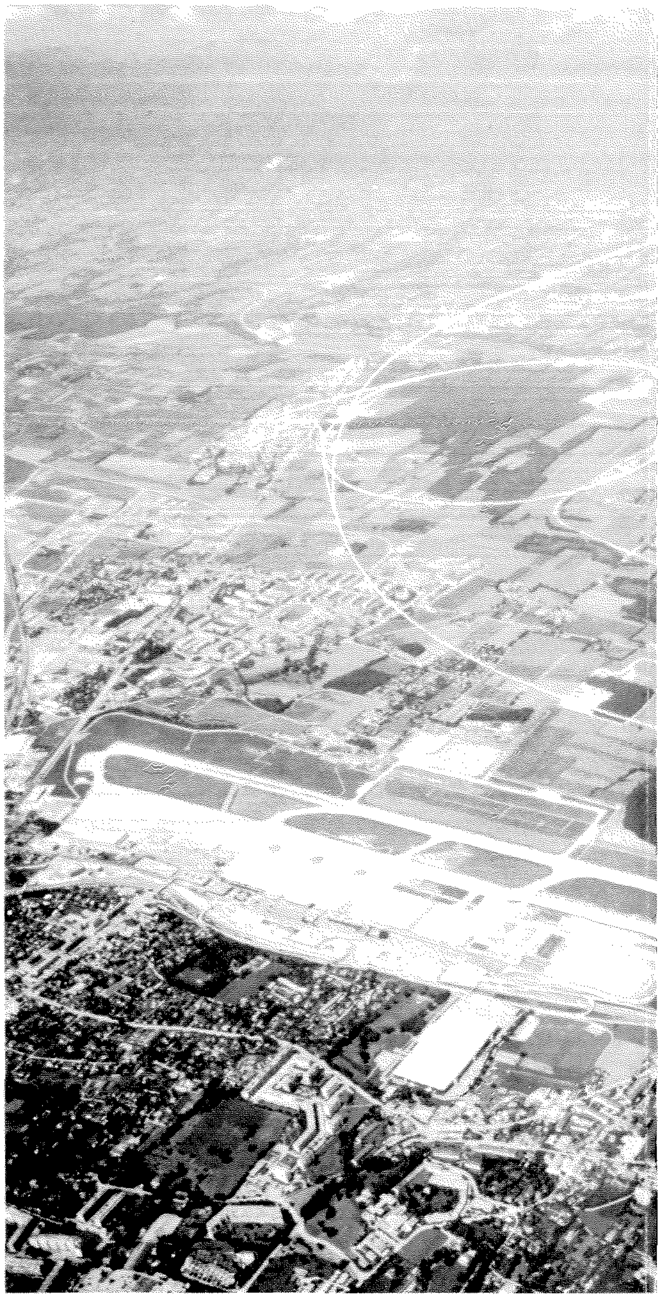
Stories about Sunraycer and the World Solar Challenge are also currently appearing in the February issues of Smithsonian *magazine and* Popular Science. *A book on Sunraycer is expected out by the middle of 1988, and a* National Geographic *television documentary on the race is scheduled for the summer. A series of papers is in preparation for technical symposia. Sunraycer will also be touring museums and schools as well as auto shows and will be demonstrated in action on the highways of many states.*

Quark Quest

THE BESTIARY OF subatomic physics draws its denizens from a world where energy and mass are one, where time slows down as speed increases, and where particles conjure new particles from the void or transmute themselves through interactions with other particles—by tossing still more particles back and forth at each other. In this world where energy transforms into mass, a particle can only appear when the available energy is more than its rest mass, with a little something left over to give the newborn particle some velocity (kinetic energy). In the search for these particles, physicists continue to build bigger and more powerful particle colliders. The particle hunters, armed with computerized detectors, hope to find ever more massive particles in a generous pool of free energy.

Research teams from Caltech are participating in several experiments. One group, headed by Associate Professor of Physics Harvey B. Newman, hopes to find new particles in the wreckage of electron-positron collisions. Newman's group is helping design an experiment to be installed at the LEP (Large Electron Positron) collider, currently under construction at CERN, the European Laboratory for Particle Physics, in Geneva, Switzerland.

Newman hopes to find the top quark and the Higgs particle. Both particles are believed to lurk in the 150 - 200 GeV range. (GeV stands for giga [read billion] electron volts. An electron volt is the kinetic energy gained by an electron passing through a one-volt electric field in a vacuum.) Both particles have tantalized physicists for years, and a false sighting of the top quark has been reported at least once. But, in fact, they have remained just beyond the view of today's accelerators.



Physicists want the top quark for aesthetic reasons, as its discovery would bolster the fundamental theory's internal consistency. Quarks bind together to form protons, neutrons, and most other particles, just as protons and neutrons form atomic nuclei. As things currently stand, five quarks have been found. The fifth, the bottom quark, represents a loose end. Quarks and another set of particles, the leptons, appear to be fundamental: they behave as points, with no signs of internal structure. There are six known leptons, not counting antiparticles: the electron, the electron neutrino, the muon, the

Aerial view of CERN with underground rings drawn in. LEP is the largest ring. (CERN's aboveground complex is at left, surrounding the smallest ring.) The Jura Mountains are in the background.

muon neutrino, the tau, and the tau neutrino. The leptons divide neatly into three pairs or "generations," each containing a particle and its neutrino. Each generation is more massive than its predecessor, but resembles it in all other properties. Quarks display a similar grouping, pairing "up" and "down," "charmed" and "strange," but the bottom quark sits in splendid isolation in the heavyweight division. The top quark would round out the roster, making the quark and lepton families symmetric. This would cause several intractable processes predicted by the theory to cancel each other out, leaving a self-consistent theory of quark and lepton interactions.

The Higgs particle would confirm the standard theory of electroweak interactions—the Weinberg-Glashow-Salam (WGS) theory. The electroweak theory unifies electromagnetism and the weak nuclear force, and is a big step toward a Theory of Everything describing the four forces of nature—gravity, electromagnetism, and the weak and strong nuclear forces—as different aspects of one fundamental force. Just as quanta of electromagnetic force are carried by photons, the weak force is carried by three particles, the W^+, W^-, and Z^0. But while photons are massless, these other particles have been found to have masses 90 to 100 times the mass of a proton. The WGS theory meets the challenge of describing how two forces can be aspects of one force when the particles that carry them appear so different. The mathematics is quite complex; but once the smoke clears several sets of infinite terms cancel each other out. The residue is a solvable set of equations with finite terms, but when all the terms describing the photon, W^+, W^-, and Z^0 have been sorted out, a set of terms is left over. These terms describe a new particle, christened the Higgs after the physicist who developed the math that creates it.

The particle collider is to high-energy physics what the telescope is to astronomers. Just as many astronomers use one telescope for different purposes, several experiments can be run on the same accelerator. In order to understand Caltech's role in the LEP project, therefore, we shall look first at the LEP itself, then at the experiment, and finish with a closer look at one of Caltech's contributions.

The idea behind a particle collider is quite simple. Take equal measures of electrons (e^-) and positrons (e^+), or protons (p) and antiprotons ($\bar{p}$), or protons and protons. Put them in a high-vacuum tube (two tubes for proton-proton collisions), goose them with a powerful electromagnetic field to rev them up to a very high kinetic energy—to a velocity close to lightspeed—and then send them headlong at each other. The collisions will have twice the kinetic energy of either particle alone, plus all the energy released in the matter-antimatter annihilation of e^+e^- or $p\bar{p}$ collisions. This energy creates new particles, which fly off in directions whose distribution may be determined by their charges, masses, and the initial collision parameters. An array of detectors around the collision zone determines the trajectories and charge/mass ratios of the departing particles. The interesting particles often don't reach the detectors, but decay into something else almost immediately. The physicists match their quarry's predicted decay patterns with observed particle distributions and energies.

Putting this simple scheme into practice is another matter. Each component has numerous parts and subassemblies of its own. Institutions around the world provide the parts, which must fit more tightly than the pieces of any jigsaw puzzle. The whole is run by a vast array (a hierarchy, really) of computers whose software was assembled the same way. The entire operation requires so much complex equipment and sophisticated computing that there are only a handful of high-energy particle accelerators in the world. The accelerator complex at CERN, LEP's future home, is one of the world's largest, most sophisticated collections.

LEP should be operational by 1989. It will operate in the 44-200 GeV range, where the top quark and Higgs particles are expected to appear. It will be the largest electron-positron accelerator in the world, and will incorporate many novel design features. The LEP ring, 27 kilometers in circumference (approximately 9 km in diameter), is buried under the French-Swiss border between Lake Geneva and the Jura Mountains.

LEP will accelerate electrons and positrons in opposite directions around a circular track. Electron-positron pairs were chosen because they have no internal structure, unlike protons, which are made up of quarks. The collisions are therefore easier to reconstruct, as there are no secondary reactions among the component quarks to confuse the picture. The price to be paid, and the reason LEP is so big, is that any particle radiates photons (called synchrotron radiation) when accelerated. The electrons and positrons in LEP radiate vast amounts of high-energy photons, requiring many megawatts of power to make up for the energy losses. If the ring were smaller, forcing the beam around tighter corners, the power loss to synchrotron radiation would be much higher.

The electrons and positrons are confined in a high-vacuum pipeline only inches in diameter. The pipe passes through a series of radiofrequency (RF) cavities and magnets. Since electrons and positrons are oppositely charged, a single RF pulse will push them in opposite directions. Similarly, a single magnetic field will bend the two beams in equal but opposite directions. The beams collide head-on at the four experimental halls.

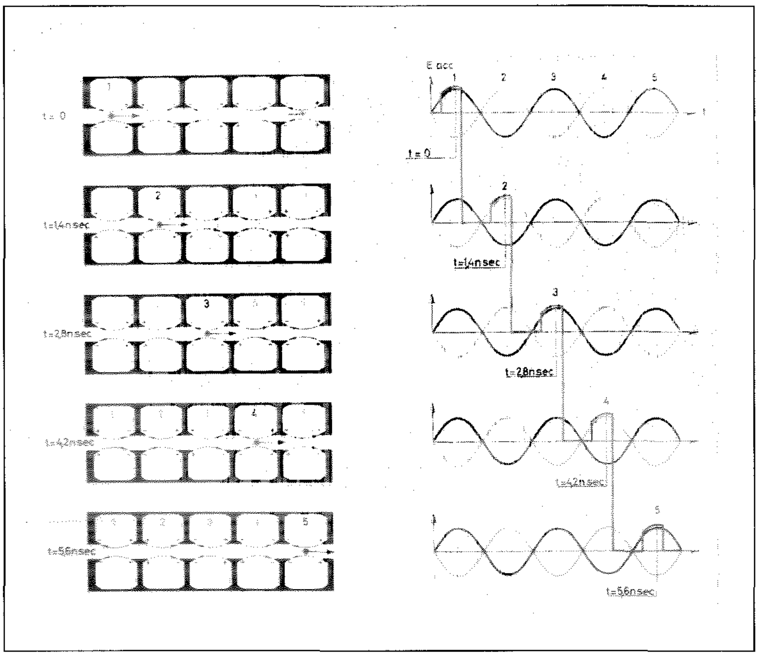
Each beam is 500 microns (μ, 10^{-6} meters) wide and 25 μ high at the interaction points, less than the thickness of a human hair. That space contains approximately 90 percent of the beam's particles. Since the number of collisions is proportional to the beam's density, or "luminosity," the accelerator physicists are working to make the beam even tighter. Initially, LEP will circulate two e and two e^+ bunches, each 1.6 mm long.

Like all particle accelerators, LEP uses the behavior of point charges in electromagnetic fields to accelerate subatomic particles. LEP uses resonance cavities—hollow, copper-lined cylinders divided into chambers by a series of plates. The plates are perpendicular to the beam line, which passes through their center. An oscillating RF field in the cavity, synchronized with the particles' passage, gives them an energy boost with every plate due to interactions with the field's electric component. The oscillations are timed so that the RF field is decreasing while the particles are passing through it. This helps keep the bunches together, as particles arriving early—having slightly less energy and thus following a slightly smaller orbit—see a stronger field and get a bigger push. Overenergetic latecomers get a smaller push, slowing them down.

The LEP has 128 RF cavities of five chambers each. They produce an acceleration of 1.5 MeV(million electron volts)/meter using an RF field of 352 megahertz (MHz) at 16 megawatts of power. The total ring will be able to produce up to 110 GeV initially. It can be upgraded by adding 64 niobium superconducting cavities producing 7 MeV/m. LEP II will eventually replace all the RF cavities with superconductors and the ring will operate at 186 GeV with no additional power consumption. According to Newman, "that's actually less than at PETRA [a 46.8-GeV machine in Hamburg, Germany]. When I was there we could draw 50 megawatts from the local net. This machine is much bigger, but it will use less power."

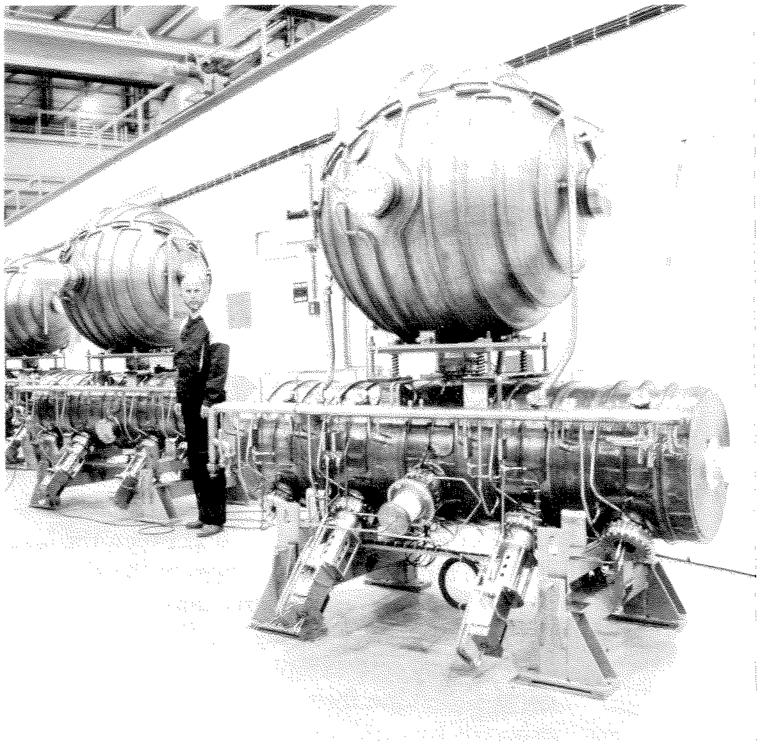
The LEP ring broke new ground in its RF cavity design. Conventional RF cavities keep the field at constant strength between bunches, even though the cylindrical design does not store the field efficiently. The time between succeeding bunches is much too small (44 microseconds for LEP) to turn the power supplies feeding the field on and off. Unfortunately, power losses from the RF cavities add a significant surcharge to the operating cost. The LEP designers added a spherical chamber atop each resonance cavity, connecting the two with a magnetic "gate." The sphere stores the RF field very efficiently. The magnetic gate opens to let the RF field down into the resonance cavity as each bunch passes, and closes again in its wake. Newman estimates the new design will save 40 percent on LEP's electric bill.

Powerful electromagnets guide the particle beams between RF cavities. Magnets exert a force perpendicular to both the field's orientation and the particle's path. Dipole magnets steer the beam around the ring. Quadrupole magnets (magnets with two opposing sets of north and south poles, and hence two opposing fields) keep the beam tightly focused. Otherwise, the repulsion between like charges within a beam would cause it to spread out as it travels. Fine adjustments to the beam's shape often require sextupole magnets. The LEP ring has 3,304 dipole magnets, 776 quadrupoles, and 504 sextupoles.



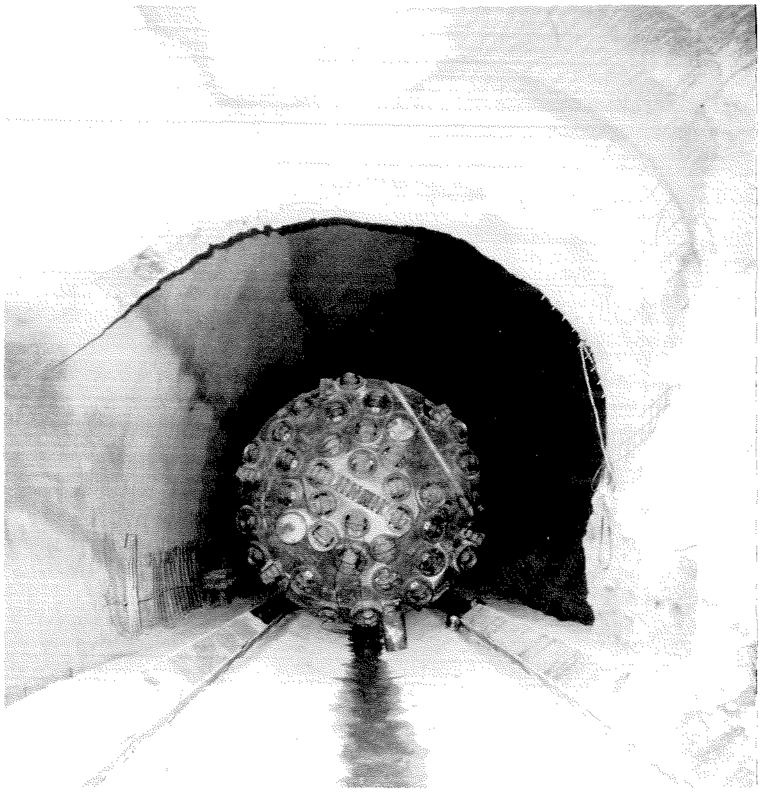
A particle moving through an RF cavity (left) and its RF field (right). The field gives the particle a boost with each chamber.

LEP's steering magnet design is another first. The magnets don't have to be very



RF cavity assemblies with storage spheres.

powerful, but they must be absolutely rigid to keep the particle beam properly aligned. The designers substituted concrete for the metal core used in conventional electromagnets. The result is an electromagnet with thin metal stampings embedded in concrete, with the concrete making up most of the structure. "The concrete magnets turned out to be very rigid, with very good geometric integrity," Newman said. "We saved over 50 percent of the cost of normal magnets."



The tunneler's cutting head. The machine bores a hole 4 meters in diameter.

Most of the ring's site has already been excavated by a tunneling machine. The machine clawed a 4-meter borehole through the local sandstone at up to 60 meters per day. Preliminary designs had a good portion of the ring under the mountains, but test borings soon revealed that the limestone there was more than a match for the tunneler. The designers were reluctant to make the ring smaller because of the synchrotron radiation problem. They couldn't put the ring under downtown Geneva or the lake, either. They wound up setting the ring on a 1.5 percent grade in order to shoehorn it between the lake and the mountains. A portion of the ring still passes under the mountains' periphery. As of December, 1987, the ring has been completely excavated except for 80 meters in a dense limestone formation, where the work proceeds by pick, shovel, and explosives.

In the meantime, the experimental halls have been excavated, and work proceeds on the magnets, detectors, and computers needed to make it all work. All the magnets have been built and are on-site. Detector components are being built around the world. Some portions are already in the final assembly and testing stage on-site. LEP3NET, an international computer network, is up and running. Administered by Caltech, LEP3NET connects American and European research centers with the first transatlantic data communications link dedicated to high-energy physics. Physicists worldwide are contributing control and analysis programming.

The LEP ring will host four experiments, ALEPH, DELPHI, L3, and OPAL. The Caltech group is part of the L3 project. While the other three experiments' names are acronyms generated by applying intense heat and pressure to a phrase describing the experiment, "L3" simply means this experiment was the third proposal submitted to run on the LEP ring.

"The L3 experiment is designed to emphasize very-high-resolution energy and momentum measurements of photons, electrons, and muons," Newman said. "We are aiming for resolutions of 1 percent at 50 GeV.

"We will make very precise measurements of the electroweak theory. LEP collides electrons and positrons in a very small energy spread, so in just a few days' running you can get a very precise mass for the Z^0. The experiment is so precise, it's a bit of a theoretical challenge. You have to do third-order calculations in order to obtain theoretical predictions as good as the experimental precision. The Z^0 mass is the most precise quantity that can be measured. It will serve as the refer-

MUON PAIR ASYMMETRY

Muon pair asymmetry is a consequence of the weak force, which is responsible for neutron decay, among other things. Weak interactions do not conserve parity, which has profound mathematical consequences. On the observable level, it means that particles formed in weak force reactions tend to be ejected in certain directions relative to an external magnetic field. If parity were conserved, muons of a given electric charge would have equal probability of being ejected "forward" or "backward" relative to one of the incoming beams. The electroweak theory predicts the degree of asymmetry that should be observed at a given energy.

ence point for further tests of the theory.

"We can then measure something else against that: the asymmetry of muon pair production. We will run for 200 days and collect about 6,000,000 Z^0s. Of these, 200,000 produce muon pairs. Then we can measure the asymmetry with a statistical accuracy of 0.2 percent.

"If the top quark has a mass of 180 GeV, it will affect the asymmetry by 0.8 percent, so that's detectable at our experimental accuracy of 0.2 percent. As the particles get heavier, they have a greater effect on the symmetry. But if the top quark gets too massive, when you go back to the low-energy experiments that have been done and reinterpret them in order from low energy to high energy, putting in corrections for the mass of the top quark, the experiments no longer agree with each other. If the mass gets very large—like 400 GeV, 450 times the mass of the proton—the whole self-consistent picture of the unified electroweak theory that occurs for a more reasonable top quark mass falls apart.

"After we study the Z^0, we'll go on to higher energies. One of the best ways to see the Higgs is to look for certain rare events. For example, at 165 GeV, electrons and positrons can collide to make a Z^0 and a Higgs. The Z^0 goes to a muon pair, which you detect, and by precise measurements of the muons you can measure the mass of the Higgs recoiling against that pair. This probably will require two years of continuous running at 4,000 hours per year, from which we may get twenty events. (This depends on the mass of the Higgs, and—of course—on its existence!)"

The cavernous L3 experiment hall lies 50 meters below the French countryside. That hall is the shallowest of the four; the hall under the foothills of the Jura Mountains is a vertiginous 150 meters (approximately 500 feet) below ground. ("It doesn't sound like much," Newman said, "but when you look down this hole 500 feet deep, it's a long way down. And people had to go up and down stairs. The elevators have only recently come into service.")

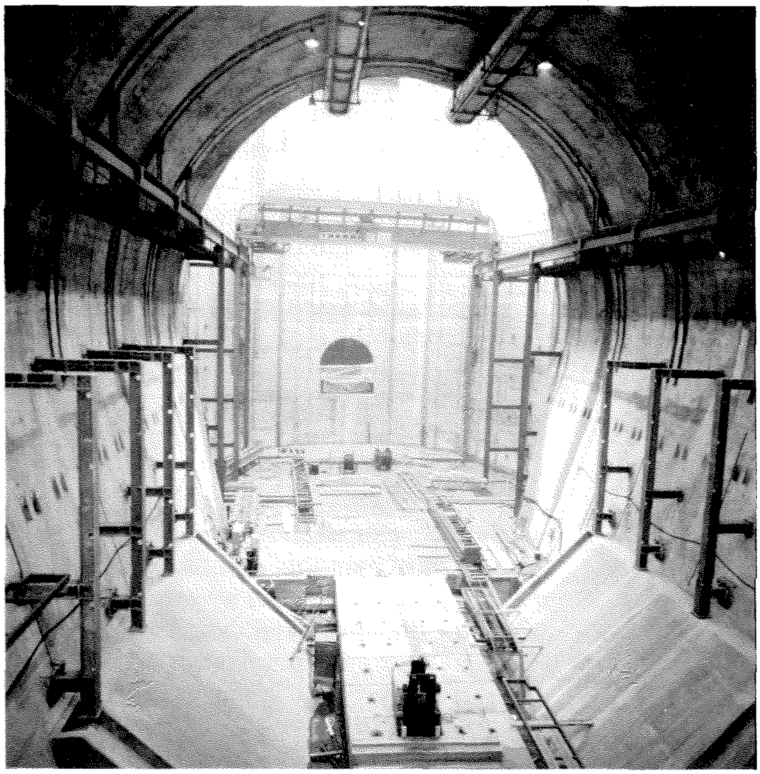
L3's massive detector assembly, bigger than a two-story house, almost fills the hall's 21.4 m diameter by 30.5 m length. The detector components must be lowered piecemeal down an access shaft, to be reassembled below. A crane traveling on rails high under the vaulted roof wrestles components weighing tons into positions accurate to fractions of a millimeter. Some components require an 800-ton crane at the surface to lower them down the shaft. There are only two cranes that big in all Europe, one of which will soon visit CERN. These cranes are itinerant specialists, always on the move from job to job.

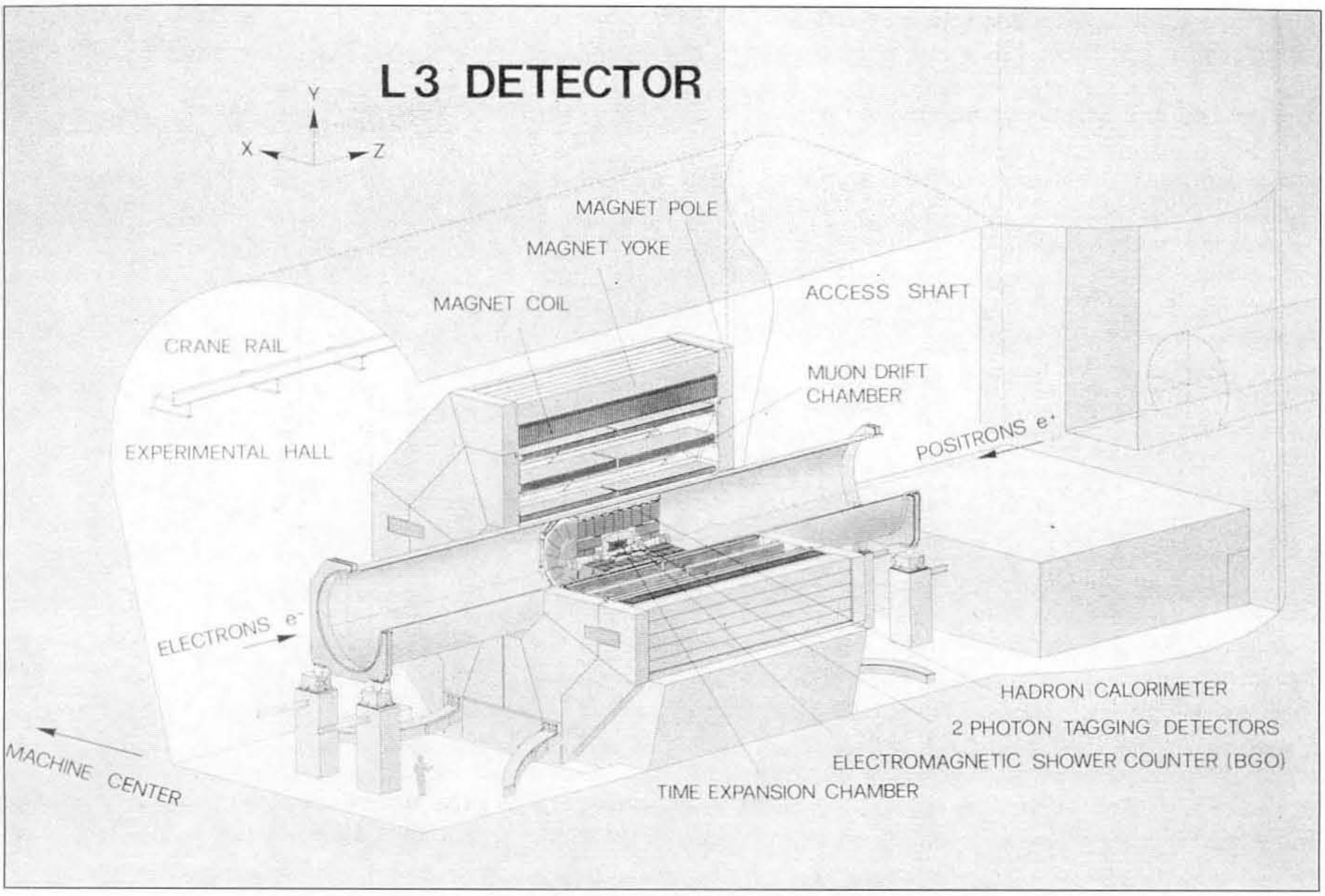
The detector assembly contains four different detectors nested around the collision point like Russian puzzle dolls. Each detector completely surrounds the beamline, so only particles leaving at very small angles, and the elusive neutrinos, will escape undetected. (All particles must be accounted for to balance the mass-energy books. If the books are too far out of balance, it can indicate that new, unpredicted particles are being formed.) The time expansion chamber (TEC) is innermost, surrounded by the electromagnetic calorimeter, the hadron calorimeter, and the muon drift chamber.

A gargantuan electromagnet surrounds the detectors. This electromagnet, the largest ever built, provides the powerful magnetic field needed to separate particles by their charge/mass ratio. The electromagnet weighs 7,600 tons. It creates a magnetic field 5,000 gauss strong, constant over a volume of 1300 cubic meters.

The TEC, according to Newman, is "a very-high-precision detector for tracking the trajectories of charged particles and measuring their momentum. It measures all the

The L3 experiment hall, looking toward the access shaft. Note the forklift in the foreground for scale.





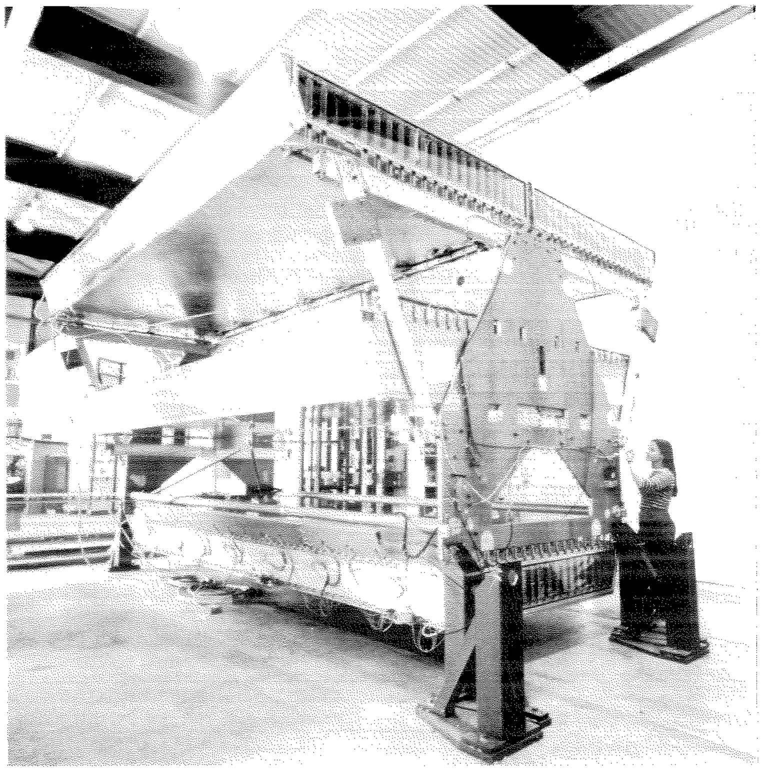
charges within 10 microseconds after an e^+e^- collision, and its hardware integrates them into particle tracks in real time." Further analysis determines how the magnetic field has deflected the particle. The direction shows whether the particle has a positive or negative charge, and the curvature gives the charge-to-mass ratio. The combination reveals the particle's identity.

The particles pass through the TEC and into the electromagnetic calorimeter. The "calorimeter" doesn't actually measure heat. It's a scintillation counter on a grand scale. A barrel-shaped array of 12,000 bismuth germanate (BGO) crystals detects photons, electrons, and positrons. A single photon penetrating the crystal dissociates into an electron-positron pair. Each particle interacts with the crystal to produce photons, creating additional electron-positron pairs. The resulting avalanche of electrons and positrons produces a lot of light that eventually reaches a photodiode on the crystal's rear surface, where the photons signal their arrival with an electrical pulse. The amount of light produced is proportional to the energy deposited in that particular crystal.

The hadron calorimeter doesn't detect heat, either. It intercepts protons, neutrons, mesons, and hyperons, all comparatively massive particles that interact with heavy nuclei. It also absorbs the small part of the electromagnetic "cascade"—electrons, positrons, and especially photons—that may slip past the BGO crystals. The densely packed nuclei in the calorimeter's 600 tons of depleted uranium—^{238}U from which all ^{235}U has been removed—are so many sitting ducks for the hadrons from the collision zone. A particle will probably ricochet off a nucleus as it passes through the detector. The particle will change direction and lose some kinetic energy with each collision. It will also produce new particles, which may interact in turn, forming a cascade of particles. Approximately 60 concentric sets of 5-millimeter-thick uranium plates alternate with parallel tubes containing a mixture of 80 percent argon and 20 percent carbon dioxide. As a particle zips through a tube, it ionizes the gas and generates a signal on a detector wire. Computer analysis of signals from successive layers of tubes helps recreate the particle's path. A particle's track length is proportional to its initial energy, which can then be deduced. The modules are being built in Michigan, Aachen, Bombay, and Beijing, with production scheduled to be completed in December 1987.

Muons, having only about one-tenth the mass of hadrons, and being immune to the blandishments of the strong nuclear force, whizz unscathed through the hadron calorimeter and into the muon drift chamber. This is actually three concentric sets of chambers. Each chamber is a long, flat box made of thin aluminum sheets. The boxes contain a total of 116 kilograms of argon and ethane. Again, as the muons pass through the gas, they leave ionized trails that are detected on a three-dimensional wire array. The innermost box has 16 wire layers perpendicular to the particle's path. The center box has 24 layers, and the outer box has 16. Each particle thus leaves a trail of 56 data points. Optically flat glass sheets keep the wires in perfect alignment down to 10-micron tolerances. The entire drift chamber system is dynamically stabilized to the same tolerance. "With the very-high-energy particles we'll be looking at, high precision is critical," Newman explained. "For example, with a 45-GeV muon the deviation from a straight line, by which you can measure the momentum, is only 4 millimeters in 6 meters. We want to reach 1 percent accuracy for the muon pair's mass reconstruction, which means 1.5 percent for each muon. To do this, we need to measure the deviation from a straight line to the order of 50 microns. The total systematic error, i. e., the total error in the computer's knowledge of the location of the detector wires in space at any instant, has to be less than 30 microns." The muon chambers will be assembled into 16 "half-octants" of five chambers each. Most of the octants have already been built and tested at CERN.

The data from the TEC, the BGO array, the hadron calorimeter, and the muon drift chambers go through a massive on-line parallel processing system. The computer has a complete picture of the detector arrays in its memory. Each component's location and orientation in space is known to a precision dictated by the physics, which in some cases is within 10 microns. The system takes all the signals from all the detectors, over 100,000 channels of data, and integrates them into a three-dimensional "picture" of all the particle tracks. Some of the computational power goes into deciding what particles came from uninteresting events, and discarding them before too much computational time or storage space is wasted on them. These decisions must be made in real time while the detector is running. Soon after, LEPICS, an off-line computer at CERN, sifts through the stored particle tracks, identifies the particles, and winnows out those combinations that could not have been produced by the particles or decay modes of interest. The off-line analysis can take many months to complete. Thanks to LEP3NET, the analysis can be coordinated among participating institutions, and some computer work can be done locally.



Muon drift chamber "half-octant" assembly. The two upper rows have two chambers each.

Most projects at CERN are international collaborations, and the L3 experiment is the largest and most widespread. Four hundred physicists from forty institutions in thirteen countries are contributing to the project. The list of American participants includes Caltech, Carnegie-Mellon, Harvard, the University of Hawaii, Johns Hopkins, M.I.T., the University of Michigan, Northeastern, Ohio State, the University of Oklahoma, Princeton, Rutgers, and Yale. Other contributors include groups from China, France, East and West Germany, Hungary, India, Italy, the Netherlands, Spain, Sweden, Switzerland, and the Soviet Union.

L3's Caltech contingent numbers only one associate professor, one senior research fellow, two postdocs, and assorted undergraduates. Yet this small group has been responsible for key elements of the basic design of the muon drift chamber; for developing LEPICS; for developing and operating LEP3NET; and for developing a calibration technique for the BGO crystals used in the electromagnetic calorimeter.

The BGO subproject preserves the international flavor of the whole. The USSR supplied some of the raw materials. The Shanghai Institute of Ceramics is making the crystals. France provided the technology to cut, grind, and polish the crystals to tolerances of 100 μ in 24 cm. West Germany furnished the photodiodes. An Italian firm specializing in helicopter rotors built the supporting barrel. Caltech is calibrating test arrays of 20 and 49 crystals.

Each BGO crystal is a long, thin, truncated pyramid. The crystal's front face is 2 × 2 cm. The back face, where the photodiode is mounted, is 3 × 3 cm, and the crystals are 24 cm long. When the crystals are assembled into a barrel, their tapered shapes aim their long axes at the barrel's center—the collision point.

Besides having the requisite transparency and scintillation properties, BGO is quite dense, almost as dense as iron. The heavier the atoms in a material, the more likely incoming particles are to interact with its nuclei. The crystals are long enough to absorb 99 percent of the energy from an electromagnetic cascade produced by incoming high-energy electrons, positrons, or photons.

Unfortunately, great density also means great weight. Each crystal weighs a kilogram. But the supporting structure between crystals must be as thin as possible to minimize the odds of any particle from a cascade missing the crystals. The support must also be very rigid to keep the crystals aligned accurately. The final design uses a lightweight grid of molded carbon fibers. The grid is only 0.2 mm thick between crystals. The grid weighs a mere 400 kg, yet it supports ten tons of crystals.

The BGO crystal array is designed to measure energies in the neighborhood of 100 GeV with a precision of 0.5 percent. The array will require frequent calibration while in use to maintain such high resolution. The Caltech group developed a calibration method using a Radiofrequency Quadrupole (RFQ) proton accelerator.

The RFQ would be installed underneath the LEP ring. An angled beamline would connect the RFQ to a lithium target in the collision zone. The RFQ would bombard the target with high-energy hydrogen atoms, producing a high-intensity flux of 17-MeV photons. The crystals' response can be calibrated to the photon's known energy. The entire system, including the vacuum line carrying the hydrogen beam, is completely independent of the LEP ring.

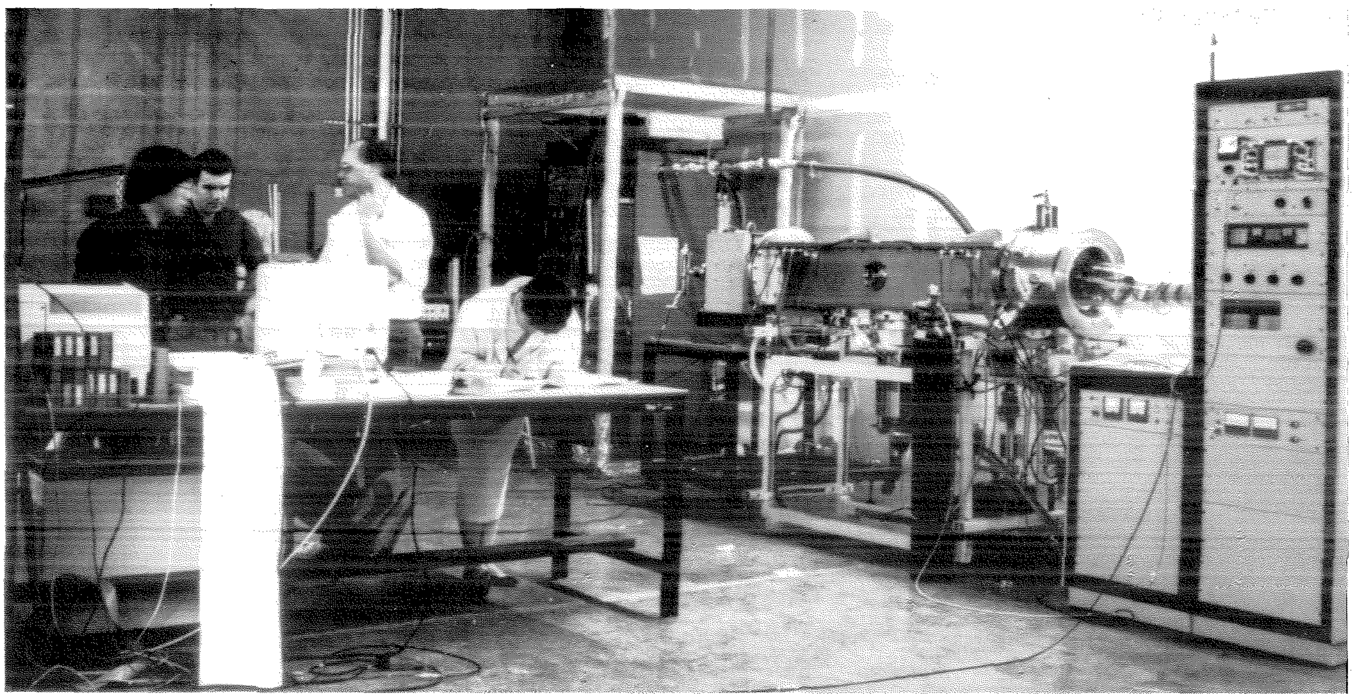
The system can operate between runs, or even while the LEP is running. The RFQ's electronics will be strobed to an external trigger. The RFQ will emit a high-intensity pulse, one to three microseconds long. The intensity must be carefully controlled: high enough that photons hit an appreciable number of crystals, yet not so high that two photons hit the same crystal. The pulse length is no less important—it must be short enough for the crystals' response to be measured accurately, and for the detector's electronics to work with a high ratio of signal to electronic noise. A single pulse calibrates only 200 to 300 of the 12,000 crystals, but at 200 pulses per second the entire array can be calibrated in an hour or two. Although RFQs running at low pulse rates have been used as proton sources in the first, or preinjector, stages of high-energy proton accelerators, no one had ever attempted to run one at 200 Hz *within* a physics experiment before.

The Caltech group tested their idea on a 20-crystal array in the first week of November 1987. They had originally planned to do it at the Los Alamos National Laboratory, but it seems international cooperation only goes so far. Graduate students Hong Ma and Renyuan Zhu, who designed the calibration setup and built the readout system, were denied security clearances. Both are from mainland China. So they wound up at a commercial RFQ manufacturer, AccSys, Inc., of Pleasanton, California, instead.

Since the calibration occurs while the experiment is running, the lithium target cannot be set up at the collision point. With an offset target, though, some photons would hit crystals at angles of up to 55° from the long axis. The test showed that good results can still be attained at 60°. Thus the entire barrel can be calibrated from a single location.

The experimenters also let the system pulse continuously for two days at an intensity equivalent to a couple of weeks' running in the LEP ring. The system proved quite stable.

Although the test was successful, the experiment hit one not-unexpected glitch. The unshielded RF source generated a power-



H. Ma, R. Mount, H. Newman and an AccSys employee (l. to r.) testing the BGO calibration system (along right-hand wall, from left:) RF source (in wood and wire enclosure), RFQ accelerator (on white cart—BGO array [not shown] would go at left end), detector electronics. The RF conduit emerges near the top of the enclosure and passes down behind the RFQ.

ful field that interfered with the detector's sensitive electronics. (This shouldn't happen at LEP, where the entire RF system will be well shielded, and the RFQ will be much farther away from the controls.) Unfazed, the team slapped an RF shield together from wood slats, chicken wire, and generous swatches of aluminum foil. This four-hour exercise in low technology reduced the RF interference tenfold. They gained another tenfold reduction by moving the RFQ away from the rest of the system. This was no mean feat—the RFQ weighs about 800 pounds. Six people and a one-ton hoist were needed to push it across the floor. Furthermore, the vacuum system had to be opened to the air while the team inserted a ten-foot extension into the RF conduit. The conduit itself is a two-inch copper pipe containing a smaller pipe held in alignment by teflon spacers. The system acts as a high-power coaxial cable, carrying the RF power to the RFQ accelerator.

Even before the calibration test was arranged, BGO crystal production entered high gear. As these are the largest BGO crystals ever made, early production runs were by trial and error. The system is up to speed now, with more than 100 people working around the clock to produce 420 finished crystals every month. The first half-barrel of 4,000 crystals has been shipped to CERN, where it was set up and precalibrated in July through August, 1987. Crystal production for the second half-barrel will be finished by early 1988, and production of the two end caps (of 2,000 crystals each) will then begin. Overall, it will take another year and a half at current production rates to finish the assembly.

And so it goes. There's still a lot to be done before L3 is up and running. The chief French mechanical engineer said it best. With elegant calligraphy, he painted an old Chinese proverb on the finished half-barrel's housing. Roughly translated, it says, "In a journey of 100 miles, 90 miles is halfway."

Will the results be worth the wait? Newman is confident. "We've been searching for the last ten years for the top quark. My last experiment was actually built to find the top quark, and in eight years of running we didn't find it. With L3, we have achieved very ambitious technological goals in electron, muon, and photon resolution. We have to be rather unlucky, or nature has to be almost perverse, for us not to see the top quark. If the standard theory is working, the top quark should be in the LEP range. And if we don't see the top quark, the self-consistency of the unified electroweak theory will be in jeopardy. Either way, we will have a new, exciting situation for the experimenters and for the theorists."□—*DS*

Newman will give the Caltech Associates President's Circle a two-day tour of CERN and L3 this May. The President's Circle will tour Europe May 3 through May 12.

Remembrances of Kurt Gödel

by Olga Taussky-Todd

This article is adapted from a talk given in Salzburg in July 1983. The remarks on the occasion were collected in a book, "Gödel Remembered," published last summer by Bibliopolis, Naples, Italy. The American distributor is Humanities Press International, Inc., Atlantic Highlands, New Jersey.

IT WAS MORITZ SCHLICK'S seminar on the philosophy of mathematics that put me in contact with Kurt Gödel in my first year (1925) at the University of Vienna. In this seminar we studied Bertrand Russell's book, *Introduction to Mathematical Philosophy*, in German translation. In the first meeting of this seminar the subject of axioms was discussed, in particular the axioms for number theory and the axioms of geometry. In the second meeting I dared to ask a question, namely about a connection between the two systems of axioms. This led, unexpectedly, to a long discussion between participants who enjoyed making lengthy speeches. Schlick never said a word, and I myself was unable to follow much of it. At the end of the meeting Schlick asked who would like to report on the seminar. Nobody replied. Then Schlick asked: "Who *will* report on this seminar?" Then Gödel volunteered. He started with the words: "Last week somebody asked the following question. . . ." He did not know my name, of course. However, from then on I was at least "somebody" for Gödel.

Although Gödel's home was in the mathematics seminar, although he was to become a student of Hahn's, although he was not a member of the Vienna Circle (*Wiener Kreis*), he was nevertheless an offspring of the Vienna Circle to which Hahn, Menger, Carnap, Waissman, and others belonged. The Vienna Circle was a group created by Schlick and concerned, if I understand it correctly, with the development of a language for science and mathematics. The time was ripe for such a creation in the late 1920s, because the necessity of testing the foundation of mathematical thinking, the methods of proofs, the axioms, the rules, had become pressing. It was a time of *Sturm und Drang* in mathematics. Wittgenstein was the idol of this group. I never actually saw him there, but I can testify to the fact that any argument could be settled by citing his *Tractatus*.

In spite of my admiration for Schlick, I myself left his seminar and even his private circle, to which I had been admitted. I was the youngest in age in the Vienna Circle, but I was disappointed that these gatherings could not give me guidance for my work in number theory. Had I realized what Gödel would achieve later, I would not have run away. For Gödel's results show that logic is not a subject that stands alone and is a *basis* for mathematical thinking; it is in fact *part* of mathematics.

Gödel and I were both born in Moravia, then a part of the Austro-Hungarian empire and now in Czechoslovakia. Gödel's birthplace was Brno (Brünn) and mine, Olomouc (Olmütz). Gödel's family had moved to Vienna in 1923, while my family had already gone there in 1909, then later to Linz, then back to Vienna. Gödel entered the University of Vienna in 1923. Among our teachers were the number theoretician Philip Furtwängler, Hans Hahn, Wilhelm Wirtinger (an expert on algebraic functions), Karl Menger, Walter Mayer (who became Einstein's assistant), Lense, Helly, and Vietoris (who is considered the founder of algebraic topology).

Furtwängler, under whom I wrote my thesis, had earned recognition through his early work in geodesy—I suppose during World War I. Later he emerged as the man who proved, and disproved, David Hilbert's conjectures in class field theory. He was self-taught and not, as is usually assumed, Hilbert's student; in fact, the two men never met. His first appointments were in his native Germany. He finally had an offer from Vienna, as successor to Mertens. It was only through the Royal Society obituary notice by G. Kreisel that I learned that Furtwängler's course on class field theory almost lured Gödel into this subject. How class theory could have profited from a man like Gödel! However, elementary number theory was an essential ingredient in Gödel's work.

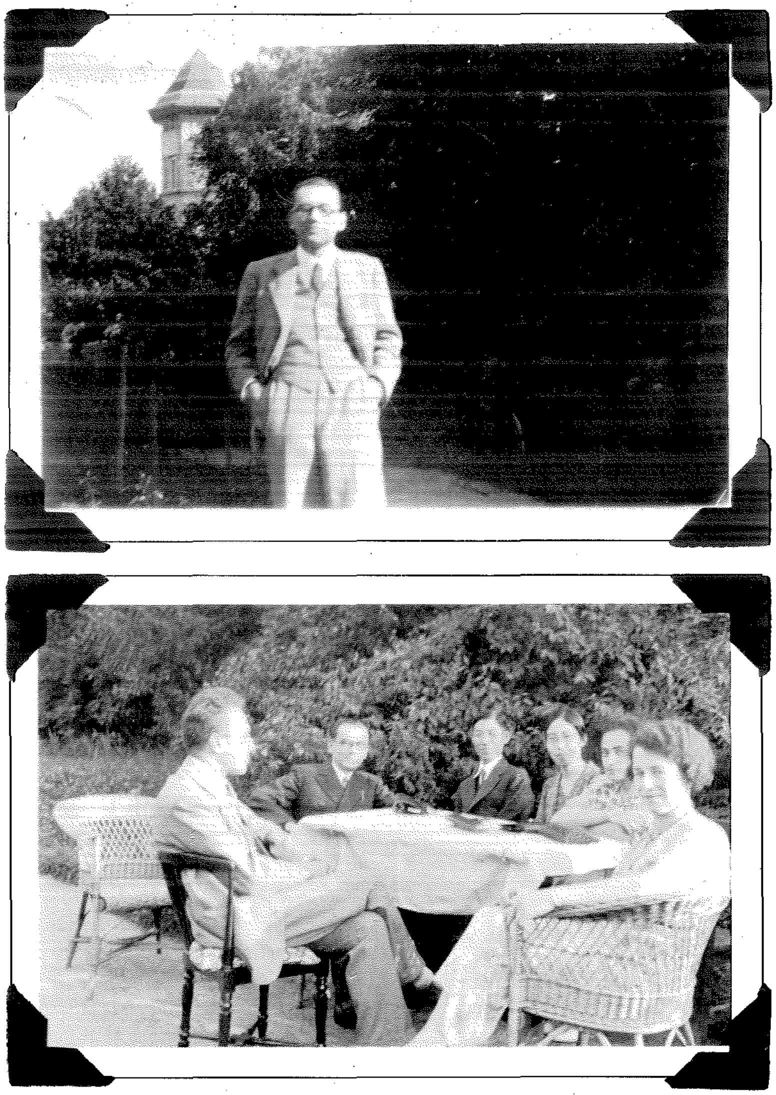
Hans Hahn was professor of geometry in the widest sense. He was also politically active for the socialist party, he wrote many papers in mathematics, he was a member of the Vienna Circle, and he was very interested in logic. But he was also an ardent follower of ESP. I myself attended one of his lectures on this subject when he fended off people who asked doubting questions. He was extremely averse to fakes who harmed the relevant research. Since Gödel was Hahn's student and had apparently similar inclinations himself, there may have been conversations between the two men in this connection. But I don't know this for certain.

Hahn had done a great deal of work in pure mathematics. He had started off as a young man in a university position in Poland and was attached to the topology school there, but his contributions were in other branches of mathematics too. I was Hahn's assistant in my last year in Vienna (1933/34), which was also Hahn's last year of life. He was already very ill, and I practically supervised a PhD thesis for which he was the official supervisor. This thesis concerned sequence spaces and used earlier papers of his that were based on work by Helly. He made no secret of this and, in fact, he asked me to be sure to cite Helly when I gave a lecture about the results of that thesis. It was through Hahn, who recommended me to Courant at Göttingen, that I later captured a prestigious temporary appointment there,

Left: Kurt Gödel

Far left: Olga Taussky in Göttingen in the early 1930s.

Below: Taussky, at left, as Hans Hahn's assistant, in a seminar in Vienna. Hahn is seated next to her.



At the Taussky home in Vienna: Above, Gödel; and below, a tea attended by Karl Menger (left), next to Gödel. Taussky is second from right.

helping with the edition of Hilbert's papers in number theory.

I know nothing about Hahn's work in logic, but he was Gödel's thesis man, and I expect he was highly competent. I was present at a lecture on logic that he gave to an audience of nonexperts. There he stressed the fact that mathematical work was nothing but a set of tautologies. This made me unhappy, for I am a devoted number theoretician. My feelings were expressed in one of my poems by the words, "Number theory is greater than what comes later in the strict athletics of mathematics" (Primary Press, 1979).

During our student years it slowly became obvious that Gödel would stick with logic, that he was to be Hahn's student and not Schlick's, and that he was incredibly talented. His help was much in demand. One day I told him of my new system of axioms for groups. He re-proved its validity immediately. Menger asked him to study one of my papers. He saw immediately that there was only one case of the discussion that could lead to difficulties. He seemed a rather silent man, but he offered his help whenever it was needed.

Austria was not a very prosperous country in those days, so the mathematical seminar enriched its library by publishing the journal *Monatshefte.* The seminar members thus had a lively exchange with the publishers of other mathematical journals in many countries. In addition, by including reviews of books, which the local reviewers had to return to the library, they acquired many books. Gödel took on a number of these reviews. In addition, he was an editor of Menger's journal *Ergebnisse eines Kolloquiums.*

I was working on my dissertation at this time. Shortly before I received my doctorate, my family moved back to Vienna. I was then allowed to invite colleagues to tea. Gödel enjoyed these invitations, but he was always very silent. I have the impression that he enjoyed lively people but didn't like to contribute to nonmathematical conversations himself. On the whole these tea parties were for colleagues of my own age group, or for visitors to Vienna whom I had met and whose work was not unfamiliar to me. They were either class field experts such as Iyanaga from Japan (a student of Takagi) or attached to Menger's school. Menger himself came too. There was also Midutani, a statistician, but I do not know how he came to join Menger's group. But, as usual, I was asked to check his work. Most visitors came on sabbatical from the U.S., or from Japan.

I did not realize that Gödel, who clearly seemed to enjoy himself, felt superior to this circle, as in fact he was. He somehow heard that I had invited Hahn and the great Takagi, on his visit to Vienna after the Zurich conference, to meet my family, and he remarked that I counted him among the *minores gentium.* This is a medical term for doctors not of the highest standing, who of course could not command the highest fees. (In Austria doctors still conversed in some sort of medieval Latin slang, partly to prevent patients from understanding them.)

There is no doubt that Gödel had a liking for members of the opposite sex, and he made no secret about this fact. Let me tell a little anecdote. I was working in the small seminar room outside the library in the mathematical seminar. The door opened, and a very small, very young girl entered.

She was good-looking, with a slightly gloomy face (maybe timidity), and wore a beautiful, quite unusual, summer dress. Not much later Kurt entered, and she got up and the two of them left together. It seemed a clear show-off on Kurt's part.

That same girl changed quite a bit later; maybe she became a student. She came to talk to me occasionally, and she complained about Kurt being so spoiled—having to sleep long in the morning and similar items. Apparently she was interested in him and wanted him to give up his prima donna habits. Quite a bit later she handed a paper to Professor Menger, something on topological spaces. Early on in my life many people have handed chores over to me, chores of all sorts. This is still the case, and I still do not know what to do about it. Hence, Menger asked me to check her work. It really was not in my line. The best I could do was to sit down with the girl and read it with her, making her explain it to me. It appeared soon that she was unable to do so but was truly grateful to have somebody to talk to about it. It also appeared that she wanted to show Kurt that she could do something.

Gödel was well trained in all branches of mathematics, and you could talk to him about any problem and receive an excellent response. If you had a particular problem in mind, he would start by writing it down in symbols. He spoke slowly and very calmly, and his mind was very clear. But you could talk to him about other things too and his clear mind made this a rare pleasure. I understand that Einstein had many conversations with him.

In due course I heard that Gödel's 1929 dissertation, *"Über die Vollständigkeit des Logikkalküls* (On the completeness of the calculus of logic)" was an extremely important achievement and that Schlick was very much impressed with Gödel's philosophicum—the one-hour examination in philosophy, which forms part of the D.Phil. examination. He achieved the position of *Privatdozent* (so-called *Habilitation*) at a very early date with a paper called *"Formal unentscheidbare Sätze* (Formally undecidable statements)." Gödel gave me copies of his first two fundamental publications. Unfortunately, I lent them to a colleague, from whom I could not extract them later. From the well-known Austrian mathematical historian Auguste Dick I learned that Hahn had written in his recommendation, *". . .Eine Lösung ersten Ranges, die in allen Fachkreisen grösstes Aufsehen erregte und—wie sich mit Sicherheit voraussehen lässt—ihren Platz in der Geschichte der Mathematik einnehmen wird."* (". . .A solution of the top rank, which provoked the greatest respect in all mathematical circles and, as can be confidently predicted, will take its place in the history of mathematics.") This did in fact happen and shows Hahn's correct appreciation. By 1931 he had already achieved worldwide fame, only a year after receiving his doctorate. He had proved the existence of undecidable mathematical statements and had given a shock to the world of logicians and mathematicians. But he had achieved even more: he had shown something that any person with a minimum of background can understand. This is a very important accomplishment in my opinion. Gödel achieved many other results, perhaps just as important, but this is the one mainly associated with his name.

I saw Gödel in 1931 at the conference of the German Mathematicians Association in Bad Elster. It was there that he met Ernst Zermelo. I think that perhaps no other person is alive who remembers this event. I had good reason to know about it, for I worked then with the number theoretician Arnold Scholz, who was a great class field theory expert. Both Scholz and Zermelo worked in Freiburg. Scholz was eager to help Zermelo and thought a discussion with Gödel would achieve this. But Zermelo was a very irascible person. He had suffered a nervous breakdown and felt ill-treated, but had actually recovered at that time. He had no wish to meet Gödel. A small group suggested lunch at the top of a nearby hill, which involved a mild climb, with the idea that Zermelo

Ernst Zermelo at Bad Elster.

should talk to Gödel. Zermelo did not want to do so and made excuses: he did not like Gödel's looks (he actually had not met him); the climb was too much for him; there would not be enough food if Gödel came along too. When Gödel joined the group, however, the two immediately started discussing logic, and Zermelo never noticed that he had made the climb.

The peaceful meeting between Zermelo and Gödel in Bad Elster was not the start of a scientific friendship between two logicians. The trouble with Zermelo was that he felt he had already achieved Gödel's most admired result himself. Scholz seemed to think that this was in fact the case, but Zermelo had not announced it and perhaps would never have done so. It is not impossible that others too had some of Gödel's results. However, it seems to me that it needs an energetic person to take over and, with full knowledge of the work that is in the air, give creative guidance for the future. I doubt that Zermelo was such a person.

Gödel suffered not infrequently from severe mental breakdowns. I do not know whether they were caused by the overstrain he suffered through the creative processes he made his brain carry out or whether they were just in his makeup. Auguste Dick has supplied me with an amusing remark by Furtwängler concerning Gödel's result when the latter had one of his paranoia attacks: "Is his illness a consequence of proving the nonprovability or is his illness necessary for such an occupation?" I felt honored when his older brother Rudolf, a medical doctor, discussed his anxiety about Kurt with me when I tried to telephone Kurt during one of these attacks. In addition Kurt had some physical ailments. But he did not spare himself—a trait already noticeable in his performance in the Schlick seminar when I first met him. He was convinced of the value of his ideas and wanted to make sure that they were known and appreciated.

The famous mathematician David Hilbert had, among other tremendous achievements, made a list in 1901 of the unsolved mathematical problems he considered the most important. By doing this he channeled mathematical research for a long time afterward. In particular, his first two problems concerned the foundations of mathematics. Although Hilbert's problems became the basis for Gödel's work, Gödel was critical of Hilbert's claims and aims. He spoke to me about this and lashed out against Hilbert's 1932 paper *"Tertium non datur,"* saying something like, "How can he write such a paper after what I have done?" (Gödel had already proven undecidability.)

Gödel's father died young, apparently leaving the family well provided for financially. But it was never clear to me whether Kurt was given his own share of the fortune then, or whether his mother received all of it. It is my guess that he did not earn a penny until his first invitation to Princeton. And then after that he presumably had no income until the second invitation. He then stayed in Vienna as an unpaid *Privatdozent* until he left Austria for good.

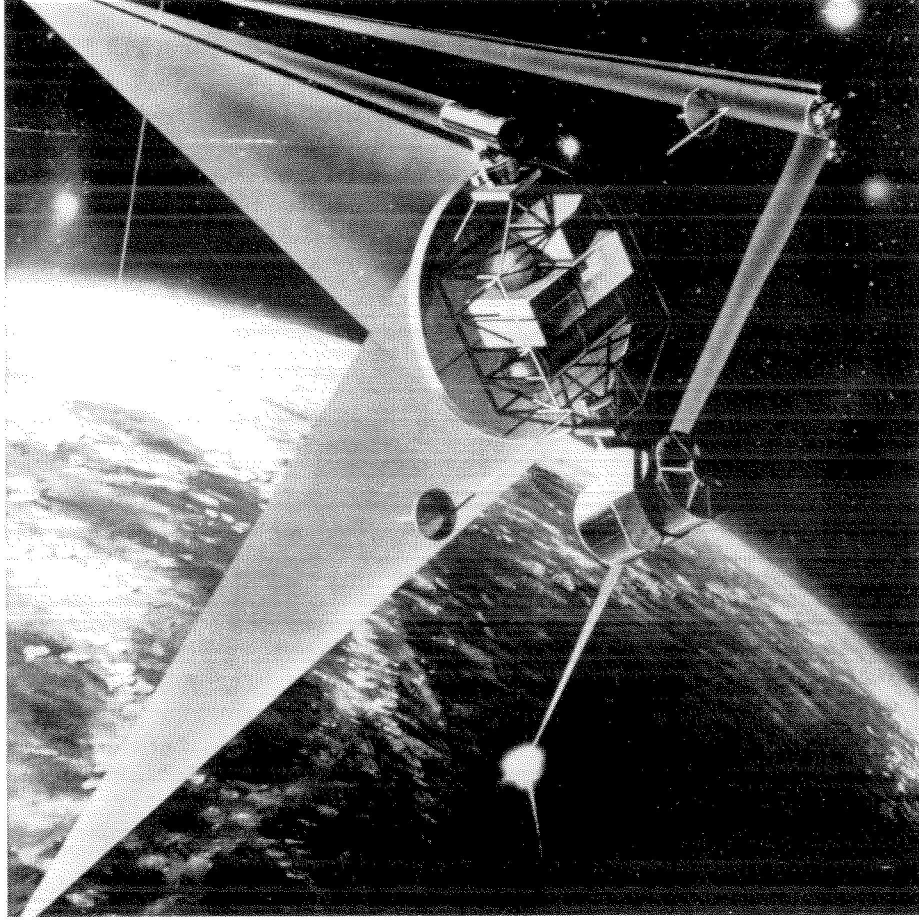
On Gödel's first visit to Princeton in 1933, several colleagues, including myself, went to see him off at the train station, where he boarded the Orient Express. Later he confided to me that this was not his actual departure from Vienna. He was taken ill before reaching his boat; he took his temperature and decided to return home. His family persuaded him to try again, however. I do not recall anything he told me about Princeton or about the United States apart from the fact that the steaks he ate were very small.

During his second stay in Princeton his health broke down. I heard about this in Cambridge about 1936 via a student of Miss Stebbing, a professor of logic in London, who had heard it from Schlick. Schlick was supposed to have been pessimistic about Gödel surviving much longer. I was truly upset when this was reported. (Gödel lived, however, until 1978.)

I saw Gödel and his wife again in 1948. Although I had not seen him since before the war, it seemed as though we had seen each other the day before. My husband, Jack, and I were staying at the Institute for Advanced Study in Princeton, attached to the von Neumann project and living in one of their little houses. (The war years had transformed us into numerical analysts, and Jack had close connections with von Neumann from when the latter had visited Great Britain.)

In 1948 Gödel had not yet obtained the title of professor. It is hard to believe. There was a time when Einstein's influence there was not strong, although I do not know whether Einstein tried to do something about Gödel's position. But Einstein had great friendship for Gödel.

In Princeton, as in the old times in Vienna, I invited Kurt to tea. □

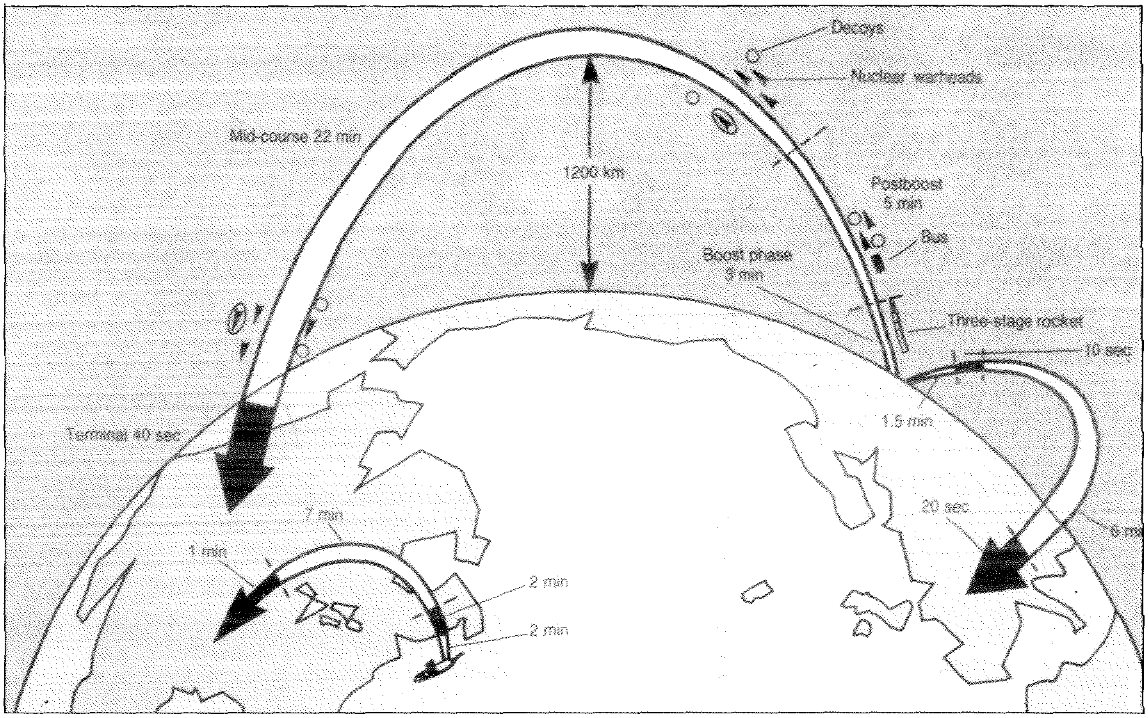


Star Wars Technology: Will It Work?

by Amnon Yariv

ON MARCH 23, 1983 President Reagan called upon the American people, and especially the technological community, to undertake a research and development effort with the goal of finding an alternative to the current policy of assuring national security through the threat of nuclear retaliation. The new defense system, which was meant to "render nuclear weapons obsolete," was organized under the control of the Strategic Defense Initiative Office (SDIO) whose mission was to accelerate and expand research in antiballistic missile defense. This organization and the program have come to be known popularly as Star Wars. Almost immediately following Reagan's speech an intense debate ensued, centered on ethical, political, and philosophical issues. What was missing, however, was an in-depth technological analysis of the feasibility of the proposed defense system.

So in November 1984 the American Physical Society constituted a committee



Of the three stages of an ICBM's trajectory, the missile is most vulnerable during the boost phase. Intercepting it during the post-boost phase may still be possible, but in mid-course it becomes immensely more difficult to stop.

of engineers, physicists, and chemists, whose charter was to study the technological aspects of Star Wars and report on them to the membership. The 17 members of the committee came from industry, academia, and the national government laboratories. Its funding came from private foundations, and it enjoyed the full cooperation of SDIO, as well as access to classified information. I was a member of that committee. But before I summarize the committee's findings, I'd like to set forth a primer on intercontinental ballistic missile (ICBM) technology and the defense strategies, mainly lasers, envisaged under Star Wars.

A missile under way from, say, the Soviet Union to the United States goes through three phases on its journey to re-entry. The first of these, the boost phase, takes the missile from rocket blast-off to an altitude of about 200 kilometers and lasts about three to four minutes. The burned-out stages of the rockets have been dropped by the end of this phase, and what is left in the post-boost phase is a big container called the bus, which is now moving at close to the orbital velocity of approximately seven kilometers per second.

The bus contains up to 10 warheads (MIRVs—multiple independently targeted re-entry vehicles), which it unloads during the post-boost phase one at a time, aiming each one at its specific target. At the same time the bus may also unload lightweight decoys. This stage lasts about five minutes. The independent warheads and the decoys make up the third and longest phase, the mid-course stage, which lasts about 20-22 minutes. The terminal stage, when these warheads re-enter the earth's atmosphere over the intended target, is very quick.

The missile is most vulnerable during the boost phase. During this phase the missile still includes the booster rockets, so the whole thing is very large—about 30 meters tall and close to 200 tons in weight. Because it's so large, it cannot be armored and is therefore relatively soft. It's also very hot, making it relatively easy to detect with infrared sensors. During the post-boost stage the bus is still relatively vulnerable but much less so than during the initial phase. Because it's no longer firing, it's much colder. In the third phase, however, intercepting the missile is immensely more difficult, because now in addition to the warheads there might be as many as 100,000 decoys moving with the speed of the warheads and, using currently available means, indistinguishable from them.

It is generally agreed that for a ballistic missile defense system to be most effective, it has to operate on the vulnerable boost phase and knock out the great majority of the missiles during that stage. Failing that, the missile could still be attacked with appreciably greater difficulty during the bus phase, when it is still a single target containing all the warheads. After that we may have to handle as many as 100,000 targets.

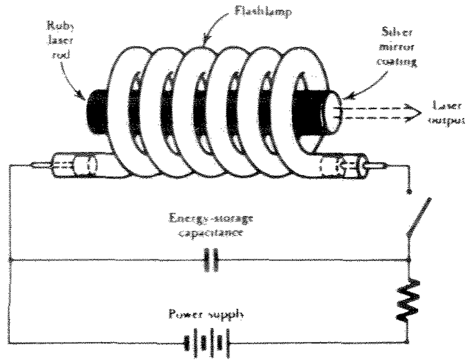
Today the Soviet arsenal consists mostly of SS-18 and SS-19 ICBMs. Altogether we assume that the Soviets have something like 1,400 missiles, each one capable of carrying six to eight MIRVs. So we are dealing with a total number of about 10,000 warheads potentially aimed at various targets in the United States or elsewhere.

Since we only have three or four minutes to destroy even the current Soviet missiles, which are relatively slow, during the boost phase, we need a weapon that can strike quickly. Nothing moves faster than light, so the main weapon proposed under Star Wars is the laser.

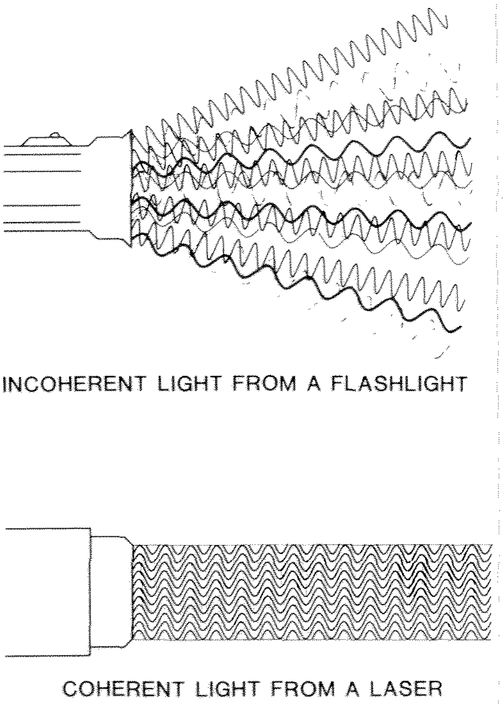
Other interesting approaches considered include charged and neutral atomic beams that move at close to the speed of light. These technologies are still very far behind the laser and are not effective in the atmosphere. We considered them less viable, although we still looked at them in great detail. The main reason for the choice of the laser, in addition to the speed of light, is the coherent nature of its light output, which in principle makes it possible to deliver the requisite level of light intensity across intercontinental distances and in many cases to penetrate the atmosphere.

The first laser was designed in 1961 by Ted Maiman at the Hughes Research Labs in Malibu and is shown schematically at right. It consisted of a helical flash lamp wound around a synthetic ruby rod, which is just aluminum oxide containing chromium ions. The end faces of the rod were polished and served as mirrors. These chromium ions are pumped by the surrounding helical flash lamp to excited states. A photon of the proper ruby frequency starts traveling between the mirrors and stimulates an excited chromium ion to make a downward transition. Now you have two photons of the same frequency. Another transition and you have three photons, and so on. So the light builds up and becomes more intense as it travels. When it hits the mirror, it turns around and comes back. In the meantime the atoms have been re-excited back to the upper state and the process continues. You end up with a very intense light beam bouncing back and forth between the two mirrors, and that's all a laser really is. What makes laser light different from the light from an ordinary light bulb is that, as the photons are forced back and forth by the mirrors, they organize themselves like soldiers marching in step. This gives a very tight wave and a single, pure color at a single wavelength, in contrast to a light bulb, which puts out light in all directions at different angles and different wavelengths. It spreads out, whereas the laser beam stays almost parallel and doesn't spread. But it turns out that the laser beam does spread just a very little bit, and this spreading limits what you can do with it in some cases.

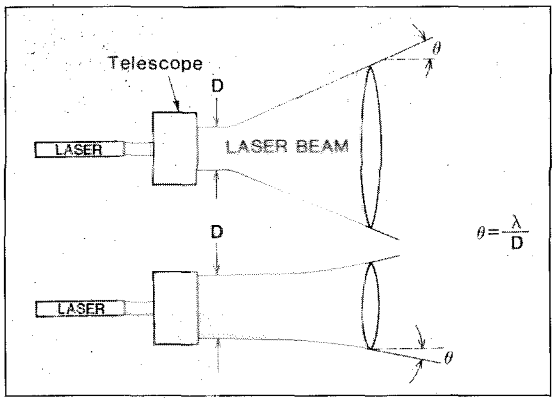
How much laser energy do we actually need for damaging a missile? We know how much power we can get from lasers, so the basic physics is very simple. The skin of a Soviet missile is usually made of aluminum, and it might have some ablative surface on it that would take more energy to burn through.



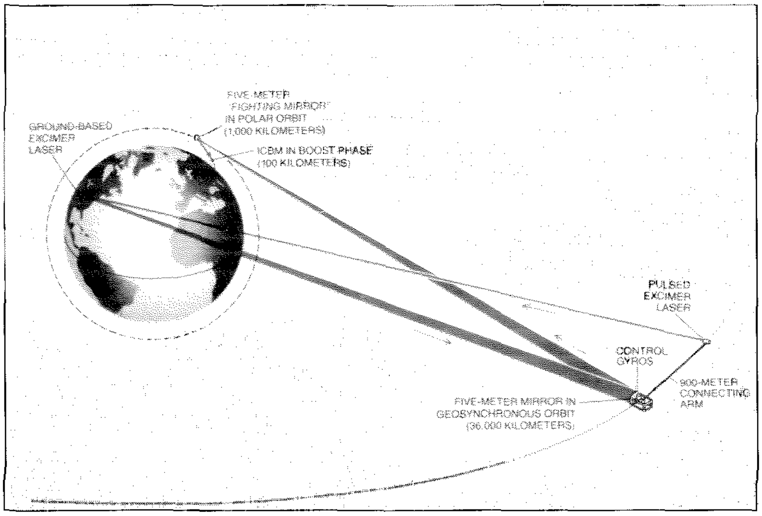
The first laser consisted of a helical flash lamp wound around a synthetic ruby rod containing chromium ions. Mirrors at the ends of the rod bounce photons (from the excited ions) back and forth, building up to an intense beam of light.



An ordinary flashlight produces light at different wavelengths and different angles spreading in all directions. Laser light is a tight, coherent beam at a single wavelength.



Diffraction of the laser beam can be decreased by a telescope. Because the spread angle is given by the wavelength over the diameter of the telescope mirror, the larger the mirror, the smaller the spread.



To decrease diffraction over long distances, a ground-based excimer laser (which produces an intense beam of ultraviolet radiation at a wavelength of .3 micrometers) could be beamed to a large mirror in geosynchronous orbit around the earth, and from there to a fighting mirror at lower orbit, which would focus it on the missile.

From "Space-based Ballistic-Missile Defense" by H. Bethe, R. Garwin, K. Gottfried, W. Kendall. © October 1984 by Scientific American, Inc. All rights reserved.

All we have to do is go to the lab and find out how much laser energy it will take to burn a hole in missile skin. This has, of course, been done, and it turns out to be roughly 30,000 watts per square centimeter of the target during an exposure of one second. But if you want to deliver concentrated light energy over long distances, you can't just point the laser at the target. Although a laser beam spreads very little in comparison to ordinary light, over 40,000 miles it spreads too much to be effective for burning a hole in anything. The requisite power of the laser for damaging a missile is given by

$$P_{laser} = \left(I_{lethal} \right) \pi R^2 \left(\frac{\lambda}{D} \right)^2$$

In this formula I_{lethal} stands for the intensity (watts/cm^2) necessary to burn through or seriously weaken the skin of the missile, assuming approximately a one-second exposure. R is the effective range from the laser to a relay mirror (to be discussed later), and D is the diameter of the laser telescope aperture, that is, the final (large) diameter of the launched laser beam. The factor $R\lambda/D$ is the theoretical radius of the laser beam at a distance R. λ is the wavelength of the laser.

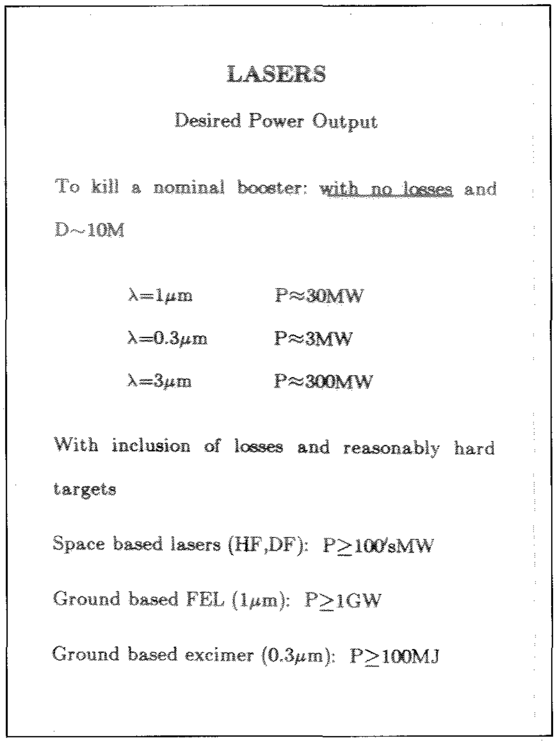
From the formula you can see that if we try to compensate for the spread (diffraction) of the beam by using more laser power to start with, the amount we need becomes exorbitantly large. But since the spread angle is given by the ratio (λ/D) of the wavelength of the radiation to the diameter D, you can decrease the spread by increasing the diameter. You do this with a telescope. Unfortunately, to get the required laser power, we will need a telescope with a mirror about 10 meters in diameter. This is pretty big for a telescope. In fact, it's the size of the Keck Telescope, which is currently under construction, and which, when finished, will be the largest in the world. So, in addition, we will need a sizable structure to aim and control the laser. Like the Keck Telescope, Star Wars mirrors will probably have to be constructed out of segments that will be carefully adjusted relative to each other to achieve a perfect surface.

And where are we going to put these huge, expensive, delicately adjusted mirrors? If we want to get a laser beam from, let's say, Wyoming to Irkutsk, we can't go in a straight line because of the curvature of the earth and the atmosphere. So the current scenario is to put these mirrors in geosynchronous orbits—about 36,000 kilometers above the earth and stationary relative to a point on the earth. Somewhere over the Soviet Union other 10-meter mirrors, called fighting mirrors, would be positioned at much lower orbits, say 1,000 kilometers above the earth. The laser would be beamed from the earth to one of about 100 geosynchronous-orbit mirrors and then relayed to the fighting mirror, which would aim and focus it down on the ICBMs as they climb during the boost phase.

What kind of power do we need to do this? We know it will take 30 kilowatts for one second to burn through the skin of the missile. The formula tells us how light diffracts as it propagates through the atmosphere, so it's just simple bookkeeping. If we were to use radiation of one micron we will need a laser of roughly 30 megawatts. If this laser is going to be based on earth, so that we have to propagate through the atmosphere to the geosynchronous mirror and down to the fighting mirror, we will need as much as one gigawatt of power to achieve the requisite power density on the Russian missile in order to burn through its skin. One gigawatt is, for example, roughly the power output from one of the nuclear units in the San Onofre power plant. The difference, of course, is that this kind of power has to be available only during the engagement period of one to three minutes. The table at right shows some of the typical power levels that result from the above considerations.

The x-ray laser, the most exotic entry in the laser weapon field, doesn't need mirrors for the simple reason that no mirror has yet been made that can withstand x-ray radiation, and its operation is not based on feedback as in our example above but, rather, on one-pass amplification of spontaneously emitted x-rays. Since most of the information on x-ray lasers is classified, a small group from our committee who had the top Department of Energy clearance was able to go to Lawrence Livermore Labs to be briefed on them. I was not one of that group, so what I am going to say about x-ray lasers comes not from our committee deliberations but from the open literature. An x-ray laser is essentially an efficient nuclear bomb surrounded by a bunch of metal or plastic rods. When the bomb is exploded, most of its output consists of x-rays. In the billionth of a second before all the rest of the junk reaches the rods, the x-rays get there first and excite the atoms in the rods. Here you are just replacing the helical flash lamp around the ruby rod in Ted Maiman's laser with a nuclear bomb. When the x-rays excite the atoms in the rods, they lase along the rod axis. It's a rather crude laser in the sense that it isn't very collimated, or tight, and you can't concentrate the power on one small spot, but that's just what you might want in this case. The x-ray laser doesn't have to be pointed very accurately because it splashes a great deal of energy all over the place. The amount of energy envisaged is large enough that it can burn and disable objects over quite a broad area, so x-ray lasers just need to be pointed at the general vicinity of the target.

It would work like this: say the Soviets launch some ICBMs. Radar and other satellite-based sensors detect them, and the information is relayed to a U.S. submarine a few thousand kilometers off shore, which launches an extremely fast rocket. The x-ray laser is very light in comparison to any other laser considered. It does not have enormous mirrors (all it consists of is a nuclear bomb, which is a relatively light device, and a few rods), so you can achieve fast acceleration from the submarine to a line-of-sight position relative to the climbing enemy missile. Then the nuclear explosion is triggered, and x-rays are beamed at the vicinity of the target. One of the main problems with the system is that x-rays don't penetrate the atmosphere, so that you have to wait until the Soviet missile has risen above most of the atmosphere.



LASERS

Desired Power Output

To kill a nominal booster: with no losses and D~10M

$\lambda=1\mu m$	$P\approx 30MW$
$\lambda=0.3\mu m$	$P\approx 3MW$
$\lambda=3\mu m$	$P\approx 300MW$

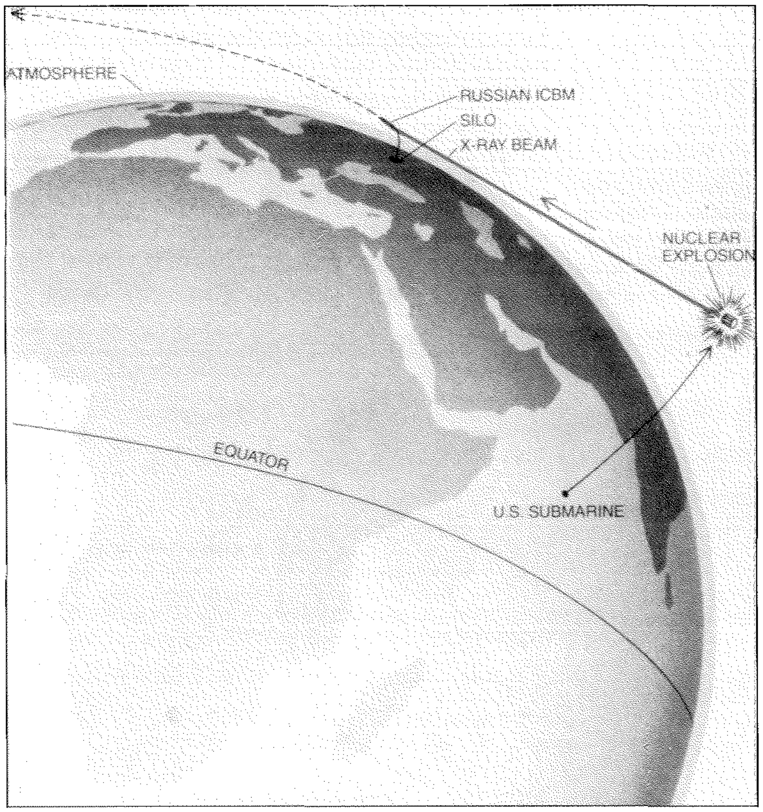
With inclusion of losses and reasonably hard targets

Space based lasers (HF,DF): $P\geq$100'sMW

Ground based FEL ($1\mu m$): $P\geq 1GW$

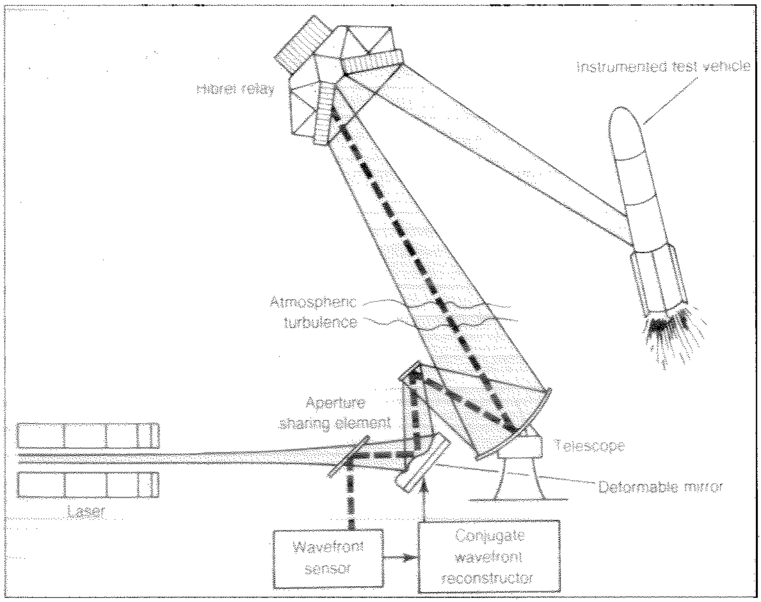
Ground based excimer ($0.3\mu m$): $P\geq 100MJ$

Bouncing an effective ground-based laser off a 10-meter mirror in space to an orbiting fighting mirror demands various power outputs depending on the laser's wavelength.



Because it's very light, an x-ray laser could be launched and accelerated quickly from a submarine to a line-of-sight position relative to the missile. A nuclear explosion triggers the laser.

From "Space-based Ballistic-Missile Defense" by H. Bethe, R. Garwin, K. Gottfried, W. Kendall. © October 1984 by Scientific American, Inc. All rights reserved.

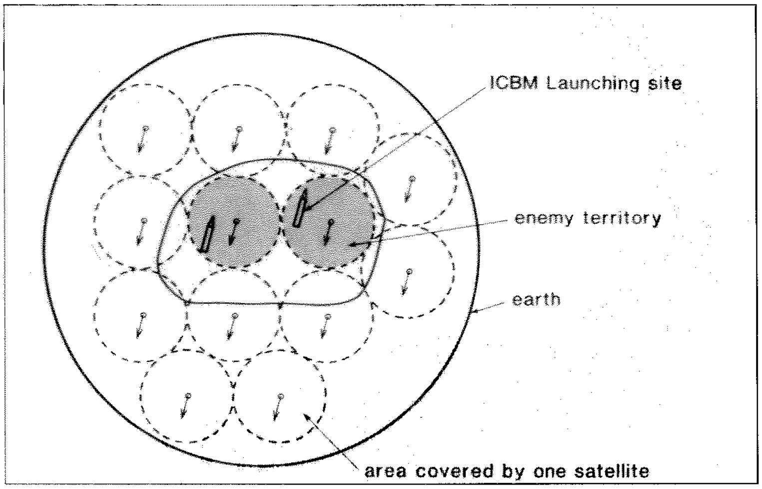


Using phase conjugate optics, a weak laser sent from a mirror in space would carry an "image" of the atmospheric turbulence in its own diffraction. This could be interpreted by a wavefront sensor and used to deform the mirror that launches the actual laser weapon, so that the distortion of the outgoing laser would cancel the effect of the atmospheric turbulence.

The atmosphere also bothers optical lasers. An ideal laser beam stays very tight and will propagate with a very small angle of dispersion. But an optical beam launched from an earth-based laser has to move through the atmosphere, and air turbulence makes the atmosphere an uncongenial medium for optical propagation. Instead of remaining narrow and tight, the beam breaks up and spreads over an angle that might be thousands of times larger than the ideal angle—with a concomitant loss in laser power on target. The intensity loss is so large that by the time the power reaches its target the intensity is too low to do any real damage. One of the major thrusts of current Star Wars research is dealing with this problem.

In one of the proposed solutions the large mirror assembly in geosynchronous orbit (36,000 kilometers above the earth) will house a small laser that shoots a beam down to the earth-based laser station. This weak beam probes the atmosphere, and when it arrives, its own distortion (spread) contains information about the atmospheric turbulence. A wavefront sensor extracts this information, which is then used to deform a mirror. The actual weapon laser beam is now reflected from this mirror and in the process gets distorted in exactly the complementary distortion necessary to balance the distortion caused by the atmospheric turbulence. The two distortions cancel each other, producing a diffraction-limited (collimated) beam. A deformable mirror would have to have as many as 100,000 little actuators that can push from below and deform the mirror locally.

Because of the earth's rotation, the number of fighting mirrors actually necessary to cover a launch site has to be exceeded by a factor of five.



Caltech has played an important role, conceptually and experimentally, in demonstrating many of the basic ideas that are involved in this technology, which goes under the name of phase conjugate optics. About 30 years ago Caltech astronomer Horace Babcock used techniques of this sort to compensate for scintillation in order to resolve astronomical objects better. In my own group we have been working for the last 10 years on phase conjugate optics and have developed, unrelated to Star Wars, nonlinear optical techniques that are relevant to correcting atmospheric distortions. The technique has many other applications, including photographing through clouds and transmitting images through fibers.

So we now know, at least theoretically, how to generate light, how to launch it, and how to compensate for distortion. What happens when the weapon beam is actually over the target? Two or three fighting mirrors at an altitude of 1,000-2,000 kilometers can cover the whole of the Soviet Union. But two or three mirrors don't have enough time during the one to four minutes or so of the boost phase to take care of all the Soviet missiles that are climbing. The Soviets can launch as many as 1,500 missiles at one time, so for an anticipated worst-case boost phase of one minute we will need some 12 mirrors, assuming half a second per kill. But these 12 mirrors can't be planted over the U.S.S.R. They will have to be orbiting all the time, and since we don't know when the missiles will be launched, because of the earth's rotation we will have to cover the whole earth with a blanket of orbiting mirrors. The factor by which you have to exceed the 12 or so that you actually need during engagement is referred to as the "absentee ratio," which turns out to be about five. So we will need about 60 orbiting fighting mirror platforms, each one 10 meters in diameter. We will also need one relay mirror in a geosynchronous orbit for each of the 12 or so fighting mirrors.

Even if we figure out how to do all this and make it work, it will take 10 to 15 years before this system is deployed, and the Soviets, of course, are not going to be sitting still during that time. They will be improving their own technology, especially in view of the fact that we are developing a ballistic missile defense system. They have many possible responses: they can attack the 60 orbiting platforms, each containing mirrors, electronics, radars, sensors, and power supplies. These platforms that we are going to hang up there are enormously complicated and expensive things, and they are relatively soft targets; that is, it will be far easier, I'd say by a factor of at least a thousand, to destroy them than for them to destroy the missiles. The Soviets would only need to explode a nuclear bomb above the atmosphere just before launching the missiles. This would disable everything we had within range and make it easier for their blind missiles to sneak through.

Our mirror platforms could also be destroyed by lasers, lasers much weaker than the ones I've discussed here, because our mirrors, electronics, solar cells, and antennas are a softer target than missiles. If the Soviets do undertake a Star Wars-type program but are unsuccessful in developing strong enough lasers to defend against our missiles, the ones they develop will very likely possess sufficient power to disable our weapon platforms with all our mirrors and electronics. We really have no clear idea how we are going to protect our assets in space. It's like buying a Cadillac and parking it in a high-crime area every night for 10 years.

Other fairly simple options for the Soviets that will make things more difficult for us include:

- Proliferation—increasing the number of targets by building more missiles.
- Booster rotation—rotating the missile as it rises so that the laser beam can't dwell on the same spot long enough to burn through. This simple move would increase the laser power requirement by a factor of approximately three—a huge factor when gigawatts are already involved.
- Ablation—using protective material that will require more power to burn a hole through.
- Fast-burn boosters—making booster rockets that will burn in one minute instead of four to five. This is possible even now and means that the critical time during the boost phase would be shortened by a factor of five. Almost every requirement would then be upped by that factor; we would need five to six times more power and so on. In addition, the boost phase would be completed at 80 kilometers or so, which is still within the atmosphere. This would reduce the effectiveness of the x-ray weapon considerably, because it can't penetrate through very much of the atmosphere. And because the nuclear bomb that triggers the x-rays has to be launched from a submarine and now would have much less time to get to its line-of-sight position relative to the target, new problems would be presented. The post-boost vehicle could also be redesigned to discharge its warheads and decoys faster, thereby spending less time in this vulnerable stage.
- Decoys and penetration aids—packing the post-boost vehicle, the bus, with 200-300 lightweight decoys. The decoys would be launched from the bus above the atmosphere and would move with the same velocity and have the same trajectory as the re-entry vehicle. They could also be shaped to look alike and to have similar responses to radar. By today's mostly passive means there would be no way of discriminating between them, with the result that, instead of concentrating on one warhead, you would have to deal with 200-300 objects that look the same. So, even if we were successful in destroying 90 percent of the launched Soviet missiles in the boost phase, so that instead of 10,000 warheads you would have only 1,000, we might still have some 100,000 decoys to deal with.

But forgetting possible Soviet countermeasures for a moment, where are we with Star Wars technologies right now and how far do we have to go? Demonstrations of correcting for atmospheric turbulence are short by a factor of 100 of what needs to be done. Chemical lasers' effectiveness has to be increased by a factor of 100 to get to the range where they can even theoretically be used. To do the job, excimer lasers need to be four orders of magnitude, or 10,000 times, more powerful than what we have today. X-ray lasers still have enormous problems.

Other exotic possibilities include free-electron lasers and particle beams. A free-electron laser uses a beam of electrons that have been accelerated to as much as 100 million volts to change the polarity of a magnetic

STATUS OF VARIOUS DEW TECHNOLOGIES

TECHNOLOGY	STATUS (ORDERS OF MAGNITUDE SHORTFALL)	
	BOOSTER KILL	DISCRIMINATION
LASERS		
Chemical Lasers (HF & DF)	P_{av} : >2	
Excimer Lasers	P_{pulse} : >4	
Free Electron Lasers	P_{av} : >6	
X-Ray Lasers	MANY	MANY
PARTICLE BEAMS		
Neutral Particle Beams	P_{av} : >2	P_{av} : >2
Charged Particle Beams	P_{av} : >3	P_{av} : >2

field in a regular fashion. This forces the electrons to undulate as they move along, and the wiggly motion forces the electrons to radiate, that is, give up energy in the form of photons. Electron-beam lasers would need to be improved by six orders of magnitude, and much of the basic physics isn't understood yet. Particle beams—beams of electrons, protons, or atoms, which can be accelerated to velocities nearly that of light—are still only a suggestion and are even further behind than lasers.

We don't know how to discriminate among warheads and decoys; only preliminary ideas have been proposed, and much work needs to be done just to establish their feasibility. We haven't yet built 10-meter mirrors, much less figured out how to put them in space and point them fast and accurately.

And system issues have yet to be addressed. We are going to have the most complicated system ever designed operating in a hostile environment of laser beams and exploding nuclear bombs. Vast amounts of information will have to be processed, including locations, decoy discrimination data, and kill verification. This information will have to be transferred and shared as the defense focus moves with the surviving missiles from one phase to the next. All the components of the system have to communicate perfectly, and we don't know how to do that. This problem is so difficult that I don't think people even know where to start. We considered this the most difficult part of the Star Wars challenge.

The degree of shortfall between other needed performance levels and present-day achievement is demonstrated in the table at left. As one can see, we need improvements of from two to six orders of magnitude in the basic technologies.

Our committee came to the following conclusion: "Although substantial progress has been made in many of the technologies of directed-energy weapons over the last two decades, the study group finds significant gaps in the scientific and engineering understanding of many issues associated with the development of these technologies. We estimate that even in the best of circumstances, a decade or more of intensive research would be required to provide the technical knowledge needed to make an informed decision about the potential effectiveness and survivability of directed-energy weapons."

It is important for us to have a sound understanding of the performance limitations of a directed-energy weapon defense system. For one thing, the system will be very expensive. Just shooting wildly from the hip I would guess thousands of billions of dollars, with tens of billions for annual upkeep and repair. Embarking on such an endeavor before we possess the basic technology and an understanding of the phenomena involved will almost surely lead to failure. And a failure of that magnitude will be a national catastrophe.

But there are already political pressures, which are increasing, to proceed with these untested ideas and technologies. This is probably due to the reluctance of Congress to shell out a few billion dollars every year for a basic research program in developing technologies. The pressure is to show results, and that pressure can force us to commit ourselves to premature technologies that are certain to fail. We hope that our report will make it easier to resist such pressures.

I want to reiterate in closing that our committee was not "for" or "against" the Strategic Defense Initiative. We concentrated on the technological and scientific issues. I personally would like one day to see an effective missile defense system developed strictly for defensive purposes, because the list of nations possessing nuclear weapons will increase and some of these nations may not be quite "reasonable." But our committee concluded that, based on present-day technology and understanding, the job cannot be done. What we need is at least 10 years of intensive research and development simply in order to find out if it *can* be done. □

Research in Progress

Photographic Memory

NEURAL NETWORK research is one of the hottest topics in computing nowadays, but the field is still in its infancy. The very features that give neural nets their unique attributes make them hard to simulate on "regular" serial computers, and harder still to model as physical devices. A number of esoteric devices are being researched that could someday revolutionize computer design. In the meantime, Aharon Agranat, a research fellow in Amnon Yariv's applied physics group, is developing a system to model the flexible complexity of neural nets using mature technologies. Caltech has several research groups working with neural nets, and the faculty includes some of the field's leading scientists.

Neural nets are loosely modeled after the brain's own structure, where every brain cell, or neuron, is connected to thousands of others. The connection strengths (or "weights") differ. Data (memories) and programs (such as how to process visual information to recognize a face) are stored as connection patterns of varying weights. When the brain learns, the patterns change.

Building a brain, with its approximately 10^{12} neurons, each with up to 10,000 connections, is still beyond anyone's wildest dreams. Scientists today are working with a handful of neurons, modeling systems from a dozen or so up to a few hundred. Even these small nets present complex problems.

Although microprocessing technology is pretty sophisticated, trying to squeeze a highly interconnected, three-dimensional structure onto an essentially two-dimensional chip is a tough proposition. With the additional condition that the connections be made variable, the problem becomes well-nigh impossible.

An alternative approach, using optical technology, shows promise. Since light beams pass through each other unhindered, and beam intensity is easily controlled, the connection problem vanishes. In fact, small neural nets have been built entirely in optics; but optical information processing technology is not nearly as advanced as its silicon analog.

Agranat decided to put the best-developed features of silicon and optical technology together. The result is a system where silicon neurons process data (connection strengths) from an optically loaded memory. He was assisted this past summer by SURF (Summer Undergraduate Research Fellowship) student Chuck Neugebauer, a senior interested in VLSI physics.

Agranat's system codes the connection weights for a chip with N neurons as an N × N matrix. Each matrix element codes the weight from the neuron in the element's row to the neuron in its column. Transformed into optical data, the matrix becomes a pattern of bright and dark dots. The brighter the dot, the greater the weight. A personal computer from a home electronics store generates the pattern according to any of several algorithms. ("It's not standard, but we got it really cheap, and it's got good graphics capabilities," Neugebauer said.) Once in the computer, the pattern can be modified at will. For example, the chip could be "taught" by modifying the pattern between successive runs until a desired output is produced.

But how does the pattern get on the chip? That's the key to Agranat's off-the-shelf design. The computer's video drive is connected to one of those tiny LCD (liquid crystal display) TV sets—the kind that have recently become the gift of choice for consumer electronics addicts. A system of lenses reduces the image 20-fold and focuses it on a charge-coupled device, or CCD. A CCD is the image-sensing device in a television camera. The dot matrix becomes puddles of electric charge on the CCD, and the chip reads them off just as a camera's chips would read a video image. "Basically, we can put any pattern of dots on the CCD we need, using the LCD screen as a spatial light modulator," Neugebauer said.

"People are using LCD-TVs in all sorts of optical computing setups," Agranat notes. "They are cheap, about $200, and readily available. There are high-quality spatial light modulators built specifically for scientific use, but they're very expensive. There's a mageneto-optical device with a 48 × 48 matrix. It's a very good device, but it costs about $5,000, and it can't make shades of gray. We need shades of gray for the weights. With the LCD-TV, we can make a 100 × 100 matrix having more information. The optical setup is routine, but it's not trivial. The image has to be placed accurately to within 10 microns everywhere on the CCD, and the brightness has to be uniform as well."

The chip assembly is enclosed in a light-tight box with a shuttered aperture, like a still camera. A single flash exposure suffices to load the pattern.

"My background is in optics," Agranat said. "I had the idea, but I didn't have the expertise to build it. Then Chuck showed up. I built the optics, and he designed the chips. Usually this would be done as a collaboration of two professionals—I would find a postdoc to share the work. But here one of the professionals is an undergraduate, and that's unique. I gave him the architecture—the CCD, the integrators, and so forth, and he developed the designs completely on his own. Without him, this project would still be on paper."

In fact, the group developed three architectures over the summer. The CCD system is a semi-parallel, synchronous architecture: Just as creating a video image requires a number of sweeps equal to the number of rows on the screen, so processing the CCD's contents takes a number of computational cycles equal to the number of neurons. The other two architectures can calculate the network's output in either a single cycle (fully parallel synchronous processing) or continuously without cycling (parallel asynchronous processing). "Chuck dreamed up the the third one himself," Agranat said. "He got the idea for it, and he went back and figured out exactly what engineering principles and what components it would take to make it work. It's actually the easiest of the three to fabricate, so it may be the first one we'll see working."

All three designs have been sent out for fabrication. Some of the chips have returned recently, and the testing process is about to begin. Several variations on each architecture will be examined, and one design each will be chosen for the next scale-up. The largest chip in the current batch has 32 neurons, enough gray matter to perform simple computations.

A 1,000-neuron chip could be built with current technology, Agranat said, but there aren't as yet spatial light modulators big enough to load them. In the meantime, the 100-neuron range accessible through the LCD-TV is sufficient for much network research that would otherwise be impossibly expensive or time-consuming to run.□—*DS*

Computer's-Eye View

IF A PROPOSED Mars rover can find its way through Congress, it may use a Caltech-designed vision system to find its way around Mars. The vehicle would have to recognize and avoid obstacles unaided, as signals from an earthbound driver would take as long as twenty minutes to arrive.

Assistant Professor of Computation and Neural Systems Christof Koch, along with Brian Wilcox of the JPL vision group, and Carl Ruoff, a graduate student in mechanical engineering, are evaluating Koch's design for space applications. The project is supported by NASA funds. Current computer vision systems are based on so-called "expert system" programs. "Expert systems are very brittle," Koch said. "You have to have rules for everything. If you built a vision system that way, it would be made up of if-then rules like, 'If you have a red blob at a one-meter height in an office, it's probably a telephone.' But it could be a cup. So you add another rule: 'If it's round, it's a cup.' But maybe it's really an apple. Our approach is much more flexible."

"You never think about vision," Koch said. "You open your eyes and the world is there. But your eyes just make a big array of numbers—they're actually voltages, but conceptually they correspond to numbers. Out of that array you have to infer that one object is in front of another, that things are moving, how they're moving. This is called early vision—getting three-dimensional information from a two-dimensional intensity array."

Koch heads a research group working on early vision and related computational problems. The group has developed an algorithm to separate objects from background based on their relative motion. Since a computer's field of vision consists of a matrix of discrete points (pixels), a velocity vector can be assigned to each pixel. The velocity vector field is generated by comparing two successive images of the same scene and determining how each point moved between images. The system actually traces the apparent motion of pixels of constant brightness. It works from two assumptions. Neighboring points in the field of view move the same way unless they are on different objects. When the points have different motions, they are separated by discontinuities (sharp changes between adjacent vectors) coinciding with the object's edges.

Koch's algorithm poses the problem in terms of minimizing an energy function (an optimization problem). The problem resembles a landscape of hills and valleys. A boulder dropped on one of the hillsides should eventually roll to the lowest point in the valley. Computing the boulder's path mathematically is time-consuming, as thousands of iterations may be required over the entire landscape.

However, the problem is directly analogous to the behavior of a network of simple resistors. The junctions, or nodes, correspond to the pixels. An external voltage fed to each node corresponds to the brightness change at that pixel. Once the system has reached a stable state (minimum power dissipation), the voltage at each node corresponds to the velocity. "You can exploit the physics of the network to get the solution, instead of going to a computer and using a set of logical rules," Koch said.

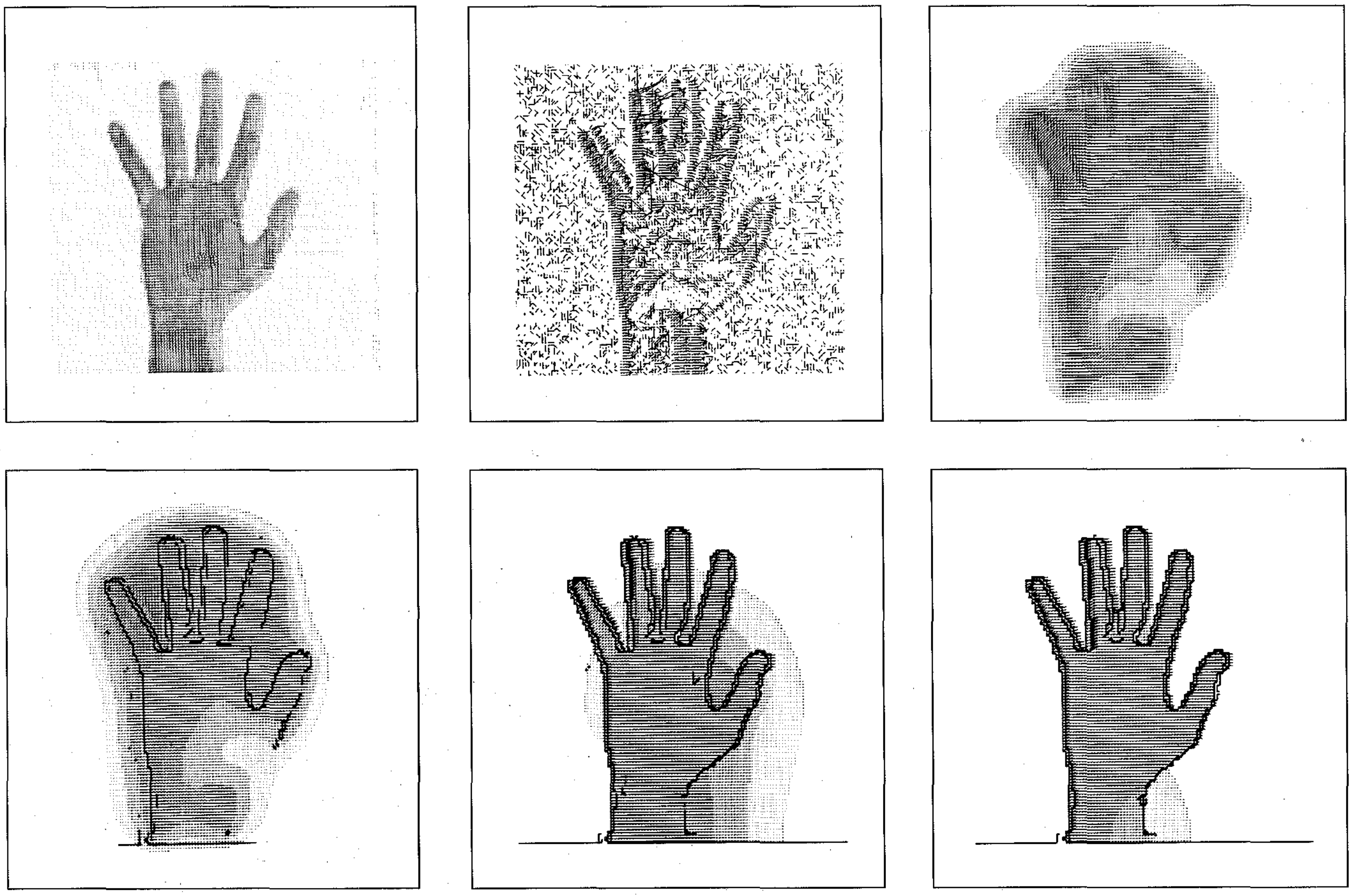
Other people have proposed relative-motion algorithms that can determine an object's direction and velocity. Unfortunately, these methods generate a velocity field that varies smoothly over the entire visual field. The smoothness hides an object's edges, leaving an unrecognizable blob. Furthermore, if overlapping objects move in opposite directions, the network averages their velocities, generating a zero-velocity region where the objects meet.

Koch's network design includes an edge simulation process. This so-called "line process" has recently been introduced in a variety of vision applications. The line process is a binary switch in each resistive link. When the line process is "off," the switch is closed and current flows—smoothing the velocity field. When it's "on," the switch is open. No current flows between the nodes, creating a velocity field discontinuity—an edge.

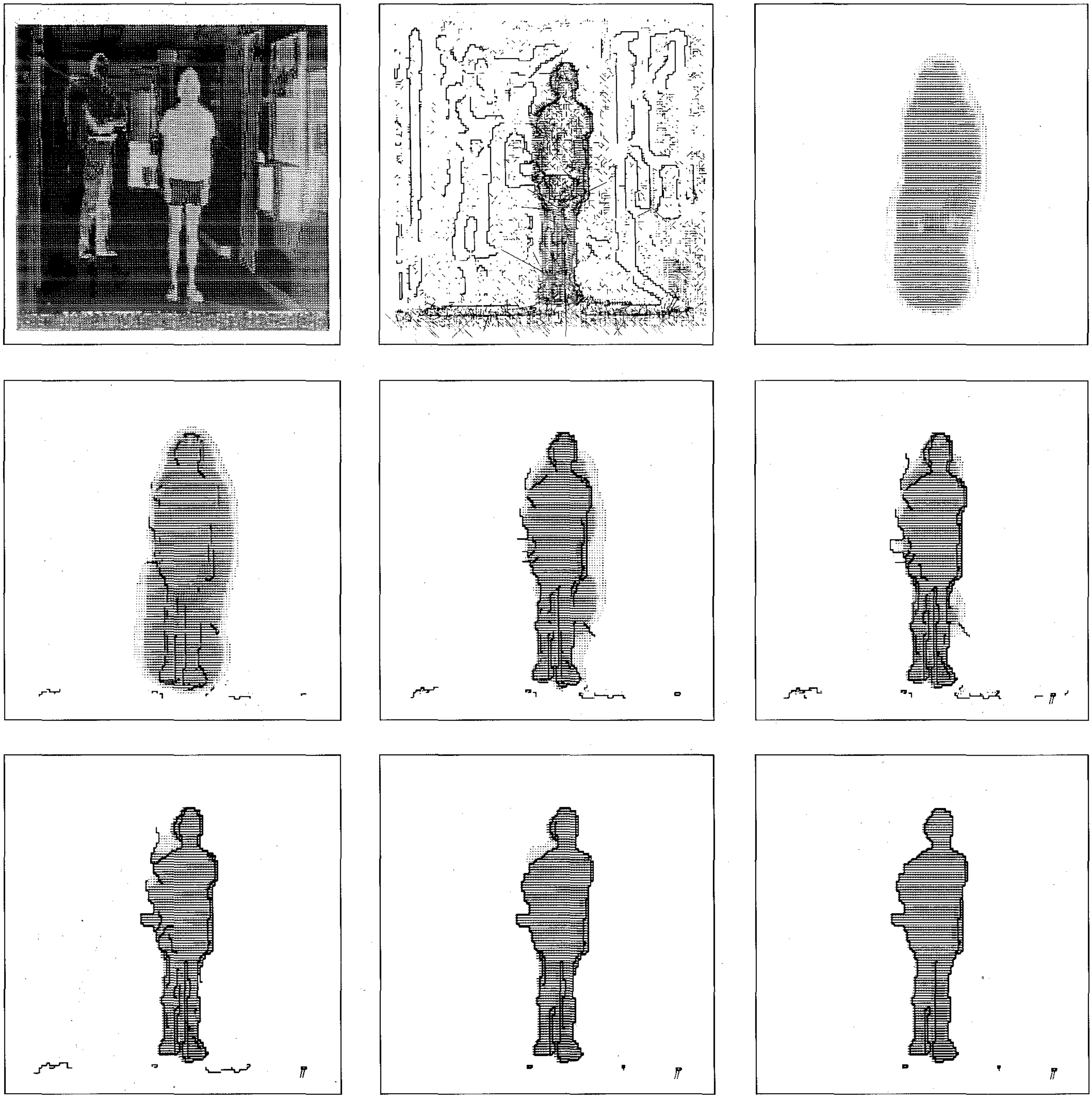
The result is a hybrid chip design with analog and digital components connecting each node. The analog components are variable resistors designed by Carver Mead, the Gordon and Betty Moore Professor of Computer Science (*E&S* June '87). The chip actually has two identical networks— one each for the x and y components of motion. Each pixel's x and y nodes are linked by a variable resistor.

The system operates in cycles. Initially all line processes are "off" and current flows until the field stabilizes. Next, an external unit evaluates each node. If a neighboring node has a significantly higher voltage, the line process between them turns "on," creating an edge. Evaluation is fast, even for large networks, because system-wide information isn't needed. Once all the nodes have been checked, the active line processes break their respective connections, and the current flows until another field stabilizes. The system re-evaluates the nodes, turning on new line processes as needed, and the cycle repeats. "In its final state, you can read off the velocities and discontinuities directly," Koch said. "This thing has almost solved the problem of object segmentation—deciding what surfaces belong to what objects. It's a very difficult problem."

The group has simulated the system on JPL's 32-node Mark III Hypercube parallel computer, and on smaller 4- and 16-node NCUBE computers on campus. The most recent work used 128 × 128 pixel "before" and "after" images from a video camera. Given a moving hand on a featureless background, the system generated an easily recognizable image, complete with fingers, in only seven cycles. (1,000 iterations of the resistive net alone generated a smooth-flow image resembling



"Seeing" a moving hand. Top row, from left: 128 × 128 pixel image from video camera; the computer compares it to a second image (not shown) in which the hand has moved as much as two pixels. Initial velocity data; "snow" in background also registers. Smooth-flow field after 1,000 iterations, with grayness proportional to velocity. Bottom row, from left: State of the hybrid network after one, three, and seven cycles respectively. Line processes grow toward each other along edges, and the velocity aura around the hand disappears. After thirteen cycles (not shown) it vanishes altogether.



In a hallway. Top row, from left: 128 × 128 video image; person in foreground is moving right and person in background is standing still. Discontinuities superimposed on initial velocity data; note band of camera noise across bottom of both images. Smooth-flow field after 1,000 iterations; noise vanishes as random variations cancel. Middle row: Hybrid network after one, three, and five cycles respectively. Bottom row: After seven, ten, and thirteen cycles. Line processes not supported by the velocity field wither, while line processes coinciding with edges grow.

a mitten.) A person walking down a hallway filled with stationary objects was cleanly separated from the background in thirteen cycles.

"Even though it's a Hypercube, it still takes 20 minutes to simulate two frames which may be a small fraction of a second apart. The chips, we think, will be able to do it in real time or very close," Koch said.

A 30 × 30 chip built to Koch's design has recently returned from the fabricator, and network testing is about to begin. If this is successful, a 128 × 128 chip could be built in two to three years with existing technology.

"The common housefly, *Musca domestica*, has 24,000 photoreceptors in each eye, or about 50,000 photoreceptors covering almost 360°. That's around 220 × 220. And *Musca domestica* is a very good flier—try to catch it. So we think with 128 × 128 we can do all the navigation we want. It may not be able to read, but our Mars rover doesn't really need to do that," Koch concluded. Even if the Mars rover never gets off the ground, this rugged, lightweight technology will find plenty of earthbound uses.□—*DS*

Books

First Light
The Search for the Edge of the Universe

by Richard Preston

The Atlantic Monthly Press, 263 pages, $18.95

I FIND RICHARD PRESTON'S book exciting, easy to read and informative, with a style that is vivid, slangy, and funny. It describes two aspects of contemporary astronomy and some of the trials and fun of people who work at Palomar. But the real heroes of this book, which reads in part like a novel but is mostly true, are two telescopes (plus attached electro-optical scientific instruments, computers and programs).

The book covers the stories of two quests. One of them is the search with the Palomar 200-inch Hale reflector for quasars at the largest redshifts attainable—and the implication for cosmology of looking back so far in time. The other, an account of which appeared in *The New Yorker* magazine in 1987, is the search with the Palomar 18-inch Schmidt telescope for asteroids whose eccentric orbits cross the path of the earth. Preston explains reasons for these searches: What fuels the enormous output of a quasar? (A black hole swallowing millions of suns?) How dangerous are asteroid impacts? (Very?)

In addition to the telescopes there are also vivid human heroes. For this remarkably intimate description of real scientists as human beings, working at their limits, Preston spent many nights at Palomar, and conducted many interviews. A particular novelty is the description of how it feels to conceive, design, build, de-bug, and use a one-of-a-kind instrument. He describes personal and emotional characteristics that make the scientists real, if somewhat larger than life. They are a varied group, many currently or formerly connected with Caltech: Carolyn and Eugene Shoemaker, Maarten Schmidt, Jim Gunn, Don Schneider. Another important and charming character in the story is Juan Carrasco, born on a small Texas farm, now senior night assistant at Palomar, the only one in this group trusted to move the 200-inch. A large supporting cast includes Caltech scientists and engineers, past and present. Many of them are my good friends, but my enthusiastic recommendation for the book is not biased by this fact—nor by my own appearance in a "walk-on" role from an older pre-electronic generation.

The Shoemakers, husband and wife, revivified the study of the asteroids, from rock to mountains in size, remnants of the origin of the solar system and fascinating hazards for interplanetary travel. They use (often in a shower of sparks) the oldest telescope on Palomar, the 18-inch Schmidt, taking photographs to find the trails of nearby, rapidly moving asteroids. Gravitational perturbations by the earth and other planets may cause eccentric, earth-orbit crossing asteroids to strike us, and Gene Shoemaker has become an expert on the geological remains (impact craters) of ones that did. Preston includes a capsule history of the solar system, a description of the Schmidt telescope, and his terrors on loading a piece of film into a holder in the darkroom. The reader will also meet some of astronomy's pioneers in anecdotal biographies of Bernhard Schmidt, Walter Baade and Fritz Zwicky.

The search for remote quasars at the 200-inch similarly introduces a number of great men; a short biography of George Ellery Hale depicts the charm and psychological stress of that founder of great institutions. The central hero, the 200-inch Hale reflector, is particularly appealing to me because of my 40-year love affair with that steel and Pyrex monster of 1930s design. What is amazing is that it still remains adaptable to the newest technologies. Preston describes the gadgeteers behind this application of electronics to the 200-inch—Jim Westphal and his "wizards of the wastebasket," Jim Gunn's home-designed, home-built electronics and his deep cosmological insight.

The central plot is about how Maarten Schmidt needed a statistically complete survey of the numbers and properties of quasars at the limit of detectability with CCDs (charge-coupled photosensitive diodes). The CCD field of view is small and quasars are rare; to obtain a large enough area, a scan is needed. The stationary telescope images a continuous strip of sky drifting by. For this, Jim Gunn invents and builds a "kludge" which transforms the "four shooter" (which carries four CCD's for stationary imaging) into a synchronized scanner, recording a night-long view of sky onto 12 large reels of tape output. The kludge is connected, fastened on with tape; the computer program fails and then triumphantly works. Juan Carrasco points the 200-inch and says "we are there"—a memorable phrase. The astronomers munch Oreo cookies, marvel at glimpses they see as the sky turns, listen to classical music and discuss why there might be so few quasars at large redshift. Are they seeing back too far in time to before galaxies existed, or before they contained all-devouring black holes? Was there an opaque screen at large redshift? Is it all only a statistical fluctuation? Twenty-five years ago we did not know that quasars existed; now we search for them near the unattainable edge of the Universe, from where the "first light" emitted billions of years ago just now reaches Juan Carrasco's 200-inch. Dawn arrives, stopping the quest. This is an excellent and true (even if somewhat romanticized) book about what it feels like to be an explorer. □

Jesse L. Greenstein
The Lee A. DuBridge Professor of Astrophysics, Emeritus

Random Walk

Four Professorships Awarded

HISTORY PROFESSORS John Benton and Eleanor Searle and economics professor Charles Plott have been appointed to endowed chairs in the Division of Humanities and Social Sciences. The Division of Chemistry and Chemical Engineering, meanwhile, has named Peter Dervan to be its first Bren Professor of Chemistry.

Benton will become the Doris and Henry Dreyfuss Professor of History. Benton is an expert on medieval Europe's social and cultural history, with a special interest in France. Benton joined the faculty in 1965.

Plott has been named the Edward S. Harkness Professor of Economics and Political Science. Plott is a pioneer in the emerging field of experimental political economy, and will direct the just-established Laboratory of Experimental Economics and Political Science. Plott has been a faculty member since 1971.

Searle is the new Edie and Lew Wasserman Professor of History. Searle, a specialist in the social and economic history of medieval England and northern Europe, is the first woman to hold a named professorship at Caltech. She joined the faculty in 1979.

Dervan, professor of chemistry and a faculty member since 1973, has been named the first Bren Professor of Chemistry. Dervan's research centers on developing chemical methods to study the mechanisms by which various drugs and proteins bind to DNA, laying the groundwork for eventual synthesis of molecules designed to bind at specific sites on the DNA.

The Bren Foundation recently gave Caltech $1.5 million with which to endow the chair. The foundation, based in Los Angeles, is headed by Donald Bren, a Caltech trustee since 1984. Bren is chairman of the Irvine Company of Newport Beach, California.

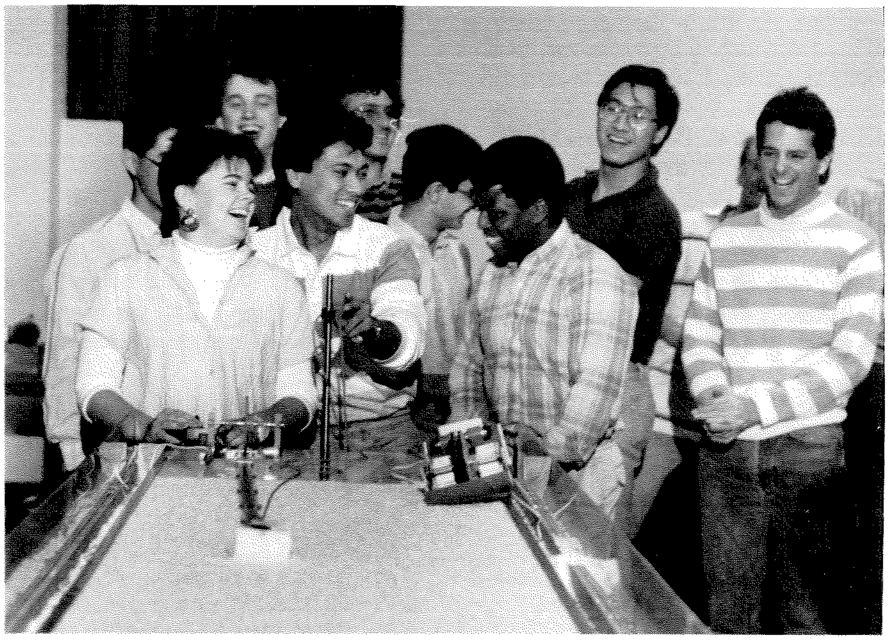
Experimental Economics Laboratory Established

A LABORATORY OF Experimental Economics and Political Science is being established at Caltech. The laboratory will use people's behavior in various simulations to study the dynamics of decision-making and the marketplace. The method has been applied to environmental and common-property resource problems, finance (including futures markets and speculative bubbles), product quality and warranties, regulation, deregulation, and anti-trust litigation.

The lab will be directed by Charles Plott, the Edward S. Harkness Professor of Economics and Political Science. Plott helped found the field of experimental economics, and, with his co-workers, developed many of the lab techniques now in use. Other Caltech researchers at the lab will include David Grether, John Ledyard, Richard McKelvey, Peter Ordeshoak, Tom Palfrey, Dave Porter, and Louis Wilde.

The Lynde and Harry Bradley Foundation of Milwaukee, Wisconsin has donated $500,000 to help establish the lab. Other major contributors include General Motors, the Alfred P. Sloan Foundation, the Pacific Telesis Group, the National Science Foundation, NASA/JPL, and Caltech.

Tug O' War



This fall's ME72a final featured a tug-of-war. Assistant Professor of Mechanical Engineering Erik Antonsson gave each student an identical set of components and a challenge: build a device to crawl, slide or fly over a bed of plastic "sand." While the challenge varies yearly, student enthusiasm is a constant. From left: Leslie McCaffree, Saroj Manandhar (TA), Brian Patterson, Kenneth Lin, and John Wiltse.

Caltech on the Air

The first broadcast of "AirTalk: The Caltech Edition" took to the airwaves on January 20. The program is heard from 6 to 7 PM on KPCC, 89.3 FM, the National Public Radio affiliate of Pasadena City College. "AirTalk," a nightly talk show hosted by Larry Mantle, will be devoted to Caltech on the third Wednesday of every month. The show includes interviews with Caltechers and JPLers—faculty, staff, students, and alumni; as well as features such as Caltech Almanac—a look at the people and events that have shaped Caltech; Caltech Calendar—a listing of upcoming public events on campus; and Caltech in the News.

The first show's guests included Vice President for Institute Relations Ted Hurwitz on Caltech's outreach activities and on finance in higher education, Institute Archivist Judith Goodstein on Caltech's history, and ASCIT president Jeff Tekanic on student life. President Everhart, JPL director Lew Allen, and Pasadena City College president Jack Scott were also heard.

KPCC has received FCC approval to relocate its transmitting tower from the PCC campus to the top of Mount Wilson, and hopes to have the move completed this summer. The station's signal will then reach from Ventura to southern Orange County, making it one of the most powerful NPR stations in Southern California.

Domesday Book Gift

William the Conqueror was an orderly chap who liked to know what he owned and how much revenue it brought in. Once he had conquered England, therefore, it was only natural to take inventory of his new domain. The result is the Domesday Book— a field-by-field record of landowners, their wealth, and their holdings: peasants and villagers, pigs and chickens, plows and grindstones, and every building down to the last beehive. The data, compiled over about seven months in 1086, give historians an invaluable picture of English life at the time. The book is considered to be England's single most important historical document.

A limited edition facsimilie (250 copies), written in Latin on parchment and bound by hand between oak boards cut from medieval timbers, was issued two years ago in honor of the book's 900th anniversary. Richard Hayman ('36), a frequent and generous donor to the Institute, formally presented a copy to President Everhart in a ceremony on January 25. The book is on display in Millikan Library's Rare Book Room.

Honors and Awards

Assistant professor of Biology David Anderson has been chosen by the Chicago Community Trust to be a 1987 Searle Scholar. He will recieve a $180,000 grant over the next three years to support his research.

Don L. Anderson, professor of geophysics and director of the Seismology Laboratory, has been awarded the Geological Society of America's Arthur L. Day medal for 1987. Anderson studies the structure and evolution of the earth, moon, and terrestrial planets.

William Goddard, the Charles and Mary Ferkel Professor of Chemistry and Applied Physics, won the 1988 American Chemical Society (ACS) Award for Computers in Chemistry in recognition of a lifetime of contributions to the field. The award is sponsored by Digital Equipment Corporation (DEC), and includes a $3,000 prize.

Chemistry professor Robert Grubbs has been selected for the ACS 1988 Award in Organometallic Chemistry. Dow Chemical Company sponsors the award, which carries a $3,000 prize.

Leroy Hood, the Ethel Wilson Bowles and Robert Bowles Professor of Biology and chairman of the division, has been given the 1987-88 Dickson Prize by the University of Pittsburgh. The award is presented annually to the foremost investigator in medicine in the United States, in this case for contributions to immunology and molecular biology.

Edward B. Lewis, the Thomas Hunt Morgan Professor of Biology, has received a 1987 Gairdner Foundation International Award for his research on genetic "master regulators"—genes that turn other genes on and off as an embryo develops, transforming a single undifferentiated cell into a complex organism of millions of specialized cells. The award includes a $20,000 cash prize.

Hans W. Liepmann, the von Kármán Professor of Aeronautics, Emeritus, has been appointed an External Scientist Member of the Max Planck Institute for Fluid Dynamics Research in Göttingen, West Germany. This honor has been granted only once before in the Planck Institute's history.

Rudy Marcus, the Arthur Amos Noyes Professor of Chemistry, has been honored by several organizations. He was elected a Foreign Associate of the Royal Society in June, was named to the International Academy of Quantum Molecular Science in July, received the 1988 Peter Debye Award in Physical Chemistry from the ACS in September, and went to Sweden in October to receive an honorary Doctor of Science degree from the University of Gothenburg.

Professor of Biology Paul H. Patterson has received an Investigator-Initiated Research Grant from the Alzheimer's Disease and Related Disorders Association (ADRDA) to study how brain cells using the neurotransmitter acetylcholine develop.

Barry Simon, the IBM Professor of Mathematics and Theoretical Physics, has been elected vice president of the American Mathematical Society.

G. J. Wasserburg, the MacArthur Professor of Geology and Geophysics and chairman of the Division of Geological and Planetary Sciences, gave the 100th Anniversary Goldschmidt Memorial Lecture to the Norwegian Academy of Sciences in Oslo. His topic was "Isotope Connections between the Solar System and the Interstellar Medium."

American Cancer Society Postdoctoral Fellowships have been awarded to chemistry research fellows Marc Greenberg, Calvin Iida, and John Termini.

Random Walk (continued)

Obituaries

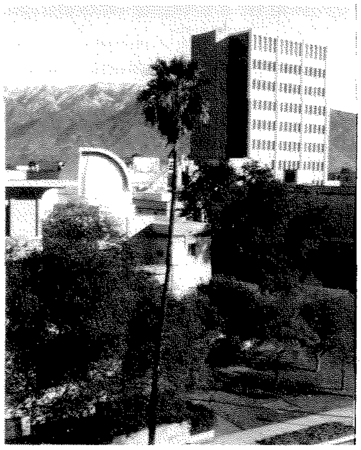
Charles D. Babcock, professor of aeronautics, died on July 1. Babcock earned a BS from Purdue University before coming west to Caltech, where he received his MS (1958) and PhD (1962). He stayed on as a research fellow in aeronautics, rising to become a full professor by 1974. Babcock's research into how structures fail has borne fruit in many branches of engineering. Babcock was 53.

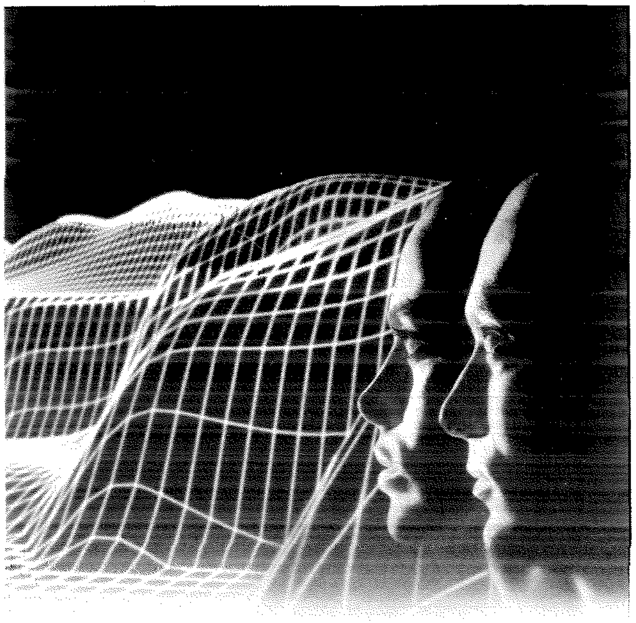
Frederick J. Converse, professor of soil mechanics, emeritus, died October 9, six days before his 96th birthday. Converse received his BS from the University of Rochester, and taught there before coming to Caltech in 1921 as an instructor of civil engineering. He had become a professor of civil engineering by 1947, retiring in 1962. Converse's pioneering research on the vibratory compaction of sands and cohesive soils made him an invaluable advisor to builders, architects, and engineers throughout southern California.

Edward W. Hughes, 83, senior research associate in chemistry, died on December 24. Hughes earned BChem and PhD degrees from Cornell University before joining the Caltech faculty in 1938. He devoted his research to X-ray crystallography, and served as president of the American Crystallographic Association.

Louis Winchester ("Winch") Jones, dean of admissions, emeritus, died on January 6. Jones was educated at Princeton University. He came to Caltech in 1925 as an instructor in English. He had become an associate professor of English by 1941, when he was named registrar and director of admissions. He became dean of admissions and director of undergraduate scholarships in 1953, and retired in 1968. Jones was 87 years old.

George P. Mayhew, professor of English, emeritus, died on October 15 in Massachusetts, following a long illness. He was 68. An expert on Jonathan Swift, Mayhew was educated at Harvard, where he earned his AB, MA, and PhD. He joined Caltech as an assistant professor in 1954, and became a full professor in 1968. He had been on medical leave since 1974.





Fellowships

Pioneer the future with us.

All of the technological advancements that have been pioneered by Hughes Aircraft Company are merely an introduction to what will come.

As a Hughes Fellow, you could be pioneering your own future, studying for your Master's or Doctorate in Engineering (Electrical, Mechanical, Manufacturing), Computer Science or Physics.

You'd be receiving full tuition, books and fees, an educational stipend, full employee benefits, relocation expenses, professional-level salary, summer employment, technical experience. . .with a combined value of $25,000 to $50,000 a year.

While you're completing your degree, you'll also have the opportunity to gain valuable experience at Hughes facilities in Southern California, Arizona or Colorado.

Hughes Fellows work full-time during the summer. During the academic year, Work-Study Fellows work part-time while studying at a nearby university; Full-Study Fellows attend classes full-time.

And Hughes has just announced a special MSEE program in Microwave Engineering in conjunction with two major Southern California universities. Microwave Fellows will be allowed time off at full pay to attend classes taught by university faculty right at Hughes' facilities.

Since Hughes is involved with more than 90 technologies, a wide range of technical assignments is available. An Engineering Rotation Program is also available for those interested in diversifying their work experience.

Since 1949, more than 5,500 men and women have earned advanced degrees in engineering and science with the help of Hughes fellowships. We hope you'll join us in creating the next generation of technological wonders, by pioneering the future—yours and ours.

Hughes Aircraft Company, Corporate Fellowship Office
Dept. MC-8788, Bldg. C1/B168, P.O. Box 45066, Los Angeles, CA 90045-0066
Please consider me a candidate for a
Hughes Fellowship and send me the necessary information and application materials.

PLEASE PRINT: Name ______ Date ______ Home Phone & Hours ______

Address ______ City ______ State ______ Zip ______

I am interested in obtaining a Master's ______ Doctorate ______ in the field of: ______

Rotation Program Interest: *Yes* ______ *No* ______ *Microwave Program Interest:* Yes ______ No ______

DEGREES NOW HELD OR EXPECTED:

Bachelor's: Field ______ Date ______ School ______ GPA ______

Master's: Field ______ Date ______ School ______ GPA ______

Minimum GPA-3.0/4.0. Proof of U.S. Citizenship May Be Required. Equal Opportunity Employer.

HUGHES
AIRCRAFT COMPANY

ENGINEERING & SCIENCE

California Institute of Technology
Pasadena, California 91125

The Sunraycer saga is illustrated by the empty bottles of victory champagne at the end of the World Solar Challenge and by Sunraycer's logo showing Paul MacCready's company, AeroVironment, positioned in the midst of the giant corporate entities of GM.

Wearing a garland of yellow roses, Sunraycer leads the Pasadena Rose Parade on January 1, 1988 as the "Pace Car of the Future."