SCIENTIFIC AMERICAN

SYNCHRONOUS FIREFLIES

$1.25

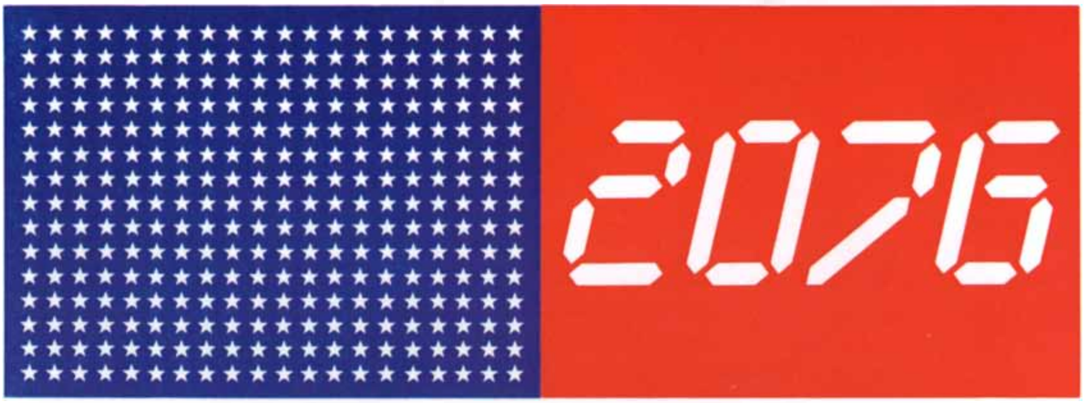
May 1976


This year, logic will drive many thinking people to Volvo showrooms.
Because Volvo has a reputation for being one of the world's most intelligently thought out cars.
But not all these people will drive out with the same Volvo.
For 1976, we have six different Volvos to choose from.
If you're interested in spending less money, you can choose one of our basic Volvo 240s.
242
245
NOT ALL PEOP
THINK
Also on the Volvo 240s, you get steel-belted radials. And orthopedically designed front bucket seats with adjustable lumbar supports.
If you want to exceed these standards, you can order options like air conditioning, power steering with automatic transmission, overdrive and a sunroof.
Of course, for some people even these options won't be enough.
So for them, there's another option.
For thoughtful car buyers to whom money is not as big an object, we have the three objects on your immediate right.
The luxurious new Volvo 260s.
264
You can choose either the 2- or 4-door sedan. Or, if you carry many of your worldly possessions around with you, a 5-door luxury wagon.
The Volvo 260s come with everything the Volvo 240s do and more.
You get a bigger engine: an overhead cam fuel-injected V-6.
You also get power steering and your choice of automatic transmission or 4-speed manual with overdrive...all at no extra cost.
© 1976 VOLVO OF AMERICA CORPORATION


Either our 2-or 4-door sedan. Or our roomy 5-door wagon.
While you may be getting the lower end of our line, you won't be getting the short end as far as a car is concerned.
Every Volvo 240 comes loaded with standards that are well above the standard. You get a quiet, responsive overhead cam fuel-injected engine. 4-speed manual transmission. 4-wheel power disc brakes and rack and pinion steering.
LE WHO THINK,
ALIKE.
In the 260 GL sedans, you'll find many other luxuries that people of means consider necessities. Things like air conditioning. Real leather to sit on. Power front windows. A sunroof. A heated driver's seat. And metallic paint. All standard.
We realize that by giving you six Volvos to choose from, we haven't made things easy for you.
But look at it this way: when you're intelligent enough to make the basic decision to buy a Volvo, you're intelligent enough to decide just how basic that Volvo should be.
262
265
VOLVO
The car for people who think.

Atlantic Richfield invites you on a journey into the future.

The Tricentennial



America will change a great deal by the year 2076. Tell us what you think those changes should be.

We have always been a nation more interested in the promise of the future than in the events of the past.

Somehow, the events of the past few years have made us doubt ourselves and our future.

Here at Atlantic Richfield, however, we see the future as an exciting time. The best of times. And we know that all of us can achieve a splendid future by planning for it now.

We'd like your help. We need your vision. We want you to tell us about the changes you would like to see take place in America – and in our American way of life.

For example:
What ideas do you have for making life more fun than it is now?

What changes would you like to see in government? (City? State? Federal?)

What do you envision as the best way to solve our energy problems?

What about the future of business? (More regulation by government? Less?)

What measures would you take to protect the environment?

Or, if those topics don't appeal to you, pick one that does.
How should our physical world be altered? Do you recommend that we live underground? In plastic bubbles?

Will family life change? Will we choose a spouse by computer? Will divorce become illegal?

What should our schools be like? Should machines replace teachers?

What will make us laugh? What will be funny that isn't funny now?

What new major sports would you like to see? Three-dimensional chess? Electronic billiards?

Whatever your idea may be, we want to know about it. Write it. Draw it. Sing it. But send it.

In about six months we plan to gather your responses, analyze them, and make a full report on what we've found out. We believe the report will provide a fascinating and valuable view of America's hopes, dreams, fears, and visions. We'll make sure it reaches the people who are in positions to consider and act on it.

Along the way we will make television commercials and newspaper and magazine ads out of many of the ideas so you can see what other people are thinking.

Please note that all ideas submitted shall become public property without compensation and free of any restriction on use and disclosure.

Send your idea to:
Tricentennial
Atlantic Richfield Company
P.O. Box 2076
Los Angeles, CA 90053

ARCO

Petroleum Products of
AtlanticRichfieldCompany

Celebrate America's Tricentennial 100 years early.

Established 1845 **SCIENTIFIC AMERICAN** May 1976 Volume 234 Number 5

ARTICLES

DEPARTMENTS

PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK, N.Y. 10017. SECOND-CLASS POSTAGE PAID AT NEW YORK, N.Y., AND AT ADDITIONAL MAILING OFFICES. AUTHORIZED AS SECOND-CLASS MAIL BY THE POST OFFICE DEPARTMENT, OTTAWA, CANADA, AND FOR PAYMENT OF POSTAGE IN CASH. SUBSCRIPTION RATE: $15 PER YEAR, U.S., ITS POSSESSIONS AND CANADA; $18 PER YEAR, ALL OTHER COUNTRIES.

THE COVER

The painting on the cover shows nine fireflies of the genus *Pteroptyx*. One (*center*) is a female; the other eight are males whose courtship is conducted while they are assembled on selected trees in large numbers and flashing in unison (see "Synchronous Fireflies," by John and Elisabeth Buck, page 74). The fireflies shown are of a species common in Southeast Asia, *P. malaccae;* the tree they occupy is a mangrove. The five males surrounding the female have tilted their abdomens toward her in order to maximize the brightness of their flashes. Males at upper right and lower left are members of two adjacent courtship groups and are tilting toward females that are out of sight.

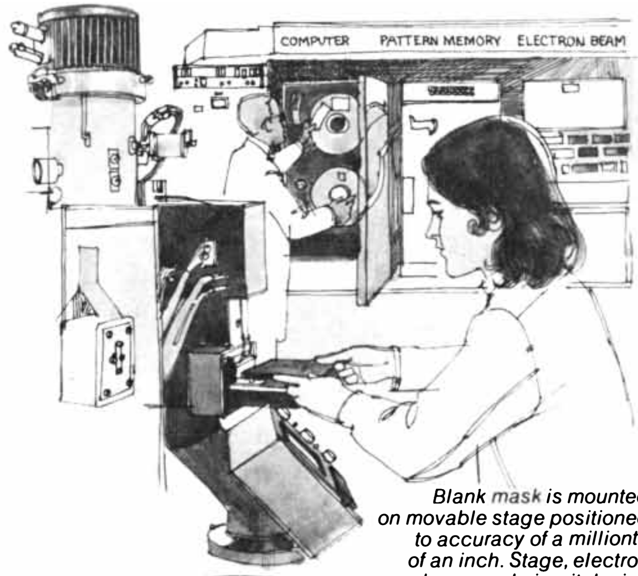
THE ILLUSTRATIONS

Cover painting by Tom Prentiss

Page	Source
25–29	Dan Todd
31	Michael A. Edidin (*top*), Martin C. Raff (*bottom*)
32–34	Bunji Tagawa
35	Bunji Tagawa (*top*), Martin C. Raff (*bottom*)
36	Martin C. Raff
38–39	Bunji Tagawa
41	J. S. Benjamin
42	George V. Kelvin
43	George V. Kelvin (*top and bottom left*), J. S. Benjamin (*bottom right*)
44	George V. Kelvin
45	J. S. Benjamin
46	J. S. Benjamin (*left and right*), George V. Kelvin (*middle*)
47	J. S. Benjamin
48	George V. Kelvin
58	Fritz Goro
60–61	Carol Donner
62	Carol Donner (*top*), Judah Folkman (*bottom*)
63	Carol Donner
64	Andrew Christie
70–72	Carol Donner
73	Andrew Christie
75	Ivan Polunin (*top*), John Buck (*bottom*)
76	Tom Prentiss
77–84	Lorelle M. Raboni
86–96	Gabor Kiss
99	I. Bernard Cohen
100	National Portrait Gallery, London (*top*); I. Bernard Cohen, (*bottom*)
101–105	I. Bernard Cohen
109	National Aeronautics and Space Administration
110	R. B. Minton (*top*), National Aeronautics and Space Administration (*bottom*)
111	University of Michigan Library
112–114	Adolph E. Brotman
116	Smithsonian Institution, Mount Hopkins Observatory (*top*); Adolph E. Brotman (*bottom*)
119–123	Andrew Christie
124	*Nuclear Tracks in Solids: Principles and Applications.* © 1975, University of California Press
126	*The Structure of the Elements.* © 1974, John Wiley & Sons, Inc.
127	*James Clerk Maxwell: Physicist and Natural Philosopher.* © 1975, Charles Scribner's Sons

Western Electric Reports:

Electron beam mask marvel.



Blank mask is mounted on movable stage positioned to accuracy of a millionth of an inch. Stage, electron beam and circuit design instructions are computer controlled.

Integrated circuits can be seen as the ultimate extension of the art of silk-screening and modern electronics. Using masking techniques which go far beyond those of silk-screen artists, it is possible to generate thousands of electronic components on a tiny chip the size of a matchhead.

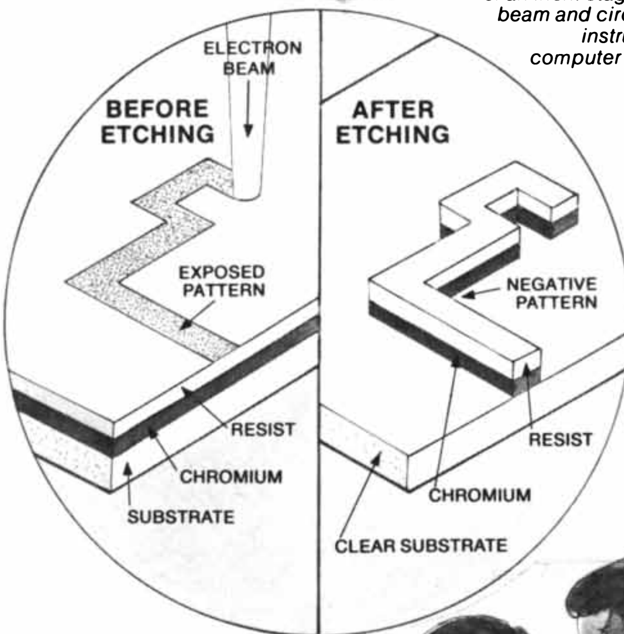
But as designers pack more and more components onto these chips, the masks used to generate them must be made with even greater precision. Conventional photographic mask-making techniques are proving too crude to produce such masks economically, severely limiting integrated circuit technology.

But now a Bell System team has made a major advance in the mass production of extremely precise masks. Bell Labs engineers have devised a method of using a beam of electrons to make the masks. And Western Electric engineers have helped design practical production equipment.

The new method is faster, more reliable, more precise and less expensive than existing photographic techniques. Because an electron beam has a shorter equivalent wavelength than light, it is a much sharper stylus. It can be focused to a spot 10 millionths of an inch in diameter.

The electron beam is used to draw an intricate pattern on a chromium-coated glass substrate, covered with a chemical film sensitive to the beam. The chemical film, called a resist, polymerizes or "sets" after exposure to the beam, becoming impervious to the chemicals that will subsequently be used to etch out the mask. The unexposed portions of this film and the underlying chromium are etched away, leaving a negative mask pattern of chromium on glass.

Benefit: Electron beam mask-making is one more manufacturing innovation that allows the Bell System to meet your communication needs reliably and economically.



Electron beam changes physical characteristics of exposed resist so that, after chemical etching, pattern is left on clear substrate.

Finished substrate may contain 10,000 mask patterns. Copies of master masks will be used in actual production.

Western Electric

How do you know if you have Isuzu?

Did you wake up this morning and find a handsome little car sitting in your driveway?

When you drove it, did you have a nice time?

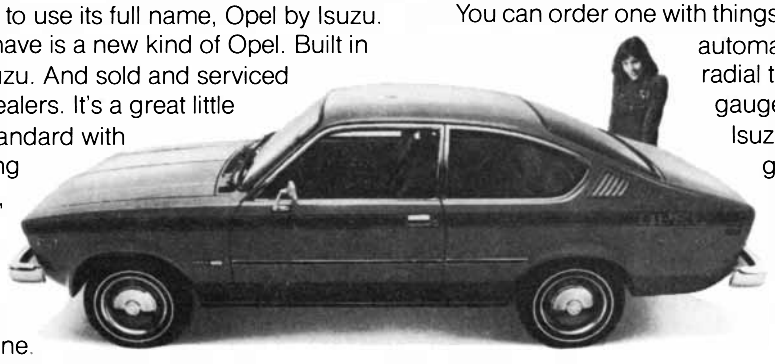
Do you seem to be developing a maniacal giggle when going past gas stations?

Have you shaken hands with a Buick-Opel dealer recently?

If you answered "yes" to the above questions, chances are, you have it.

Isuzu. Or to use its full name, Opel by Isuzu.

What you have is a new kind of Opel. Built in Japan by Isuzu. And sold and serviced by Buick-Opel dealers. It's a great little car that comes standard with things like reclining bucket seats, tinted glass, flow through ventilation, and an 1817 cc overhead cam engine.



Equipped with hemispherical combustion chambers, cross-flow head and five main bearings.

Which, when coupled with Isuzu's standard short throw four-speed transmission, delivered 23 mpg in the EPA city test. And 36 in the highway test. (Of course, these are estimates.

The mileage you get may vary depending on how you drive, where you drive, and the condition of your car.)

You can order one with things like air conditioning, automatic transmission. radial tires, a console full of gauges and more. Opel by Isuzu. If you'd like to get it, go see your Buick-Opel dealer.

For those of you who already have it, there's only one thing to do. Go take it for a drive.

OPEL ISUZU

SOLD BY BUICK

In California see your Buick-Opel Dealer for EPA information.

GM

MARK OF EXCELLENCE

LETTERS

Sirs:

I read with interest, and with growing indignation, the lead article in the February issue of *Scientific American,* "The Ethics of Experimentation with Human Subjects." It is an important and troublesome subject, and the author of the article, Bernard Barber, professor and chairman of the department of sociology at Barnard College, had many provocative observations on strict and permissive investigators and on the difficult concept of obtaining truly informed consent from subjects. Indeed, there is an urgent need for constant vigilance in the field of experimentation with human subjects and for scrutiny of the ethics of clinical investigators. There may also, however, be a need to scrutinize the ethics of some sociological investigators.

In the article Professor Barber describes among other data the feedback he and his group, named the Research Group on Human Experimentation, received from investigators responding to a mailed questionnaire. The questionnaire included six simulated detailed research protocols constructed with careful attention to the research literature and reportedly checked with specialists and pretested on a dozen chiefs of research at medical centers, who found them to be convincingly real. Two of the six protocols are reproduced in the article. One outlines a study in which a randomly selected sample of children and adolescents with correctable congenital heart disease would undergo thymectomy at the time of surgery, after which they would receive a full-thickness skin graft from an unrelated adult donor and would be observed for the survival of the graft. The second study involved injecting radioactive calcium with a recognized leukemogenic potential into healthy children in order to use them as normal controls in a metabolic study of children suffering from a serious bone disease. These protocols are said to have been sent to 300 biomedical research institutions. Most remarkable of all, busy and dedicated investigators in 293 of the institutions took the time to respond to them. Although a 98 percent return on a mailed questionnaire is unique, the analysis of the windfall is even more fantastic, revealing that 28 percent of investigators would approve removing a normal thymus, the master organ for immunologic defense in children, in order to see how a skin graft would do, and that 46 percent were willing to allow the injection of radioactive calcium into normal children. It is hard to believe a dozen chiefs of medical research could find these protocols "convincingly real," that 98 percent of busy investigators would waste their time and energy on this preposterous questionnaire and that Professor Barber and his group could have found investigators who would have approved such criminal procedures. I do not know how the former obtained these data, but the article certainly raises some questions about ethics, and not necessarily those of the biomedical profession.

ALLAN J. ERSLEV, M.D.

Jefferson Medical College
Philadelphia, Pa.

Sirs:

First, with regard to our sample and our response rate, I should like to inform Professor Erslev that the 293 investigators from the same number of institutions are only those out of a total of 681 institutions to which we sent our questionnaire. In my article I did not go into all the details of sampling and representativeness. (The nearly 300 and the 293 are meant to refer to the same number, and that is the representative sample we got from the 681.) Similarly, the 350 individual interviews are only those we were able to get out of the larger number that fell into our two-institution universe. If Professor Erslev would like more details of our methodology, he can find them in Chapter 2 of our book *Research on Human Subjects* (Russell Sage, 1973).

Second, as to Professor Erslev's complaint that our protocols are not, as I say, "convincingly real," I shall have to stand on the evidence I presented as to how they were selected, discussed, criticized, tested by distinguished medical researchers and then all too realistically responded to by our final sample. If such results still seem unreal to Professor Erslev, he might want to look at further detailed evidence on unethical

Scientific American, May, 1976; Vol. 234, No. 5. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and secretary; George S. Conn, treasurer; Arlene Wright, assistant treasurer.

Editorial correspondence should be addressed to The Editors, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. Manuscripts are submitted at the author's risk and will not be returned unless accompanied by postage.

Advertising correspondence should be addressed to C. John Kirby, Advertising Director, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

Offprint correspondence and orders should be addressed to W. H. Freeman and Company, 660 Market Street, San Francisco, Calif. 94104. For each offprint ordered please enclose 30 cents.

Subscription correspondence should be addressed to Subscription Manager, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. For change of address, notify us at least four weeks in advance. Send both old and new addresses and enclose an address imprint from a recent issue. (Date of last issue on your subscription is shown at upper right-hand corner of each month's mailing label.)

Name ______

New Address ______

______

______

Old Address ______

______

______

studies presented by two medical men. The first is Professor Henry K. Beecher of the Harvard Medical School. Professor Erslev might want to examine Professor Beecher's article in *The New England Journal of Medicine* in 1966, listing 25 unethical studies actually published in leading medical journals. (These 25 were only part of a larger number he had found.) Professor Erslev might also want to read Professor Beecher's book *Research and the Individual* (Little, Brown, 1970). Finally, Professor Erslev might want to examine a book by M. H. Pappworth reporting similar unethical researches in England: *Human Guinea Pigs* (Beacon Press, 1968).

In sum, if Professor Erslev would look further into our methodology and into other materials, I think he would come to the conclusion that our questionnaire is not, as he says, "preposterous."

I do think that ethics of medical research have improved somewhat over the past five or six years. They have not, however, improved enough.

BERNARD BARBER

Barnard College
New York

Sirs:

Referring to my article on the prevention of smallpox before Jenner [SCIENTIFIC AMERICAN, January], I have received an interesting letter from A. Maugham of the Institute of Animal Physiology (Babraham, Cambridge, England). Dr. Maugham enclosed a photograph of a tombstone he had discovered some 40 years ago in the cemetery of a small village in the Purbeck Hills of southeastern Dorsetshire. He writes that he again visited the cemetery within recent years and found the tombstone intact, and in fact somewhat refurbished. The inscription on the tombstone seems to me to be of some interest and reads as follows:

"Sacred to the Memory of Benj^m Jesty of Downshay who departed this life April 16, 1816, aged 79 years. He was born at Yetminster in this County and was an upright, honest man particularly noted for having been the first Person [known] that introduced the Cow Pox by inoculation, and who from his great strength of mind made the Experiment from the [Cows] on his wife and two sons in the year 1774."

There is nothing implausible in this claim, since it was popularly believed in the dairying counties (including Jenner's native Gloucestershire) that the beautiful complexion of dairymaids was due to their having contracted cowpox and thus having acquired immunity against smallpox. The notion had come to Jenner's attention as early as 1770, when he was still an apprentice. Impressed by the possibility of employing cowpox, which he believed to be a variant of human smallpox, he discussed the subject with his eminent London teacher, John Hunter, and with other physicians, none of whom seems to have raised serious objec-

*Details on request. Call CDC collect (612) 853-7600 for **Delta Air Lines** System Summary. Or write Control Data Corporation, P.O. Box 1980, Twin Cities Airport, St. Paul, MN 55111.

CONTROL DATA CORPORATION

tions. It is quite likely that Jesty gave his family immunity against smallpox by using the virus of cowpox, but this does not diminish the discovery by Jenner, who in 1796, after years of study, inoculated a young woman with cowpox and, after a decent interval, "vaccinated" a boy with a virus not from a cow but from the young woman's pustule. He was able to demonstrate that the boy acquired the same immunity against smallpox as the young woman. In short, he proved that the relatively innocuous cowpox virus could be used in place of the dangerous smallpox lymph.

It may be noted that Jesty, although he lived for almost two decades after the publication of Jenner's essay and the widespread excitement over Jenner's achievement, never advanced a claim to prior discovery. His name is therefore of interest rather than of importance in the history of the battle against one of the direst of human afflictions.

WILLIAM L. LANGER

Cambridge, Mass.

Sirs:

I must object to Randall Gloege's letter [SCIENTIFIC AMERICAN, March] concerning Genevieve Atwood's article "The Strip-mining of Western Coal" [SCIENTIFIC AMERICAN, December, 1975]. Gloege, the Friends of the Earth, the Sierra Club and various other "environmentalists" and environmental groups all want radically new "clean" energy technologies. So far I have not heard any of them describe in detail any feasible alternatives of their own to our energy problems. Gloege wants a radically new energy technology. What are his suggestions? What are we as a nation and a people supposed to do while the Friends of the Earth demand new technologies yet offer no new alternatives or suggestions to efficiently replace existing technologies? I suggest that these so-called environmental groups do not have the knowledge to fully understand the technologies that exist today, let alone the knowledge to implement the radical new energy technology Gloege is calling for. . . .

It is just as ridiculous to rule out mining as a necessary land use as it is to rule out agriculture or lumbering as necessary land uses. It is just as possible to reclaim mined lands as it is to replant "mined" forests. In states where reclamation laws are somewhat flexible and where mining companies are allowed to participate in the design of the laws, reclamation does take place and the land is returned again to a natural condition, often in a better and more productive condition than before it was used to produce coal. "Tough" legislation, bureaucratic threats and harassment from people who do not know the difference between "tough" and "cooperative" are the direct cause of reclamation programs that will not and cannot work.

I am in full agreement that better energy-production techniques do exist, and that there should be a national commitment to the development of new energy technology. We need a national awareness of the need to conserve what we have while we develop new technologies for our future needs.

The opportunity to work with people in order to produce sound environmental controls that will enable us to exist in an advanced state and will enable us to develop better futures for those who come after us is an exciting proposition. Restrictive laws pushed through Congress by extremists will only get us into an energy hole we might never get out of.

Mining and agriculture are the world's two basic industries. Both industries have existed throughout the development of man. In fact, advances in both industries result in direct advances in man's way of life. The two industries are closely interrelated. Modern agriculture depends on machinery, and there has to be coal in order to make steel. Unless we all live on farms, which we cannot, we need high-production agriculture not only to feed ourselves but also to help alleviate world food shortages when they occur. High-production agriculture needs steel and fuel. Miners need to eat too.

Output from underground mines is not enough to supply future needs for coal as world oil reserves are depleted. Not only will new jobs be created in new strip mines but also old jobs in underground mines will remain, since the demand for Eastern coal in the East will not end. I suggest that the Friends of the Earth should investigate more thoroughly the projected future demands for coal and the need for more miners, not fewer, before they publish views on the labor needs of an industry they know nothing about.

It is my view that the strip-mining of coal does serve the needs of the people. At least the mining industry is trying to offer an alternative. The mining industry is not perfect. It needs the help of people with practical environmental advice. Our industries need the cooperation of everyone to help clean up our country. Restrictions on development without proper foresight can only lead to self-destruction. We need new technology, but we cannot scrap what we have until what we think is possible does in fact exist.

GARTH COLWELL

Reno, Nev.

Sirs:

In "Mathematical Games" [SCIENTIFIC AMERICAN, March] Martin Gardner cites a paper by the undersigned as a real-world demonstration of Simpson's paradox ("Sex Bias in Graduate Admissions: Data from Berkeley" in *Science,* Vol. 187, pages 398–404; February 7, 1975). He says: "Independent studies of admissions of men and of women . . . showed a positive sex bias against female applicants. Then when the data for men and women were combined, there was a small but statistically significant bias *in favor* of women."

The contrast given is misleading. When the data from the different *departments* of the university were simply added up and the differential rates of admission for the two sexes were examined at the *aggregate* level, there was a bias against women. When the departments were examined *individually,* there was no consistent bias against women. When the departmental data were properly *pooled,* taking into account the relation between the probability of admission regardless of the sex of the applicant and the propensity of the two sexes to apply in different proportions to departments of differing ease of admission, there emerged a small bias in favor of women.

P. J. BICKEL

E. A. HAMMEL

J. W. O'CONNELL

Department of Anthropology
University of California
Berkeley

We built this Toronado Brougham for Mark Pierce, who likes the feeling that no matter how bad the weather, front wheel drive will pull him through.

Mark doesn't exactly look forward to driving through a rainstorm. Or a snowstorm. Or ice. Or sleet. But sometimes he has no choice.

That's when he really appreciates Toronado's front wheel drive.

By pulling the car around corners and along straightaways instead of pushing it, front wheel drive provides impressive traction on rainy or snowy pavement.

Of course, people like Mark appreciate Toronado's engineering and its beautiful styling. But what you'll really enjoy is the "inner world" of Toronado—that feeling of serenity, of confidence. Even when weather or road conditions vary, you'll know your Toronado will get you through.

There's a lot to enjoy in the 1976 Toronado Brougham: beauty, personal-sized luxury, and the confident feel of front wheel drive. Come rain or come shine.

1976 TORONADO

Oldsmobile

Can we build one for you?

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1926: "Most earnestly do we commend to the attention of the public of America, and particularly of those who control the vast industrial interests of the country, the protest of Secretary Herbert Hoover against our failure to make adequate provision for research in the realms of pure science. In the past, thanks to our universities, industry has been well supplied with modern representatives of the great prototype, Isaac Newton. But the captain of industry has gathered in these gentlemen and set them to the special task of applied science research in the one limited field covered by his particular industry, so that today, for one investigator devoted to the detached field of pure science, there are ten at work in the special and limited fields of applied science in steel, textiles, chemical products, oil and so forth. It is the aim of Secretary Hoover and the National Academy of Sciences, which will administer the fund, to secure the sum of $20,000,000—the interest on which will be devoted entirely to pure science research."

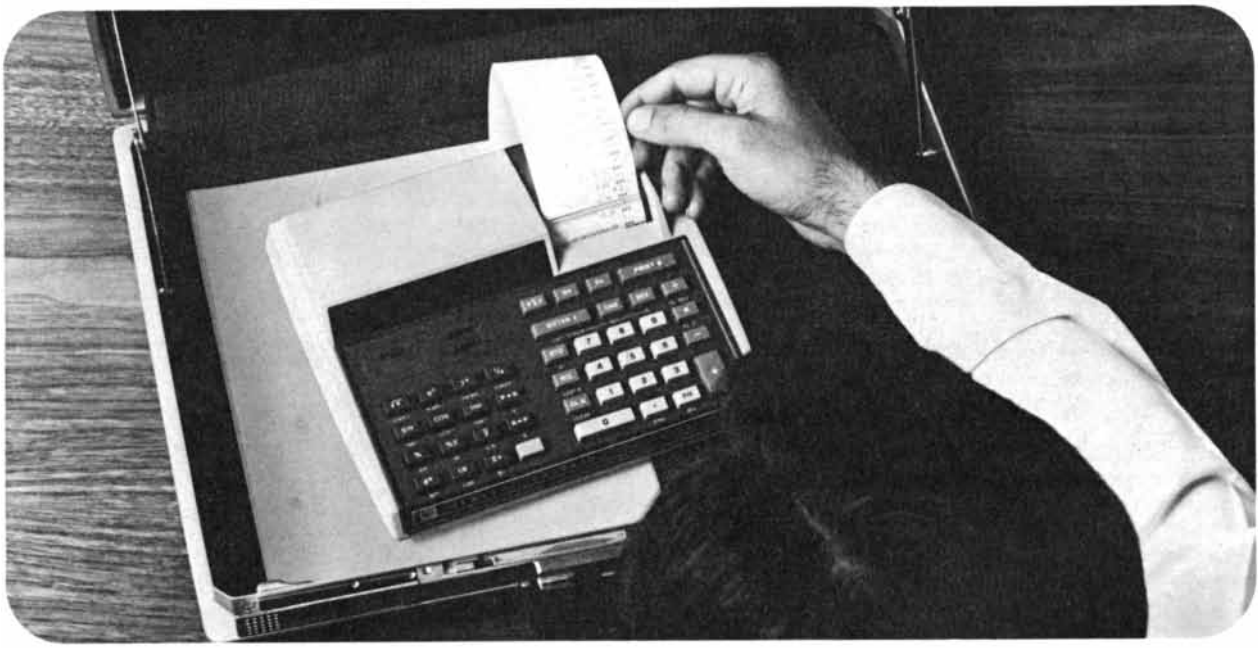
"The great outer planets of our system have been studied telescopically ever since the instrument was invented, yet there remains more to be done in our time, and more is still to be accomplished. Harold Jeffreys has recently calculated that the known facts about Jupiter could be explained by assuming that the planet has a solid core—as dense as rock—58,000 miles in diameter, surrounded by an ocean (or a layer of ice) 11,000 miles deep, and this again by an atmosphere of very low density, and 4,000 miles in height. The surface of the planet is very cold. Measures of the heat which it sends us show that almost all of it comes with the reflected sunlight, and very little from the surface itself, and that the temperature of the surface must be at least 120 degrees below zero on the Centigrade scale, and probably lower still. The conspicuous and rapidly changing markings on Jupiter's surface, which have long been recognized as of a cloudy nature, must therefore be due to clouds of some substance which condenses at a far lower temperature than water."

"Lieutenant Macready is trying hard to regain the world's altitude record, which the Army Air Service lost to the French aviation service. In a special Army Air Service plane he has reached a height of 37,579 feet. The world's record is 39,586 feet. At the side of the engine in Lieutenant Macready's plane is a new gear-driven super-charger. At high altitudes the air has so low a density that the power of the motor falls off very quickly. The super-charger compresses the rare air before it is delivered to the motor. It was a mechanical failure in the super-charger that prevented Macready from reaching his goal, which was 40,000 feet."

"Radio during the past winter season won many noted artists to the microphone, prominent among them Mme Schumann-Heink, John McCormack, Lucrezia Bori, Mary Garden, Louise Homer and Charles Hackett. All seem to have been attracted to the radio studios under the auspices of advertisers. Thus the desire to get the name of a firm or product known has greatly improved the quality of radio entertainment. Mme Homer was asked whether artists missed the applause they are accustomed to receiving from concert-stage audiences. 'Yes and no,' answered the prima donna. 'The hall may be filled with a storm of applause, but the artist alone knows whether it is deserved.'"

SCIENTIFIC AMERICAN

MAY, 1876: "The ceremonies of the opening day of the Centennial International Exhibition were grand, simple and impressive. The magnificent front of Memorial Hall formed the background for an immense platform 400 feet long, on which was seated the President of the United States, the Emperor and Empress of Brazil, the Foreign Ambassadors, members of the Supreme Court, Senate and House of Representatives, the Governor of Pennsylvania and a great throng of other distinguished personages. Memorial Hall has the main entrance in its centre, consisting of three colossal arched door-ways. Swinging open, the doors disclosed the interior of the Grand Central Pavilion, 120 feet square and nearly 100 feet high, surrounded and partly occupied by the richest exhibitions of the United States, Great Britain, France and the German Empire. The twenty-one acres to the east and west, sheltered by a single roof, were occupied by the exhibitions of thirty countries and their colonies, the richest and most powerful in the world. The transept gave passage to the procession, which moved up through the hall to where the Corliss engine appeared in repose. Surrounding this stupendous object stood seven railroad locomotives and numerous massy piles of stationary mechanism. The guests drew aside, leaving the President and Mr. George H. Corliss together in the centre. 'Now, Mr. President,' said Mr. Corliss. 'Well,' said the President quietly. 'How shall I do it?' 'Turn that little crank around six times.' In another half minute the screw was turned by General Grant, the colossal machine above him began to move, the miles of shafting along the building began to revolve, several hundreds of steel and iron organisms were set going, and a visitor who retraced his steps could



The HP Professionals—the calculators with the specialized capabilities you need—have a new member: the HP-91. It's scientific, it's portable, and it prints.

Our first battery-operated portable printing calculator, the HP-91 weighs only 2½ pounds (1.13 kg) and fits in your briefcase with plenty of room to spare. Like all the other HP Professionals, it uses HP's logic system with a four-register stack and a unique ENTER key that opens the door to answers you can trust. In addition, it gives you a complete printed record of your scientific calculations, whether you use it on battery power or line current.

The HP-91 Scientific Printing Calculator retains the convenience of a hand-held calculator while providing a "hard copy" record from a quiet thermal printer. So small and light that you can easily carry it in a briefcase, it operates on its own batteries for as long as seven hours before they need recharging.

Its comfortably large LED display shows up to 10 significant digits, plus a two-digit exponent and appropriate signs. While the HP-91's display shows all keyed numbers and answers, its printer operates in any of three modes: one provides a complete record of your calculations—all entered data, all functions, and all intermediate and final answers; the second records only entered data and functions; in the third, the printer operates only on keyed command.

The HP-91's buffered keyboard lets you enter data as fast as your fingers can press the keys—up to seven characters ahead of the printer—while the printer records the calculations at its own pace.

In terms of calculating power, the HP-91 provides a full range of functions for scientists and engineers. Its math capabilities include log; trig in degrees, radians, or grads; rectangular/polar conversions; and three separate percent functions. Its statistics capabilities include summations, two-variable mean and standard deviation, linear regression, linear estimates, and factorial.

The HP-91 also has 16 addressable memory registers, with register arithmetic capability in 10 of them; a "Last-X" register for easy error recovery; four convenient clearing operations; and a choice of display and printing in fixed decimal, scientific notation, or engineering notation (values with exponents that are multiples of three).

Price is $500* for the calculator with battery pack, recharger/AC adapter, case, 220-page applications and instruction handbook, and two rolls of thermal paper for the printer. Try the HP-91 at selected local retailers. You'll find it a new and recording experience.

Call 800-538-7922 in the U.S.A. (in California, 800-662-9862) for detailed information and the name of the HP retailer nearest you.

Now you can fully automate your chemical analysis lab without being a programming specialist—or hiring one.

The new Hewlett-Packard 3354A disc-based lab automation system acquires data from most analytical instruments on-line, is easily programmed to provide fully automatic data processing and report generation that's customized for each instrument, and uses easy-to-learn BASIC.

While full automation is the avowed goal of many computerized laboratory data systems, few actually achieve it. The discrepancy lies in two causes: either the data system hardware is not quite powerful enough to handle all the lab's requirements, or the software is too demanding, even with expert programming help—or both.

For the vast majority of analytical instruments in research and quality control labs, the new HP 3354A Laboratory Automation System completely eliminates both problems.

Based on HP's 15-million-byte cartridge disc and 21MX high-speed minicomputer, the 3354's hardware is powerful enough to handle as many as 30 instruments on-line while allowing concurrent program development on up to eight terminals.

But it's the 3354's applications software that makes it a true lab automation system rather than just another computerized data system. Through it, you can access full system power—including multiprogramming capability—in BASIC and computer-aided dialog. Even with no previous computer programming experience, your technicians will need only a few hours to learn enough dialog to operate the system—and you and your chemists can learn to use BASIC effectively for writing applications programs within a few days.

Most analytical instruments, and their accessories such as samplers, stream selection valves, and other relay-operated devices, are easily interfaced with the system's remote modules. In addition, you are assured of convenient communication between your applications programs and 3354 system programs for data acquisition, file creation, instrument control, and system status check. The result is that you can concentrate on processing and reporting instrument data your way—all completely automatically.

To give you an idea of the system's power and versatility, here's a sampling of some of the things you can do with it:

- Preprogram *each* channel independently of all others, for automatic selection of samples, calculation parameters, analysis routines, and reporting devices.
- Develop, debug, and test new programs on-line without disrupting system operation.
- Create your own interactive dialog to request and store parameters for your basic programs.
- Always store raw analytical data, and re-analyse it at any time.
- Generate files to structure a data base automatically, for managing your lab information.

Standard system prices including installation start at $51,250.*

For more information on these products, write to us, Hewlett-packard, 1504 Page Mill Road, Palo Alto, California 94304.

HEWLETT hp PACKARD

Sales and service from 172 offices in 65 countries

Mail to: Hewlett-Packard, 1504 Page Mill Road, Palo Alto, CA 94304.
Please send me further information on

( ) HP-91 Scientific Printing Calculator
( ) 3354A Laboratory Automation System

Name ____________________
Company ____________________
Address ____________________
City ____________ State ______ Zip ______

*Domestic USA prices only.

00644

examine the processes of half of the important manufactures on the globe."

"In Machinery Hall at the Centennial Exhibition, Messrs. Lange & Otto have now erected five of their 'atmospheric gas engines,' ranging from 1/4 to 3 H.P., and a petroleum engine of similar design. For all purposes requiring small powers the gas engine is fast becoming a quite formidable competitor to the steam engine. Messrs. L & O claim to have more than 3,000 of their engines now in use. This engine differs very materially from the Lenoir, Brayton and other gas engines, and in several respects it may be regarded as an advanced step toward the solution of the grand problem of the day, that of converting the potential energy of heat into work."

"Whoever has occasion to travel back and forth on the boats of the Fulton Ferry must frequently be amused by the somewhat crude guesses he hears made as to the height, breadth and total weight of the New-York and Brooklyn Bridge towers. From the high-water line to the flooring the vertical distance is 119 ft., and from the flooring to the roof 149 ft., thus making a total height of 268 ft. This height has been based upon a careful classification of the vessels sailing in and out of the harbor, and is sufficient to afford free passage to all steamers and all barks, sloops, schooners and brigs under 1,000 tons. Ground was broken for the Brooklyn tower in the summer of 1870 and for the New-York tower two years later. The former is now entirely completed with the exception of the balustrade, which can not be added till the cables are in place."

"According to Professor A. Guyot of Princeton, N.J., the islands of the Pacific are of two kinds, called the lower and the higher. The lower rise but 7, 10 and rarely as high as 100 feet above the level of the sea, while the higher islands reach an elevation of 10,000, 12,000 and even 15,000 feet. There is no transition between them. The most remarkable are the lower islands. Their appearance is very peculiar. The eye is arrested by a white beach; then comes a line of verdure, due to tropical trees; then a lagoon of quiet water of a whitish or a yellowish color, then another line of verdure, and finally, beyond all, the dark blue waves of the ocean. The lagoon inside is but a few fathoms deep, but on the outside of the island the water is 15,000 feet deep. Here then we evidently have a tower-like structure reaching up from the bottom of the sea, and having a depression in its summit."

"The Western Union Telegraph Company have begun the work of laying the telegraph wires in New-York underground. It is greatly to be hoped that this system of underground telegraphy may be extended throughout the whole city, to the exclusion of the present unsightly poles. That the plan is fully practicable has been amply demonstrated in London and other cities."

“The most complete and most scholarly dictionary of the English language”

—The Christian Science Monitor

As an introduction to membership in the

BOOK-OF-THE-MONTH CLUB®

yours for only $17.50

[Publisher's list price $90]

THE SUGGESTED TRIAL: You simply agree to buy four Club choices within a year at substantial savings on most books you choose.

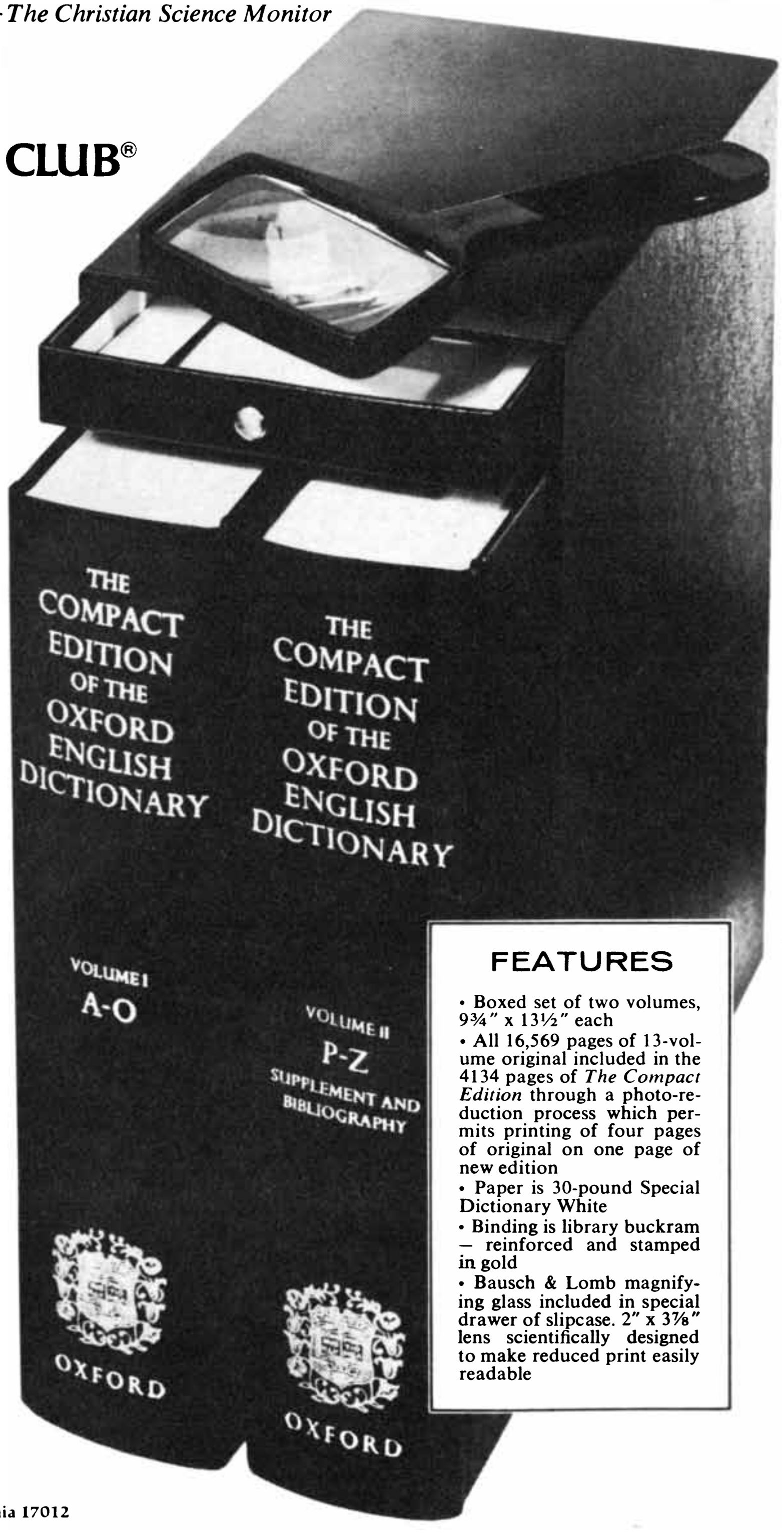
THE OXFORD ENGLISH DICTIONARY is generally regarded as the final arbiter of the English language. Until recently it had been available only as a thirteen-volume set, currently priced at $395. Now, through the combination of an ingenious method of micrographic reproduction and a fine Bausch & Lomb optical lens, every single one of its 16,569 pages, fifty million words and close to two million illustrative quotations appears, in easily readable form, in *The Compact Edition.*

> The *New York Times* book critic Christopher Lehmann-Haupt has said of this edition: “It is something of a miracle. . . . *The Compact Edition* is easier to work with than the original with its 13 separate volumes.”

Even more extraordinary, as a trial member of the Club you may obtain the two-volume set for only $17.50. And as long as you remain a member, you will receive the Book-of-the-Month Club *News*,® a literary magazine announcing the coming Selection and describing other important books, known as Alternates, most of which are available at substantial discounts – up to **40%** on more expensive volumes.

If you continue after your trial membership, you will earn at least one Book-Dividend® Credit for every Selection or Alternate you buy. These Credits enable you to acquire for your library a wide variety of books, called Book-Dividends, at astonishing savings—*at least 70% of publishers' list prices.*

All Book-of-the-Month Club books, including Book-Dividends, are identical to the publishers' editions in content, format, size and quality.



FEATURES

- Boxed set of two volumes, 9¾" x 13½" each
- All 16,569 pages of 13-volume original included in the 4134 pages of *The Compact Edition* through a photo-reduction process which permits printing of four pages of original on one page of new edition
- Paper is 30-pound Special Dictionary White
- Binding is library buckram – reinforced and stamped in gold
- Bausch & Lomb magnifying glass included in special drawer of slipcase. 2" x 3⅞" lens scientifically designed to make reduced print easily readable

BOOK-OF-THE-MONTH CLUB, INC., Camp Hill, Pennsylvania 17012

Technology: Adam Smith,

In 1776, Adam Smith wrote *The Wealth of Nations,* the first definitive treatise on a free-market economic system. From it every schoolchild learns about "laissez-faire": the principle that government should adopt a "hands off" attitude toward business.

That principle brought about a reciprocal relationship between technology and the marketplace that has been the motivating force behind our development.

Technology, directed towards real needs, fostered economic growth. And economic growth generated capital for further investment in technology.

But a parallel relationship between government and technology has also developed. Now we realize that, if it continues, technology's future may not be as bright as its past.

The two marketplaces.
There are two marketplaces in our economic world. The first is a competitive marketplace in which technology has always enjoyed a human dimension. People have wanted a better way of life, and industry has responded with the workaday technologies and new products to make it possible. This is Adam Smith's "invisible hand" working its magic in the marketplace, or the law of supply and demand.

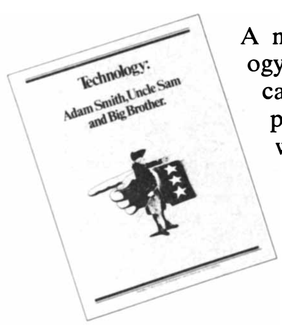
For the past 35 years, however, there has been a second, noncompetitive, marketplace for which technology has worked a different kind of magic. From the Manhattan Project to the first footsteps on the moon to the energy shortfall, government has called on technology to fill its needs, its wants. But there are only so many scientists, engineers, factories, and hours.

The second, noncompetitive, marketplace has operated at the expense of the first.

The second marketplace has moved away from the workaday technologies.
Government technology tends to divert resources from the everyday marketplace problems of supply and demand. It operates with a singlemindedness of purpose very different from the give-and-take technology of the first marketplace.

Perhaps it works too well. We have defended ourselves, and we have turned science fiction into

We believe in the promise of technology.



A misunderstanding of technology's role in man's advancement can only diminish its ability to provide solutions. Therefore, we're sponsoring a series of "white papers" to foster a clearer understanding of technology. Excerpts from number six are published above. For the complete text, write Gould Inc., "Dialogue on Technology," Dept. SA6, at the address below.

Gould is an electrical, electronic and industrial products company, committed to above-average earnings, growth and new product development. Technology is important to us because we put it to work in products like batteries, instruments, electric motors and controls, and other industrial components. For a copy of our annual report write Gould Inc., "Annual Report," Dept. SA6, 10 Gould Center, Rolling Meadows, Illinois 60008.

Uncle Sam and Big Brother.

science fact. As a result, we have become the world leaders in high technology.

But now the long-neglected, everyday problems of the first marketplace are rearing their heads: energy, communications, mass transit, health and raw materials.

The needs of the first marketplace are becoming first priority once again.

Technical bureaucracy—
an "invention" in the way of invention.
Just when we need all the free-wheeling creativity and imagination we can muster, it is apparent that our free enterprise system isn't quite as free as it once was. The government has built a technological launch pad from which all projects, ideas and dollars seemingly must spring.

But the hard task of creating new workaday technologies is not the same as single-goal projects like splitting the atom or designing a rocket.

There are now too many problems and too many technologies to be centrally controlled—better gas mileage, oil-from-shale removal schemes, electrochemical advances and new ideas in metallurgy.

The great workaday technologies of the past could not have been developed on that basis. Today's problems can't be solved that way either.

Government and technology.
Not just government technology.
Industry needs more help from Uncle Sam and less from Big Brother. Incentives to compete with federal R&D programs, not subsidies, are required. Antitrust policies that don't break up our best chances for discovery must be initiated. Space and defense technologies, developed at the expense of the workaday technologies, should be made more available. There must be less technological intervention, more technological freedom.

Does this mean government must withdraw from research and development, science and technology? No, but it does mean government must stop dictating their direction.

A new technological laissez-faire.
A restoration of the dynamic relationship between technology and the marketplace is required if we wish to solve the problems at hand and continue to advance our material well-being.

The purposeful application of free-market forces—capital investment, technical know-how, organizational skill, and public need—can do it.

Let's not forget how we got where we are today. Let's put the magic back in the marketplace.

Science and technology can solve many problems. If they don't, what else will?

GOULD

The product development company

THE AUTHORS

NEAL P. COCHRAN ("Oil and Gas from Coal") is acting deputy director of the Demonstration Plants Division of the Energy Research and Development Administration (ERDA). A 1939 graduate of the University of Notre Dame, where he majored in chemical engineering, Cochran served in the armed forces during World War II as a member of the Chemical Warfare Service and the Corps of Engineers. After his discharge in 1946 he worked in industry for several years, primarily as a designer of chemical-processing equipment. He was recalled to military service during the Korean war, and for the next decade or so he worked on a variety of projects for the U.S. Army Chemical Corps; his final assignment was as chief engineer and head of the technical engineering division of the Corps's Biological Laboratories at Fort Detrick in Maryland. In 1961 he joined the Office of Coal Research, where he was put in charge of a research and development program on ways to improve and increase the use of coal in the U.S. In his present position he is responsible for the design, construction and operation of large-scale demonstration plants designed to establish the technical and economic feasibility of coal-conversion processes.

MARTIN C. RAFF ("Cell-Surface Immunology") is a member of the department of zoology at University College London, where he serves as codirector of the Medical Research Council's Neuroimmunology Project. A native of Canada, he received his undergraduate degree from McGill University in 1959 and his M.D., also from McGill, in 1963. He then worked for two years as an intern and medical resident at the Royal Victoria Hospital in Montreal and three years as a resident in neurology at the Massachusetts General Hospital. "After spending nine years training to become a clinical neurologist," he writes, "the threat of being drafted into the American armed forces catalyzed my migration from Boston to London to spend two years as a postdoctoral fellow in experimental immunology at the National Institute for Medical Research in Mill Hill. My plans to return to America and clinical medicine evaporated in the sun of science and the charm of Europe."

J. S. BENJAMIN ("Mechanical Alloying") is head of the materials-research group at the International Nickel Company's Paul D. Merica Research Laboratory in Suffern, N.Y. He received his professional training at the Massachusetts Institute of Technology, acquiring a doctorate in metallurgy there in 1965. In addition to his primary research-management responsibilities for INCO, he reports, "I find some release and relief in totally unrelated activities. I have enjoyed hiking in the Adirondacks for about 10 years, and to date I have climbed 35 of the 46 peaks in that range with altitudes exceeding 4,000 feet.... I have also pursued painting for about 20 years, and I occasionally take both a passive and an active role in the science of zymurgy (a branch of applied chemistry that deals with fermentation processes)."

JUDAH FOLKMAN ("The Vascularization of Tumors") is Andrus Professor of Pediatric Surgery at the Harvard Medical School and chief surgeon at the Children's Hospital Medical Center in Boston. He was graduated magna cum laude from Harvard Medical School in 1957 and trained in general surgery at the Massachusetts General Hospital and in pediatric surgery at the Philadelphia Children's Hospital. Ever since medical school, he notes, "my paramount interest has been in bringing the problems of the patient into the laboratory and the advances of research to the bedside. For me personally, the union of basic biology and clinical medicine can best be forged by active involvement in both disciplines."

JOHN and ELISABETH BUCK ("Synchronous Fireflies") have collaborated on one thing or another since their student days at Johns Hopkins University in the 1930's. John Buck, who obtained his Ph.D. in zoology from Johns Hopkins in 1936, is currently chief of the laboratory of physical biology at the National Institutes of Health. The present article, he writes, "brings full circle a story that began more than 40 years ago in the depths of the Great Depression when I spent my unemployable student summers at Johns Hopkins in breaking the communication code and establishing circadian rhythmicity in a local Baltimore firefly. Then, after a long interlude in chromosome cytology and insect respiration, I managed to trap a couple of young neurophysiologists into retreading me, and this led in due course to the exciting travels to the Far East and the chance to study firefly synchrony at first hand.... If I have an epitaph, it should read: 'Lived through the golden age of science and worked on a lovely and mysterious animal.'" Elisabeth Buck, who has an A.B. in zoology from Radcliffe College and an M.A. in psychology from Johns Hopkins, was introduced to firefly research by her husband on an expedition to Jamaica in 1941. She has recently resumed full-time involvement in the work, following an extended hiatus during which she raised their four children.

ALFRED SCHARFF GOLDHABER and MICHAEL MARTIN NIETO ("The Mass of the Photon") are theoretical physicists. Goldhaber is associate professor at the Institute for Theoretical Physics of the State University of New York at Stony Brook. A graduate of Harvard University, he obtained his Ph.D. from Princeton Uni-


I always drink Cuervo Gold.
Now & then.
When the usual begins to feel a bit too usual, try some Cuervo Especial on the rocks.
Not to replace your scotch or vodka or whatever. But to substitute for it, now and then.
Of course you might cause a slight lowering of voices and raising of eyebrows.
Common folk tend to do that sort of thing.
Cuervo Especial
Try it on the rocks.
CUERVO ESPECIAL® TEQUILA. 80 PROOF. IMPORTED AND BOTTLED BY © 1976 HEUBLEIN, INC., HARTFORD, CONN.

versity in 1964. After three years at the University of California at Berkeley he went to Stony Brook, where his collaboration with Nieto began. A specialist on the theoretical side of both nuclear physics and particle physics, he describes himself as having "recently been obsessed with the ramifications of the controversial report of a magnetic-monopole observation." Nieto is currently a member of the theoretical division of the Los Alamos Scientific Laboratory. He did his undergraduate work at the University of California at Riverside and went on to acquire his Ph.D. in 1966 from Cornell University. Before joining the staff at Los Alamos in 1972, he worked at a number of institutions in the U.S. and abroad, including Stony Brook, the Niels Bohr Institute of the University of Copenhagen and the Research Institute for Fundamental Physics of Kyoto University. Apart from the subject of this article his interests in physics range from applications of wave equations in high-energy particle interactions to many-body problems in astrophysics. He has written a book on the Titius-Bode law of planetary distances and is also an active violinist; he notes that he therefore belongs to the musicians' union as well as the physical society.

I. BERNARD COHEN ("Stephen Hales") is professor of the history of science at Harvard University. His association with Harvard spans more than 40 years. He was an undergraduate there, acquiring his B.S. in 1937, and returned to do his graduate work, obtaining his Ph.D. in 1947. He has been a member of the faculty since 1942. Past president of the International Union for the History and Philosophy of Science and of the History of Science Society, he is a specialist on the history of the exact and experimental sciences in the 17th and 18th centuries. He is currently completing a history of the concept of scientific revolution.

DALE P. CRUIKSHANK and DAVID MORRISON ("The Galilean Satellites of Jupiter") are on the staff of the Institute for Astronomy of the University of Hawaii. Cruikshank, who is associate director of the institute, is a graduate of Iowa State University and the University of Arizona; his Ph.D., which he received from the latter institution in 1968, is in lunar and planetary geology. Morrison did his undergraduate work at the University of Illinois and his graduate work at Harvard University, where he was awarded his Ph.D. in astronomy in 1969. Both Cruikshank and Morrison were amateur astronomers before they became professionals. Their primary interest at present is in the smaller bodies of the solar system, and both are active users of the Mauna Kea Observatory on the island of Hawaii. In addition to their astronomical work together, they share an interest in the active volcanoes of the Hawaiian islands; their spectroscopic study of the gases emitted by Kilauea led to the discovery of hydrogen-burning in that volcano.

United States Steel asks a prominent American to speak out.

"What makes America work?–education...

by Sidney P. Marland, Jr.,
President, College Entrance Examination Board

Since our earliest days as a nation, we have esteemed universal education. Our schools and colleges have been the rootstock of our democracy. Jefferson wrote:

"I know of no safe depository of the ultimate powers of society but the people themselves; and if we think them not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them, but to inform their discretion."

Until very recent times our institutions of education were accepted as inviolable. Teachers and professors were held as the stewards of truth and beauty, and the rightness of education was taken for granted. Economists calculated as recently as the 1960's that between 23 and 40 per cent of our growth in real national income was attributable to education.

Yet the past twenty years have brought sharp criticism upon education. Schools and colleges are being held accountable for unfulfilled expectations that our society asks of its education system.

We in education must remind ourselves that this generation of critics is a product of our system. We taught them to question the status quo; we encouraged their hope and aspiration for all; we trained them to seek reform through the democratic process. We have let them abide with the myth that education conquers all.

When the democratic process seems unresponsive and frustrating, when deep social problems remain unconquered—education, we hear, has failed.

It is now time for reconciliation. The schools and colleges must listen more closely and respond more quickly to the evolutionary expectations of the American people and they must work harder, with a deeper sense of urgency to fulfill those hopes.

Education and work in the American society have become separate and alienated from each other. This divorcement, I believe, lies at the heart of our discontent. They must be

brought back together for all ages of learners, and for all kinds of educational institutions.

Today, enlightened leaders in business, labor and industry have begun to take part in the education of our people, not merely as taxpayers, advisors or consultants, but as *working companions* to teachers and professors.

The schools and colleges have no monopoly on the development of the young. But they are responsible for the transmission of our cul-

but our system needs some important changes."

tural and intellectual heritage, and the academic skills necessary thereto. They must reaffirm and sustain the standards of intellectual excellence which have been entrusted to them. They must find the exquisite balance between enduring and immutable academic and social standards and the response to the call for reform.

This is not impossible, but it is not easy. It is the evolving nature of a free society in which the job of *informing the discretion* of the people is more complex than even the genius of Jefferson could have imagined.

★ ★ ★ ★ ★

Education at U.S. Steel

Within our company, we offer an unusually wide range of educational programs—because we're committed to encouraging the personal growth of our employees, as well as increasing their job satisfaction and helping them become more useful and productive.

Development opportunities for employees include basic on–the–job training for each employee, apprentice training for various crafts required by the steel industry and management development programs which foster growth at all levels of management. For the employee motivated to continue his or her education, the in-house Industrial Studies Program and the Tuition Refund and Assistance Program are available at colleges and universities to meet this need.

We're convinced that our continuing commitment to education at all levels is of immeasurable benefit to our employees, to our company and to American industry, both now and in the future.

United States Steel, 600 Grant Street, Pittsburgh, Pa. 15230.

USS TRADEMARK **We're involved.**

Established 1845 SCIENTIFIC AMERICAN May 1976 Volume 234 Number 5

Oil and Gas from Coal

The conversion can be accomplished by several tested processes. The present effort is to combine such processes in a large-scale system that will manufacture the oil and gas at reasonable cost

by Neal P. Cochran

For both political and economic reasons it seems clear that sooner or later the U.S. will come to rely much more on coal as a source of energy than it has over the past few decades. Except in large installations such as power stations, however, coal is not the ideal fuel both because it is not fluid and because it usually burns less cleanly than either oil or gas. Moreover, since coal-driven locomotives and ships have almost disappeared from the scene, coal can scarcely serve at all as a fuel for vehicles. Success in exploiting the nation's huge reserves of coal therefore depends on the development of a technology that will convert coal into oil and gas on a large scale. The principles of the technology already exist, as do a number of pilot and demonstration plants where the conversion is being accomplished on a small scale. The problem, then, is to mobilize the financial and industrial resources that are needed to put the technology on a commercial basis.

The fuller exploitation of coal will entail a substantial shift in the economics of energy. For the past decade or so the sources of energy in the U.S. have been predominantly oil and gas (44 and 31 percent respectively), with coal accounting for 21 percent and all other sources, including hydroelectric and nuclear plants, accounting for 4 percent. In contrast, coal accounts for 75 percent of the nation's fossil-fuel resources.

It is also instructive to look at the markets for energy. Industrial and commercial activities take about 40 percent of the energy produced in the country each year, transportation 25 percent, electric utilities 20 percent and homes 15 percent. The direct consumption of coal is virtually ruled out in transportation and seems unlikely to expand much in industrial, commercial and residential markets because of restrictions against air pollution. To reach those markets coal must be converted into oil and gas.

The conversion of coal into gas was an established commercial technology in the U.S. as early as the 1820's. The "gas works" became a familiar feature of cities of the Northeast and the Middle West, manufacturing gas from coal for illumination and cooking. The gashouses disappeared after World War II as natural gas came to be widely distributed by pipeline, and the technology that sufficed then would be inadequate now because the gas it made from coal could not match the heating value of natural gas.

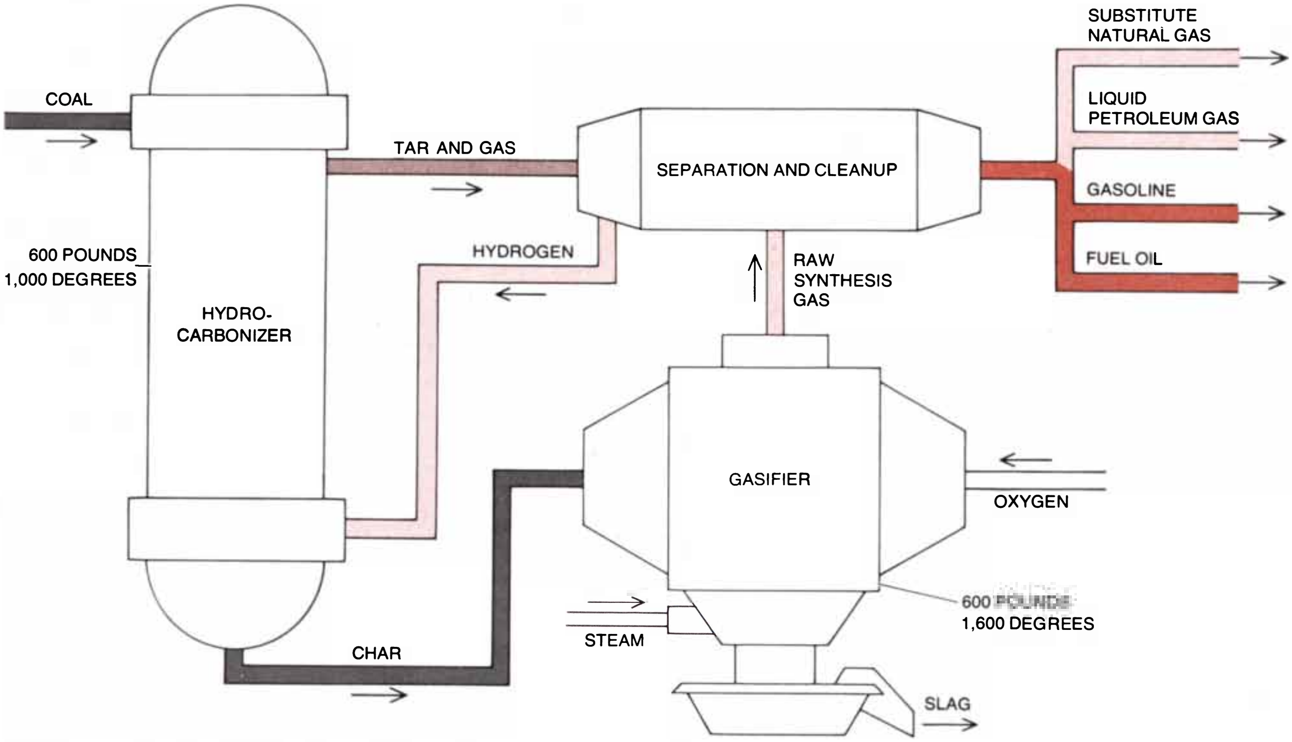
Although the conversion of coal into oil has not been accomplished commercially in the U.S., it was a large-scale operation in Germany during World War II and is being pursued on a substantial scale in South Africa today. The German production of synthetic gasoline from coal reached the level of 12,000 barrels per day, with the largest plant turning out nearly 4,000 barrels per day. The Sasol synthetic-fuel plant in South Africa, which has operated for 20 years, converts coal into more than 300 million cubic feet of gas per day and then converts the gas into liquids that are similar to petroleum. Neither the German undertaking nor the South African one would be considered large by U.S. standards; the German plants at the time of peak production were processing about 600 tons of coal per day, and the input to the Sasol plant is about 3,500 tons per day. The plants envisioned for the U.S. would process upward of 25,000 tons of coal per day, a level of operation to which the German or South African processes cannot be economically adapted.

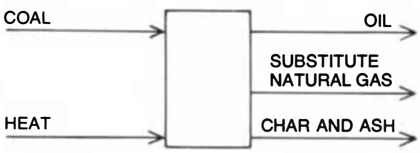
The amount of work done to study and develop processes for converting coal into oil has tended to rise and fall with estimates of how adequately the known and projected reserves of petroleum would supply the projected markets for gasoline and other petroleum products. Until recently most of the research in the U.S. was done by two agencies of the Department of the Interior: the Bureau of Mines and the Office of Coal Research. Those programs are being continued by the Energy Research and Development Administration (ERDA), which was established in 1975 to coordinate the Government's research and development efforts to make the U.S. independent of foreign energy resources.

Enough work has been done to make it possible to predict the development of a scaled-up technology that can convert coal into oil and gas at prices that are competitive with the current prices of such products in the U.S. In terms of actual cost, of course, oil and gas from coal cannot now compete with crude oil from the Middle East. One should remember, however, that the cost and the price of Middle East crude are not related, as was demonstrated by the embargo and price increases the exporting countries of the Middle East imposed starting in 1973. In many ways those actions may prove to have benefited the U.S., since they could encourage the development of domestic sources of oil and gas and hasten the production of synthetic fuels from coal. The price of coal can be expected to rise with the price of oil, but the price of synthetic oil and gas will decline with respect to the price of the natural product because the capital charges for plants making the synthetic fuels will stabilize.

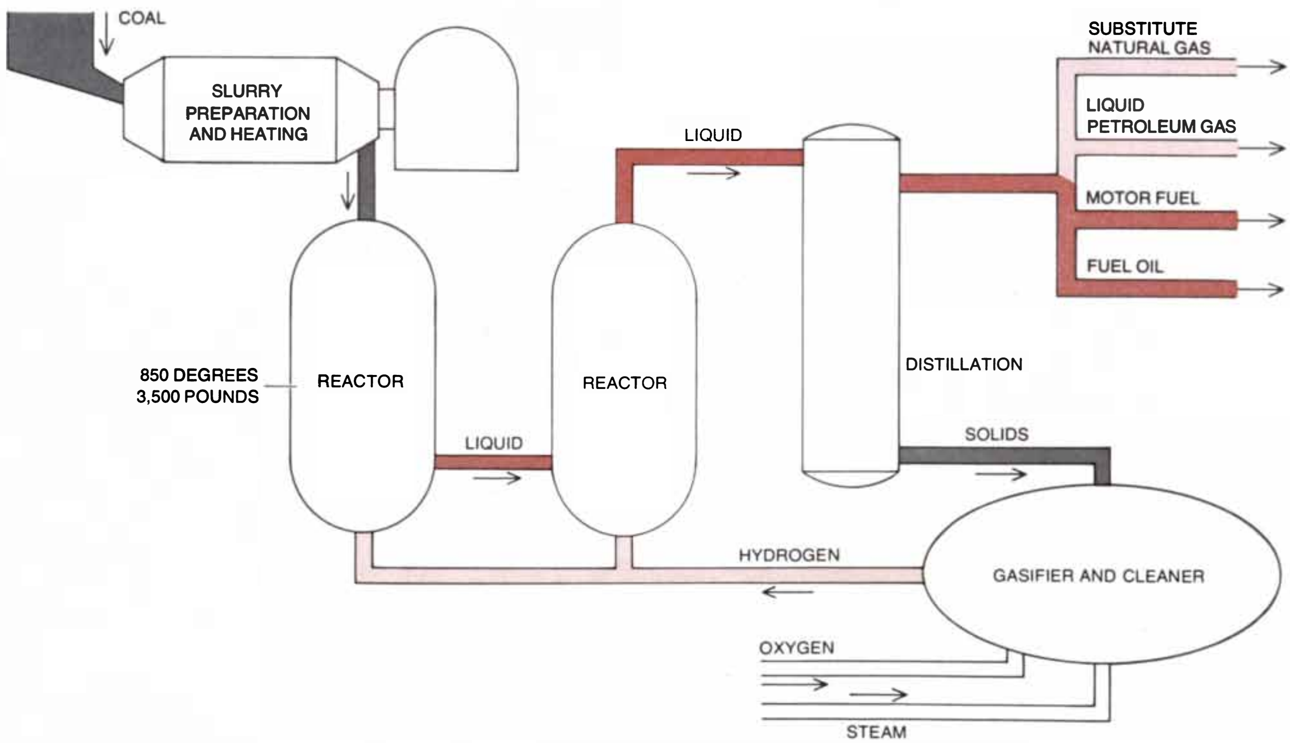
In the simplest terms the conversion of coal into oil or gas calls for adding hydrogen to the coal. (The ratio of hydrogen atoms to carbon atoms in coal is .8 to 1; in oil it is 1.75 to 1.) The source of the hydrogen is water (as steam). The energy for the process by which hydrogen is separated from water must be obtained from the coal itself if the economics of the conversion technology are to be favorable. The production of hydrogen is a major cost in the conversion of coal into oil.

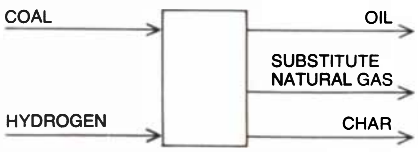
It follows that every conversion process



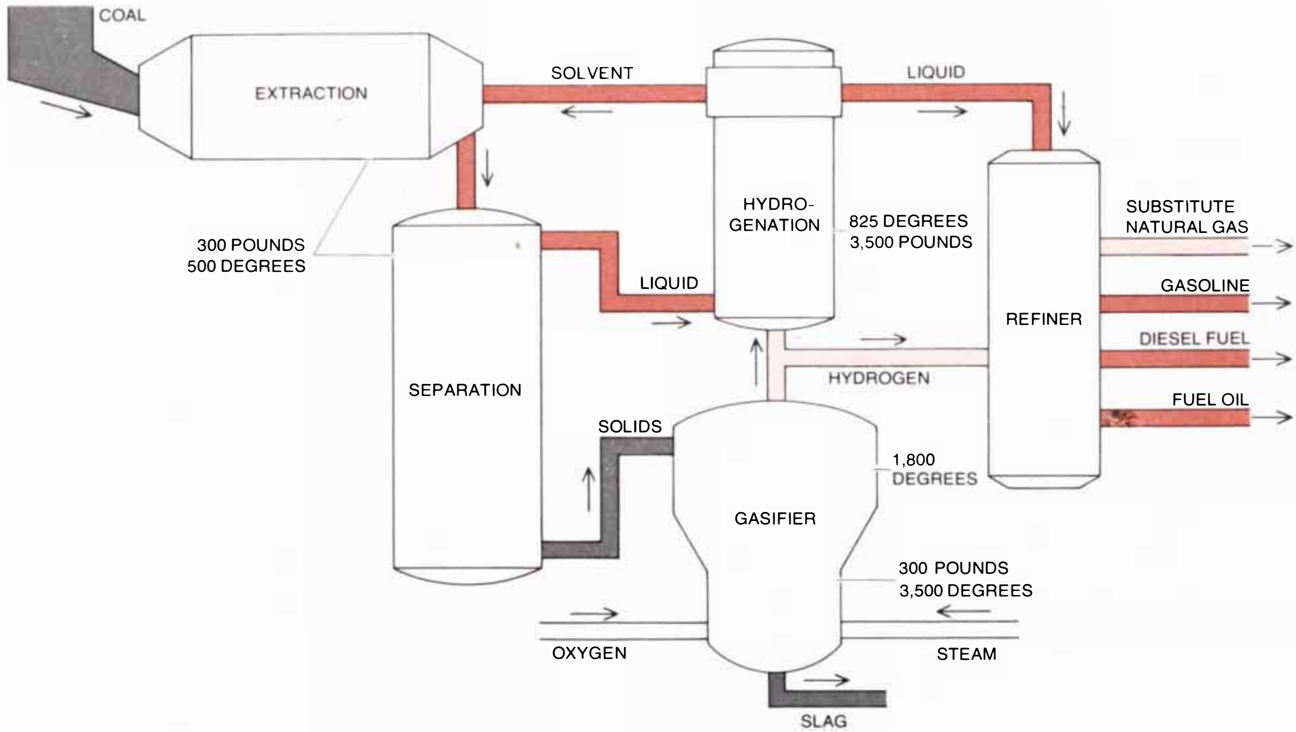


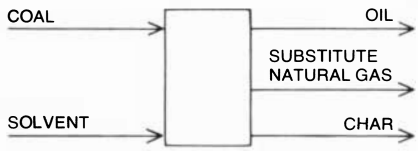
CARBONIZATION is one of four basic methods of converting coal into oil or gas by adding hydrogen to the coal. As is depicted schematically here, with a synopsis at bottom left, it involves heating coal in the absence of air, causing the coal to decompose and to evolve tar and gas. Tar and gas are treated in the separation and cleanup stage to yield a clean gas and liquid fuels. Solid char leaving the hydrocarbonizer is gasified to produce hydrogen. Numerals give pressure in pounds per square inch and temperature in degrees Fahrenheit at various stages.



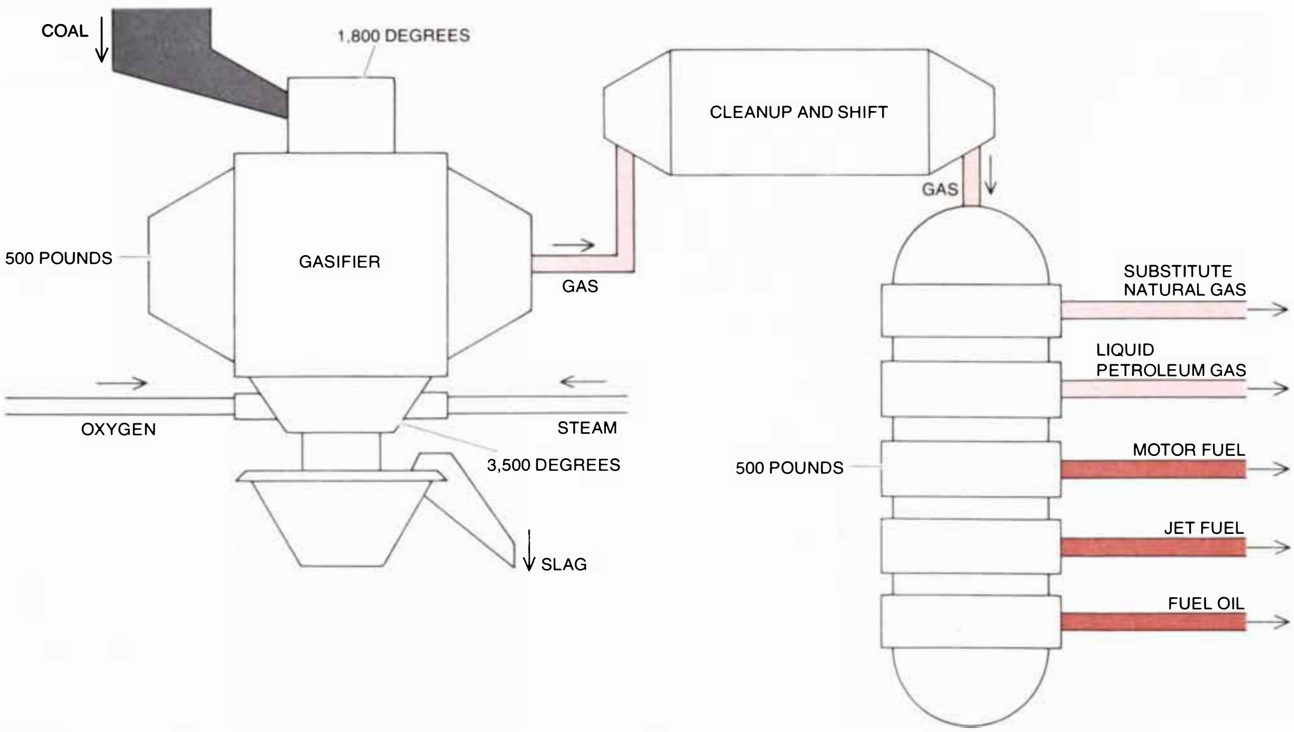


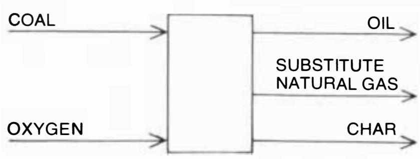
DIRECT HYDROGENATION of coal is a process that begins with the coal in the form of a slurry. The slurry is fed into a reactor, where it is reacted with hydrogen at high pressure. The reactor usually contains a catalyst, such as cobalt molybdenum, that facilitates the process. After hydrogenation the liquid yielded by the reaction is distilled to remove solids, which are gasified to provide hydrogen for the operation. In this process, as in others, water in the form of steam is the source of the hydrogen that must be added to the coal to convert it into oil and gas.





EXTRACTION PROCESS for converting coal into oil and gas involves dissolving the coal in a solvent. The hydrogen-donor process, which is one of two methods of extraction, is depicted here. The coal is dissolved by being mixed with the solvent at low pressure. The liquid that results is hydrogenated, yielding both a synthetic crude oil and the solvent for extraction. Since the solvent is rich in hydrogen, it transfers hydrogen to the coal during the extraction process. Part of the coal remains undissolved; it is gasified, as in other processes, to yield hydrogen.





FISCHER-TROPSCH SYNTHESIS is the fourth basic method of converting coal to oil and gas. Coal goes into a gasifier, where it is burned in the presence of oxygen and steam. The combustion generates a gas consisting mainly of carbon monoxide and hydrogen. In the cleanup-and-shift stage the gas is purified. Then it is passed over a catalyst, producing not only substitute natural gas of pipeline quality but also a variety of liquid products. Fischer-Tropsch synthesis is employed in a South African plant that processes some 3,500 tons of coal per day.

must involve a gasification step, in which the coal is reacted with steam. The aim is not primarily to get pipeline gas but to make a synthesis gas ($CO + H_2$) that can be modified with more steam ($CO + H_2O \rightarrow CO_2 + H_2$) to obtain more of the hydrogen needed to convert coal into oil and hydrocarbon gas. Moreover, all conversion processes yield a mixture of hydrocarbon gases, including methane (CH_4), which is a substitute for natural gas. Since the national economy requires both gas and oil, the aim of a conversion technology should be to conserve the gas generated in the liquefaction of coal and to regard it as a coproduct with the oil.

The simplest of the four basic processes for producing oil from coal is carbonization, which consists in heating coal in the absence of air. The heat causes the coal to decompose, evolving tar and gas and leaving a solid residue (coke). Carbonization has long been employed in making coke. Even though it also yields a liquid and a gas, it is not economically practical for the production of oil because the capital charge for coke ovens is high in relation to the unit cost of the oil produced.

Research is therefore focused on improved carbonization processes. A consortium of companies is developing the COGAS (coal-oil-gas) process, in which carbonization is accomplished in a fluidized bed of coal at comparatively low temperature. The fluidized bed improves the efficiency of decomposition of the coal. The next steps are the combustion of the solid char with air and the reaction of steam with the hot char. Typical products are tar and pipeline gas.

A hydrocarbonization process is the basis of a demonstration plant that will be built in Illinois under a $237-million contract awarded to the Coalcon Company by ERDA. The process yields products ranging from substitute natural gas to a high-quality (low-sulfur) fuel oil by heating coal to about 1,000 degrees Fahrenheit in the presence of hydrogen at a pressure of about 600 pounds per square inch. In the basic carbonization step a moderate hydrogen pressure is established to improve the yield and quality of liquid products (by facilitating the reaction of hydrogen with the products of pyrolysis) and to reduce costs. Material leaving the top of the reactor as a gas is cooled to condense a heavy oil and is then treated to remove sulfur compounds, so that the gas coproduct is clean. The liquid product is distilled to yield a light motor-fuel fraction and a heavy fuel-oil fraction. The gas is distilled at cryogenic (very low) temperature to separate hydrogen, which is recycled to the reactor. The char leaving the reactor is gasified to produce the hydrogen required by the process, and energy for the entire operation is obtained by burning part of the char or the excess gas. The process can be adapted to the recovery of chemicals, but that is not the objective of the present work.

A recent report issued by Coalcon indicates that a full-scale plant would produce the substitute natural gas to sell at a price of $2.40 per million cubic feet. Fuel oil would be priced at $15 per barrel and gasoline at 33 cents per gallon (not including tax). The prices are comparable to current prices charged by producers for natural products and are typical of the prices of synthetic oil and gas.

The second basic conversion process is hydrogenation. It calls for reacting coal with hydrogen at high pressure, usually in the presence of a catalyst. (This was one method employed to convert coal into oil in Germany during World War II.) The coal can be hydrogenated directly by feeding it into a reactor in the form of a slurry. In a system that is being developed for ERDA by Hydrocarbon Research, Inc., the reactor contains a catalyst of cobalt molybdenum, which is kept in motion by the recycling of liquid in the reactor. Intimate contact is achieved between the solid (the catalyst), the liquid (oil) and the gas (hydrogen).

Another system of direct hydrogenation is being investigated by the Pittsburgh Energy Research Center of ERDA. In this system the catalyst bed is fixed, which simplifies the construction of the reactor but complicates the removal of heat and thus the control of the temperature in the reactor. (Recent work seems to indicate that the catalyst is not required.) Control of the temperature in the reactor is crucial in both systems if the formation of carbon and the ultimate plugging of the reactor is to be avoided. The temperature of the reactor also affects the nature and quality of the products.

These systems and other methods of hydrogenation call for a temperature of about 850 degrees F. and pressures ranging from 2,000 to 4,000 pounds per square inch. A lower pressure and a shorter time for reaction limit the reaction between the coal and the hydrogen and favor the production of heavy fuel oil; a higher pressure and a longer time for reaction favor the production of lighter fractions. Following the hydrogenation step the liquid fraction of the product is distilled and decompressed so that solids can be removed. The heaviest oil fraction contains the unreacted solid coal, which must be separated from the liquid. The solid fraction is gasified with additional coal to provide hydrogen for the operation. Direct hydrogenation provides more liquid than any of the other processes discussed here. The selling price of the product will range from $14 to $18 per barrel.

The third basic conversion process is extraction, in which coal is partly or completely dissolved. Two systems are being investigated commercially and in the program of ERDA. They differ in the method of bringing hydrogen to the coal. In the solvent-refined-coal system coal is dissolved in an organic liquid in the presence of hydrogen gas that is under high pressure (about 2,500 pounds per square inch). The process dissolves nearly all the coal and in subsequent steps filters the resulting slurry, distills the liquid fraction to recover solvent and re-forms the coal by cooling. If the starting coal has a high sulfur content (about 3 percent), the remaining solid fuel will contain from .5 to .8 percent sulfur. The products of the system can be improved by further hydrogenation in the presence of a catalyst.

In the hydrogen-donor process coal is dissolved by being mixed with the solvent at a low pressure (about 300 pounds per square inch). The resulting liquid is separated from the undissolved coal and then hydrogenated to obtain a synthetic crude oil and the solvent required for extraction. In other words, the solvent is derived from the process; because it is rich in hydrogen, it transfers hydrogen to the coal during extraction. The hydrogen-donor system has two key features: the extraction process is carried out at low pressure and the hydrogenation step employs a clean feed. In terms of 1975 dollars the selling price of the products of extraction systems is about $2.30 per million cubic feet for the substitute natural gas and $15 per barrel for the oil.

The fourth basic method of liquefying coal is usually called Fischer-Tropsch synthesis, after the German chemists Franz Fischer and Hans Tropsch, who originally developed it. Coal is burned in the presence of oxygen and steam, generating a gas composed mostly of carbon monoxide and hydrogen. The gas is purified and then passed over a catalyst, yielding liquid products ranging from methanol ("wood alcohol") to hydrocarbons of high molecular weight, including waxes and oils. The process can be directed primarily toward the production of motor fuel and substitute natural gas. This process is employed in the Sasol plant to produce waxes, oils, motor fuel and chemicals. It has been estimated that a Fischer-Tropsch plant in the U.S. with the capacity to produce 50,000 barrels per day would be able to sell its output at about $2.25 per million cubic feet of substitute natural gas and $13.05 per barrel (31 cents per gallon) for gasoline.

It is useful to compare the four basic processes in various ways. One is by yield per ton of coal. For carbonization the yield is from one barrel to 1.5 barrels of liquid products and from 4,000 to 5,000 cubic feet of gas products; for direct hydrogenation it is 2.5 to 3.5 barrels and 2,000 to 3,000 cubic feet; for extraction-hydrogenation it is two to three barrels and 3,500 to 4,500 cubic feet, and for Fischer-Tropsch synthesis it is 1.5 to two barrels and 8,000 to 10,000 cubic feet. Another measure is the pressure at which the process operates, since the cost of the equipment rises with the pressure. Carbonization is done at from atmospheric pressure (14.7 pounds per square inch at sea level) to 70 atmospheres, direct hydrogenation at 200 atmospheres, hydrogen-donor extraction at 20 atmospheres followed by hydrogenation at 200 atmospheres and Fischer-Tropsch synthesis at 30 atmospheres. In thermal efficiency the range for carbonization is from 55 to 65 percent, for direct hydrogenation 60 to 65 percent, for the extraction processes 60 to 70 percent and for Fischer-Tropsch synthesis 55 to 70 percent.

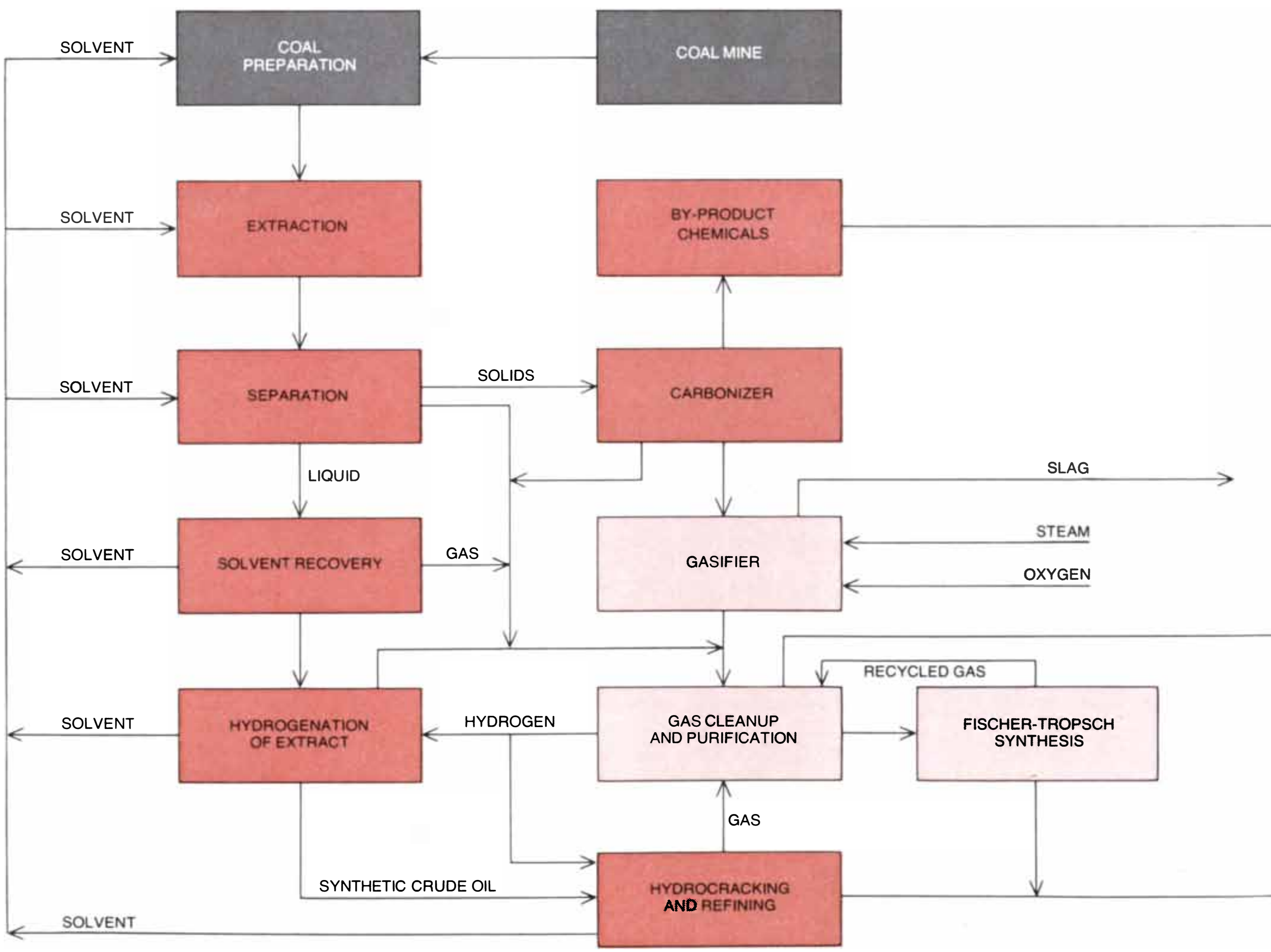
Although each of the four basic conversion processes will work by itself, it may be that the most successful commercial operation will be one that involves a combination of processes. Such a plant could be described as a coal refinery. One attractive possibility is a combination of hydrogen-donor extraction and Fischer-Tropsch synthesis. This possibility arises because the synthesis step in the Fischer-Tropsch process proceeds at a pressure of from 350 to 500 pounds per square inch, which is also the range of pressure in the extraction phase of the hydrogen-donor process.

Coupling the extraction and synthesis steps in the low-pressure zone also couples them in the sections of the plant handling coal solids. It is always difficult to handle such solids, and the low-pressure feature therefore simplifies the design of such components as feeders, reactors, piping, pumps, valves and instruments. Low pressure also reduces the cost of the equipment for handling gas.

The steps in a combined process could go as follows [*see illustration below*]. Coal from the mine, which is treated as an integral part of the plant, is handled directly, with little or no storage. (If oil and gas made from coal are to compete with natural oil and gas supplies, a conversion plant must have a high capacity. Coal-handling is expensive in any case, and the cost rises if the coal has to be put into and withdrawn from a storage pile. Hence it is economical to gear the plant to a large and close supply of coal and to put the coal through the plant at a high rate with minimal storage.)

Leaving the mine, the coal is ground fine and made into a slurry with a solvent that has been produced in the plant and recycled. The solvent, a mixture of compounds that are saturated with hydrogen, serves as a source of hydrogen to aid the dissolving of the coal. The slurry of coal and solvent is heated to about 500 degrees F. in a fired heater and then is pumped to the extractor, which can be visualized as two simple agitated tanks. The time the mixture spends in the extractor depends on the feed rate of the plant and the level of slurry maintained in the vessels. With a long residence time the extraction can dissolve more than 90 percent of the coal, but the economics of the process is most favorable when the rate of extraction is between 60 and 75 percent.

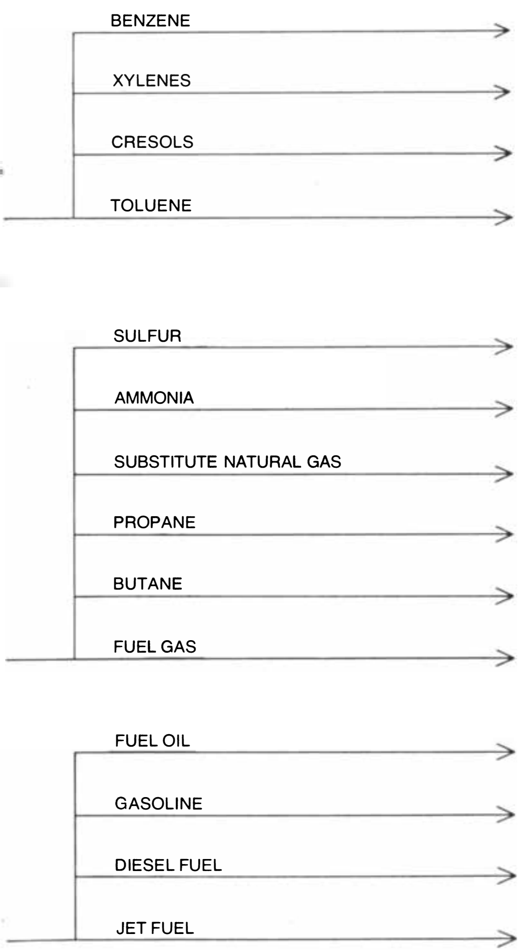
The ratio of solvent to coal in this step is about 2 : 1 by weight. Hydrogen can be added to the reactor to enhance the transfer of hydrogen from the solvent to the coal. After extraction the mixture of solvent, liquid extract and undissolved coal is pumped to a filter for separation. The filter, with a diatomaceous earth as the medium, works well



COAL REFINERY as envisioned by the author combines extraction, hydrogenation and Fischer-Tropsch synthesis to yield a large variety of products. Coal moving directly from a nearby mine is ground fine and made into a slurry with a solvent. That is an extraction process. In the next step the liquids and undissolved coal are separated. Solvent is recovered and the remaining liquid is hydrogenated. Solids remaining after extraction go as a sludge to a carbonizer, where the sludge is heated with recycled gas to generate gas and a char. The for the separation of solids from a liquid that would clog conventional filter cloth.

The filter cake, consisting of undissolved coal and ash-producing minerals, leaves the filter as a wet sludge. The sludge is moved to a fluid-bed carbonizer, where it is heated with recycled gas to recover tar acids and also gases of low molecular weight. Another product of the carbonizer is a solid char similar to the char produced in conventional carbonization. This char serves as a source of energy for the entire process and of hydrogen for the hydrogenation step.

The char is gasified (with oxygen) in a high-temperature, entrained-bed gasifier operating under slag-forming conditions. The gasifier is designed to conserve much of its own waste heat, which is recovered as high-pressure steam. The gasifier also achieves a total utilization of carbon by producing a slag that contains no carbon. Without carbon the slag is inert, which simplifies its disposal as waste.



char is gasified and the gas is purified. The resulting clean gas proceeds to a Fischer-Tropsch step. The liquid extract (*bottom left*) yields a synthetic crude oil that can be refined.

After the gas from the gasifier has passed through the waste-heat recovery system it goes to a purification section of the plant, where acid gases, hydrogen sulfide and carbon dioxide are removed. The ratio of carbon monoxide to hydrogen is adjusted by the addition of hydrogen recovered from gases generated in other processes of the plant. Hydrogen is separated from those gases in a cryogenic separation step. The adjusted char gas then goes to the Fischer-Tropsch synthesis, where it passes over a catalyst. The primary products of this step are naphtha, diesel fuel and premium fuel oil. In addition the synthesis manufactures large quantities of gases of low molecular weight, which become the primary source of substitute natural gas and liquid petroleum gas from the plant.

The liquid extract from the filtration step, representing about 60 percent of the coal brought in from the mine, is distilled to recover solvent, which is employed in extraction and as the wash in the filtration step. Further distillation yields a primary material, the coal extract, which becomes the feed material for the hydrogenation step. Hydrogenation is conducted at a temperature of from 750 to 850 degrees F. and a pressure of about 3,000 pounds per square inch. Both the temperature and the pressure can be varied to alter the proportions of gas and liquid in the product.

The hydrogenated liquid is distilled to make both a solvent fraction, which is recycled, and a synthetic crude oil, which serves as the primary feed for a "cracking" step that yields gasoline. In locations that already have petroleum refineries the synthetic crude oil could be diverted to them. The gasoline produced by cracking would be combined with motor-fuel fractions produced in the Fischer-Tropsch section of the plant.

As I have indicated, a plant making oil and gas from coal must be located at the mine; otherwise the cost of moving from 25,000 to 100,000 tons of coal per day would make the plant uneconomical. Coal varies considerably from one area to another. For example, in the Appalachian region the coal is bituminous and high in volatiles; on the northern Great Plains it is lignite. Energy markets also vary from region to region. The coal refinery I have described, combining extraction, hydrogenation and Fischer-Tropsch synthesis, can be adapted to fit the characteristics of any coal, and the mixture of products can be adjusted to any market. In the Appalachian region the main products might be fuel oil for utility plants and substitute natural gas for residential and commercial consumption. A plant on the northern Great Plains would probably produce a higher proportion of liquids, since they could be transported economically by pipeline.

Suppose such a plant was designed to produce 50,000 barrels per day of liquid products. The plant would require about 25,000 tons of coal per day. The total capital investment would be about $1.5 billion: $200 million for equipment to mine and prepare coal, $200 million for extraction and separation, $300 million for gasification and synthesis, $100 million for equipment to handle by-products, $200 million for a utilities and services unit, $100 million for the air-separation plant, $250 million for contingencies and $150 million for engineering. Once the plant was operating it would manufacture daily 205 million standard cubic feet of gas, 5,000 barrels of liquid petroleum gas, 40,000 barrels of motor fuels, 5,000 barrels of fuel oil and (as by-products) 500 tons of sulfur and 3,000 tons of slag. The sulfur could be sold or stockpiled; some of the slag could be sold for making concrete blocks and other construction materials, but much of it would have to be returned to the mine as waste.

Twenty plants would produce a million barrels per day of liquid products and 4.1 billion cubic feet of gas. In a year, operating at 90 percent of capacity, the plants would make some 330 million barrels of nonpolluting liquid fuel and 1.353 trillion cubic feet of substitute natural gas. The output would meet about 6 percent of the nation's present demand for energy.

The coal requirement for 20 plants would be 165 million tons per year, which is about 25 percent of the national production of coal in 1975. The U.S. has nearly two trillion tons of recoverable coal. Therefore 100 plants, producing about 30 percent of the nation's energy requirement (stated in terms of consumption in 1975), could be operated for 30 years on approximately 1 percent of the coal resources. In Eastern locations the system would entail a land use of about 10 acres of coal per day.

The total capital investment for this array of plants would be about $30 billion, which is a large figure but a modest one on a national scale. If construction were spread over 10 years, expenditure would be at a maximum of $4 billion per year from the third year through the sixth. Plants could be added at the rate of four per year by increasing the expenditure to $6 billion per year. With this investment and production costs of from $160 to $180 million per year, the output of the plant would sell for $2.10 per million British thermal units to yield a rate of return of 12 percent on a discounted-cash-flow basis. The availability of nonpolluting fuels of high quality at $12.20 per barrel is an attractive alternative to imported oil at steadily rising prices.

To achieve a capacity of a million barrels per day of synthetic fuel calls for a vigorous Government program. Plants would be funded by the Government and operated by industry, which ultimately would buy the successful plants. The creation of a synthetic-oil industry would assure the nation of ample supplies of oil and gas. Moreover, the synthetic fuels would act as a ceiling on the price of crude oil from abroad. At the same time the country would have the assurance that it was no longer dependent on foreign supplies of oil.

Cell-Surface Immunology

Antibodies can serve as precise tools for the study of cells and cell surfaces. As such they have revolutionized immunology in the past decade and helped shape new concepts of cell-membrane structure

by Martin C. Raff

The remarkable capacity of the immune system to respond to many thousands of different substances with exquisite specificity saves us all from certain death by infection. When foreign materials such as large molecules, bacteria or viruses—all operationally referred to as antigens—are introduced into an animal, the immune system responds in two ways. It makes the special class of proteins called antibodies and it produces sensitized cells, both of which fit the particular antigen as a key fits a lock. The binding of antibodies and sensitized cells to antigen initiates a series of reactions that contribute to the destruction of the antigen and/or its elimination from the body.

The precise antigen-specificity of antibodies makes them versatile and powerful tools. Since they can be made against almost any substance, antibodies can detect, quantify and localize a large variety of biologically interesting molecules. For example, they can serve to diagnose bacterial and viral infections, to measure the concentration of hormones and drugs in the blood or to localize specific substances in certain types of cell and in particular components of a single cell. Of the many applications of antibodies in biology and medicine I shall discuss only one: the detection and study of antigens on the surface of cells. The first—and clinically still the most important—example of this application was Karl Landsteiner's demonstration in 1900 of different blood-group antigens on the surface of human red blood cells, an advance that made possible the transfusion of blood between individuals who have the same blood group. Now antibodies directed against a class of cell-surface proteins called the major histocompatibility antigens are serving similarly for typing tissue in order to make transplantation of organs possible. The experiments I shall review are less directly clinical in their impact. They deal with investigations of the cells involved in the immune process and of the structure of the cell's surface membrane, which is itself the site of the primary immune reaction and whose complex structure and functions are currently a subject of great interest in biology.

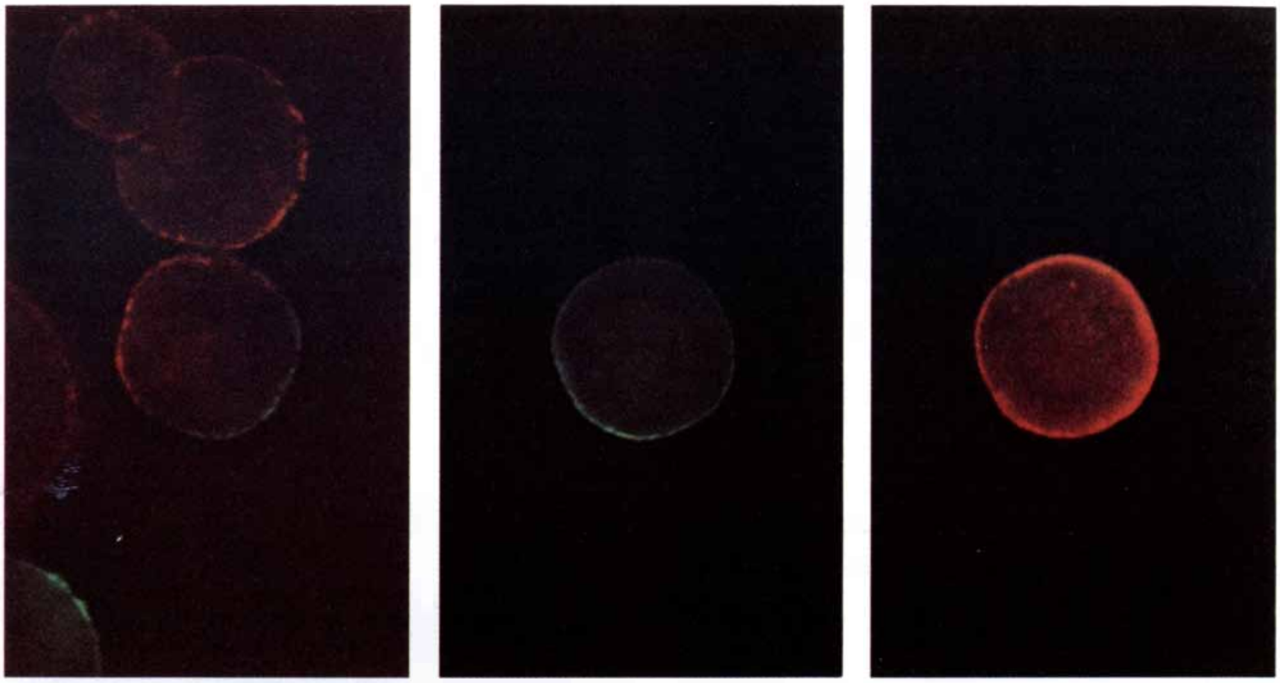
My own interest in cell-surface antigens began at the end of 1968, when I went to the National Institute for Medical Research at Mill Hill in England to work with N. Avrion Mitchison. It was an exciting time in immunology, as may become evident if I briefly review some history. In the 1950's it had finally been established that the cells responsible for immune reactions are the white blood cells called lymphocytes. In the 1960's it gradually became clear that there are two distinct classes of lymphocytes: *B* cells, which in mammals develop in the bone marrow, and *T* cells, which develop in the thymus gland [*see top illustration on page 32*]. When stimulated by antigen, the *B* cells become the synthesizers and secretors of antibody and the *T* cells become the sensitized cells responsible for immune responses that do not involve antibody. That is, the two different immune reactions, antibody production and cell-mediated responses, are effected by two different classes of lymphocytes. Both types of cells and both responses are essential for life; if either fails, the animal dies of infection.

As Sir Macfarlane Burnet had suggested in 1959 in his clonal-selection theory of acquired immunity, the immune system functions as a warehouse with a vast store of ready-made antibodies and sensitized *T* cells. Each lymphocyte is committed to respond to a particular antigen, and it expresses this commitment by displaying receptors on its surface that fit the antigen; the binding of antigen to those receptors triggers the cell to make its response [*see bottom illustration on page 32*]. When a foreign substance enters the body, it selects from the thousands of clones, or families, of *T* and *B* lymphocytes those cells already committed to respond to it and thereby provokes its own destruction.

By 1968 it was becoming clear that the two-lymphocyte model, which had been originally suggested by experiments done with chickens, was also valid for mice and men. Mice are particularly valuable in immunological research because inbred mouse strains are available in large numbers. Cells transferred between the genetically identical individuals of the same strain are not recognized as "foreign" by the host animal. Irradiating a mouse with X rays and thereby killing most of its lymphocytes provides an immunologically inert host into which lymphocytes from another animal can be transferred so that their responses can be studied. By this approach of adoptive transfer of cells in inbred mice investigators in a number of laboratories were gathering strong circumstantial evidence that *B* and *T* lymphocytes could collaborate with each other in making antibody responses. Immunology was in the midst of a revolution: two cells were taking over from one. The two types of lymphocytes looked exactly the same, however, and were always found together in the lymphoid tissues. In order to study the properties, functions and interactions of *T* and *B* lymphocytes, ways had to be found to distinguish and separate them.

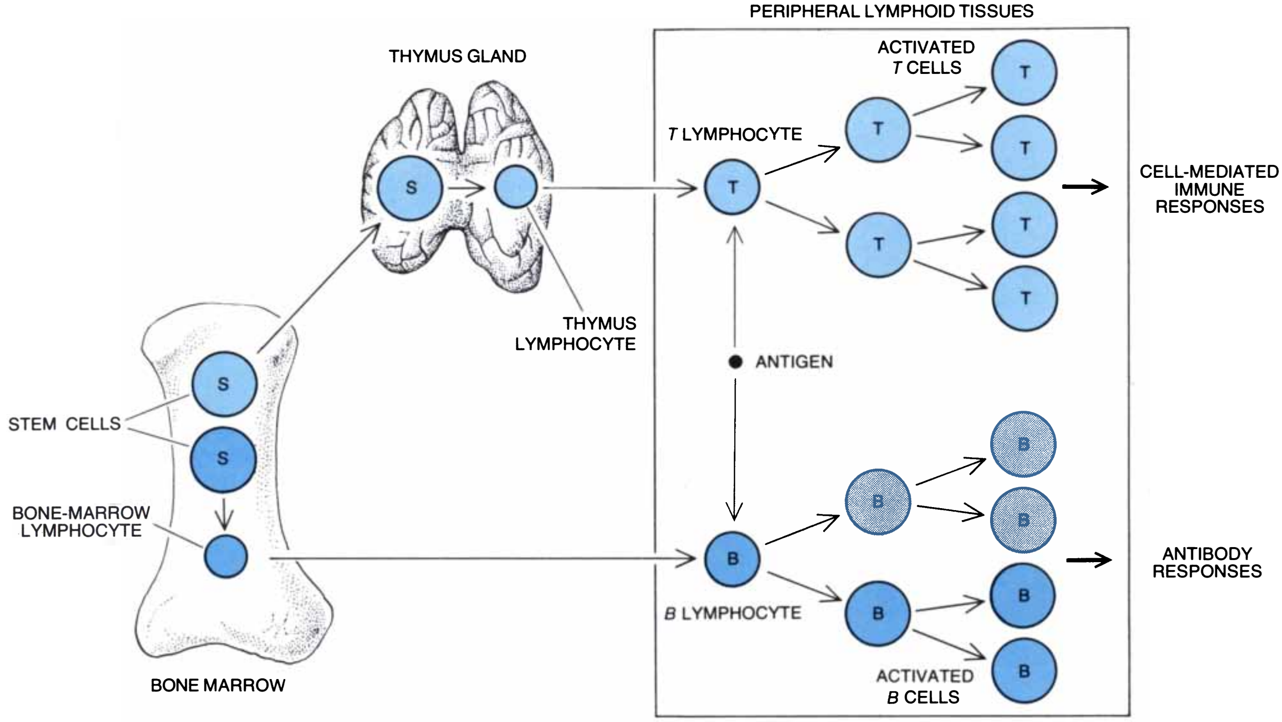
Mitchison had been rereading the papers in which Arnold E. Reif and J. M. V. Allen of the Tufts University School of Medicine had described the cell-surface antigen theta, so named because it was present on mouse thymus lymphocytes. (The antigen has recently been redesignated thy-1.) Since *T* cells are derived from thymus lymphocytes, Mitchison suggested that I see whether theta was also present on peripheral *T* cells; if it was on *T* cells but not on *B* cells, theta would be an invaluable cell-surface marker for *T* lymphocytes in mice. Cell-surface markers, as opposed to intracellular ones, would make it possible to identify and separate living cells by means of antibodies, because antibodies can readily bind to cell-surface antigens, whereas they cannot enter living cells.

Cell-surface antigens can be detected in various ways. The most common method is cytotoxicity testing, in which the binding of antibodies to antigens on the surface of living cells in the test tube is demonstrated by the death of the cells in the presence of fresh serum (the yellow fluid remaining when red cells are removed from blood). The constituents of serum that are responsible for killing the cells are collectively called complement and consist of a series of nine proteins. Following the binding of antibodies to antigen, the first component of complement binds to the antigen-antibody complex, triggering a chain reaction of component-bind-

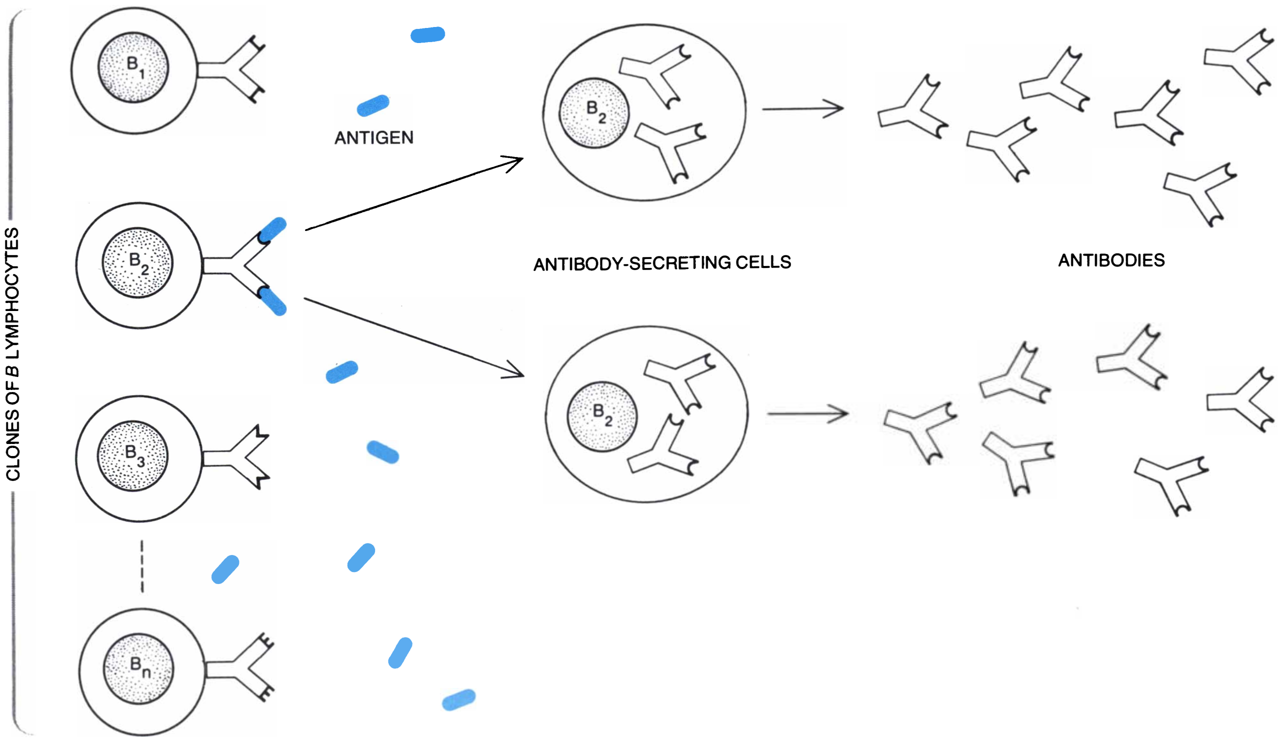


INTERMIXING of human and mouse cell-surface antigens on fused hybrid cells provided the first definitive evidence that proteins can move about in the cell membrane. Larry D. Frye and Michael A. Edidin of Johns Hopkins University treated human and mouse cells with a virus that promotes fusion. Then they applied antibodies directed against antigens in the human membrane and in the mouse membrane. Each antibody was coupled to a different fluorescent dye. Immediately after fusion (*left*) human antigens (marked by the red dye rhodamine) and mouse antigens (marked by the green dye fluorescein) were each confined to their own half of a fused cell. After 40 minutes at 37 degrees Celsius both antigens were distributed all over the membrane of a fused cell (*middle and right*). (Dyes are excited by different wavelengths, and so the micrograph at left is double exposure; micrographs at middle and right are both of a single fused cell.)

REDISTRIBUTION by a single antigen of all the immunoglobulin receptors on a *B* lymphocyte demonstrated the monospecificity of such cells. When the author, Marc Feldmann and Stefanello de Petris added flagellin to a preparation of mouse *B* lymphocytes, the protein was bound by immunoglobulin receptors on a small fraction of the cells and the resulting antigen-antibody complexes were "capped," all moving to one part of the antigen-binding cells; the capped complexes are visualized on one such cell by antiflagellin antibody coupled to rhodamine (*left*). Labeling the same cells with fluorescein-coupled antibody against immunoglobulin under noncapping conditions shows that the capping of flagellin redistributed all the receptors on the flagellin-specific cell: all the immunoglobulin is localized in the cap (*right*). The green fluorescein-coupled anti-immunoglobulin antibody also stains previously unseen cells in the same field that have not bound the flagellin and whose receptors, which are specific for other antigens, remain distributed all over the cell surface.



LYMPHOCYTES, the cells responsible for immune reactions, develop from stem cells. Some stem cells migrate from the bone marrow to the thymus and develop into thymus lymphocytes, which in turn migrate to peripheral lymphoid tissues and become *T* lymphocytes. Other stem cells develop into bone-marrow lymphocytes, which migrate to peripheral lymphoid tissues and become *B* lymphocytes. On meeting specific antigen, *T* cells are activated to produce cell-mediated immune responses and *B* cells are activated to secrete antibody.



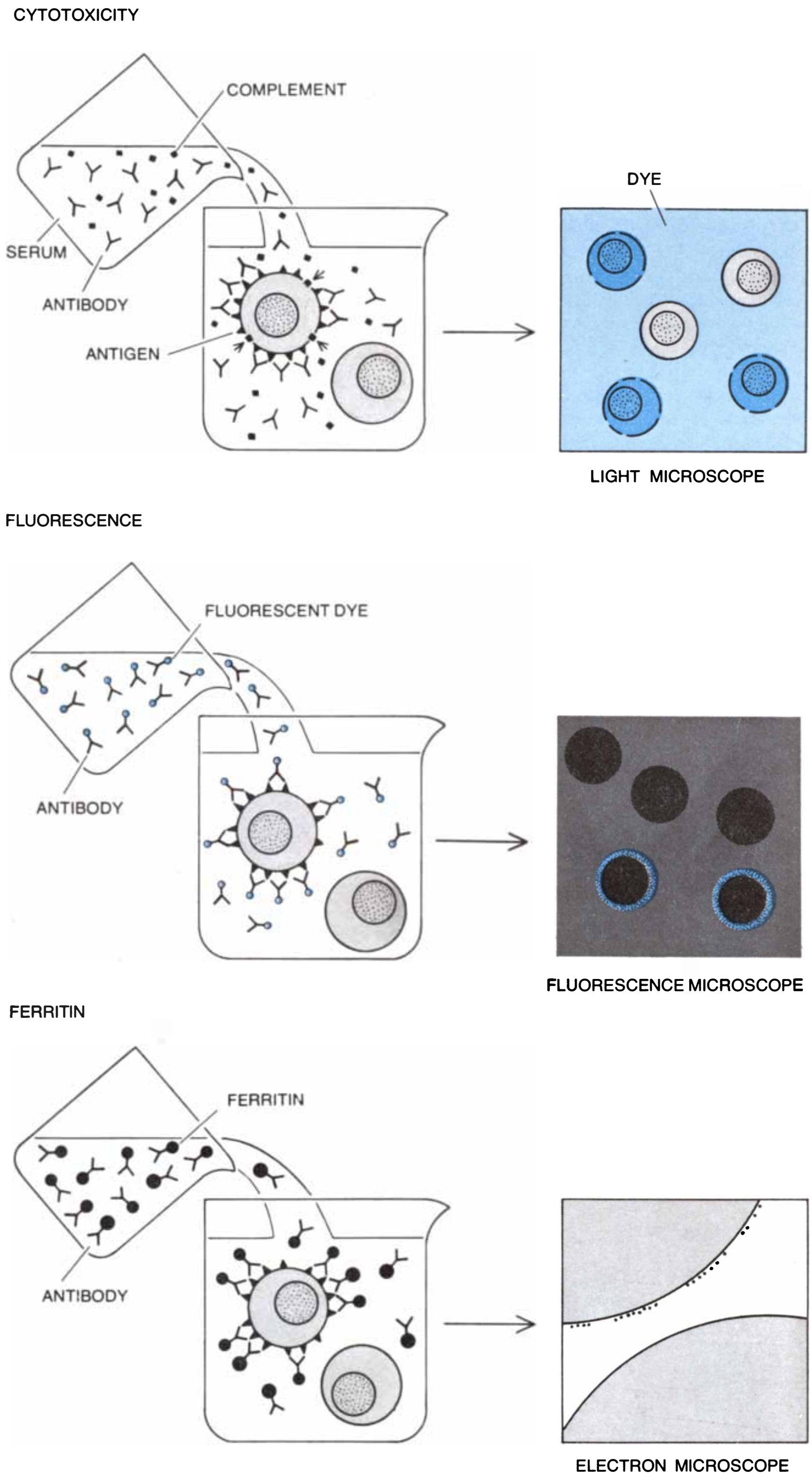
CLONAL SELECTION, illustrated here for *B* cells, operates also in the case of *T* cells. There are large numbers of clones, or families, of *B* lymphocytes, each committed to respond to a specific antigen; they make antibodies to that antigen before ever "seeing" the antigen and insert them into their surface membrane as receptors (*left*). An antigen entering the body binds only to those lymphocytes that have appropriate receptors on their surface. The binding triggers those cells to proliferate and to make more of the same antibody and secrete it.

ing and activation; ultimately the final components bind and are inserted into the cell membrane, causing it to become leaky, and the cell dies. The extent of cell death—and hence of antibody binding—can be visualized directly if a dye is added that is excluded from living cells but readily enters leaky dead ones.

Reif and Allen had shown that anti-theta antibodies killed 100 percent of thymus lymphocytes in the presence of complement. I found that only 30 to 40 percent of spleen cells and 60 to 80 percent of lymph-gland cells could be killed by anti-theta antibodies and complement, no matter how much antibody and complement were added. This suggested that there are two distinct populations of lymphocytes in these tissues, only one of which has theta on its surface. It was an encouraging start, since both *T* and *B* cells were known to be present in spleen and lymph glands. The next step was to see whether the theta-bearing cells were *T* lymphocytes. We did that by studying spleen and lymph-gland cells from three types of mice known to have markedly reduced numbers of *T* cells: mice whose thymus glands had been removed early in life, so that *T* lymphocytes could not develop; mice treated with anti-lymphocyte antibodies, which destroy *T* cells preferentially, and mice designated *nude*, which are hairless mutants that have small, nonfunctional thymus glands and therefore almost entirely lack *T* cells. In all these mice the proportion of theta-bearing cells was strikingly reduced, as would be expected if only *T* cells have the theta antigen.

The experiments on *nude* mice, which were done in collaboration with Henry H. Wortis, were particularly convincing: although the mutants appeared to have normal numbers of *B* lymphocytes, they lacked *T*-ceil responses and had almost no theta-bearing cells in their blood, spleen or lymph glands. It was clear that theta was the *T*-cell surface antigenic marker we had been looking for. At the same time Michael Schlesinger and Ilana Yron of the Hebrew University–Hadassah Medical School in Jerusalem were doing similar experiments independently, and they came to the same conclusion.

Having a surface marker for mouse *T* cells made it possible for John J. T. Owen and me to directly determine the distribution of these cells in the various lymphoid tissues of the mouse and to study their development in and migration from the embryonic thymus gland. It also enabled one to study the functions of *T* cells more directly than before. Much of the excitement in Mitchison's laboratory at that time centered on some new observations that had been made by Mitchison, Klaus Rajewsky and Roger B. Taylor on antibody responses to small chemical antigens, such as dinitrophenol (DNP), that were coupled to a larger protein carrier. For antibodies to be produced against DNP two types of cell were



SURFACE ANTIGENS ARE DETECTED by several methods. In cytotoxicity testing (*top*) cells are killed by antibody in the presence of complement, a series of protein components in blood serum. The first component binds to antigen-antibody complexes; the final components insert themselves into the membrane and make it leaky, so that the cell dies. Dead cells are identified by adding a dye that is excluded from living cells but taken up by leaky ones. In the immunofluorescence method (*middle*) antibodies are coupled to fluorescent dyes; labeled cells fluoresce under light of the proper wavelength. In immunoferritin electron microscopy (*bottom*) antibodies are coupled to the electron-dense protein ferritin, which shows up as a black speck in an electron micrograph; individual antibody molecules are visualized by this method.

needed. One, almost certainly a *B* lymphocyte, reacted with DNP and made the anti-DNP antibody; the other reacted with the protein part of the molecule and somehow helped the *B* cell to respond to the DNP. Indirect evidence suggested that these helper cells were *T* lymphocytes.

The first direct evidence was provided by an experiment in which I showed that the helper cells were killed by anti-theta antibody and complement, whereas the cells capable of producing anti-DNP antibodies were not affected by such treatment. Taken together, these observations established an important immunological concept: *T* cells, recognizing one antigenic determinant on a molecule, can help *B* cells to make antibody against another determinant on the same molecule. The ability to abolish an immunological function by treatment with anti-theta antibody and complement still remains the best evidence that the function requires *T* lymphocytes.

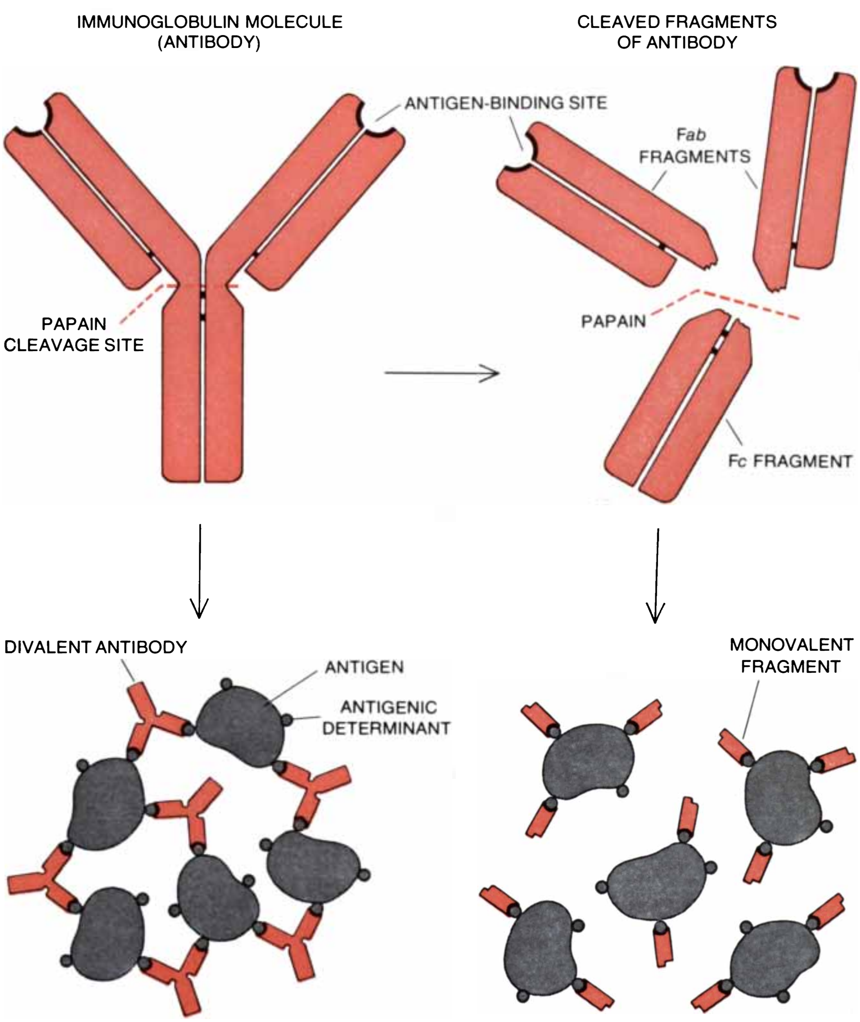
The usefulness of theta as a *T*-cell marker emphasized the value that a similar marker for *B* cells would have and at the same time made it easier to look for one. Mitchison, Siglinda Nase and I succeeded in defining a *B*-cell surface antigenic marker. We immunized rabbits with mouse *B* cells and then absorbed the resulting antiserum with mouse thymus lymphocytes to remove antibodies common to both cells, until the point was reached at which the antiserum reacted only with *B* lymphocytes and not with theta-bearing *T* cells. This principle is now applied to produce antibodies that distinguish *T* from *B* lymphocytes in various species, including man.

More than a dozen distinct surface antigens have now been defined that distinguish lymphocyte subpopulations in mice, most of them discovered by Edward A. Boyse and his colleagues at the Sloan-Kettering Institute for Cancer Research in New York. These antigens have played a major role in the explosive advance of immunology in the past seven years and should continue to do so. For example, Harvey Cantor of the Harvard Medical School and Boyse are currently defining and studying, on the basis of surface antigens, distinct subpopulations of *T* lymphocytes that have different functions, heralding yet another immunological era: one in which *T* and *B* cells themselves are being further divided into subclasses.

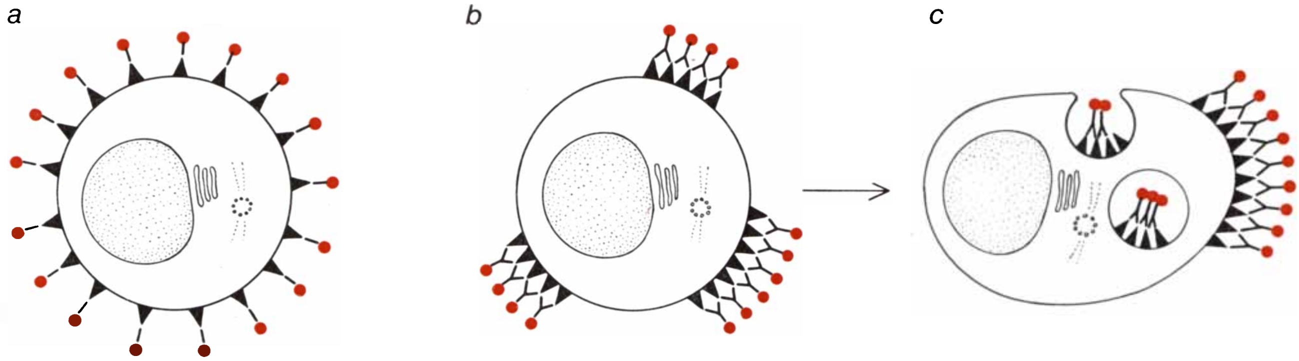
Antibodies against cell-surface antigens serve not only to identify cell types but also to separate them. One way, of course, is by killing specific cells in a mixed population in the presence of complement. In order to separate live cells antibodies can be coupled to various materials such as glass or plastic to form immunoabsorbents, to which only cells bearing the appropriate surface antigen will adhere; these cells can then be recovered by gentle shaking or, in the case of a digestible material (such as collagen), by digesting away the immunoabsorbent with enzymes. A more sophisticated technique has been developed by Leonard A. Herzenberg and his colleagues at Stanford University in which living cells are labeled with antibodies coupled to a fluorescent dye, so that the cells fluoresce when they are exposed to light of the appropriate wavelength [see "Fluorescence-activated Cell Sorting," by Leonard A. Herzenberg, Richard G. Sweet and Leonore A. Herzenberg; SCIENTIFIC AMERICAN, March]. The fluorescent cells can then be separated in a fluorescence-activated separator, which can sort 10 million cells an hour. In this apparatus individual cells in a fine stream are assessed for fluorescence after activation by a laser beam; the stream is then broken up into fine droplets by a vibrating nozzle. The droplets are automatically given a positive or negative charge at the moment of formation, depending on whether or not they contain a fluorescent cell, and are deflected by an electric field into an appropriate container. The separation of cells by means of antibodies has revolutionized immunology and is spreading to other areas of biology.

The clonal-selection hypothesis predicted that lymphocytes would have receptors for antigen on their surface. Since a primary function of such receptors would be to recognize specifically a large number of different antigens, just as antibodies do, it seemed a reasonable guess that the receptors would be antibodies; since antibodies belong to the class of proteins collectively called immunoglobulins, a corollary of this prediction was that lymphocytes should have immunoglobulin molecules on their surface.

The first indication that this might be the case was provided inadvertently in 1961 by Göran Möller at the Karolinska Institute in Stockholm. Möller was detecting histocompatibility antigens on the surface of mouse lymphocytes, using antibodies against those antigens that he prepared by immunizing one strain of mouse with lymphocytes from another strain. Instead of coupling the antibodies to a fluorescent dye in order to visualize them, he detected their binding to surface antigens indirectly: he applied a fluo-



ANTIBODY MOLECULES are divalent, that is, they each have two antigen-binding sites. The antibody can therefore cross-link multivalent antigen molecules, which have several antigenic determinants (*bottom left*). When an antibody molecule is digested with the enzyme papain, it is cleaved into two F*ab* fragments, each of which has only one antigen-binding site, and also an F*c* fragment. The monovalent F*ab* fragments cannot cross-link antigens (*bottom right*).



REDISTRIBUTION OF SURFACE ANTIGENS is induced by the binding of divalent antibody. The antigen is normally distributed diffusely over the surface, as revealed by labeling with monovalent F*ab* fragments (*a*). Divalent antibody cross-links antigen molecules and clusters them into a patchy distribution (*b*), even in metabolically inactive cells; if patched cells are warmed to from 20 to 37 degrees C. and are metabolically active, the patches move to one pole to form a cap and there is pinocytosis, or ingestion, of labeled membrane (*c*).

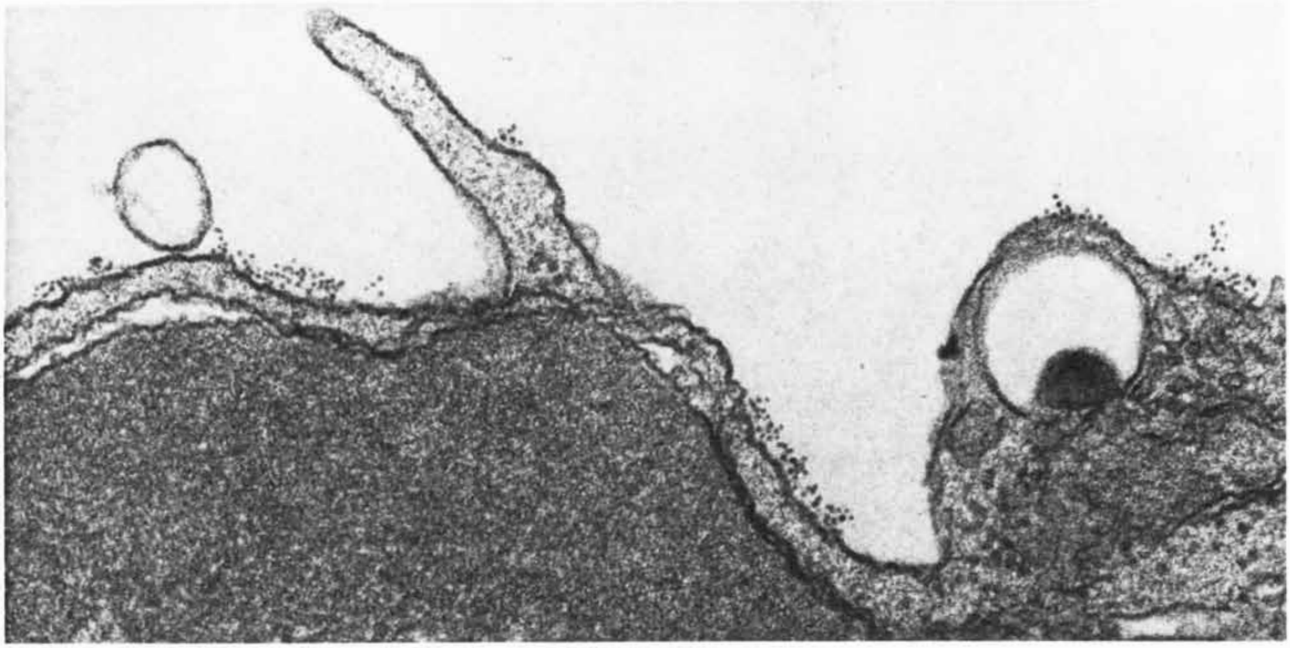
rescent second antibody directed against mouse immunoglobulin, that is, against the first antibodies. (Since immunoglobulin molecules are good antigens as well as being antibodies, and since anti-immunoglobulin antibodies are relatively easy to make, "sandwich" binding tests of this kind are common.) In control experiments in which Möller omitted the first layer (mouse antibody against surface antigens) and expected to find no binding, he was surprised to observe that some lymphocytes were labeled directly by the fluorescent anti-immunoglobulin antibody. Although he concluded correctly that these cells were probably producing antibody, the concept of antibody-like surface receptors on lymphocytes was not yet lodged in immunologists' minds, and so the implications of this important observation were missed. In 1965 Stewart Sell and Philip Gell of the University of Birmingham demonstrated that rabbit lymphocytes were stimulated to divide when they were exposed to anti-immunoglobulin antibodies, which implied that they had immunoglobulin on their surface. Later Mitchison showed the ability of mouse spleen cells to take up and respond to antigen could be inhibited by pretreating the cells with anti-immunoglobulin antibodies, providing indirect evidence for specific immunoglobulin receptors on lymphocytes.

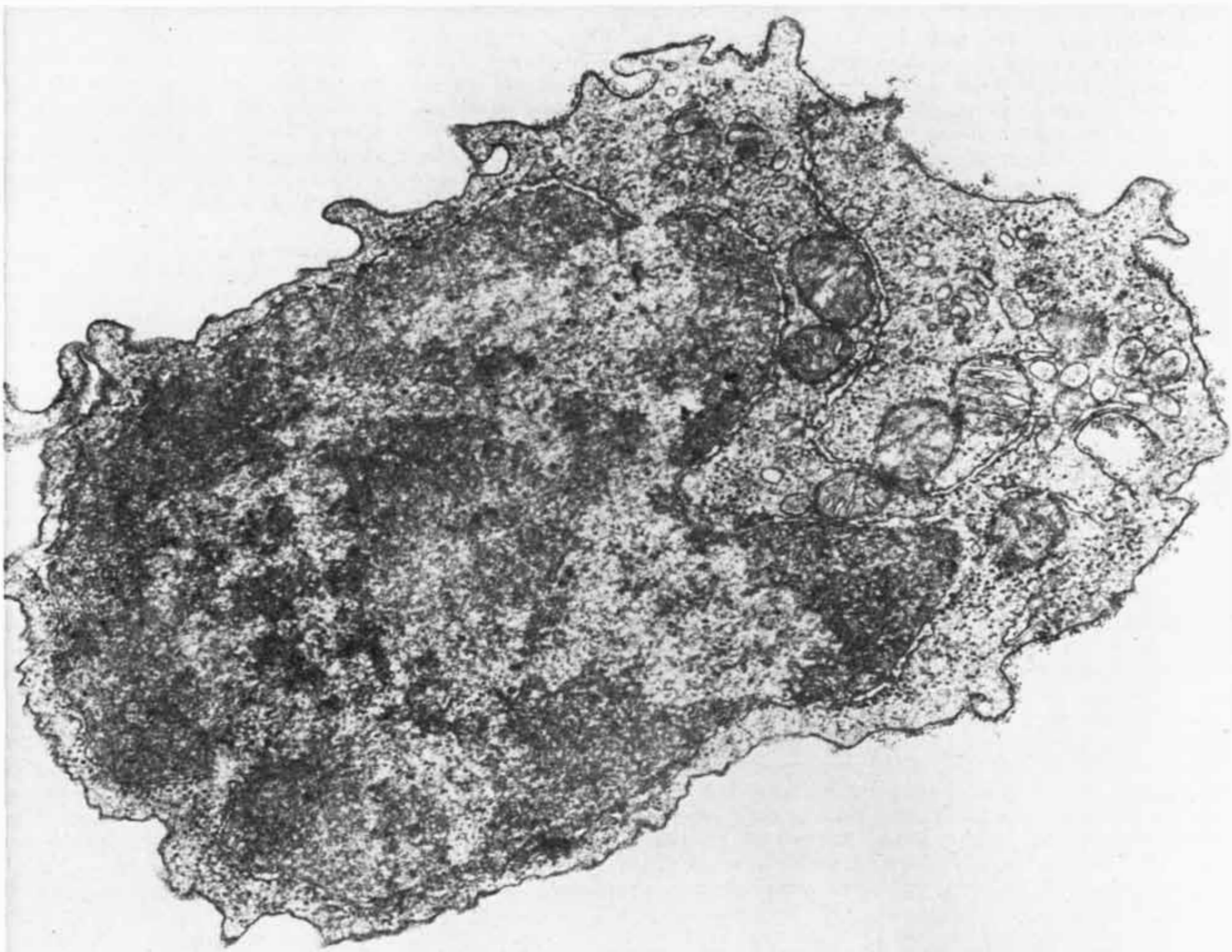
In 1969 Taylor, Michel Sternberg and I directly visualized immunoglobulin molecules on mouse lymphocytes with anti-immunoglobulin antibodies coupled to radioactive iodine or to the fluorescent dye fluorescein. In these experiments it was clear that some, but not all, of the lymphocytes in mouse spleen and lymph glands had detectable immunoglobulin on their surface. The next year I was able to show that the immunoglobulin-bearing lymphocytes were *B* cells, and that theta-bearing *T* lymphocytes were not labeled with fluorescent anti-immunoglobulin antibodies. Emil R. Unanue and his colleagues at the Harvard Medical School later reported similar findings. These results suggested that the *T*-cell receptors for antigen might not be conventional antibodies. Just what they are is not at all clear; there has been a long and heated controversy about the chemical nature of *T*-cell receptors, which is still unresolved. Cell-surface immunoglobulin has nevertheless been adopted as a definitive marker for *B* cells in various species, including man.

When we visualized immunoglobulin on the surface of mouse *B* lymphocytes with fluorescent antibody, a remarkable feature of the staining was its location: it was usually at one pole of the cell, where it formed a fluorescent "cap." At first I assumed that this localization, which had also been noted by Möller eight years earlier, represented the usual distribution of immunoglobulin molecules on *B* cells. We learned that the situation was more complex than that when Benvenuto Pernis and his colleagues at the University of Milan subsequently reported that immunoglobulin on rabbit lymphocytes was always distributed in discrete spots all over the cell surface.

To help resolve this discrepancy and to learn whether there were any special features of the cell in the region of the immunoglobulin cap, Stefanello de Petris and I decided to look at the distribution of immunoglobulin on lymphocytes under various experimental conditions and at high resolution. The technique we applied had been developed in 1959 by S. J. Singer at Yale University. It involves the coupling of antibody to ferritin, a large iron-containing protein that shows up as a black spot in an electron micrograph. De Petris, who was

FLUORESCENCE MICROGRAPHS demonstrate the distribution patterns shown schematically at the top of the page. Cells labeled with monovalent F*ab* fragments of anti-immunoglobulin antibody (*left*) show diffuse ring staining. (Antibody is all over the cell surface, but fluorescence is best observed by focusing on the periphery of the cell and is therefore seen as a ring of dye.) A cell that has been labeled with divalent antibody shows patchy staining at four degrees C. (*middle*); such a cell shows a cap at between 20 and 37 degrees (*right*).





FERRITIN LABELING shows redistribution of surface immunoglobulin in electron micrographs made by de Petris. The rim of a mouse *B* cell labeled with ferritin-coupled divalent anti-immunoglobulin antibody shows a patchy distribution of antibody at four degrees C. (*top*). At 20 degrees another cell labeled with divalent ferritin-coupled antibody shows a cap around the right-hand pole (*bottom*); this cell has also pinocytosed (ingested) some of the labeled membrane, seen as a ferritin-lined sac near the right pole of the cell.

experienced in immunoferritin electron microscopy, elected to label lymphocytes with ferritin-coupled anti-immunoglobulin antibodies at two different temperatures, four degrees and 20 degrees Celsius. The result was surprising, dramatic and unequivocal: at four degrees the ferritin-coupled antibody was distributed in small patches over the entire cell circumference, whereas at 20 degrees (room temperature) it was seen almost entirely in caps at one pole of the cell.

The caps were always over the pole of the cell opposite the off-center nucleus—the pole that would be the tail end of one of these motile cells if it were moving over a surface. The implications were exciting. It appeared that under normal circumstances immunoglobulin was distributed over the entire cell surface, and that the capped distribution was an induced change. This implied that the molecules were able to move about in the plane of the membrane—that the membrane was behaving like a two-dimensional fluid rather than a deformable solid. The notion that membranes were fluid and their proteins mobile dramatically changed the way one thought about membrane structure and function. Although that concept had been suggested by experiments done a year earlier, in 1971 most biologists still imagined membranes were relatively static structures.

The next few months were the most productive I have known. De Petris and I returned to the immunofluorescence technique so that we could do several capping experiments a day. The procedures were remarkably simple and the results were directly visible within a few hours in the fluorescence microscope. Mouse *B* cells that were labeled with fluorescent anti-immunoglobulin antibodies at four degrees showed uneven staining distributed in small patches all around the circumference of the cell, just as Pernis had described it for rabbit lymphocytes; when the cells were warmed to 37 degrees, these patchy fluorescent rings changed to caps within minutes. The capping process proved to be an energy-dependent, active phenomenon, since it could be prevented by treating the cells with a variety of metabolic inhibitors such as sodium azide. It was also not limited to immunoglobulin molecules; under appropriate conditions other surface antigens, such as theta, could be capped.

The molecular mechanism underlying capping remains unclear. Since lymphocytes change their shape during capping, much as they do when they move, it may be that similar mechanisms are involved in the two processes, even though cell locomotion is not a requirement for capping. This view is supported by the fact that the drug cytochalasin B partially inhibits capping. The drug is thought to inhibit the function of musclelike structures inside cells called microfilaments, which are important in cell movement.

In addition to capping, another kind of redistribution of surface immunoglobulin molecules was induced by the binding of anti-immunoglobulin antibodies. This was pinocytosis, the ingestion by the cell of a part of its membrane. We saw it first in the electron micrographs of cells labeled with ferritin-coupled antibody at 20 degrees: bits of labeled cell membrane had folded inward and pinched off to form vesicles, or sacs, within the cell. In immunofluorescence experiments conducted at 37 degrees we were able to follow the progressive pinocytosis of the membrane-bound fluorescent antibody. It was apparent within five minutes of adding the antibody, and by one hour virtually all the label appeared to be inside the cell. By relabeling such cells we could show that all the immunoglobulin had been cleared from the cell surface, whereas other surface antigens were unaffected.

The phenomenon whereby the binding of antibody to a surface antigen specifically induced the disappearance of that antigen had been described several years earlier by Boyse, Lloyd J. Old and their colleagues at the Sloan-Kettering Institute, who called it "antigenic modulation"; the underlying mechanism was unknown. Our observations made it clear that at least in the case of immunoglobulin, antigenic modulation was due to pinocytosis, induced by antibody, of the antibody-antigen complexes bound to membrane. Like Boyse and his colleagues, we found that the disappearance of immunoglobulin was not permanent; if the modulated cells (cells that had ingested their immunoglobulin) were cultured in the absence of anti-immunoglobulin antibodies, immunoglobulin reappeared on the cell surface within six to 12 hours; it was later shown that the recovery process required new protein synthesis—presumably the synthesis of fresh immunoglobulin.

Recently Jesse Roth and his colleagues at the National Institute of Arthritis, Metabolism, and Digestive Diseases have described a strikingly similar phenomenon: The binding of insulin to specific insulin receptors on a variety of cell types specifically causes the reversible disappearance of those receptors, a process they have called "down regulation." It is still not clear whether the loss of insulin receptors is the result of pinocytosis or of shedding. Similar observations have been made with other hormones and with some neurotransmitters, the small molecules that transmit the nerve impulse from one cell to another. It seems likely that this represents an important mechanism whereby the concentration of hormone or neurotransmitter can control the concentration of the specific receptors for that particular substance on the cell surface and thereby modulate the cell's sensitivity to the hormone or neurotransmitter.

In addition to capping and pinocytosis a third type of antibody-induced redistribution was occurring on cell surfaces in our experiments. We had initially overlooked it, and it only became apparent when we digested anti-immunoglobulin antibodies with the protein-cleaving enzyme papain before coupling them to fluorescein. Normally the *Y*-shaped antibody molecules are divalent, that is, they have two sites that can bind antigen, one at the end of each arm of the *Y*. As R. R. Porter had shown at Mill Hill in 1959, digesting immunoglobulin with papain cleaves the molecule into two identical monovalent fragments designated F*ab* (because each fragment has one antigen-binding site) and a third fragment designated F*c* (because it crystallizes readily). The fact that antibodies are normally divalent allows them to cross-link multivalent antigens (antigens with two or more antigenic determinants where antibody can bind) and thus to form large antigen-antibody lattices that precipitate out of solution [*see illustration on page 34*].

It occurred to us that perhaps the surface immunoglobulin molecules on *B* lymphocytes had to be cross-linked by divalent anti-immunoglobulin antibodies for capping to occur. We therefore split off monovalent F*ab* fragments from anti-immunoglobulin antibodies and coupled the fragments to fluorescein. The monovalent antibodies, which could not cross-link, did not give rise to capping, indicating that capping did indeed require cross-linking. They also did not give rise, however, to the distribution we were accustomed to seeing when *B* cells were labeled with divalent antibodies under noncapping conditions: an uneven distribution in patchy fluorescent rings. Instead the distribution was completely diffuse, forming smooth, continuous fluorescent rings such as we had not seen before.

Apparently, then, the patchy distribution itself represented an induced redistribution of the membrane immunoglobulin molecules. Unlike capping, however, patching was seen even at four degrees and in cells that had been metabolically poisoned, suggesting that it was a passive process that did not require metabolic energy. When de Petris and I repeated these experiments at University College London with F*ab* fragments of anti-immunoglobulin antibodies conjugated with ferritin, we found that even at the resolution of electron microscopy the immunoglobulin molecules (and other antigens) normally were distributed diffusely on the cell surface. (Surprisingly, although ferritin-coupled monovalent antibodies did not induce patching or capping, they did cause pinocytosis, but to a lesser extent than divalent antibody.)

For a *B* lymphocyte the binding to its surface of anti-immunoglobulin antibodies is an experimental aberration; what its surface receptors normally react with is their specific antigen. It was therefore important that we could show that multivalent antigens having two or more identical antigenic determinants, and therefore able to cross-link the immunoglobulin receptors on lymphocytes, could also induce patching, capping and pinocytosis of the receptors. This suggested that the redistribution of receptors was not merely a test-tube artifact but something that happens normally after the binding of antigen, and it raised the possibility that such redistribution could have an important role in somehow giving a signal to the *B* cell.

While we were in the process of these experiments we learned from Roger Taylor, who had left Mill Hill for the University of Bristol, that he and W. P. H. Duffus had been doing similar experiments and had reached the same conclusions. These observations on the induction of patching, capping and pinocytosis were soon confirmed and extended in many other laboratories: by Francis Loor, Luciana Forni and Pernis at the Basel Institute for Immunology, by Unanue and Morris J. Karnovsky and their colleagues at the Harvard Medical School, by Gerald M. Edelman and Ichiro Yahara at Rockefeller University and by François M. Kourilsky and his colleagues at the Hôpital Saint-Louis in Paris. All three forms of redistribution were demonstrated in a variety of cell types.

The main importance of these observations was that they provided direct evidence that cell membranes are dynamic fluid structures in which various components can move about. At the time concepts of membrane structure were evolving rapidly. It was known that membranes are composed of proteins and lipids and that the lipids, in the form of a bimolecular leaflet, or bilayer, constitute the framework of the membrane, as had been proposed as long ago as 1925 by E. Gorter and F. Grendel of the University of Leiden. The lipid molecules' hydrophilic heads, having a high affinity for water, are exposed to water at both surfaces of the bilayer and their hydrophobic tails are buried in the interior to avoid contact with water. In 1971 Roger Kornberg and Harden M. McConnell of Stanford University had just demonstrated that the individual lipid molecules in membranes move about rapidly in their own monolayer, indicating that the lipid bilayer is fluid. At the University of Cambridge, Mark S. Bretscher was in the process of showing that in the membrane of the red blood cell some of the proteins, which are inserted into the lipid bilayer in an asymmetrical manner, penetrate the bilayer and are exposed on both sides of the membrane.

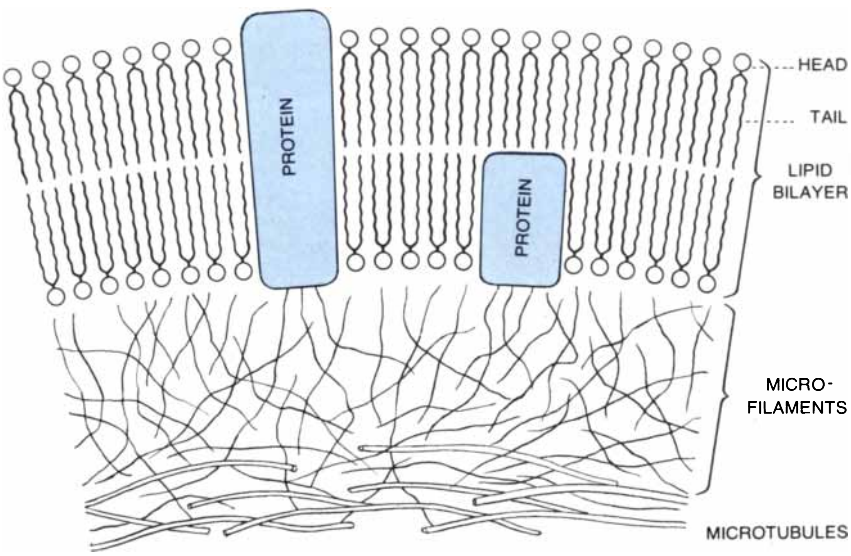
The first hint of membrane-protein mobility had come in 1969 from X-ray-diffraction studies on the membrane of the disks in rod cells of the retina, conducted by J. Kent Blasie and C. R. Worthington of the University of Michigan. Their findings indicated that the light-sensitive molecules of rhodopsin, the principal proteins in these membranes, were mobile and in a "liquid" state. Definitive evidence for the mobility of membrane proteins had been provided in 1970 by the dramatic experiments of Larry D. Frye and Michael A. Edidin of Johns Hopkins University, who followed the fate of surface antigens on human and mouse cells that had been fused together (by means of inactivated Sendai virus) to form human-mouse hybrid cells.

With antibodies coupled to different fluorescent dyes (fluorescein, which fluoresces green, and rhodamine, which fluoresces red) they showed that immediately following fusion the human and mouse antigens were each confined to their own half of most hybrid cells, forming fluorescent harlequins. Within one hour at 37 degrees the human and the mouse antigens had spread over the entire surface of most cells. Frye and Edidin recognized that their results indicated the antigens were free to move in the plane of the mixed membrane [*see top illustration on opposite page*]. Our finding the following year that divalent antibodies could redistribute membrane antigens into patches and caps confirmed this important concept and overcame a possible objection to the hybrid-cell experiments, namely that the membranes of virus-fused cells might not be normal.

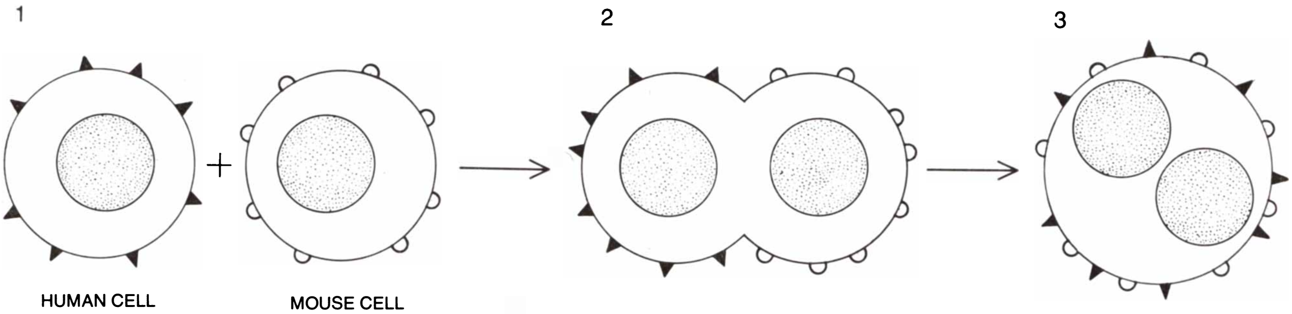
By 1971, then, it was becoming clear that biological membranes are two-dimensional fluid bilayers of lipids into which proteins (which are responsible for most of the functional properties of membranes) are inserted, and that in at least some cases these proteins are mobile in the plane of the membrane. In 1972 Singer, who was now at the University of California at San Diego, and Garth L. Nicolson integrated these and other important observations into the "fluid-mosaic model," which served to crystallize and popularize these concepts of membrane structure and is now widely accepted. There are such obvious advantages in having a fluid membrane in which molecules can diffuse that it is surprising that membrane fluidity was not predicted long ago a priori. Such a structure enables membrane molecules such as enzymes and their membrane-bound substrates to move about and interact with one another. It also provides a simple means of distributing membrane constituents from sites where they are inserted to other regions of the cell, and of dividing them evenly between the two daughter cells at the time of cell division.

On the other hand, the picture of a biological membrane as a lipid sea in which proteins float freely is overly simple. There are many cases where membrane proteins are restricted in their mobility, for example at cell junctions, where cells make contact with each other. In fact, current interest is shifting from the mobility of membrane proteins to the mechanisms that restrict their mobility. In particular, workers in many laboratories are attempting to study the interactions of membrane proteins and various fibrous components of cells, such as microfilaments and the larger microtubules, that are thought to play a role in controlling the distribution and movement of some membrane proteins. One of the few ways of investigating these interactions in intact cells, although it is an indirect way, has been to study the effect on capping of various drugs that are known to inhibit microtubules or microfilaments.

The antibody-induced redistribution of membrane antigens has also provided a useful approach to the mapping of cell surfaces. One can determine the relation between two antigens, *A* and *B*, on a cell by



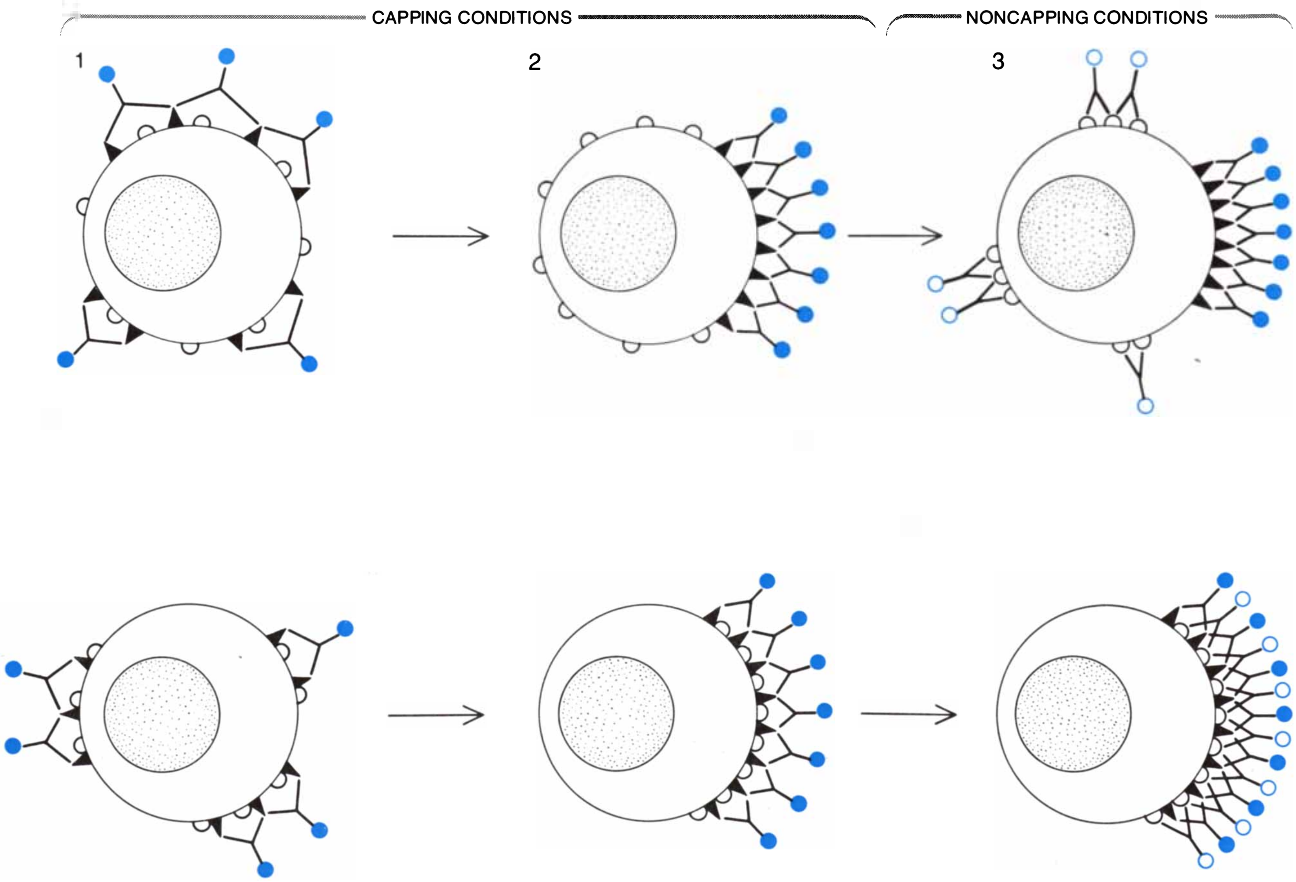
CELL MEMBRANES are composed of a lipid bilayer, a bimolecular sheet of lipid molecules whose hydrophilic head groups are exposed to water on both surfaces and whose hydrophobic tails are buried inside the membrane. Into this matrix specific proteins are inserted that are responsible for such functions as transport, intercellular communication and energy transduction. Cell membranes are fluid, and so individual protein molecules can move about in the plane of the membrane. There is evidence that filamentous structures in the cytoplasm such as microfilaments and microtubules can influence distribution and mobility of some membrane proteins.



HYBRID-CELL EXPERIMENT of Frye and Edidin (*see top illustration on page 31*) is diagrammed. Human cell and mouse cell (*1*), each with its own surface antigens, are fused by means of a virus. In a resulting heterokaryon, or multinucleated fused cell, the two antigens at first remain localized (as visualized by specific fluorescent antibodies not indicated here) in their own half membrane (*2*). After 40 minutes at 37 degrees C. the antigens have migrated in the plane of the fluid membrane and are intermixed on surface of a fused cell (*3*).

redistributing *A* with anti-*A* antibodies and seeing what happens to *B;* if *B* moves with *A,* the two antigens must be associated in the membrane, whereas if *B* is left behind, they must be independent [*see illustration below*]. The two antibodies can be followed by coupling them to two different fluorescent dyes. Such "co-capping" experiments are now being carried out widely to determine the relations among various antigens on the lymphocyte surface. With this approach Marc Feldmann, de Petris and I were able to show that a single antigen could redistribute all the immunoglobulin molecules on the surface of *B* cells that have any immunoglobulin receptors for that antigen. This was the first direct demonstration (indeed, it is still the only one) that all the immunoglobulin receptors on an individual *B* cell have the same antigen specificity, a central prediction of the clonal-selection hypothesis.

It is difficult to overestimate the value of antibodies as tools in biology. As probes for studying cell surfaces, they already have changed the face of immunology and our views about the structure of the cell membrane. It would be surprising if this promising beginning failed to lead to even more rewarding applications in the future.



"CO-CAPPING" EXPERIMENTS similar to the one pictured in the bottom illustration on page 31 can be modified to determine the relation between two antigens on a cell surface. In the top example capping an antigen with antibody coupled to one fluorescent dye (*solid color*) fails to cap the second antigen (*1, 2*), which is subsequently visualized (*3*) by antibody coupled to a different dye (*open colored circles*) under noncapping conditions. This indicates that the two antigens must be on separate, unassociated molecules. In the bottom example, on the other hand, capping one antigen "co-caps" the other one, showing that the two antigens are associated in the membrane.

Mechanical Alloying

Many useful combinations of metals cannot be achieved by melting or by conventional powder metallurgy. Such materials can be made by cold-welding metal powders in a special high-energy ball mill

by J. S. Benjamin

One of the serious limitations of modern technology is the reluctance of some metals to form alloys. For example, it is quite difficult to alloy by conventional techniques a metal with a high melting point and one with a low melting point. Even though two such metals may form a solution in the liquid state, the metal with the lower melting point tends to separate out in the course of cooling and solidification. Over the past few years a new technique of combining metals has been developed that circumvents many of the limitations of conventional alloying. Called mechanical alloying, it creates true alloys of metals and metal oxides that are very difficult or impossible to combine by other means. Mechanical alloying has produced high-strength superalloys for jet engines, and there is good reason to believe the technique will find a rich diversity of other applications.

It was discovered early in human history that the use of certain copper ores in smelting resulted in a metal with properties superior to those of metal produced from other copper ores. This was owing to the unrecognized presence of traces of arsenic and antimony. Hence some "copper" was in fact an alloy rather than a pure metal. In particular the melting point of the alloy was lowered, making it easier to cast, and the strength of the alloy was increased, making it more useful for weapons and tools. Somewhat later tin was deliberately alloyed with copper to produce bronze.

Today the large majority of alloys are still made by heating different metals together to temperatures above their melting points so that they form a solution with each other. For combinations of metals that resist such alloying metallurgists have resorted to the mechanical blending of powders, for example mixing powdered tungsten carbide, which has a high melting point, with powdered cobalt, which has a low melting point. The mixed powders are formed into solid metal by the application of high pressure and heat. These two operations can be performed in sequence (cold-pressing and sintering) or simultaneously (hot-pressing). The result is an alloy consisting of discrete particles of tungsten carbide embedded in a matrix of cobalt.

When solid articles are made from blends of different metal powders, the degree of homogeneity attained in the final product is limited by the size of the particles in the powders. If the particles are too coarse, the different ingredients will not interdiffuse during consolidation or prolonged heating. This problem can be overcome to some extent by starting with very fine powders.

One way to make a fine metal powder is to grind a coarse powder in a ball mill. There is, however, a practical limit to the fineness of the powder that can be obtained in this way: the particles begin to weld together as the milling continues. Sometimes lubricants such as kerosene or fatty acids are added to prevent the particles from coming in contact. Although lubricants make finer grinding possible, they may severely contaminate the powders and degrade the alloy made from them. Another serious limitation on fine grinding is the tendency for fine metal powders to burn spontaneously.

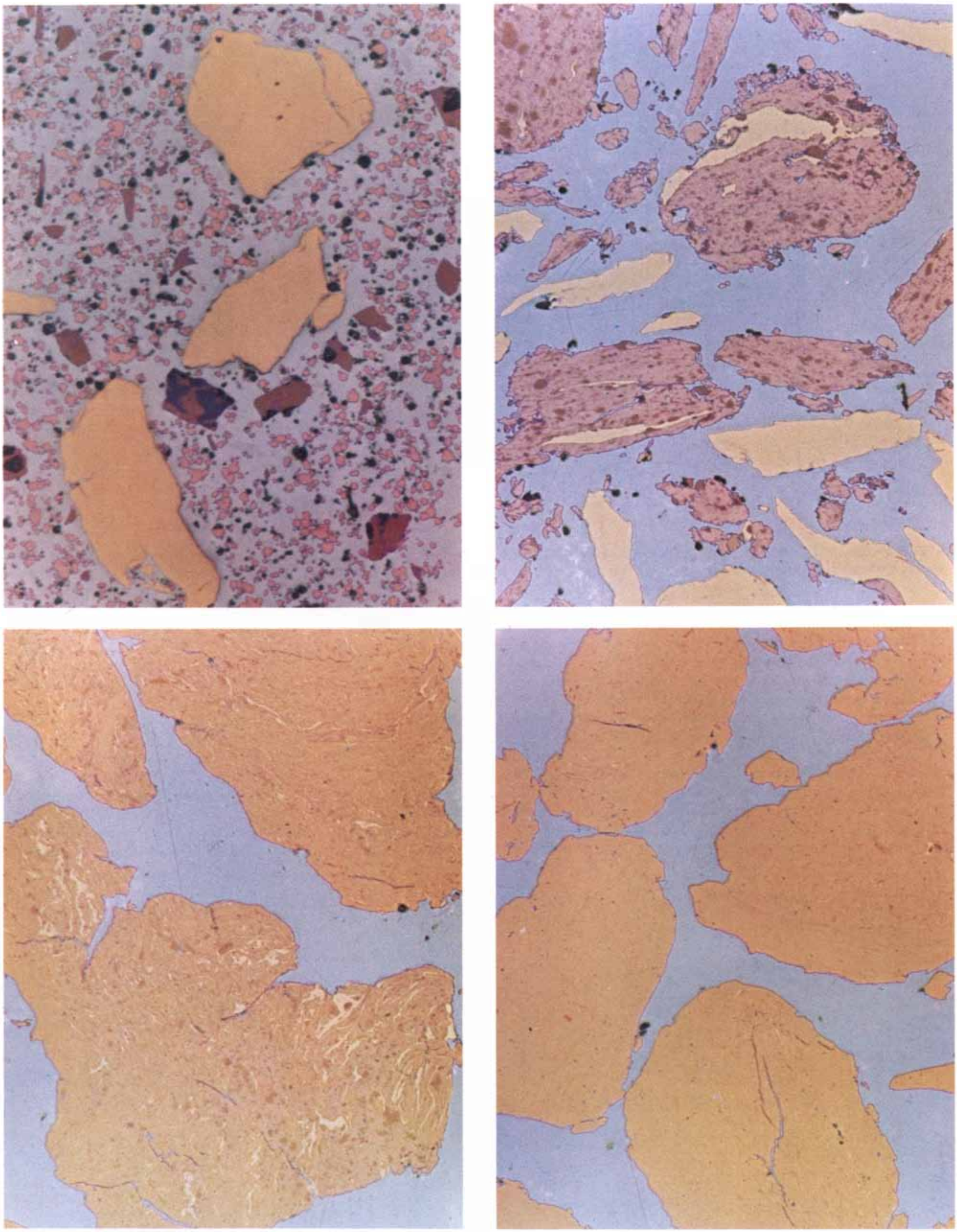
Mechanical alloying was developed as a means of overcoming the disadvantages of powder-blending without encountering the difficulties associated with ultrafine powders. It was found that when certain combinations of metals were milled together in the absence of a lubricant, they tended to form metal composites. Hard powders such as tungsten carbide, which normally do not form composites, can be made to form a solid with a soft powder such as cobalt by tumbling a mixture of the powders in a ball mill. Because the rolling and falling balls in a conventional ball mill have a limited energy, however, the formation of composites in this way took an exceptionally long time. For example, to produce a fine dispersion of tungsten carbide in cobalt by conventional milling one must first intensively mill the carbide so that it is broken down into fine particles before the cobalt is added.

In order to accelerate the formation of metal composites, to eliminate the dependency of final powder homogeneity on initial powder size and to avoid the hazards of fine powders, my colleagues and I at the Paul D. Merica Research Laboratory of the International Nickel Company turned to ball mills that would generate higher energies than conventional ball mills. A conventional ball mill consists of a rotating horizontal drum half-filled with small steel balls. As the drum rotates, the balls drop on the metal powder that is being ground; the rate of grinding increases with the speed of rotation. At high speeds, however, the centrifugal force acting on the steel balls exceeds the force of gravity, and the balls are pinned to the wall of the drum. At this point the grinding action stops. A ball mill capable of generating higher energies consists of a vertical drum with a series of impellers inside it. A powerful motor rotates the impellers, which in turn agitate the steel balls in the drum. Such a machine can achieve grinding rates more than 10 times higher than those typical of a conventional mill. Still higher grinding rates can be achieved on a small scale with a high-speed shaker ball mill. Such a mill produces only a few grams of powder, but it is a useful tool for testing new processes.

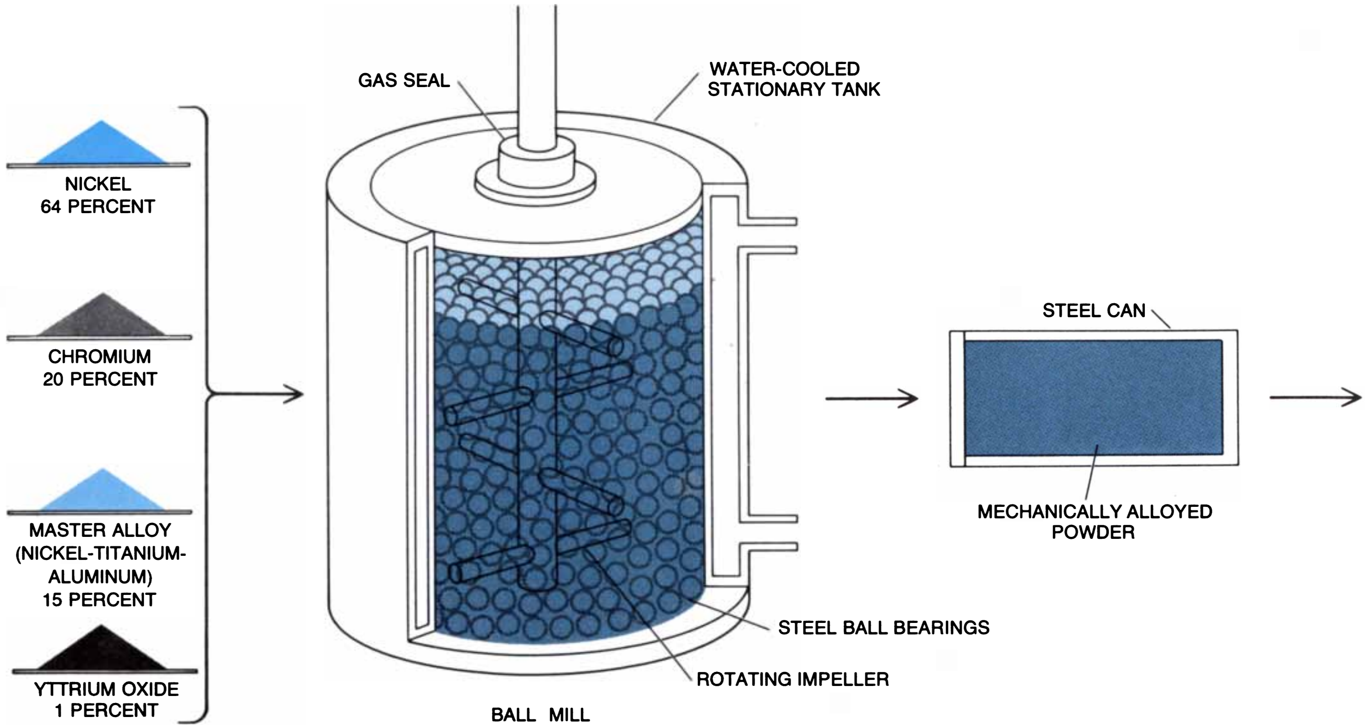
In a high-energy mill the particles of the metal powder are repeatedly flattened, fractured and rewelded. Every time two steel balls collide they trap powder particles between them. The force of the impact deforms the particles and creates atomically clean new surfaces. When the clean surfaces come in contact, they weld together. Since such surfaces readily oxidize, the milling operation is conducted in an atmosphere of nitrogen or an inert gas.

At early stages in the process the metal powders are still rather soft, and the tendency for them to weld together into larger particles predominates. A broad range of particle sizes develops, with some particles being two to three times larger in diameter (10 times larger in volume) than the original ones. As the process continues the particles get harder, and their ability to withstand deformation without fracturing decreases. The larger particles are more likely to incorporate flaws and to break apart when they are struck by the steel balls. In time the tendency to weld and the tendency to fracture come into balance, and the size of the particles becomes constant within a narrow range.

The composite particles that are formed by the welding of smaller particles have a



WELDING OF METAL PARTICLES and refinement of their structure during mechanical alloying are shown in this sequence of micrographs. (The metal particles were embedded in plastic and then polished and etched to bring out the different colors.) The particles in the raw powders (*upper left*) vary in size. The large gold particles are chromium, the purple and magenta particles are an alloy of nickel, aluminum and titanium and the small pink particles are nickel. After half an hour of processing in a high-energy ball mill most of the chromium and alloy particles are welded together in a matrix of nickel (*upper right*). After four hours of processing, all the ingredients have been welded together (*lower left*). After 10 hours the individual ingredients of the composite particles are nearly invisible (*lower right*). The uniform color of the particles indicates that a true alloy has been formed. The enlargement of the micrographs is about 250 diameters.

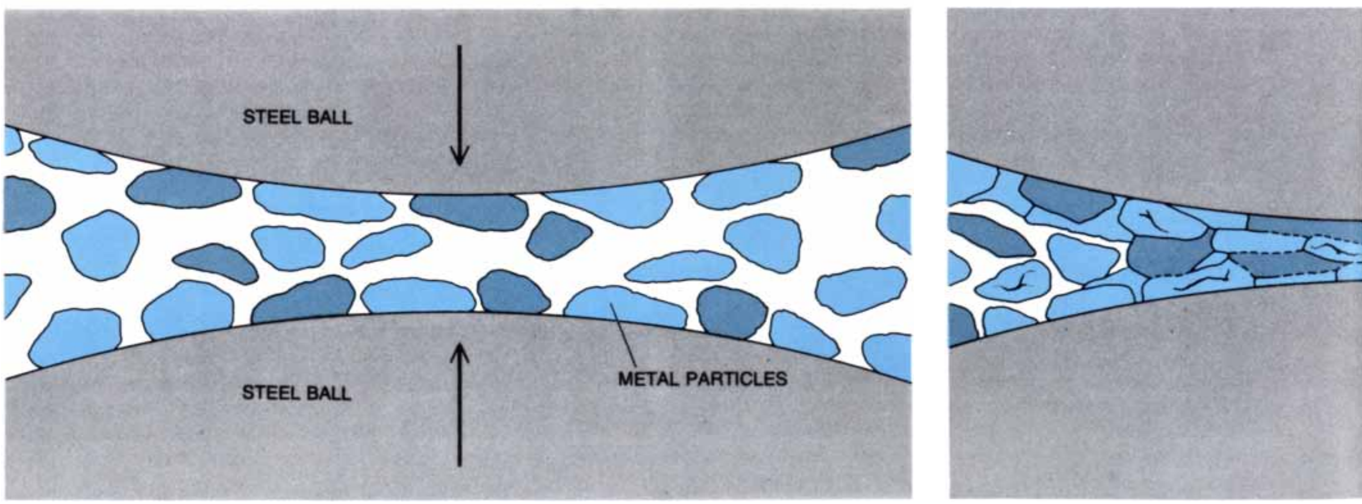


MECHANICAL-ALLOYING PROCESS for making a superalloy begins with grinding metal powders in a high-energy ball mill for about 20 hours. The mechanically alloyed powder is sealed in a steel can and formed into a metal bar by hot-extrusion. The extruded bar is

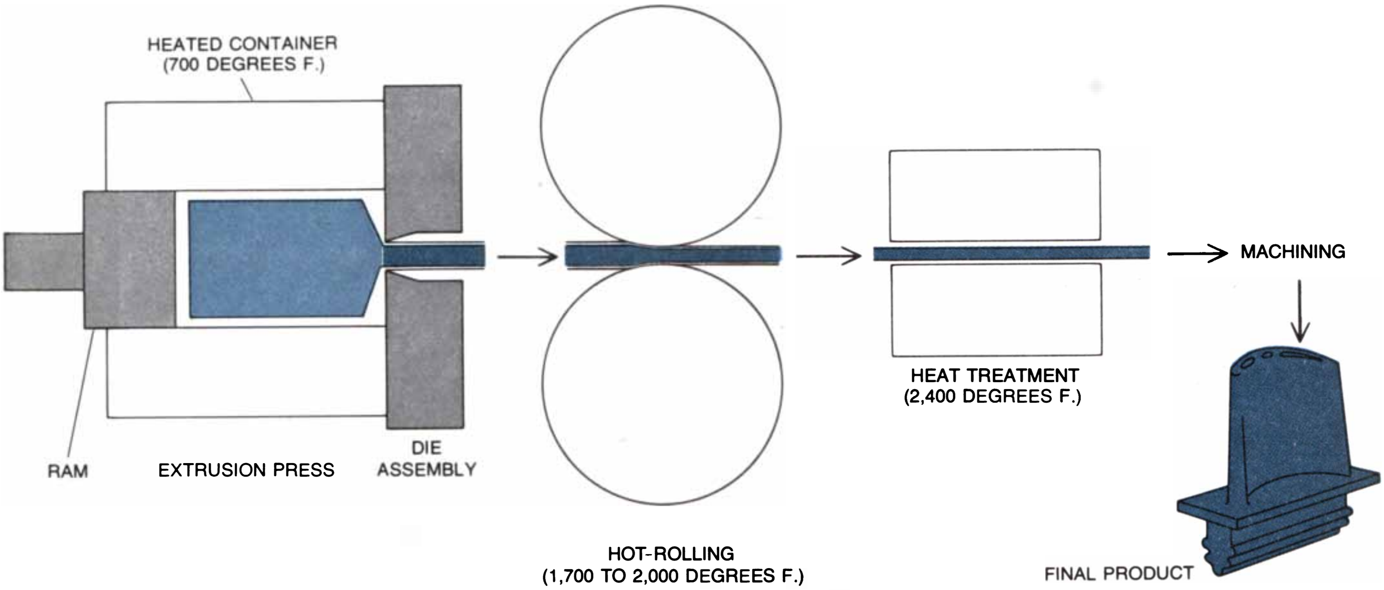
characteristic layered structure. Although there is little change in the size of the particles after the balance between welding and fracturing is attained, the structure of the particles is steadily refined. The thickness of each layer in the composite particles decreases because of the repeated impact of the steel balls, and at the same time the number of layers within each particle increases. The rate of refinement of the internal structure of the particles is roughly logarithmic with processing time. As a result the penalty for starting with coarser powders is not severe. For example, when the particles are initially some nine micrometers in diameter, it takes about 48 minutes to process them in a high-energy shaker mill, and increasing the size of the particles by a factor of 10 increases the processing time by only 22 minutes.

There is a slight tendency for the rate of refinement of the internal structure to decrease after a long period of processing because the particles get exceedingly hard. The hardness is the result of the accumulation of strain energy. Eventually a constant value called the saturation hardness is attained.

My colleagues and I have followed the refinement of the structure in mechanical alloying to the point where the layers in the particles cannot be resolved by light microscopy. It could be assumed that with further processing the powders still consist of discrete fragments of ever decreasing size, but that is not the case. John H. Weber and E. Lee Huston of our laboratory have shown that true alloying has



PARTICLES OF METAL POWDER in a ball mill are trapped between colliding steel balls. The force of the impact flattens the particles. The deformation spreads out the surface of the particles, creating gaps in the layer of adsorbed gases and exposing atomically clean metal. Where the clean surfaces come together cold pressure welds are formed. The force of the impact also causes some particles to frac-

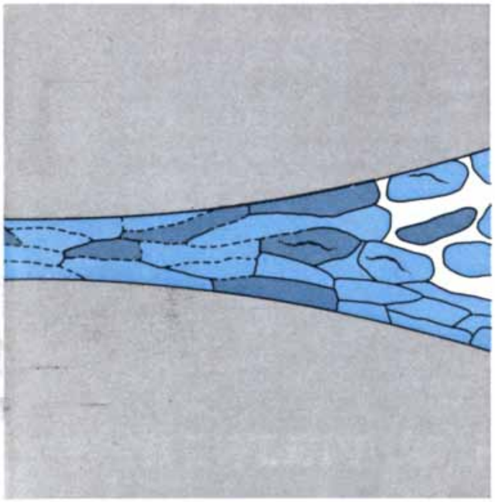


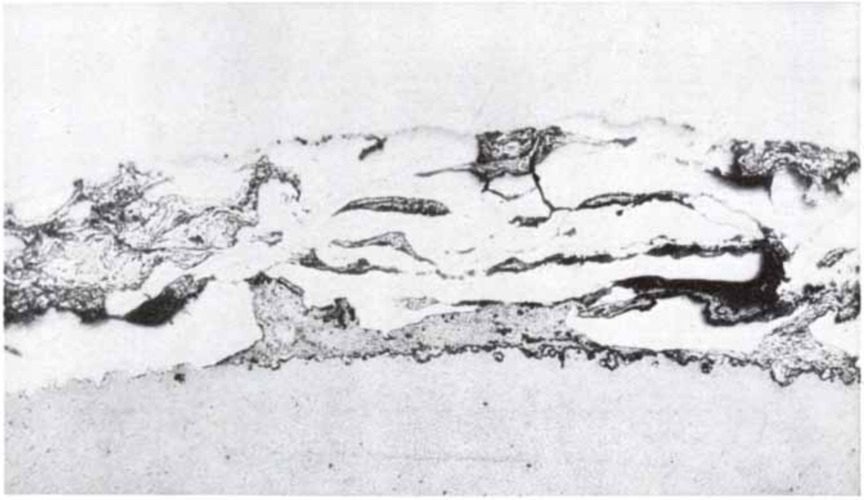
reduced in thickness by hot-rolling. The steel jacket of the bar is removed before the bar is annealed. During annealing the superalloy develops coarse grains that improve its strength at high temperatures. The product, a jet-engine blade, is machined from a section of the bar.

reached a significant point when the layers of a particle can no longer be optically resolved. In their experiment they worked with a mixture of nickel, which is magnetic, and chromium, which is nonmagnetic and destroys the magnetic response of nickel when alloyed with it. Weber and Huston processed the metals in a high-energy ball mill that produced a homogeneous powder in 10 to 15 hours. The magnetic response of the nickel decreased rapidly in the early stages of the processing. As the layers of nickel and chromium in the composite particles were brought into more intimate contact, more of the nickel was demagnetized. When the layers could no longer be resolved optically, the magnetic response had reached a value as low as that of a completely homogeneous nickel-chromium alloy produced by melting and working. This showed that the two metals were now intimately mixed on an atomic level. They had formed a true solid solution rather than a mixture of fine fragments.

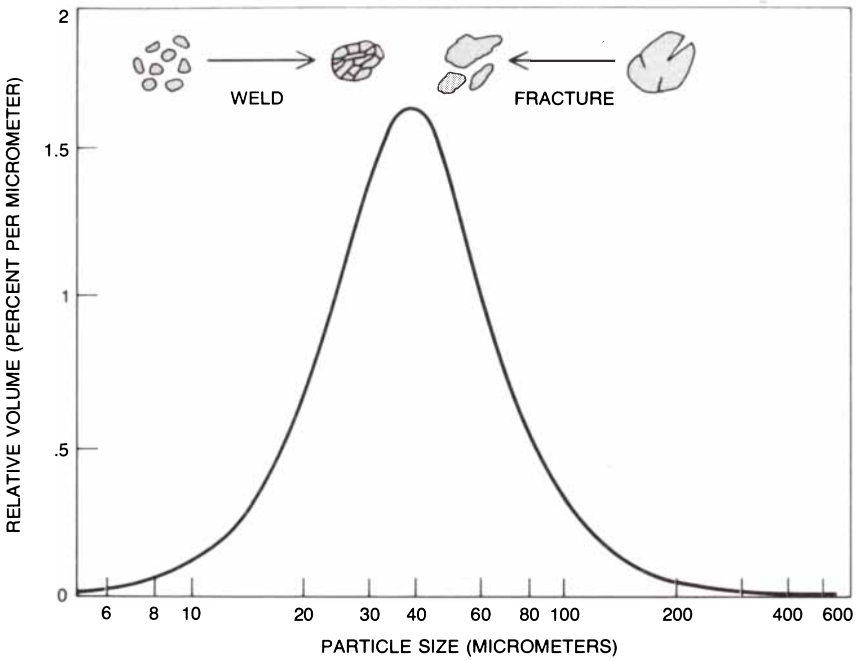
There is surprisingly little contamination of the powder by the iron in the steel grinding balls. In the course of the grinding process the balls become coated with a layer of the metals in the mixture. This layer and the free powder that is trapped in each collision absorb most of the energy when the balls collide.

Although mechanical alloying can produce composite metal particles with a homogeneous internal structure, there is no particular advantage in applying the technique to many combinations of metals, including the combination of nickel and chromium. The same results can be obtained by

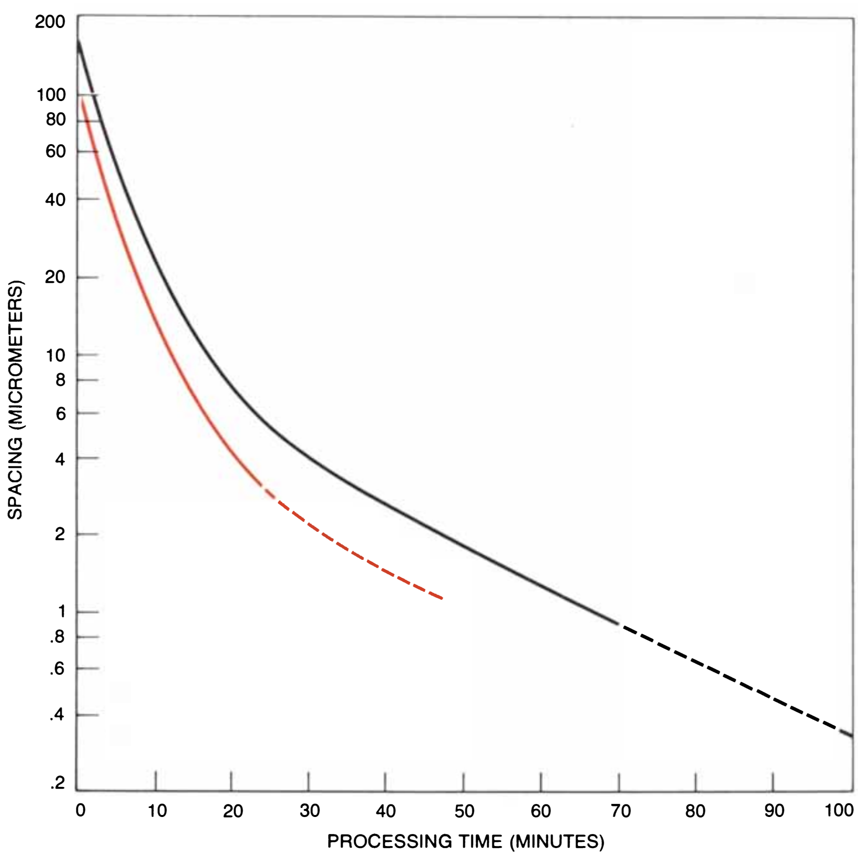




ture. The repeated flattening and rewelding of the particles build up composite particles with a characteristic layered structure. The micrograph at the right shows the result of processing iron powder (*dark particles*) and chromium powder (*light particles*) in a high-energy shaker ball mill for a few minutes. Even in this early stage of processing, cold welds between particles of iron and chromium are evident.



BALANCE BETWEEN WELDING AND FRACTURING is achieved during mechanical alloying, which leads to a relatively constant particle size. Smaller particles are more likely to be able to withstand deformation without fracturing when they are struck by the steel balls, and they tend to be welded into larger pieces. Larger particles, on the other hand, are more likely to have flaws and to fracture when they are struck. The overall tendency is therefore to drive the very fine particles and the very large particles toward the middle of the size distribution.



REDUCTION IN THICKNESS of the layers within a composite iron-chromium particle during mechanical alloying is approximately logarithmic with time (*black curve*). The average spacing of the layers is about twice the average spacing of the welds (*colored curve*) because of the formation of chromium-chromium and iron-iron welds that do not decrease layer spacing.

conventional means. The value of mechanical alloying becomes apparent when one attempts to make an alloy that cannot be made any other way.

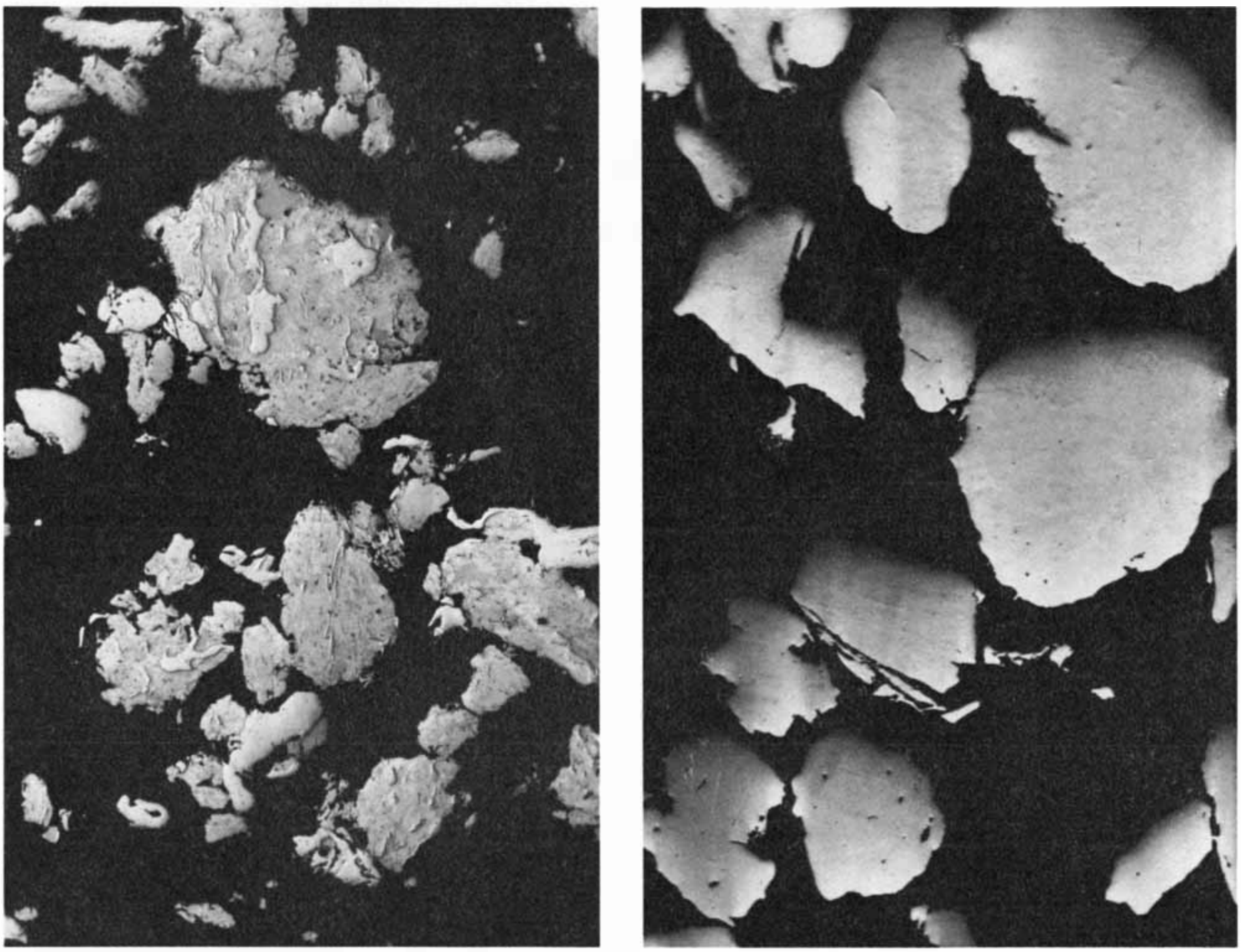
There are some applications where high strength at temperatures approaching the melting point of a metal can be of great value. For example, the propulsive thrust and fuel economy of a jet engine can be greatly improved if the engine can be operated at higher internal temperatures. One component of a jet engine that limits its internal operating temperature is the turbine blades. These blades are small airfoils that extract energy from the stream of hot gas passing through the engine. They are located at the periphery of the spinning turbine rotor, where they are subjected to a rigorous combination of stress, temperature and hot, corrosive exhaust gases. Under these conditions turbine blades tend to creep, that is, to gradually extend with time, and they can be seriously damaged by attack from the oxygen and sulfur in the hot exhaust gas.

Most jet-engine turbine blades are currently made out of nickel-base alloys containing small but critically important amounts of chromium, aluminum and titanium. These alloys are strong enough at moderate temperatures and resist corrosion by the hot gases, but they lack strength at higher temperatures. It has long been known that the high-temperature strength of metals can be greatly improved by dispersing a very fine stable oxide in them. Dispersion-strengthened nickel containing thorium oxide or yttrium oxide has good strength at high temperatures, but its ability to withstand stress at lower temperatures is poor. In addition dispersion-strengthened nickel does not possess adequate resistance to corrosion by hot exhaust gases.

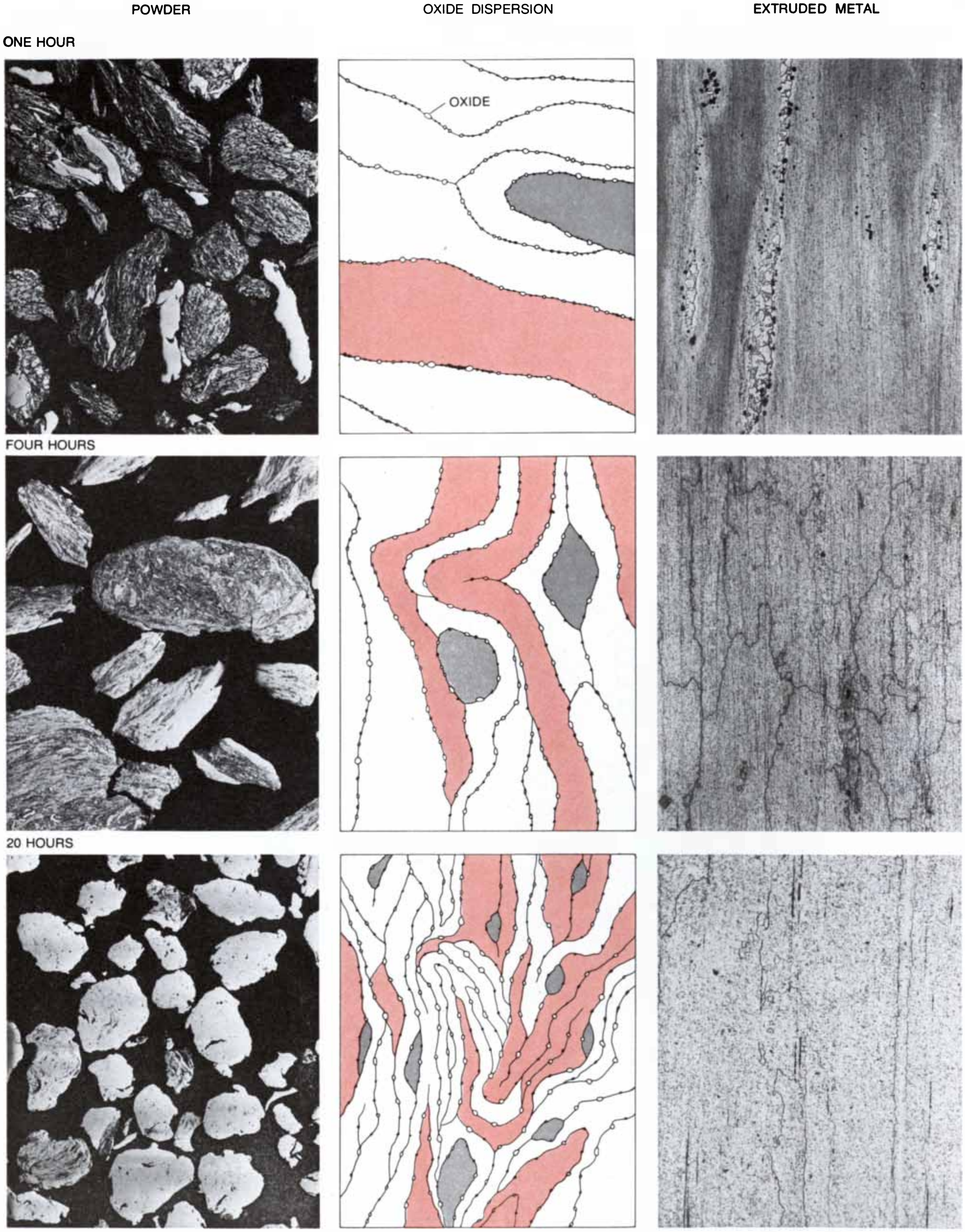
An alloy that combines the properties of nickel-base alloys and those of dispersion-strengthened nickel has been a goal of metallurgy for many years. Such an alloy, however, cannot be made by conventional means. Simple mixing techniques do not disperse the oxide well enough, or they require a powder so fine that it burns spontaneously, or they introduce so much contamination that reactive metals such as aluminum and titanium are also converted into oxides. Aluminum and titanium oxides are so stable that they cannot be reduced to the metallic state required in an alloy without reducing the deliberately dispersed oxide as well.

We attempted to produce a dispersion-strengthened nickel-base superalloy by simply blending a very fine high-purity nickel powder, a fairly coarse chromium powder, a master-alloy powder of nickel, aluminum and titanium and a very fine powder of yttrium oxide. The powders were hot-extruded into a bar, which was then heat-treated in an attempt to force the chromium, aluminum and titanium to diffuse into the nickel. The result was an inhomogeneous product

REFINEMENT OF INTERNAL STRUCTURE of composite iron-chromium particles at various stages of mechanical alloying is shown enlarged about 160 diameters. After five minutes of processing (*left*) the structure of the welded particles is still coarse. After about 20 minutes the particles have developed a striated structure (*middle*). The thickness of the layers continues to be reduced, and after 100 minutes of processing, the composite particles have been refined to the point where individual layers of iron and chromium are barely visible.



POWDERS FOR A HIGH-TEMPERATURE SUPERALLOY are shown at an early stage of mechanical alloying (*left*). The initial ingredients can be seen within the composite particles. Some fragments are still unprocessed. When alloying is completed, the powders have been processed to visual homogeneity, and individual layers within the composite particles cannot be resolved with a light microscope.



DISPERSION OF A REFRACTORY OXIDE at various stages of mechanical alloying is depicted. The oxide particles become trapped in the welds of the composite particles. After an hour of processing, the welds are far apart and the concentration of the oxide particles at the welds is fairly dense. A metal bar made from this powder consists of fine crystals and large fragments and is unsuitable for high-temperature applications. After four hours of processing, the welds have moved closer together and the spacing of the oxide particles has increased. Consolidation of the powder and heat treatment yield a metal bar that has a coarser crystalline structure but still shows some striations where certain constituents have not been adequately dispersed within the crystals. Finally, after 20 hours of processing, the oxide is evenly distributed along the welds. A metal bar made from this powder has a fine, uniform structure with coarse, elongated crystals.

with none of the desired high-temperature properties.

We now processed the same blend of powders in a high-energy ball mill. When such a mixture is mechanically alloyed, the degree to which its various constituents maintain their form depends on their relative hardness and their ability to withstand deformation. Nickel, which is the softest constituent of the mixture, is the cement that binds the other constituents together. Chromium is somewhat harder and less ductile than nickel, so that it tends to form platelike fragments that are embedded in the nickel. The master alloy of aluminum, titanium and nickel is the most brittle constituent; it tends to break up into small rectangular fragments that also become embedded in the nickel.

The yttrium oxide disperses along the welds in the composite particle. At first the welds are far apart, and the concentration of the oxide particles at each weld is rather dense. With further processing the spacing between the welds decreases, but the spacing of the oxide particles along each weld increases. Finally, when the powder has been processed to the point where the welds cannot be detected with a light microscope, the spacing between the welds is less than half a micrometer, a distance about equal to the spacing of the oxide particles along the welds. This nearly random dispersion of oxide particles in the metal matrix cannot be enhanced by further processing. At this point the powder is considered to be adequately processed for a dispersion-strengthened superalloy.

The effective dispersion of an oxide within a nickel-base alloy is only the first step in obtaining the full benefits of the material. When the mechanically alloyed powder is converted into a metal bar by hot-extrusion, the grain structure of the extruded bar is very fine. In order to gain the maximum high-temperature strength the grains must be induced to recrystallize to make them coarser. That can be achieved by reducing the thickness of the metal bar by hot-rolling and then annealing it at about 2,400 degrees Fahrenheit for about 30 minutes. The bar develops quite coarse grains that are elongated in the direction of extrusion.

More complex dispersion-strengthened nickel-base alloys can be made by mechanical alloying. In addition to nickel, chromium, aluminum, titanium and yttrium oxide, other elements such as tantalum, molybdenum and tungsten, which give added strength at lower temperatures, can be incorporated. We made such a complex alloy and found that it combined the high strength of nickel-base alloys at moderate temperatures and the strength characteristics of dispersion-strengthened nickel at high temperatures. In addition the mechanically alloyed material had superior corrosion resistance. These results demonstrate that the long-sought combination of high- and low-temperature strength in alloys can be achieved by the mechanical-alloying process.

The mechanical-alloying process is not limited to the production of nickel-base superalloys. Indeed, the process should be viewed as a new means of assembling many metal composites with controlled microstructures. The ways in which mechanical alloying can overcome problems inherent in forming metals by conventional casting, working and heat-treating can best be shown by considering some simple alloy systems. For example, a mixture of equal amounts of copper and lead forms a complete liquid solution at a sufficiently high temperature. Lead, however, has a lower melting point than copper, and a casting made of a copper-lead alloy tends to separate into large blobs of copper and lead even if it is stirred while it is cooling. Mechanical alloying of equal volumes of copper and lead, on the other hand, will give rise to a highly uniform dispersion of fine copper particles in the softer lead matrix. With a much smaller proportion of lead the copper forms the matrix, and the resulting material is similar to the leaded brasses that are used in bearings.

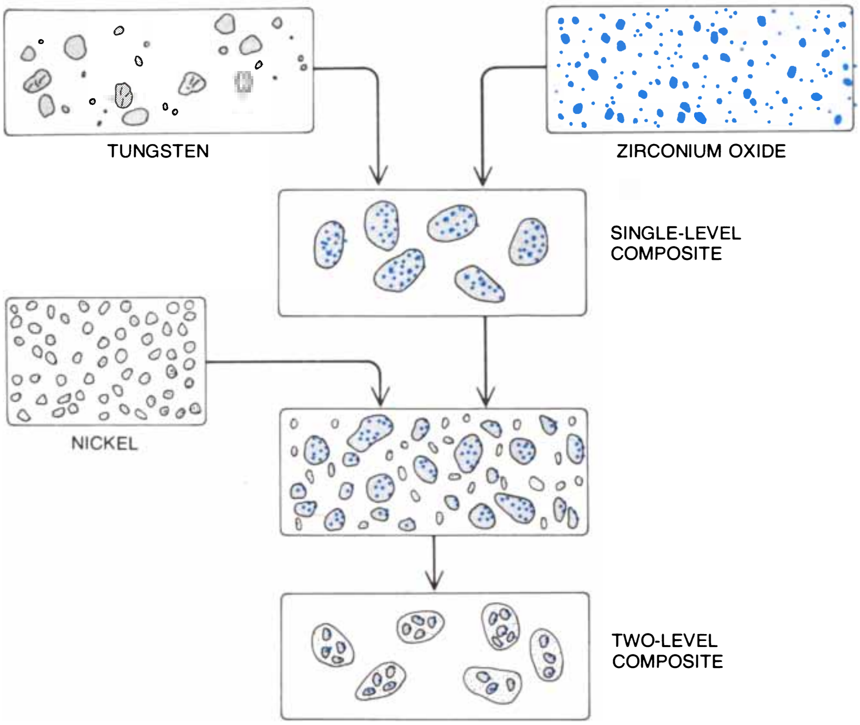
Fine dispersions of one metal in another have been produced by a technique known as solution treatment and aging. The technique takes advantage of the fact that a solid metal will dissolve more of another solid metal at a higher temperature than it will at a lower one. For example, if a mixture consisting of 97 percent copper and 3 percent iron is heated to 1,900 degrees F. and cooled rapidly, the iron will remain dissolved in the copper. If the alloy is later heated to 1,400 degrees F., the iron will be precipitated as fine particles. Unfortunately the technique is limited by the relatively low solubility of solid metals. For example, the maximum amount of iron that will dissolve in copper is about 4 percent. The addition of more iron results in the formation of large, coarse iron particles.

The limitations of the iron-copper system can be overcome by mechanical alloying. Almost any ratio of iron in copper can be achieved in this way. After the iron and copper have been processed in the high-energy ball mill the resulting alloy powder is heated to about 1,200 degrees F. The heat causes the thin plates of iron in the copper matrix to break up into small spheres. The end result is a dispersion of fine iron particles in copper.

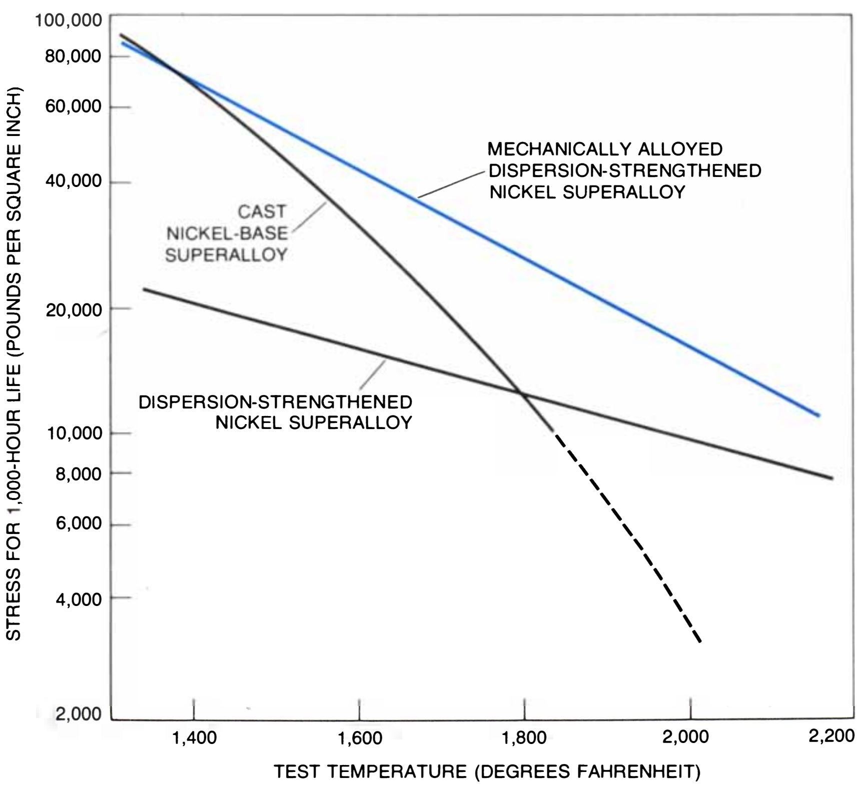
In mechanical alloying soft, ductile metals have a tendency to coat and surround hard, brittle materials. In general softer materials tend to form the matrix and the harder materials disperse within it. This tendency, together with the tendency of mechanically alloyed materials to become harder with increased processing, can be utilized to make complex, multilevel metal composites. For example, if tungsten, a relatively ductile metal, is mechanically alloyed with a very fine zirconium oxide powder, the result is a dispersion of zirconium oxide in tungsten. If nickel powder is now added and is processed with the zirconium oxide–tungsten composite, a two-level composite is formed: the hard, brittle zirconium oxide–tungsten is broken up and dispersed in a continuous matrix of the more ductile nickel. Contact between the zirconium oxide and the nickel is minimal because the zirconium oxide remains coated with tungsten. With a little imagination one can see that the number of levels within such a composite and the relative degree of dispersion of different ingredients that can be obtained by this technique are almost limitless. One potential application for such hierarchical composites might be the production of superconducting materials.

We have produced an austenitic stainless steel by mechanical alloying that is much stronger than conventional Type 304 stainless steel both at room temperature and at elevated temperatures. A potential application for this material might be a skin for

UNPROCESSED POWDERS for a high-temperature superalloy are shown enlarged 160 diameters in the micrograph at left. The fine particles are nickel, the large white particles are chromium and the medium-sized gray particles are a master alloy of nickel, aluminum and titanium. A fine powder of yttrium oxide is also added. Consolidation of a blend of these powders by hot-extrusion results in an inhomogeneous product with no useful properties (*right*).



MULTILEVEL METAL COMPOSITES can be created by mechanical alloying. For example, when tungsten and zirconium oxide are mechanically alloyed, a single-level composite of zirconium oxide in tungsten is produced. During the processing the composite becomes hard and brittle. Following the addition of nickel powder further processing yields an unusual two-level composite: zirconium oxide dispersed in tungsten, which in turn is dispersed in nickel. There is very little contact between the zirconium oxide and the nickel because the zirconium oxide is coated by the tungsten. It is possible to make even more complicated structures in this way.



SUPERALLOY FOR JET-ENGINE BLADES produced by mechanical alloying combines the very high strength of cast nickel-base superalloys at moderate temperatures and the stability and creep resistance of dispersion-strengthened nickel at high temperatures. In addition the mechanically alloyed material exhibits superior resistance to corrosion by exhaust gases.

supersonic aircraft. The superior strength of the material is due in part to an even dispersion of chromium oxide throughout the alloy.

If one considers the mechanical-alloying process from a more general standpoint, its potential uses become even more apparent. Mechanical alloying was first developed in order to add to alloys phases (oxides) that are insoluble in liquids. The tendency of extremely stable compounds not to form solutions with liquid metals is common and is true not only of oxides but also of nitrides and carbides. Mechanical alloying can be regarded as a way of forming a dispersion of any liquid-insoluble phase in a metal or an alloy provided that enough ductile metal powder can be introduced.

The mechanical-alloying process was extended to making alloys of metals with quite different melting points, such as copper and lead. The process might also be applied in more extreme cases where the metal with a low melting point would actually vaporize at temperatures above the melting point of the second metal. Exotic metals with a very low melting point, such as lithium and cesium, could be added to metals with a high melting point, such as nickel and iron, in quantities that could not be achieved by other methods. Such additions could have unanticipated effects on strength and corrosion resistance.

We have shown that the degree of dispersion of one metal or nonmetal within another can be closely controlled by the mechanical-alloying process. If the two metals will form a solid solution, the mechanical-alloying process can in fact be used to accomplish this end without resorting to very high temperatures. On the other hand, if the two metals are insoluble in the solid state (as is the case with iron and copper), an extremely fine dispersion of one of the metals in the other can be achieved.

Certain combinations of metals form structures, known as intermetallic compounds, that have definite formulas. Some of these compounds, which are of great importance for their superconducting properties, are extremely difficult to produce. There is a very real possibility that the atomically intimate mixture of different metals produced by mechanical alloying could represent a new procedure for making these superconductors.

So far the major application of mechanical alloying has been the production of dispersion-strengthened superalloys for jet-engine parts. It is clear that there are many other potential applications for the technique. Metal composites of a type and complexity that cannot be achieved by other methods can be assembled by mechanical alloying. In addition the process can produce relatively large quantities of alloyed powder, which indicates that it can be applied on a substantial scale. The most exciting application of mechanical alloying, however, may be the creation of entirely new metallic materials that have unique properties.

This was Slunchev Bryag, Bulgaria in October, 1973.

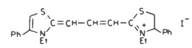
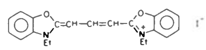
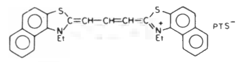
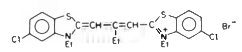
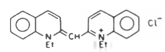
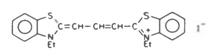
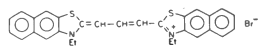
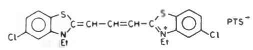
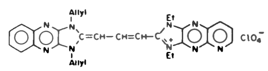
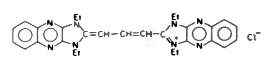
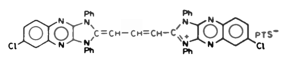
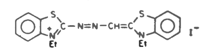
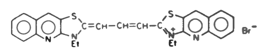
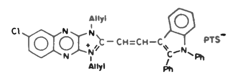
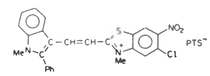
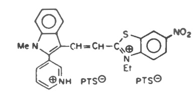
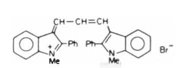
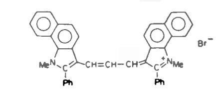
Data we presented here on reduction potentials of sensitizing dyes may interest cell biologists.

When the International Symposium for Model Investigations of the Photographic Process was hosted by the Bulgarian Academy of Sciences, any laboratory doing fundamental work in the field needed a seat at that game. Such occasions call for keen judgment. What with proprietary considerations, commercial or political, there is an inclination to listen hard, smile pleasantly, and say nothing. If all yielded to the inclination, an exercise in mass meditation would replace the demanding game in which one gives something, gets something, keeps something back, and comes home with enhanced respect for the other players.

Our contribution concerned redox potentials of sensitizing dyes. Specialists in that field do not think of a dye as a compound that imparts color; to them, a dye is a molecule rigged to receive photons in a certain energy range to effect a change of state as reflected in the strength of the molecule's grip on an electron. In the long run—and it is indeed a long run of deduction—this does affect color and ultimately vacation pictures and the late news in color on the tube.

Old photographs date themselves by their look almost as much from progress in sensitizing dyes as through dress and architecture. Generations of chemists have been making and testing dyes for effect on photographic sensitivity. H. W. Vogel in 1876 even tried morphine acetate, not in his veins but in his photographic emulsions. In the past decade it has become apparent that the effective spectral sensitizers work by delivering electrons or holes (electron vacancies) to the silver halide crystal. This is what starts the train of events that render the crystal convertible to silver by the developer (which is thereby enabled to become part of the molecular structure of quite other dyes that constitute the color in modern color photography). Oxidation potential states the electron hunger of a substance; reduction potential, its prodigality with electrons.

Though from our business viewpoint it is electron traffic with silver halide crystals that matters, the electron traffic that constitutes life itself at the cellular level is obviously even more important. Workers in that field may be interested in the existence of such series of compounds with graded redox potentials as these:

	E_R	E_{OX}
	-1.35	+0.54
	-1.26	+0.94
	-1.12	+0.62
	-1.06	+0.87
	-1.03	+0.99
	-1.00	+0.78
	-0.90 calc.	+0.95 calc.
	-0.86	+0.85
	-0.81	+0.95
	-0.79	+1.00
	-0.65	+0.77
	-0.64	>+1.00
	-0.63	>+1.00
	-0.54	>+1.00
	-0.41	>+1.00
	-0.32	>+1.00
	-0.20	>+1.00
	-0.11	+0.91

Whoever would have liked to talk to our man who presented these data at the Bulgarian symposium can reach him under the name Paul B. Gilman, Jr. at the Kodak Research Laboratories, Rochester, N.Y. 14650.

Kodak

SCIENCE AND THE CITIZEN

National Resource

Federal funding of university science, expressed in constant 1967 dollars, has declined by more than 20 percent since that year. Increasing emphasis on applied research—with 50 percent of National Institutes of Health funds going to cancer and heart disease and with most of the new money for the physical sciences coming from the Federal Energy Research and Development Administration (ERDA) and the Research Applied to National Needs (RANN) program of the National Science Foundation—has still more severely reduced the support of basic research in the universities. A 50 percent cut in funds for equipment has correspondingly discouraged the start-up of new experimental ventures, particularly those of young scientists. All these untoward pressures have been felt most heavily in the 20 foremost "research universities" that have seen their share of the diminishing Federal support decline by nearly 25 percent, from 46 percent of the total in 1967 to 35 percent in 1975.

To this recital of negative numbers, in the keynote address to the 1976 convention of the American Association for the Advancement of Science, Derek C. Bok, president of Harvard University, had to add that there are "two sides to the Federal coin." The new poor-relation relationship of the universities to Washington is vexed by the readiness of officials to invoke the money power in disputes arising from "a growing number of regulations affecting employment practices, admissions procedures, student records, safety measures and even the process of scientific investigation itself." It is vexed still further by a mounting controversy over university overhead charges, which claim 50 percent and more of research-grant and contract payments and whose reimbursement constitutes the largest source of unrestricted institutional support for the major research universities. That controversy is a divisive three-sided one, pitting the university administration against its science faculty as well as the granting agencies. Moreover, tighter budgets are developing strains "between scientists working in such Federally favored fields as cancer research and their colleagues in less popular areas such as systematic biology" and are stretching the old tensions strung by "the contrast between the perquisites of scientists and the ruder lot of humanists."

"In short," Bok concluded, "there is little evidence today of a cooperative effort to maintain the health and vitality of the great research institutions. Instead, Government agencies are more inclined to bargain at arms length with educational institutions to buy their services at the least possible cost."

The country's major universities can no longer depend for their support on the laissez-faire play of transactions between university scientists and the "multiplicity" of granting agencies. There is need, Bok declared, for a "national research policy" and the commitment of Federal support to those universities as a "critical national resource." A sound policy would sustain "a vigorous research effort in all basic fields of knowledge" as opposed to the "use of universities as vehicles to attack immediate problems." Bok shied away from the notion of "some master agency for science that will formulate a detailed and monolithic national plan." He summoned his fellow university presidents to join with "interested scholars and scientists" in a "broader dialogue with . . . members of Congress and key officials in the Executive Branch" to consider "not only the national priorities for research but also the long-term needs of the institutions that are responsible for so much of that research."

Breeders on Line

The multinational research effort aimed at developing an economically competitive nuclear-power industry based on breeder reactors before the end of this century, when rising uranium costs are expected to militate against further construction of less efficient nuclear-power reactors, is scheduled to move another step closer to its goal soon, when the British Prototype Fast Reactor (PFR) at Dounreay in Scotland begins operating at its rated capacity of 250 megawatts. The British breeder, which has been generating electricity at a level of 30 megawatts since last October, will thus become the second prototype breeder-reactor power station to reach full power, joining the French Phénix installation near Avignon, which began contributing 250 megawatts of electricity to the national power grid in July, 1974. Since that time the French breeder has compiled an impressive operating record. In its first year it produced full power more than 80 percent of the time, a measure of reliability substantially higher than the 60 percent figure typical of present-day light-water reactors in their first year of operation. Owing to the higher temperature at which a breeder reactor operates, the Phénix is currently achieving a thermal efficiency of 43 percent, again well above the average 33 percent thermal efficiency of light-water reactors.

The main anticipated advantage of breeder reactors, however, lies in the area of fuel economy. By converting nonfissionable uranium 238 into fissionable plutonium 239 in a fast-neutron-absorbing "breeding blanket" surrounding the core of the reactor, a breeder reactor is capable of producing more nuclear fuel than it consumes. In effect the breeder-reactor economy will then extract energy not only from the rare, easily fissionable isotope uranium 235 but also from the much more plentiful, nonfissionable isotope uranium 238, thereby increasing the amount of available energy in uranium about sixtyfold. The key measure of the fuel-production rate of a breeder is its doubling time: the time needed for it to double its original inventory of fuel. So far the Phénix has attained a doubling time of 30 to 60 years, whereas the doubling time of the British PFR is expected to be closer to 30 years. A doubling time of 20 years or less has been set as a standard that would allow a nuclear-power industry based on breeders to expand at a reasonable rate after the year 2000.

Both the Phénix and the PFR employ liquid sodium as a core coolant, the approach favored by all the nations with active breeder-research programs. Another technical characteristic shared by the two on-line prototype breeders is that both are reactors of the "pot" type, that is, systems in which most of the large components (the reactor core, the primary sodium pumps and the intermediate heat exchangers) are immersed in one large tank of liquid sodium. In the alternative "loop" design, preferred by U.S. breeder engineers on the ground of safety, the reactor core is in a separate vessel and is connected to the other components by pipes.

In both France and Britain plans are going forward to build full-scale breeder-reactor power stations based on the prototype designs. The Superphénix, a 1,200-megawatt breeder to be built in southeastern France and paid for by a combine of French, German and Italian electric-utility companies, is scheduled to be completed as early as 1982. In addition the French are planning to order two more 1,200-megawatt breeders before 1980. The British expect to start construction within this decade of a 1,300-megawatt plant, to be called the Commercial Fast Reactor (CFR).

Other countries with large breeder-reactor programs include the U.S.S.R., the U.S., West Germany and Japan. The U.S.S.R. has had a 350-megawatt prototype breeder plant of the loop type completed for more than three years, but it has not yet reached full electric-power production because of numerous failures in the steam-generating equipment. In addition the Russians are building a 600-megawatt breeder of the pot type that is due to be completed by the end of next year.

In spite of the early U.S. lead in the development of experimental breeder reactors (the first nuclear reactor in the world to generate electricity was a small breeder built in the U.S. in 1951) and the fact that the breeder program remains the biggest item in the U.S. energy-research budget, there is no prospect of a fully operational prototype U.S. breeder comparable to the Phénix or the PFR until 1983 at the earliest. The first U.S. prototype breeder, the 380-megawatt Clinch River demonstration plant at Oak Ridge, Tenn., recently received a strong endorsement from the Ener-

1. LANCIA BETA COUPE
a sporty, front-wheel drive car with a 5-speed transmission, rack-and-pinion steering, plus real leather bucket seats.

2. LANCIA BETA SEDAN
technically identical to the Coupe yet also has an adjustable steering column, reclining bucket seats, and deep, plush carpeting.

3. LANCIA BETA HPE ESTATE WAGON*
a genuine sports wagon. Flip down the rear seats and toss in almost anything — from a pair of skiis to a six piece set of luggage.

4. LANCIA BETA SCORPION*
the most exciting Lancia of all. It's a 5-speed, mid-engine, 2-seater sports car. And it's the result of 68 years of European racing.

LANCIA

The intelligent alternatives.

The one thing that's come between most people and a European grand touring car has been an outrageous price tag. Fortunately, there's now an intelligent alternative. Four to be exact. Because Lancia, one of Europe's oldest and most respected car manufacturers, has recently introduced to America a complete new line of cars. Each one is a classic example of sophisticated engineering as well as unhurried European craftsmanship. And each is realistically priced. So now that the financial barrier between you and a European grand touring car has been removed, we suggest you visit your nearest Lancia dealer soon.

* Subject to availability.

For the name of your nearest Lancia dealer call toll free (800) 447-4700 or in Illinois (800) 322-4400.

Overseas delivery, leasing and daily rental arranged through your participating dealer. Lancia of America, Division of Fiat Distributors, Inc., 155 Chestnut Ridge Road, Montvale, N.J. 07645.

gy Research and Development Administration (ERDA). By 1986, when the Clinch River reactor is scheduled to be completed and tested at full power, the U.S. will decide whether to proceed with a large-scale commercial breeder, which could then be expected to go critical in about 1993. Nevertheless, according to a recent statement by Thomas A. Nemzek, who has just retired as director of ERDA's Division of Reactor Development and Demonstration, liquid-metal fast breeder reactors (LMFBR) can still be "well established as competitive" in the U.S. by the turn of the century if utilities and the nuclear-power industry "will recognize the great benefits of LMFBR technology and act accordingly."

The Missing Neutrinos (Cont.)

Five years ago students of how the sun generates energy were disturbed to learn that the number of neutrinos—the massless particles originating in nuclear reactions—arriving on the earth from the sun appeared to be less than a thirtieth of the number predicted by the generally accepted theory of what goes on in the sun's core. One result was that a number of investigators undertook to develop alternative models of the sun's interior that would account for the missing neutrinos. Now it appears that there may be more neutrinos than there have seemed to be.

The apparatus that was set up to detect the neutrinos, designed by Raymond Davis, Jr., of the Brookhaven National Laboratory, basically consists of a tank of 100,000 gallons of the common dry-cleaning fluid perchloroethylene set up under a mile of solid rock in the Homestake Gold Mine near Lead, S.D. Perchloroethylene (C_2Cl_4) contains an abundance of chlorine atoms, specifically those of the isotope chlorine 37. When a neutrino passes through the tank and interacts with an atom of chlorine 37, it transmutes it into an atom of the radioactive isotope argon 37. After each experimental run, lasting up to six months, the tank is swept with helium to remove the argon. The argon is then introduced into a proportional counter that detects its radioactive decay.

The flux of neutrinos is measured in solar neutrino units, abbreviated SNU; one SNU is defined as the flux giving rise to one neutrino-induced event per second per 10^{36} atoms of chlorine. In Davis' tank, which contains some 10^{30} atoms of chlorine, one SNU corresponds to the formation of one atom of argon 37 every five days, or .2 atom per day. Current models of the sun predict that the flux of neutrinos at the distance of the earth should be 6 ± 2 SNU; about the minimum flux one can obtain from current models of the sun's interior without radically changing their assumptions is 1.5 SNU. A series of 10 runs of Davis' experiment over a period of three years showed that the tank was detecting an average flux of approximately $.28 \pm .09$ SNU. Three recent runs, however, have each detected neutrinos at a flux of approximately four SNU.

There has been no change in the sensitivity of the detector, in the background level of radiation from cosmic rays and the natural radioactivity of the surrounding rocks or in the way the sample is removed from the tank. To the best of the experimenters' knowledge the tank has not been contaminated. The only change that has been made in the detector is the temporary draining off last summer of the water surrounding the tank (to shield it against the radioactivity of the rocks) so that the tank could be inspected for corrosion and given a new coat of paint.

Davis is reluctant to attribute the recent high runs to the possibility that the sun has somehow "turned on." The high runs are within the range of statistical fluctuations; in fact, in 1972 there was an even higher run: one of about 5.5 SNU. While awaiting further data, Davis has averaged the three recent runs with the preceding 10 and has calculated that all 13 runs yield a solar-neutrino flux of $1.2 \pm .5$ SNU.

Unmasking an Agent

Multiple sclerosis is a disease, primarily of young adults, characterized by such neurological symptoms as speech and ocular defects, tremor and various degrees of paralysis. The immediate cause of the symptoms is apparently damage to the myelin sheath protecting the axon of nerve cells; it is scar tissue in the demyelinated areas that produces the hard plaques in the white matter of the brain for which the disease is named. The cause of the nerve damage is not known. In recent decades there have been increasing indications, largely from epidemiological considerations but also by analogy with certain other diseases, that multiple sclerosis is somehow caused by a virus. Now for the first time there is confirmed laboratory evidence that implicates some kind of infectious agent, presumably a virus.

Actually it was in 1972 that the presence of a transmissible factor in multiple-sclerosis patients was first reported by Richard I. Carp and his colleagues at the Institute for Basic Research in Mental Retardation, a New York State facility on Staten Island. They inoculated mice with a filtrate from the brain, spleen, cerebrospinal fluid or blood serum of patients. The response was a marked depression in the number of polymorphonuclear neutrophils—one kind of white blood cell—in the mice. Serum from the affected mice in turn had the polymorph-depressing effect on other mice. Carp's findings were difficult to reproduce in other laboratories, largely because many mice have a low polymorph count to begin with and the count can fluctuate even in the absence of a specific agent; there had been reports of multiple-sclerosis agents before, and workers in the field were skeptical. Carp's group went on to develop a cell-culture test for the agent. The multiple-sclerosis agent slowed the rate of cell division in a line of cultured mouse cells; when the cells were broken up after a number of serial passages, a filtrate from the cell fluid was again capable of depressing the polymorph count in mice.

Late last year the Staten Island results were confirmed by a group at the Children's Hospital of Philadelphia. Werner and Gertrude Henle and Ursula and Paul Koldovsky and their colleagues reproduced the polymorphonuclear-neutrophil depression in mice and in other small animals. They also confirmed that the agent was one that would pass through a filter with 50-nanometer pores but not one with 25-nanometer pores, suggesting that it is somewhere between the poliomyelitis and the influenza viruses in size. The Henles and the Koldovskys also found what may be an antibody to what may be a multiple-sclerosis virus: the white-cell depression could be neutralized by a substance in the immunoglobulin fraction of the blood serum of multiple-sclerosis patients. The same substance was present in the serum of some relatives and nurses of patients—and also in a large proportion of blood-serum samples that had been collected in East Africa. The last result is consistent with epidemiological data, collected over many years, suggesting that multiple sclerosis is prevalent as a minor childhood infection in many countries with poor sanitation and that it is in the industrialized (largely northern) countries that it is contracted later in life, when it is apparently more likely to have serious effects.

Galaxies Primeval

One of the felicitous features of the big-bang model of the universe is that the past becomes visible: when we look at a very distant object, we see it at an early epoch. We shall probably never see back to the big bang itself (although the cosmic background radiation provides a glimpse of an event only a few minutes after it). We should, however, be able to see the first distinct large objects in the universe: galaxies in the process of formation. Such primeval galaxies would be distinguished by their large velocity of recession from us, which could be detected in their spectra as a large shift toward longer wavelengths (a red shift). Because the galaxies would be in an early stage of their evolution, their spectra would also differ in form from those of galaxies contemporary with our own.

David L. Meier of the University of Texas at Austin suggests that two primeval galaxies may already have been observed and catalogued but not recognized. The two candidates, designated OH 471 and 4C 05.34, are now classified as quasi-stellar objects, or quasars. Writing in *The Astrophysical Journal,* Meier proposes that they may be primeval galaxies "masquerading as red objects that are quasi-stellar in appearance."

Models of the evolution of galaxies have been constructed by several authors; Meier's calculations are based on one developed by Richard B. Larson of Yale University. The model describes the formation of a giant elliptical galaxy from a collapsing cloud

The Black Watch Kit $29.95

The Black Watch by Sinclair is unique. Controlled by a quartz crystal... powered by two hearing aid batteries. Styled in understated elegance the Sinclair way. No knobs or buttons. To see the exact time or date just touch the face of the case. A re-set control is on the back.

Correctly assembled watches are guaranteed for a full year... Accuracy within a second per day.

The kit contains:

1. Printed Circuit Board.
2. Unique Sinclair Designed IC.
3. Encapsulated Quartz Crystal.
4. Trimmer.
5. Capacitor.
6. LED Display.
7. 2-Part Case with Window in Position.
8. Batteries and Clip.
9. Black Strap.
10. Full Instructions.

All you provide is a fine soldering iron and wire snips.

Build Your Own Scientific Calculator in 3 Hours for $14.95

Designing the Sinclair Scientific was no small feat of engineering. You don't have to be an engineer to assemble it yourself with our kit.

Put together this thinnest, lightest scientific calculator from eight groups of components, using only a soldering iron and wire snips. Complete instructions are included.

The assembled calculator can do:

- Sin and Arcsin
- Cos and Arccos
- Tan and Arctan
- Automatic Squaring
- Automatic Doubling
- Log and Antilog (Base 10 giving quick access to X^y – powers and roots)
- Four basic arithmetic functions plus scientific notation (10^{-99} to 10^{+99})

sinclair™

Sinclair Radionics Inc.
375 Park Avenue, New York, N.Y. 10022

Please send me:

________	Sinclair Black Watch Kit(s) with date @ $29.95 ea.	$________
________	Sinclair Scientific Calculator Kit(s) @ $14.95 ea.	$________
	Sales Tax (N.Y. Residents)	$________
	Shipping & Handling $2.50 per unit	$________
	Enclosed is my check/m.o. for total	$________

Name ________________________________

Address ________________________________

City ________________________________

State ____________________ Zip ____________ of hydrogen. The first region of the galaxy to brighten significantly is an envelope of stars near the perimeter; only later does the core of the galaxy become densely populated with stars. It was originally thought that the evolving galaxy would be at its brightest during the stage of envelope formation, and that a primeval galaxy could therefore most readily be detected as an extended object with a large red shift. No such objects have been found. Meier's revision of the model does not alter the sequence of these events, but it suggests that the brightest phase may come later, when most of the galaxy's light would be emitted by stars in a relatively small region near the galactic core. At a great distance such an object would approximate a point source.

From the model Meier calculates a theoretical spectrum for a primeval galaxy in its brightest phase. The shape of the spectrum is determined largely by the optical properties of hydrogen; in particular its most distinctive feature is a sharp reduction in intensity at the Lyman limit, the wavelength where the Lyman series of hydrogen emission lines ends. At wavelengths shorter than the Lyman limit hydrogen atoms are no longer excited by radiation but are completely ionized. As a result the radiation is strongly absorbed. The principal reason for suspecting that OH 471 and 4C 05.34 are primeval galaxies is that their spectra exhibit such a discontinuity at the Lyman limit. Indeed, their spectra are in good agreement with the theoretical one throughout the measured range of wavelenths.

Meier emphasizes that the identification of these two objects as primeval galaxies is only a tentative one, and that there are a number of possible objections to it. The discontinuity at the Lyman limit, for example, could have several other explanations. The spectra imply that the velocities of stars in the galaxies are much greater than those predicted by the model. Moreover, OH 471 and 4C 05.34 are much more luminous than would have been expected, so that if they are primeval galaxies, the model must be adjusted to give them greater mass or to account for accelerated stellar evolution.

Finally, Meier proposes two possible tests of his hypothesis; one might help to confirm it, the other could refute it. First, if OH 471 and 4C 05.34 are indeed galaxies, their images might be somewhat fuzzy; true quasi-stellar objects, on the other hand, have genuinely stellar images. Second, quasi-stellar objects often vary in luminosity over a period of weeks or months. If OH 471 and 4C 05.34 exhibit such variability, they cannot be galaxies; no object of galactic size can change throughout its volume in such a short period.

Filling the Gap

Fossils discovered in recent months go a long way toward narrowing a major gap in human evolutionary history: the multimillion-year interval between the appearance in the Miocene epoch of apes ancestral to the higher, hominoid primates and the emergence of man's earliest representative, *Homo erectus.* The narrowing is proceeding from both ends of the gap.

Students of human evolution have long recognized the primates at the early end of the gap. They are the dryopithecines, a group of extinct apes that take their name from *Dryopithecus,* a fossil primate unearthed in France in the mid-19th century. Their status as forebears of the hominoids, man included, was first suggested by William K. Gregory of the American Museum of Natural History in the 1920's, even though only a few dryopithecine jaws and teeth were then available for study.

In the decades that followed Gregory's proposal one particular genus among the dryopithecines, *Ramapithecus,* has come to be viewed as the evolutionary pioneer of the group. The type species, *R. punjabicus,* is represented by a partial upper jaw found in the 1930's in the Siwalik Hills, a fossil-rich exposure of Miocene and Pliocene sedimentary rocks in what was then northwestern India. Its discoverer, G. Edward Lewis, was the first to suggest that *Ramapithecus* was a member of the hominid family, the division in the superfamily of hominoids that includes man. If this were true, the evolutionary gap could be redefined as one lying between two members of the same family: an ancestral hominid and *Homo.*

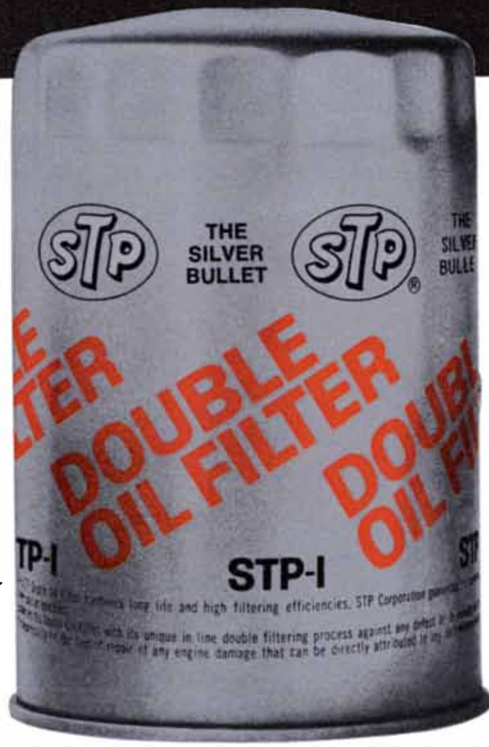
No other *Ramapithecus* fossils were recognized until 1962, when L. S. B. Leakey found a similar jaw fragment in Kenya. Potassium-argon analysis showed that Leakey's fossil was between 12.5 and 14 million years old. This dating confirmed the earlier estimate, based on Siwalik stratigraphy, that had placed *Ramapithecus* close to the boundary between the Miocene epoch and the Pliocene. Scholars nonetheless remained wary; only the two fossil fragments were recognized, and the gap of some 13 million years separating *Ramapithecus* from *Homo* was still uncomfortably wide.

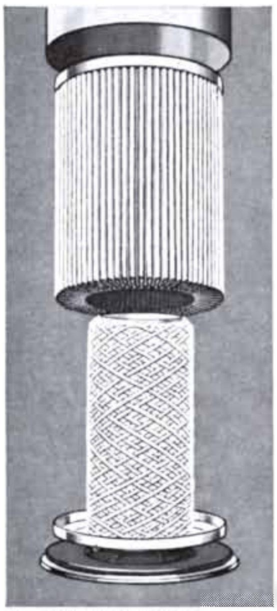
In March, David R. Pilbeam of Yale University announced major dryopithecine discoveries in Siwalik strata of unquestionable Pliocene age in Pakistan. The new fossil find, made by a joint expedition of Yale and the Geological Survey of Pakistan, includes two species of *Sivapithecus* and one of *Ramapithecus.* The specimens' age, although not precisely determined, appears to be between eight and 12 million years, thus filling in between two and six million of the blank 13 million years.

Meanwhile a number of recent African discoveries have continued the filling in from the other end of the gap. In March Richard E. Leakey announced the discovery in northern Kenya of a skull, with many facial bones preserved, that appears indistinguishable from *Homo erectus* and that is shown by radioactive-isotope dating to be some 1.6 million years old. This is perhaps half again as old as the estimated age of the earliest *H. erectus* fossils found in China and Java. Another investigator who has added to the African fossil record is Donald C. Johanson of the Cleveland Museum of Natural History. The senior American

Introducing The Silver Bullet.

STP announces a significant advance in filter technology...a new Double Oil Filter that actually filters every drop of oil twice on every filter cycle. In lab tests, following SAE Oil Filter Test Procedure J-806a, it delivered a better combination of long life and high efficiency than any of the 5 other best-selling filters. Read why it's the oil filter you should buy.





The outer filter: a 6 foot phenolic impregnated cellulose element. The inner filter: a fiber strand more than 60 feet long, wound on a steel core. Your oil goes through both approximately once every 30 seconds!

An oil filter has an incredible job to do.

In average driving it filters all the oil in your crankcase approximately once every 30 seconds!

In other words, in 7500 miles of driving (at average speed 40 mph), over 28,000 gallons of oil pass through your oil filter.

To handle this tremendous task, STP now introduces a new Double Oil Filter that gives you a better combination of long life and high efficiency than the 5 other best-selling filter brands.

The problem with filters.

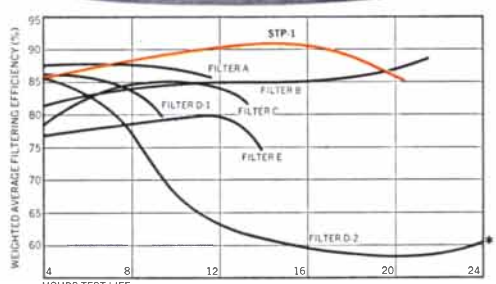
Grit, sludge, and microscopic bits of metal find their way into every engine's oil. Left there they can play hell with the guts of an engine and can seriously shorten its life.

So good filtration and long filter life are both important. And that's where the problem lies.

Historically, lab tests have shown long-life oil filters to be relatively short on efficiency, while the highly efficient ones have tended to clog up relatively quickly.

Once a filter becomes sufficiently clogged, its by-pass valve opens and oil begins to circulate freely without being filtered at all.

In either case you may have a problem. A filter that isn't filtering with high efficiency. Or a filter that isn't filtering at all.



Test results, certified by The American Standards Testing Bureau Inc. For a more complete test report write: The Silver Bullet, c/o STP Corp., 1400 W. Commercial Blvd., Ft. Lauderdale, Florida 33310.

**Test terminated at 24 hours. Lack of pressure build-up was abnormal indicating internal leakage.*

Why The Silver Bullet is superior.

The engineering ideal is to get both long life *and* high efficiency out of an oil filter.

And none of the 5 best-selling filters comes as close to the ideal as STP's new Silver Bullet.

It contains two filter elements made of different filtering media. One filter nests inside the other and all your oil goes through both filters on every pass through the canister.

This may sound elementary. But the fact is, no other leading filter manufacturer builds a filter this way.

Laboratory tests, certified by The American Standards Testing Bureau, Inc., prove The Silver Bullet delivers a better combination of long life and high efficiency than any of the 5 other best-selling brands.

Can a better oil filter save you money?

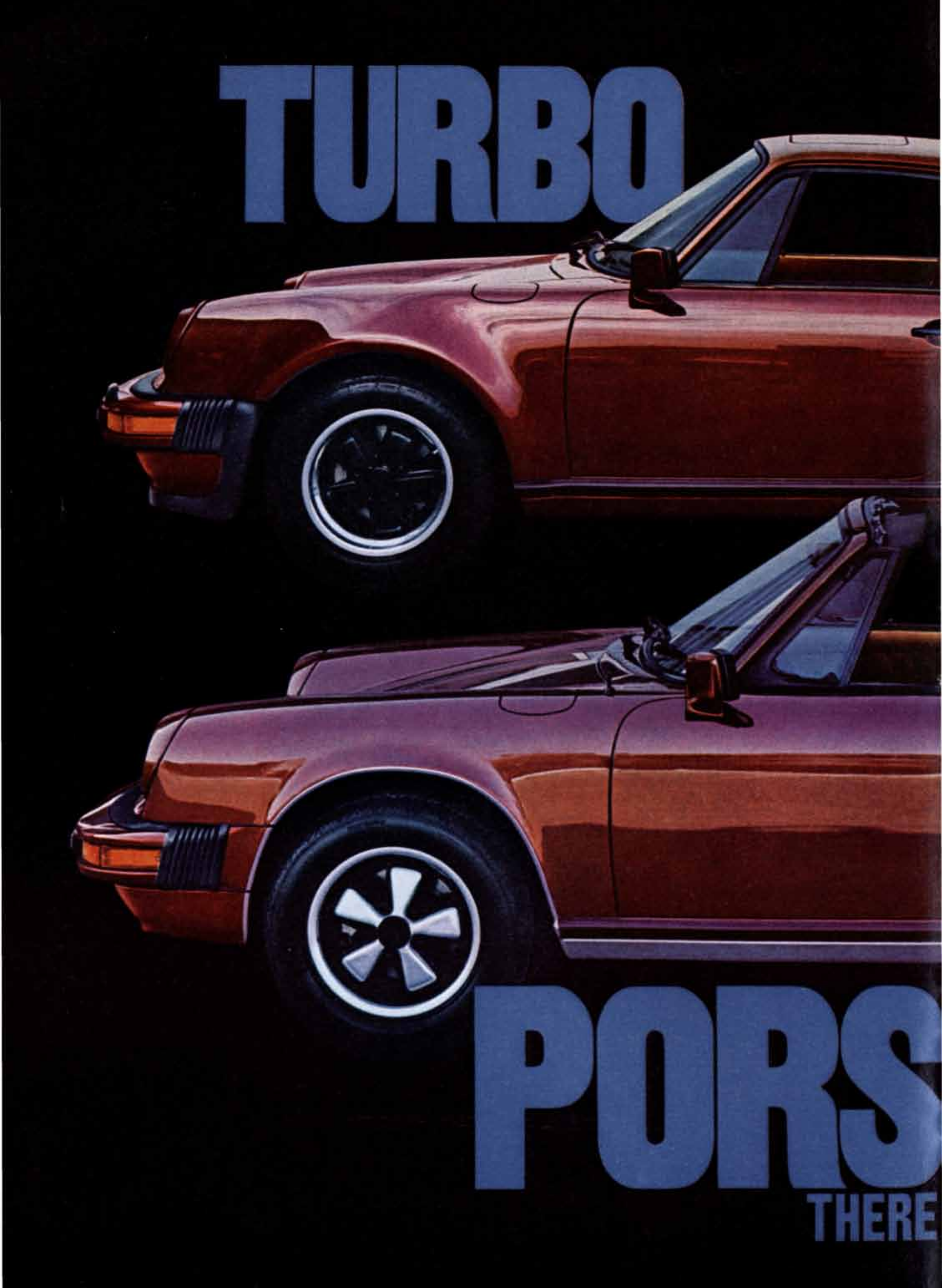
Like life insurance, good oil filtration is a long term proposition. And we at STP definitely do not recommend that you use a better filter as an excuse for skipping filter changes or as an excuse for extending oil change intervals.

But certain facts can't be ignored. Your car represents a big investment. Dirt and abrasives *are* bad for its engine.

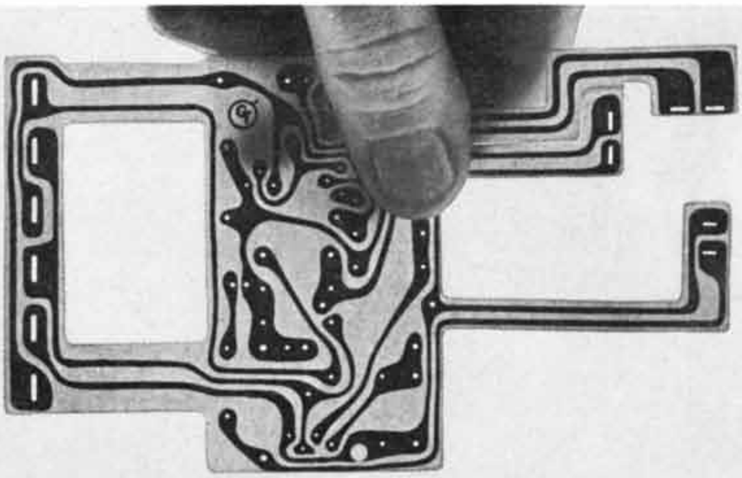
Install The Silver Bullet and you can be sure you've given your engine the protection it deserves. How much is that assurance worth?

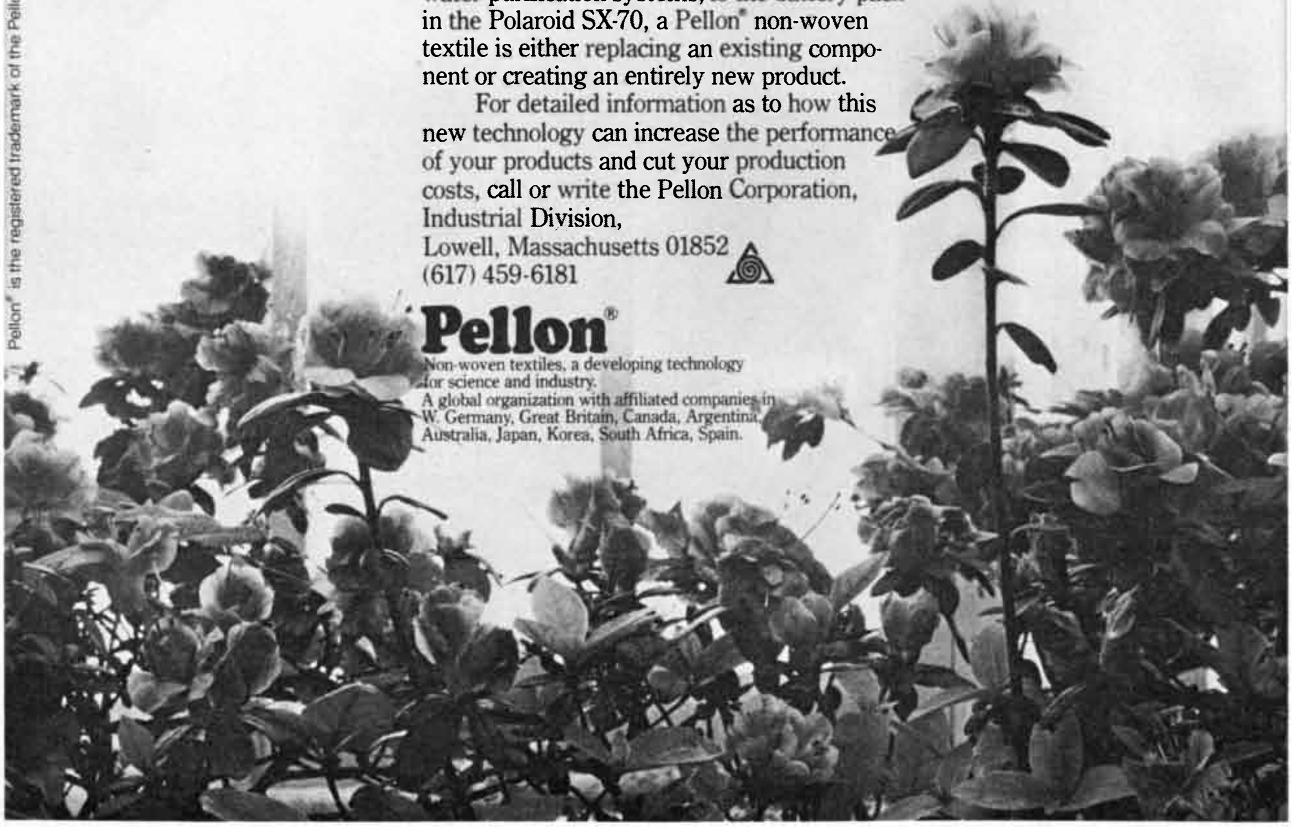
You'll have to be the judge of that.

New from STP


TURBO
PORS
THERE


The Turbo Carrera is the fastest production Porsche ever made. And the only car sold in America with a turbocharger as standard equipment. (A Porsche turbocharger, that dramatically increases horsepower without attendant increases in fuel consumption or pollutants.)
Yet this ultimate road machine also sets a new standard for comfort and elegance. With everything from air conditioning and leather interior to a four-speaker stereo radio and tape deck and an electrically-operated side-view mirror with a built-in de-icer.
And everything is put together with such painstaking pride that fewer than 600 people can own one this model year.
Certainly, the Turbo Carrera is the crowning achievement of Porsche engineering. But just as certainly, the 911S Targa provided the supreme challenge:
TARGA
To improve a car year after year until it became a contemporary classic—a legend in its own time.
Consider these features, the products of more than 25 years of no-compromise engineering: The combination of a built-in roll bar, Targa roof and fixed rear window that provides the safety and practicality of a hardtop and the excitement of a roadster.
The accessible controls and functional instrumentation derived from Porsche racing and rallye experience.
And the ability to run on regular gas and go 15,000 miles between maintenance services.
Plus other Porsche attributes like rack-and-pinion steering, four-wheel, vented disc brakes and fully independent suspension.
The 911S Targa. Or the Turbo Carrera. To own one is to own a car unlike any other in the world.
A car for which there is no substitute. A Porsche.
CHE
S NO SUBSTITUTE.





member of a French-American group surveying the Afar region of Ethiopia, Johanson recently reported the discovery in 1974 of jaw fragments and teeth that resemble those of *H. erectus;* they are more than three million years old and may prove to be close to four million years old. In March, simultaneously with Leakey's announcement, Johanson reported unearthing the remains of a group of three to five hominid adults and two children in Afar. The fossils are at least three million years old; Johanson proposes that they belong in the genus *Homo* but has not yet come to any conclusion about the species they represent.

In addition to his *H. erectus* find Richard Leakey has turned up a second hominid cranium of the kind he first discovered in the Lake Rudolf area in 1972 and assigned to the genus *Homo,* species undetermined. Like the earlier skull, the new find is between 2.5 and three million years old. If one accepts both the proposed generic assignments and the maximum age estimates for the new African fossils and also accepts the minimum age estimate for the Pakistan finds, the gap between the ancestral hominid and *Homo* is reduced from 13 to four million years.

Cutting It Rather Fine

When a piece of wood is sawed, a significant amount of it is made into sawdust, which is either valueless or worth much less than the finished material. The same is true of other materials; indeed, the saw blade needed to cut a wafer of silicon for microelectronic purposes is a third the thickness of the wafer. The reason circular saw blades are not made thinner is that a thin blade tends to wobble. C. D. Mote, Jr., of the University of California at Berkeley has studied the operation of such blades and has found that they can be made considerably thinner if they are initially stressed and then operated with controls that keep them from wobbling while they are running.

One of Mote's findings is that the distribution of temperature in a running blade is much different from what had been thought; the blade is usually hottest not at the cutting edge but behind it. The stability of the blade can be improved by monitoring the temperature with radiation scanners and controlling its distribution by supplying heat to the blade as required. Wobbling can be controlled by placing the pole of an electromagnet on each side of the blade and applying a force that prevents the wobble from developing.

Testing his ideas in a sawmill, Mote found that the thickness of the cutting edge of the blade could be reduced by as much as a third. He notes that the potential saving from thinner blades and reduced vibration is substantial. A large company cutting a million board feet of lumber per day could save thousands of dollars per day if the cutting edges of its saws were reduced by only .001 inch. The combination of thinner blades and stabler saws could save 10 percent or more of the material being cut.

The Vascularization of Tumors

Unless a solid tumor is provided with blood vessels by its host it remains small and dormant. The substance that is released by tumors and promotes vascularization is under intensive study

by Judah Folkman

In every human being myriads of normal cells are busily reproducing day and night. In an adult at least four million cells divide every second; 350 billion divide in a day; more than 10^{14} divide in a year. When a normal cell passes through a cycle of division, it has the potential of becoming malignant. Nevertheless, the majority of people go through life without developing a fatal cancer. Clearly the body must possess remarkable control systems for preventing aberrant cells from arising or from progressing to a terminal malignancy.

The cancer statistics give the impression that few if any control systems are at work. In the U.S. about 600,000 new cases of cancer are diagnosed every year, or approximately 1,600 every day. Closer analysis provides a different perspective. In each person with cancer the tumor probably arises from a single aberrant cell. Since the 215 million people in this country generate about 10^{20} normal cells every day, the probability that a given cell will be a deviant one capable of initiating a tumor is exceedingly small, on the order of one in 10^{17}.

How is this extraordinary "quality control" accomplished? Why does it fail? How does a lone malignant cell survive? What characteristics must such a survivor acquire to ultimately become a "successful" tumor?

Our knowledge is meager. There is some information about control points at the molecular level. For example, there are monitoring systems that inspect the DNA of dividing cells and repair breaks, deletions and errors in transcription. There is also some information at the level of individual cells and cell populations. Here I should like to discuss a critical period in the development of solid tumors. For a number of years my colleagues and I have been studying the period after a tiny colony of malignant cells has become firmly established but before it has acquired the capacity for rapid proliferation and invasiveness. In human beings the *in situ* lesion is often the earliest stage at which a solid tumor can be detected. Such a lesion is usually only a few millimeters in diameter and semiflattened. If it is present in the skin, the bladder or the cervix, it can be seen and recognized. Similar tumors in other organs of the body cannot be diagnosed at present.

At this harmless stage the tumor is still avascular, that is, it lacks its own network of blood vessels for supplying nutrients, including oxygen, and for removing wastes. Because the transfer of nutrients and wastes has to be accomplished by diffusion through the surrounding healthy tissue the *in situ* lesion cannot grow beyond a certain volume. A steady state is reached in which newly generated cells are balanced by dying cells. In a population that is roughly spheroidal the steady-state diameter is usually a few millimeters or less. Unless the colony flattens completely into a thin sheet, growth stops. Even tumors that are potentially the most malignant may linger in this "dormant" stage for years. Since cells within such early microtumors seem to adhere strongly to one another, they usually do not invade, wander through or otherwise violate the integrity of their host.

The Tumor Angiogenesis Factor

The critical event that converts a self-contained pocket of aberrant cells into a rapidly growing malignancy comes when the tumor becomes vascularized. The tumor must induce the host to provide it with its own network of blood vessels. This event is triggered when the tumor cells release a diffusable chemical substance, which we have named tumor angiogenesis factor (TAF). As the term implies, TAF has the capacity to stimulate nearby blood vessels to send out new capillaries that grow toward the small colony of tumor cells and finally penetrate it. The tumor now becomes pink. Fresh nutrients pour in and wastes are speedily removed. Rapid growth follows; the tumor quickly grows to the volume of a cubic centimeter or more. Nearly all solid tumors, including cancers of the colon, lung, breast, cervix, bladder, prostate, pancreas and skin, probably evolve through these two phases: avascular and vascular.

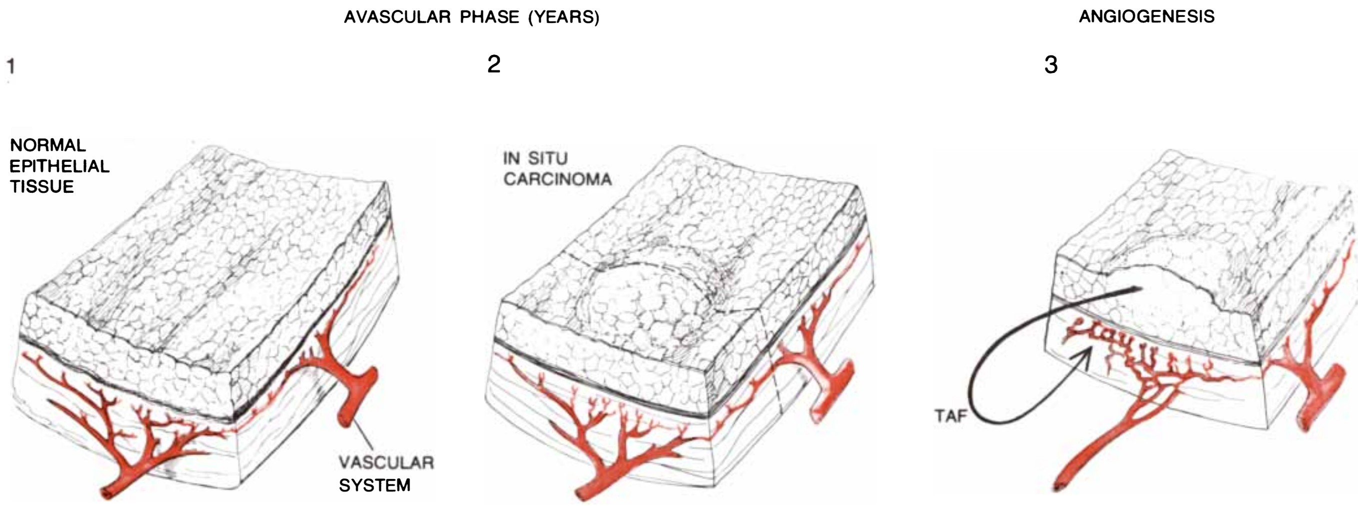
The vascularized tumor compresses, invades and destroys neighboring tissue. It bleeds, it can readily be seen or felt, and it may spread cells that are capable of setting up secondary tumor colonies elsewhere in the body. A solid tumor of about one cubic centimeter can consist of as many as a billion cells. For most tumors this size is just within the capability of current medical diagnosis.

The picture I have proposed is based on experimental and clinical observations of many investigators, including the work of my own group at the Children's Hospital Medical Center in Boston. Only some of the proof is in, however, and the ideas were not arrived at as directly and as tidily as their description implies. Let me therefore briefly review the steps leading to them.

For more than 100 years pathologists had observed that most solid tumors are richly supplied with blood vessels. Various hypotheses were suggested to explain the origin of the vessels. Perhaps they were simply vessels that had dilated in response to the increased metabolic load created by the tumor. Perhaps they were blood vessels like those commonly seen in inflamed areas; the inflammation might be caused by waste material that was seeping out of the tumor from dying cells.

In 1945 Glenn H. Algire, working at the National Cancer Institute, was among the first to appreciate that growing tumors continuously elicit new capillary growth from the host: the process called tumor angiogenesis. Algire suggested that the process might be partly responsible for autonomous tumor growth. Tumor angiogenesis could be observed directly in living animals by

GROWTH OF NEW BLOOD VESSELS in the cornea of a rabbit's eye is stimulated by a few micrograms of tumor angiogenesis factor (TAF), which is slowly released from an otherwise inert bit of polymer implanted in the cornea. A substance normally released by solid tumors, TAF causes nearby blood vessels to send out new capillaries in the direction of the tumor and bring about its vascularization. Only when the common types of solid tumor are provided with their own blood supply can they grow rapidly and spread. When polymer impregnated with TAF is implanted in a rabbit's cornea, new capillaries soon begin sprouting from nearby blood vessels. This picture was made by Fritz Goro in the author's laboratory 16 days after implantation.



AUTHOR'S HYPOTHESIS proposes that vascularization is required to convert an *in situ*, or dormant, carcinoma into a rapidly growing malignancy capable of killing its host. Most cancer deaths in the U.S. are caused by carcinomas that arise in the epithelial lining of the bronchus, the stomach, the colon, the uterine cervix and the ducts of the breast. Normal epithelial tissue (*1*) is isolated from the vascu-

implanting a tumor in a transparent plastic chamber set in the ear of a rabbit or in the cheek pouch of a hamster. Sumner Wood, Jr., of the Johns Hopkins School of Medicine and Bruce A. Warren and Philippe Shubik of the Chicago Medical School were among those who conducted investigations of tumor angiogenesis by this method. Until the 1960's, however, the studies were mainly descriptive and threw little light on the mechanism of tumor angiogenesis.

The first experiment to suggest a mechanism was reported by Shubik and Melvin Greenblatt in 1968. They implanted in the cheek pouch of hamsters tumors that were separated from healthy tissue by a Millipore filter, which has very fine pores. A tumor on one side of a filter proved to be capable of inducing new blood vessels in the tissue on the other side. The pore size of the filter was .45 micron, so that tumor cells could not cross it. This implied that vascularization was induced by some diffusible material that had passed through the filter.

Angiogenesis in Tissue Culture

My own interest in tumor angiogenesis arose from an entirely different line of investigation. Frederick Becker and I, working at the Naval Medical Research Institute in 1960, were searching for a way to study the early phase of tumor growth. Experimental animals were unsatisfactory because the early phase was invisible. The culture of tumor cells in laboratory glassware was also unsatisfactory because the techniques then available only allowed the cells to form flat sheets, which is not how they usually grow in animals.

Hoping to find a better way, we perfused small organs with serum in isolated glass chambers and inoculated the organs with tumor cells. Thus we could view tumor growth hour by hour. We assumed that these tumors would eventually develop links to the vascular bed of the host organ. Instead all the tumor implants failed to vascularize and stopped growing at a diameter of less than two millimeters. The tumors did, however, remain alive. Moreover, when they were implanted in normal animals, they vascularized and grew rapidly.

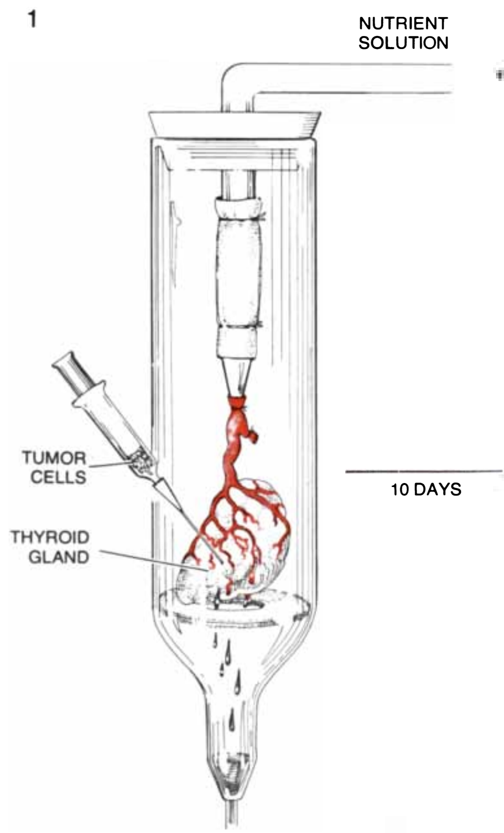
I resumed these experiments in 1965 at the Boston City Hospital, assisted by a medical student, Michael A. Gimbrone, Jr. We finally realized that the tumors in the perfused organs failed to vascularize because of an artifact of perfusion itself, which did subtle damage to blood vessels in the isolated organ. A more significant finding was that tumors implanted in isolated organs stopped growing at a small diameter. I began to realize that the absence of vascularization might limit the growth of a variety of solid tumors.

At the time one could not have drawn this conclusion from animal studies because there was no way to inhibit or delay angiogenesis in an animal. Furthermore, the interval between the avascular phase and the vascular phase for most transplantable tumors in animals is imperceptible and exceedingly brief. When highly malignant tumor cells are injected under the skin of an animal, the prolonged *in situ* phase of spontaneous human cancer is not observed. Instead the avascular phase is short (a few days), and by the time a palpable tumor can be detected it is already vascularized.

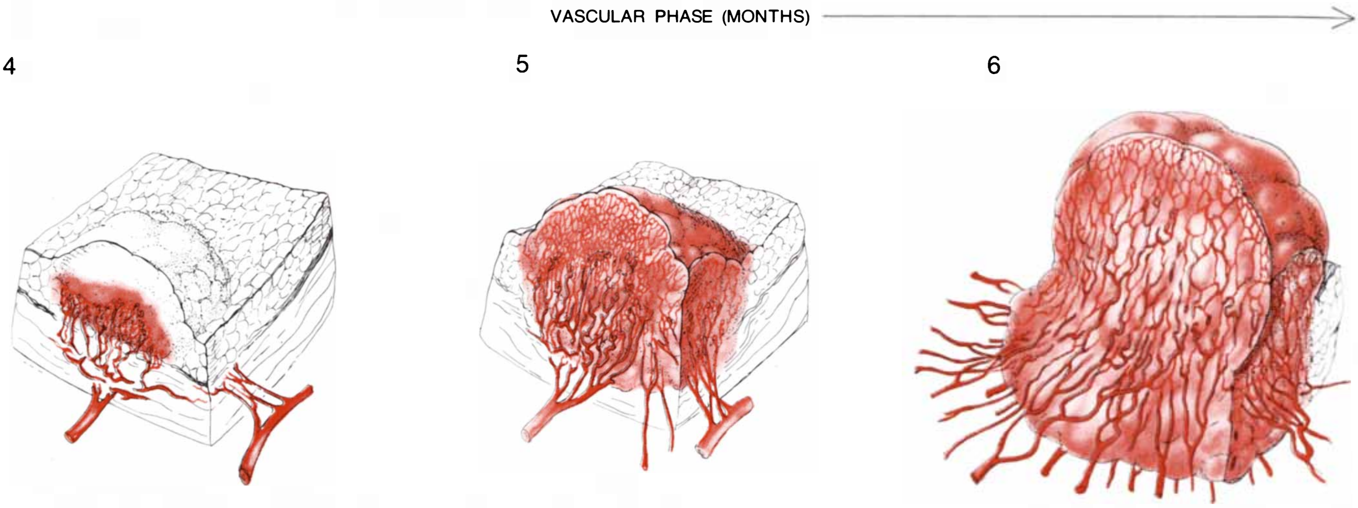
The next problem was to discern the nature of the vascular response. Was it a dilation of existing vessels or a proliferation of new ones? In order to find out we developed a system in which tumors or tumor extracts could be separated from the vascular bed. For this purpose we modified a system originally used by Hans Selye of the University of Montreal to study inflammation.

Special pouches were made by injecting air under the skin of a rat. We then implanted Millipore chambers containing rat tumor cells in the pouches and examined the tissue below the filter. Microsections and autoradiography demonstrated that new capillary blood vessels were actively proliferating. This neovascularization was not observed when nontumorous tissue was placed in the Millipore chamber.

We then found that a soluble fraction extracted from the cytoplasm of tumor



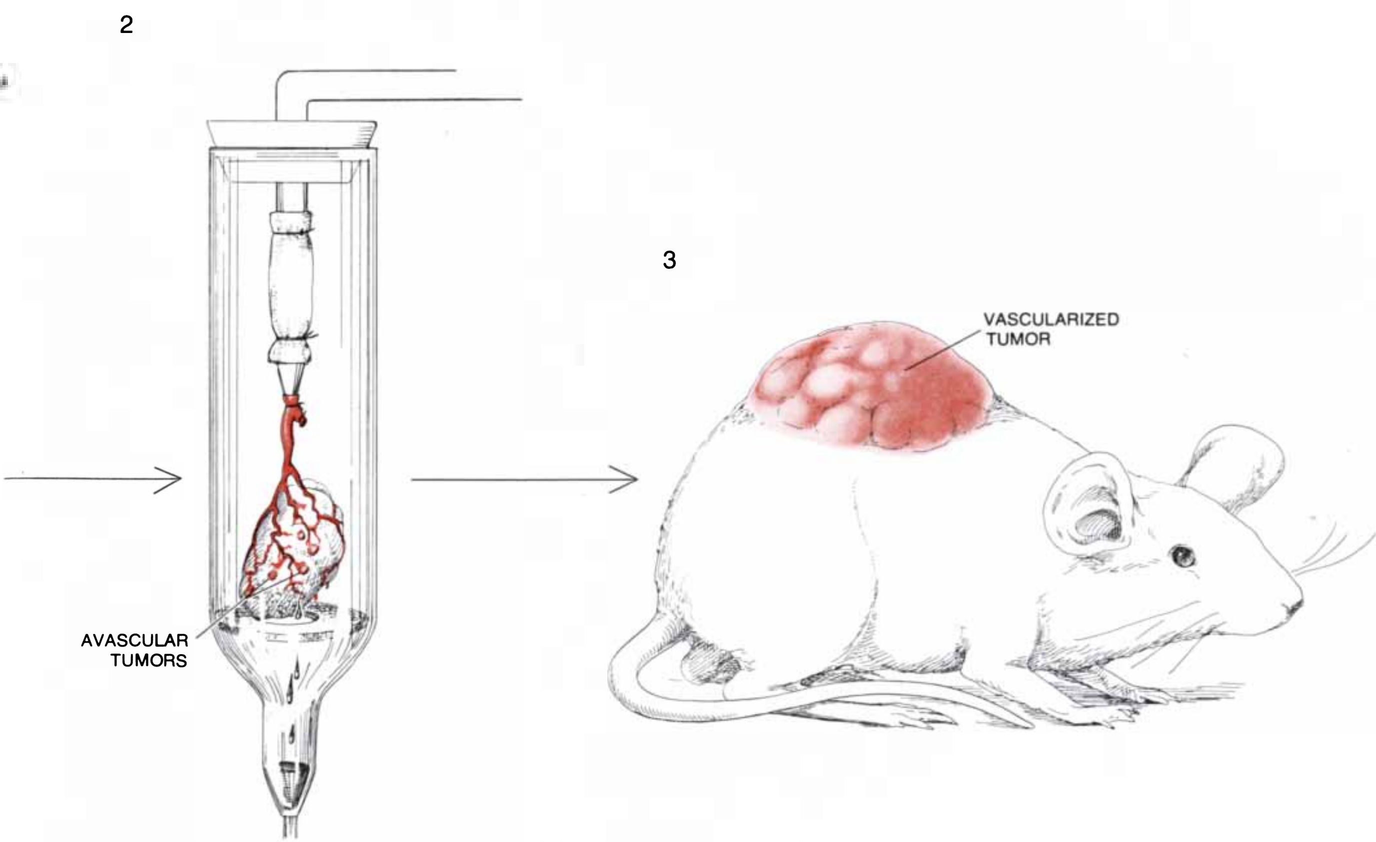
ISOLATED THYROID GLAND of a dog or rabbit can be kept alive for one or two weeks by perfusion with suitable nutrients (*1*). If tumors from other animals are implanted in the



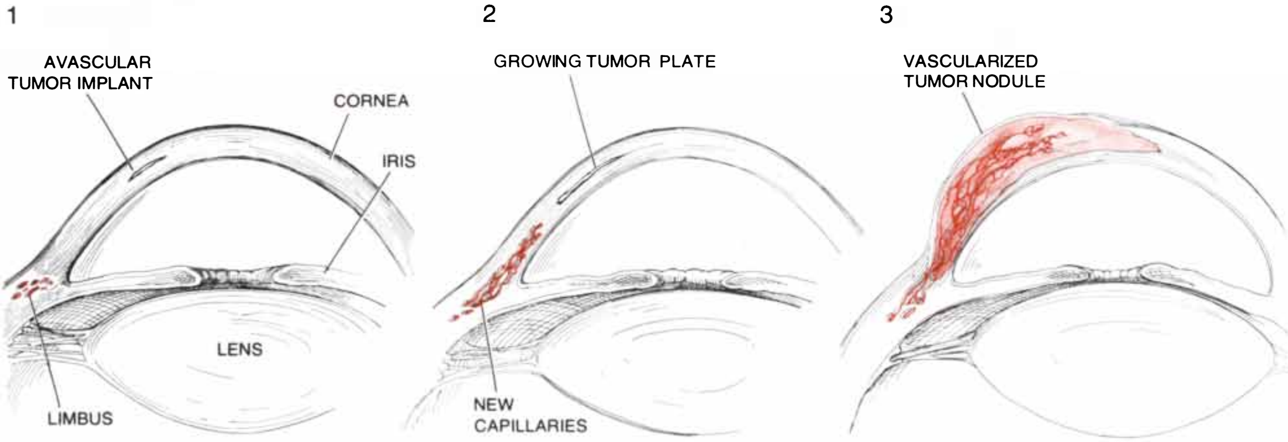
lar system by a basement membrane. In the avascular phase (*2*) the initial clump of malignant cells may exist as a harmless *in situ* carcinoma for many years. The author's studies suggest that the tumor must release a chemical messenger (TAF) before nearby blood vessels will send out capillaries that are capable of penetrating the tumor (*3*). Once the tumor is vascularized rapid growth follows (*4–6*).

cells—a fraction that is not found in normal cells—also gave rise to neovascularization when the fraction was infused intermittently into the Millipore chamber. This is the material we called tumor angiogenesis factor. Experiments conducted in association with Tito Cavallo and Ramzi S. Cotran of Peter Bent Brigham Hospital in Boston showed that cells in the endothelium, or lining, of the capillary blood vessels began synthesizing DNA, which is essential for cell division, as early as eight to 10 hours after exposure to TAF. The proliferation of endothelial cells was observed within 48 hours, and newly formed capillaries began to bud from small existing veins.

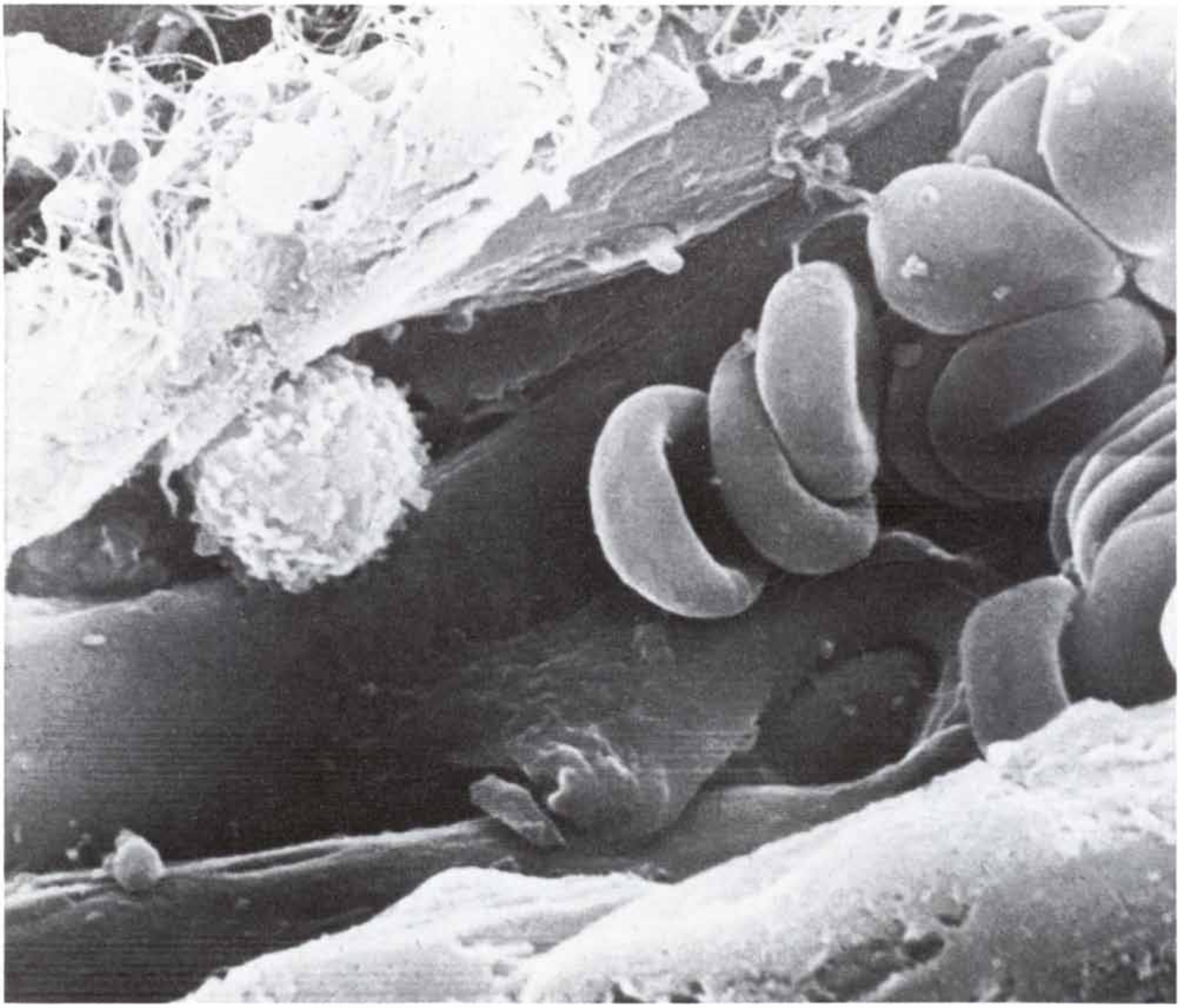
Detailed studies revealed that tumor-induced vascularization was a distinct phenomenon, unaccompanied by inflammation. Furthermore, neither necrotic tumor nor killed tumor proved to be capable of



perfused organ, they survive but do not become vascularized. A mouse melanoma, for example, stops growing on reaching a diameter of about one millimeter (*2*). If, however, the dormant melanoma is removed and reimplanted in a mouse, the tumor becomes vascularized within a few days and grows rapidly (*3*). Neovascularization fails to occur in the isolated organ because perfusion damages the organ's small vessels. The experiment suggested that absence of tumor vascularization restricts tumor growth or brings about tumor dormancy.



TUMOR IMPLANTED IN CORNEA of a rabbit grows slowly as a thin plate during the avascular phase (*1*). After a week or so, in response to the tumor angiogenesis factor, capillaries begin growing toward the tumor from the limbus of the cornea, which is some 2.5 millimeters away (*2*). Within two or three weeks the capillaries penetrate the tumor, and it begins to grow rapidly in three dimensions (*3*).



TINY BLOOD VESSEL growing through the cornea of a rabbit's eye in response to a tumor implant is shown in this scanning electron micrograph. The interior wall of the capillary, which has been sectioned lengthwise, extends in a wide band across the picture from lower left to upper right. The large fuzzy ball is a white blood cell; the disk-shaped structures at the right are red blood cells. The tunnel in the wall below the red blood cells is an opening created by a new branch of the capillary. The magnification is some 4,700 diameters.

releasing TAF or stimulating neovascularization. (Additional evidence for the absence of inflammation in tumor angiogenesis came later from studies conducted in the cornea of rabbits.)

Implantation in the Cornea

We were now quite certain that TAF was a real entity and that we should try to purify it. Simultaneously we set out to create, if we could, an in vivo model of tumor dormancy similar to what we had observed in isolated perfused organs. I therefore suggested to Gimbrone, who had completed his internship and had returned to our laboratory, that we implant tumors in the cornea of the rabbit, where there are no blood vessels. In that location a tumor might remain avascular, and hence dormant, until it was moved to a nearby vascular bed. We hoped in this way to observe the avascular phase of tumor growth over a prolonged period.

No one had implanted a tumor in a cornea before. The cornea consists of many layers of tough collagen, assembled like plywood. We selected a tumor indigenous to the rabbit and placed one-millimeter pieces of it between the layers of collagen. The tumors were observed and measured every day under a stereoscopic microscope.

The experiment did not turn out as we had expected. After a week small capillaries entered the cornea from the edge nearest the tumor implant and began growing toward it, initially at a rate of .2 millimeter per day and finally at a rate of up to one millimeter per day. When the capillaries reached the tumor, there was rapid cancerous growth. After four weeks the vascularized tumor was as large as the eye itself.

Moreover, even before the capillaries had reached the tumor it had continued to expand, instead of remaining dormant as we had hoped. The answer was found in histological sections of the cornea. The avascular tumor grew laterally in a thin plate only a few cells thick. In the isolated perfused organ, on the other hand, the tumor had grown in three dimensions as a small spheroid. It finally dawned on us that the three-dimensional configuration of an avascular tumor is the key to its dormancy.

In order to achieve three-dimensional avascular growth in vivo we proceeded to suspend tiny pieces of tumor in the liquid-filled anterior chamber of the rabbit's eye. Tumors suspended in this way remained viable but did not grow much beyond a millimeter in diameter. They were nourished by fluid in the anterior chamber, but new vessels from the nearby iris could not reach them. When the tumor spheroids were implanted on the iris, they became vascularized and grew rapidly. Many grew to 16,000 times their original volume within two weeks.

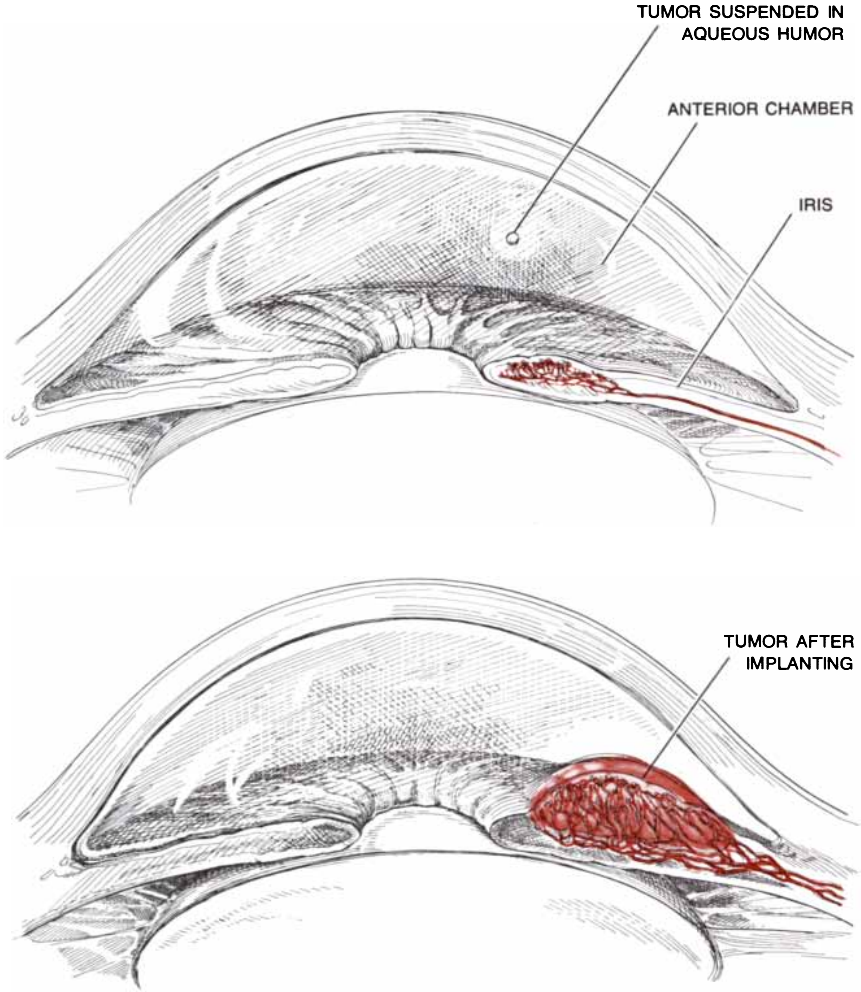
With these experiments and similar ones carried out in soft agar we demonstrated that a spheroidal tumor nourished solely by diffusion from a surrounding medium stops growing at a diameter of a few millimeters even though the medium is frequently renewed. Although the cells on the surface of the tumor continue to divide, the cells in the center die. A steady state of "population dormancy" is finally reached when the number of viable cells is between half a million and a million. In contrast, when the same cells are grown in two dimensions on a flat surface, the cell population expands indefinitely, reaching a billion cells long before its three-dimensional counterpart stops expanding.

Assays of the Factor

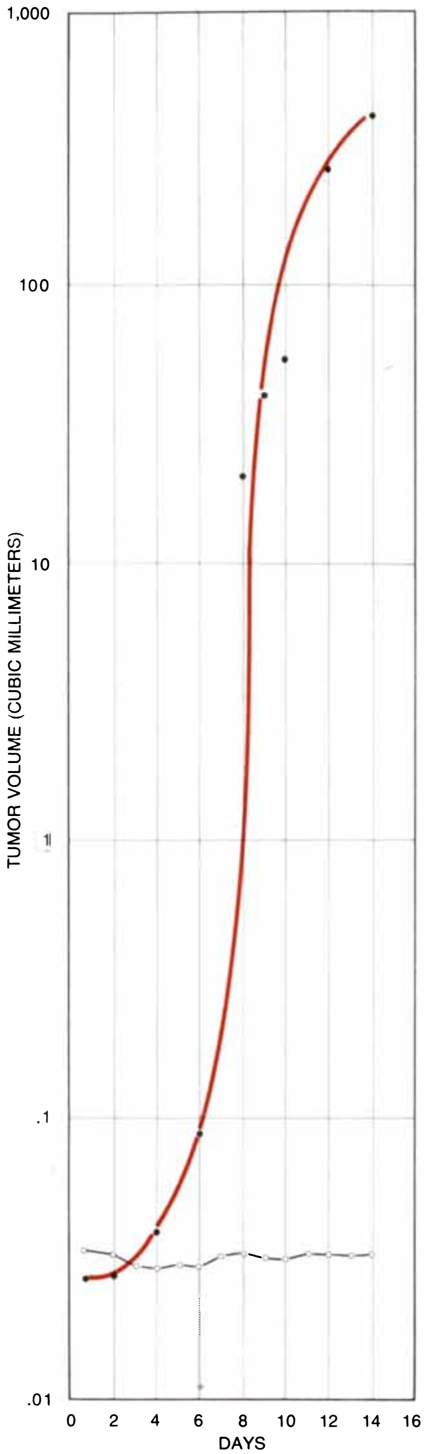
Geometry is therefore the critical variable. In a spheroidal tumor the cell population grows in proportion to the cube of the radius, whereas the surface increases only as the square of the radius. The tumor becomes dormant when the surface area gets too small for nutrients to diffuse into the central region and wastes to diffuse out of it. In a tumor growing only in two dimensions, as in the cornea or on the floor of a Petri dish, volume and surface increase together, so that diffusion places no upper limit on expansion.

One weakness in the TAF hypothesis was that the most rapidly growing tumors seemed to be associated with the most intense neovascularization, which suggested that cell division itself might stimulate the proliferation of capillaries. Alternatively, rapidly dividing cells, because of their high metabolic rate, might induce new vessels by releasing some nonspecific waste product, such as lactic acid.

These possibilities were ruled out by experiments we performed in collaboration with Robert Auerbach of the University of Wisconsin, who was spending a year in our laboratory. In one series of experiments we exposed tumors to sufficient X-radiation to stop cell division before implanting them in rabbit corneas. The irradiated implants retained their ability to induce new capillaries for as long as three weeks, even though the implants themselves did not grow. Implants of normal tissue, whether they were irradiated or not, did not induce capillary



TUMOR CELL AFLOAT IN ANTERIOR CHAMBER of a rabbit's eye (*top*) survives but stops growing before it reaches a diameter of one millimeter. Capillaries in the nearby iris, however, begin to proliferate, providing evidence that TAF is being released. When the avascular spheroid is intentionally placed on the iris (*bottom*), it is soon penetrated by new vessels.



EXPONENTIAL GROWTH of a vascularized tumor is compared with the dormancy of an avascular tumor. The white dots represent the mean daily volumes of 10 avascular tumors floating in the anterior chamber of a rabbit's eye (*see illustration on preceding page*). The black dots represent the volume of a single tumor spheroid that was placed on the iris, where it became vascularized. A small amount of fluorescent dye fluorescein was injected into rabbit every day. Onset of vascularization was indicated by fluorescence of the tumor on sixth day. By 14th day tumor had grown to 16,000 times its original volume.

growth. Furthermore, cornea implants consisting of healthy, rapidly dividing embryonic tissue did not induce new vessels. TAF thus seems to be released independently of the rate of division of tumor cells.

The cornea also became useful for assaying protein fractions for their TAF content. The method finally developed was to impregnate one-millimeter pellets of a special polymer with 150 micrograms of the fraction to be assayed. The pellets release the material at a rate of up to one microgram per day and thus make possible a measurement of any capillary growth they induce.

The cornea method serves for assaying small numbers of highly purified TAF samples. For rapid screening of many crude samples, however, we use the chorioallantoic membrane of the chick embryo. The richly vascularized membrane is exposed by making a window in the shell of a fertile egg. Test fractions containing TAF are applied directly to the membrane as a powder or in a slow-release polymer pellet. After three or four days we score the vascular response according to the intensity of new capillaries and venules converging on the inoculation site.

In our early work we obtained crude extracts of tumor cells containing TAF by disrupting cells and fractionating their cytoplasmic components. Later we found that TAF can be obtained from a buffered water solution that is temporarily substituted for the medium overlying tumor cells growing in culture. Large-scale tissue culture has supplied ample material for further purification. We are now collaborating with Bert L. Vallee and his colleagues at Peter Bent Brigham Hospital on purification and chemical studies.

The Possibility of Inhibition

Ever since we recognized that tumor-induced neovascularization represents the breaching of an important barrier in the control of tumor growth we have spent considerable effort searching for ways to inhibit neovascularization. One obvious approach is to try to make an antiserum against TAF. This awaits further purification of the material. A second approach is to try to find some general inhibitor of capillary proliferation, which might or might not act directly against TAF. A clue suggesting how one might interfere with capillary proliferation came from an unexpected source.

In 1972 Steven S. Brem, a fourth-year medical student working in our laboratory, Cotran and I showed that a variety of human tumors could be arranged in a hierarchy according to the increasing density of new blood vessels in them. Brain tumors were at the top of the list; chondrosarcoma (a tumor of cartilage) was at the bottom. In fact, chondrosarcoma is the least vascularized of all solid cancers. In this respect it resembles its normal counterpart, cartilage, which is usually not vascularized at all.

At first it seemed more rewarding to investigate why brain tumors induce such intense neovascularization than to inquire why cartilage tumors are so sparsely supplied with blood vessels. Our interest was focused on cartilage again, however, after Harold C. Slavkin of the University of Southern California had visited our laboratory. He mentioned certain of his own observations and those of Klaus Kuettner and Reuben Eisenstein of Rush Medical College in Chicago. They had observed that when pieces of normal cartilage are implanted on the chorioallantoic membrane of the chick embryo, the pieces survive without ever becoming vascularized.

How could this observation be explained? Our first thought was that cartilage might present such a tough mechanical barrier that capillaries could not penetrate it. We learned, however, that in the early mammalian embryo cartilage is filled with blood vessels. Only later does it become avascular.

The next year, when Steven Brem's brother Henry arrived in the laboratory as a graduate student in biochemistry, I suggested that we examine cartilage to see if it might contain an inhibitor against capillary proliferation. We soon learned that if we placed a TAF-containing pellet and a bit of cartilage from a newborn rabbit side by side on exposed chorioallantoic membrane, new capillaries converged on the TAF pellet but avoided a zone of inhibition surrounding the cartilage. We were not able, however, to exploit this preparation to measure the degree of inhibition quantitatively.

It proved to be possible to make accurate measurements by employing the rabbit cornea as a test site. A tumor was implanted in the cornea, and a one-millimeter piece of cartilage was placed between it and the vascular bed at the edge of the cornea. As experimental controls for the active cartilage we used boiled cartilage, bone and pieces of cornea from newborn rabbits.

When a tumor was implanted alone or with any of the inactive control substances, capillaries grew toward the tumor at the rate of about .2 millimeter per day during the first week. By the second week the rate had more than doubled; by the third week capillaries were growing at the rate of .6 millimeter per day. Within three weeks all the tumors in this group had been penetrated by new vessels, and the tumors had enveloped the entire eye.

In contrast, when the tumor was implanted with active cartilage between it and the nearest blood supply, capillary proliferation was sparse. By the second week the rate of blood-vessel growth was barely half what it had been during the first week of the control experiments. In many corneas the capillaries stopped advancing and regressed. In other corneas vessels approached a zone of inhibition around the cartilage and oscillated between brief periods of growth and of regression without forward progress. Twenty-eight percent of the tumors had not become vascularized by the end of three months. The remainder

ECONOMY CAR POOL FROM DATSUN.

B-210: DATSUN'S ECONOMY CHAMP. 41 MPG/HIGHWAY. 29 MPG/CITY.*

710: THE FAMILY CAR WITH GUTS. 33 MPG/HIGHWAY. 23 MPG/CITY.*

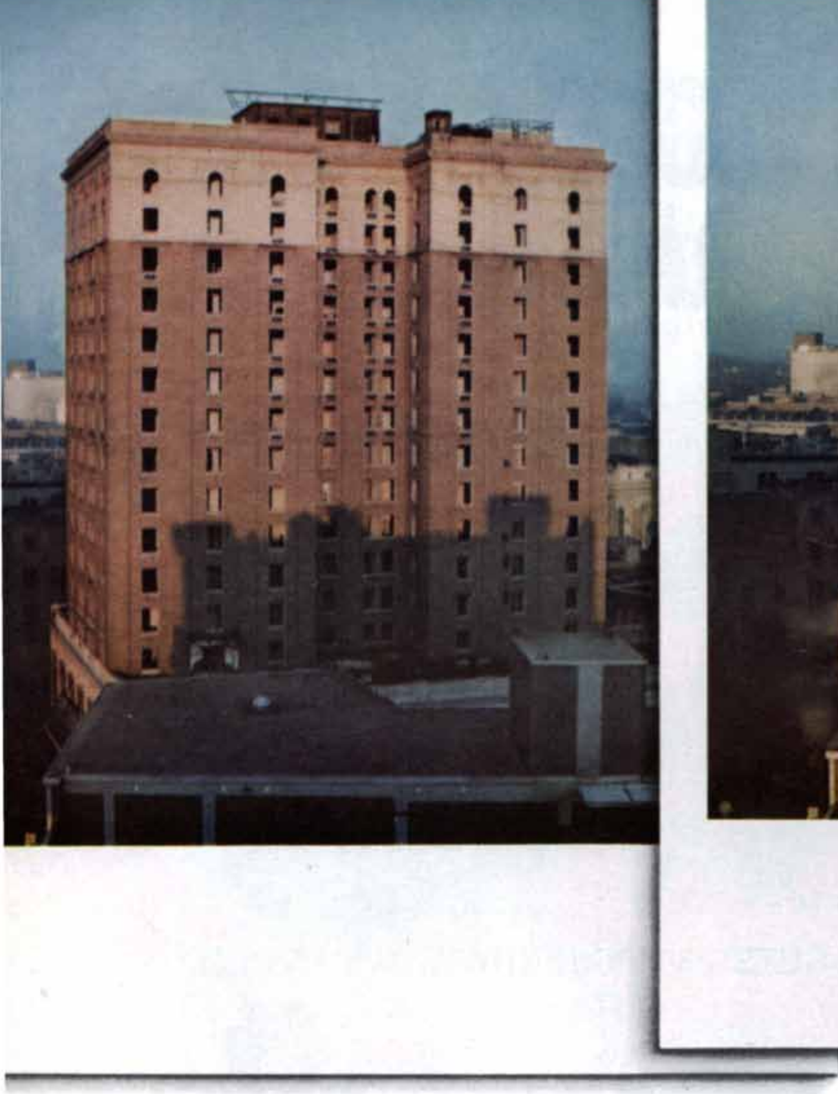
610: THE LOGICAL LUXURY CAR. 32 MPG/HIGHWAY. 23 MPG/CITY.*

280-Z. FUEL INJECTED PERFECTION. 27 MPG/HIGHWAY. 16 MPG/CITY.*

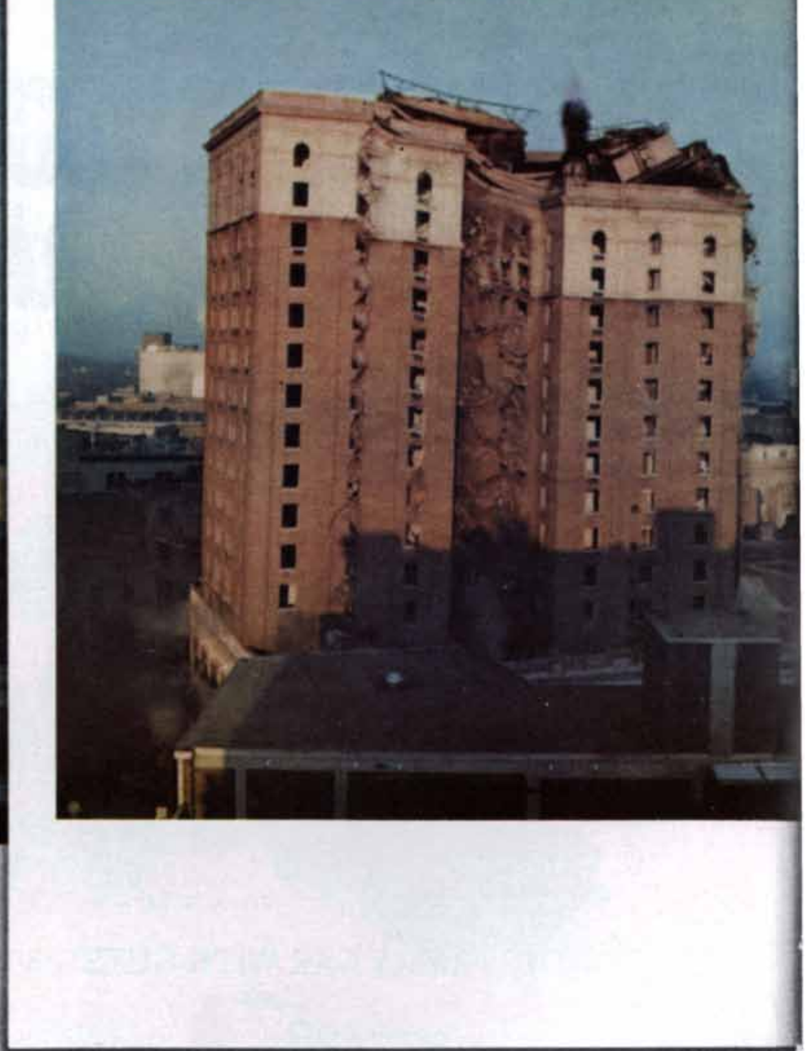
Datsun Saves

America's #1 Selling Import.

*ALL MILEAGE FIGURES ARE EPA MILEAGE ESTIMATES. MANUAL TRANSMISSION. ALL STATES EXCEPT CALIFORNIA. ACTUAL MILEAGE MAY VARY WITH THE CONDITION OF YOUR CAR AND HOW IT'S DRIVEN.



December 14, 1975



8:00:01.5 AM

"When every job you do falls flat, you need all the document you can get." —John D

The president of Controlled Demolition, Inc. thinks the SX-70 is a dynamite camera.

And he's an expert.

He uses precisely applied explosives to reduce huge edifices to neat piles of rubble. Without so much as jarring neighboring structures.

And he uses the SX-70 Land camera to photograph every aspect of the work. For his own records. And to help sell his services to potential customers.

Why the SX-70? It's simple:

With this one camera, he gets instant aerial photos of prospective demolition sites (for planning purposes). And close-ups from 10.4 inches of dynamite placement locations (to help him brief his crew).

He also gets sequential photos at 1.5-second intervals of the demolition in progress (for publicity purposes).

8:00 : 03.0 AM

8:00 : 04.5 AM

ıtion

˛oizeaux

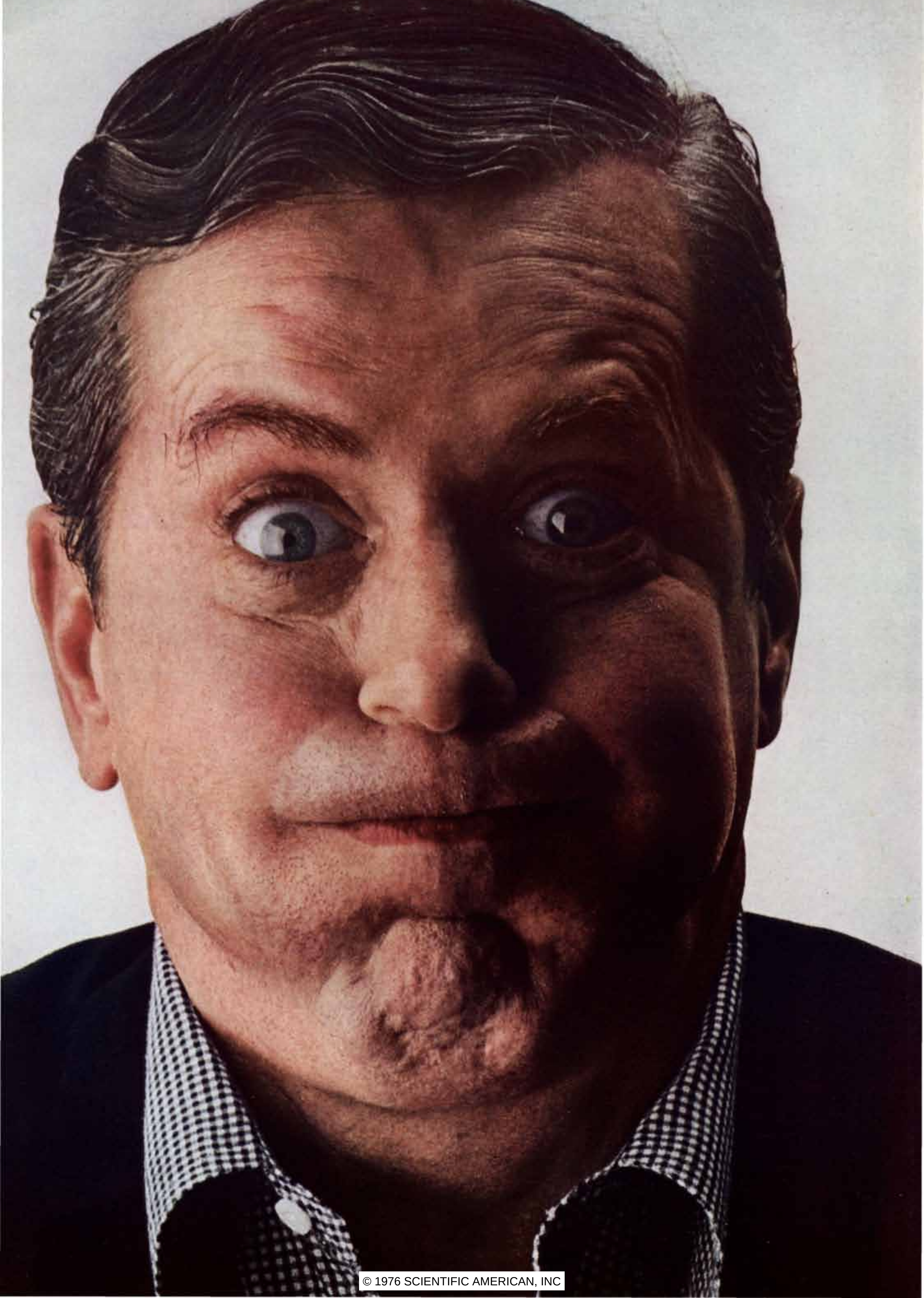
The pictures are virtually grainless. So he can analyze the smallest details under a magnifying lens.

And he gets all these pictures, on the spot, at the push of a button. Without worrying about light conditions. Or shutter speeds. Or development timing.

Some business people used to think that photography was a complicated way to make records.

But the SX-70 has exploded *that* theory.

The SX-70 camera from Polaroid makes instant records for any business.



eventually became vascularized. In these latter instances a few vessels were able to reach the tumor by traversing an area outside the inhibitor zone. Recently we have isolated from cartilage a diffusible factor that has an inhibitory effect on the tumor-induced proliferation of capillaries.

If an inhibitor of angiogenesis were to be effective against the kinds of tumors commonly observed, it would probably have to be administered systemically, that is, administered to the body as a whole. One would like to try such an experiment in a rabbit or some other small animal, but at present not enough inhibitor from cartilage is available.

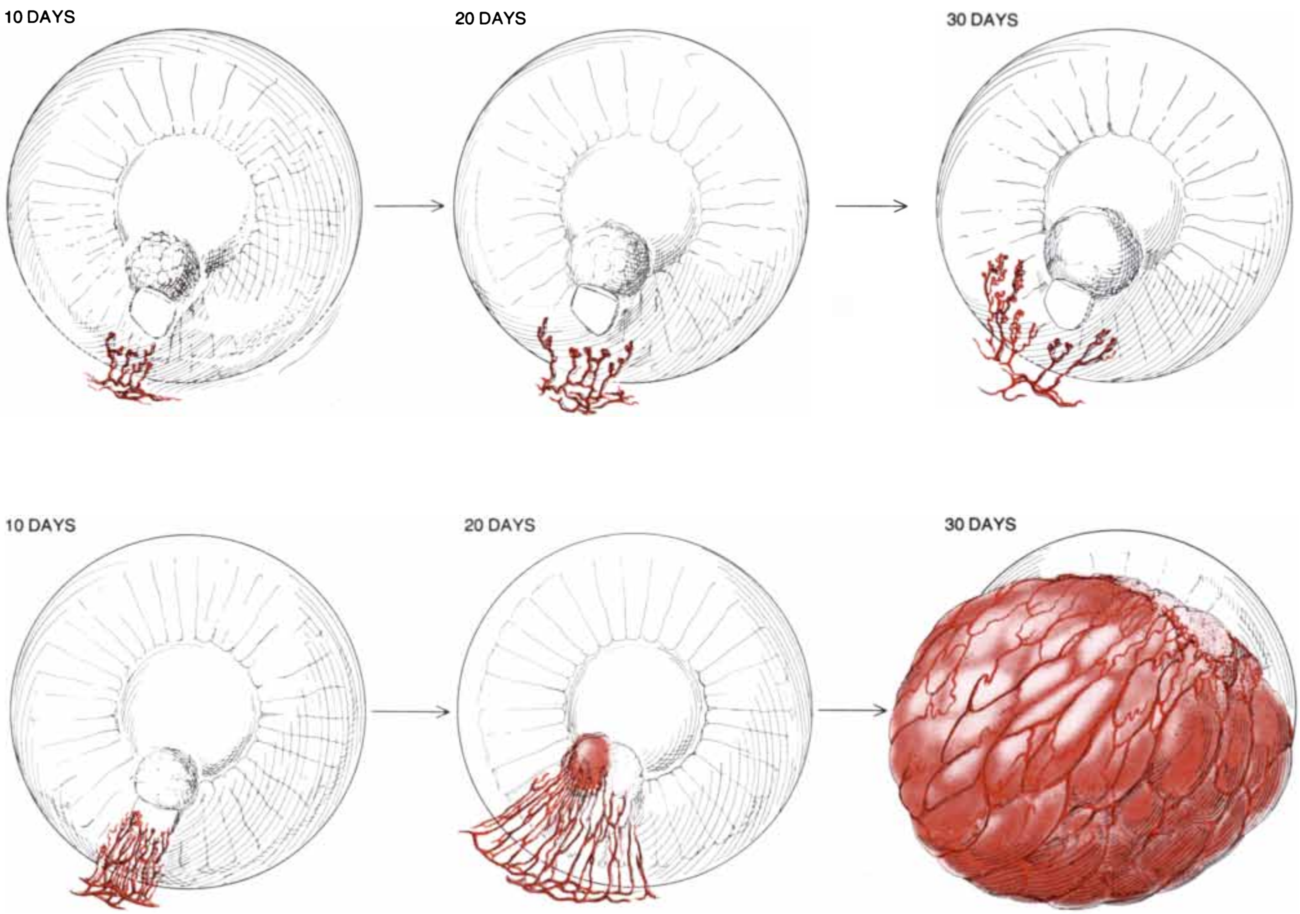
Nevertheless, the demonstration that tumor growth can be limited by a substance that inhibits neovascularization further emphasizes the crucial role the proliferation of capillaries plays in the continuous growth of a tumor. At the moment a cell anywhere in the body becomes cancerous its advantage over the host cells is probably minuscule. Even after it has managed to give rise to perhaps 1,000 daughter cells the malignant microcolony lives a precarious existence in a sea of trillions of normal cells. At any instant it may be shed in the menstrual blood, sloughed off into the feces or coughed up in sputum. The probability that it will someday kill its host must be exceedingly low. Once this tiny clump of cells develops the capacity to induce new capillaries from the host, however, it has achieved a major advantage. It can then grow rapidly and make its way in the host without hindrance.

Normal cells seem to be unable to induce angiogenesis in our assay systems. At this writing TAF has not been found in a variety of normal animal and human tissues, either adult or embryonic. It is possible that certain pathological processes in which neovascularization is prominent (such as chronic inflammation, delayed hypersensitivity and wound healing) may be found to depend on factors that induce angiogenesis but that differ from TAF. At present no one knows how such pathological processes stimulate vascularization.

The Vascularization of Grafts

If the continuous induction of capillary proliferation is a property generally unique to tumors, how can the vascularization of free grafts of normal tissue be explained? It is known that when embryonic tissues (and under certain conditions adult skin tissues) are excised and grafted, blood flow reappears in the grafts after a few days. Do such grafts induce new vessels from the host to which they have been transplanted?

To learn the answer Dianna Ausprunk of our laboratory and David Knighton, a medical student, conducted the following experiment. They excised one-millimeter pieces of tissue from adult rats, from embryonic rats and from a rat tumor and compared what happened when the three kinds of tissue were implanted in the chorioallantoic membrane of the chick embryo. Although the preexisting blood vessels in the tumor grafts disintegrated within 24 hours, the grafts were able to survive without blood flow for about three days, at which time the tumor grafts were penetrated by new vessels from the host. There was also a marked proliferation of capillaries in the vicinity of the tumor graft. In contrast, in the grafts of normal embryonic tissue the preexisting vessels did not disintegrate but reattached themselves to the host vessels by a process



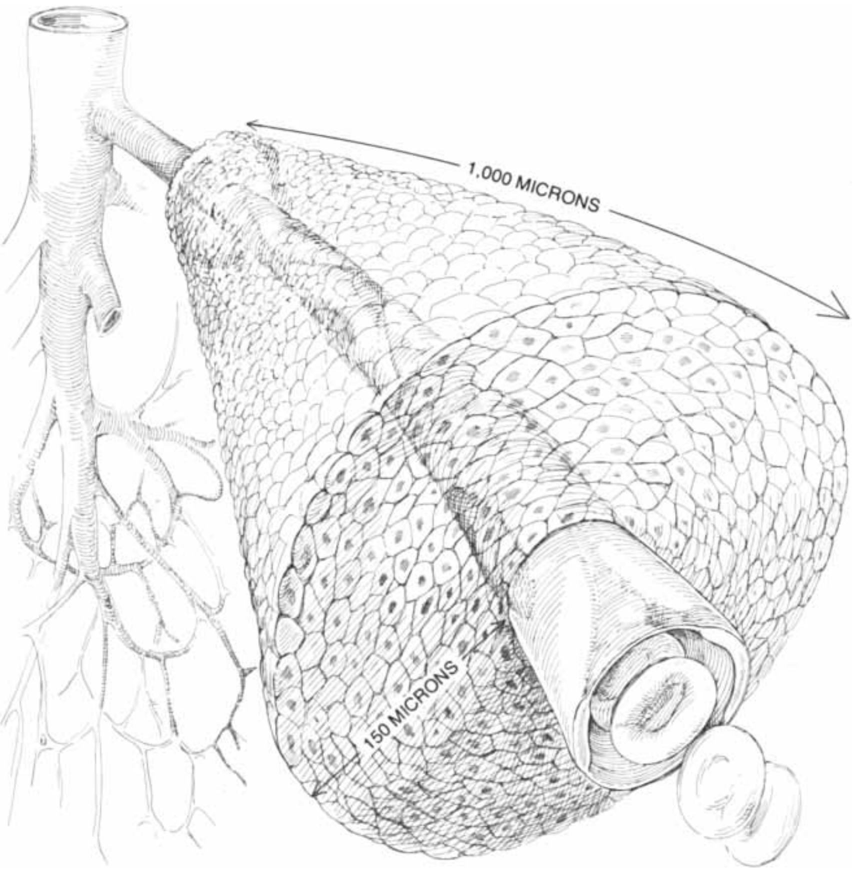
INHIBITOR OF TUMOR VASCULARIZATION is present in cartilage, a tissue that contains blood vessels during fetal development but that becomes avascular after birth. In the corneal experiment shown at the top a piece of normal adult cartilage is placed between an implanted tumor and the vascular bed at the edge of the cornea. Although capillary growth is induced by angiogenesis factor released by the tumor, the new vessels are inhibited in the vicinity of the cartilage. If the cartilage has been inactivated by boiling before it is implanted next to the tumor (*bottom*), there is no inhibition of capillary growth and the tumor becomes vascularized by the 15th day.

of fusion within a day or two. It was clear from the experiment that the embryonic tissue did not stimulate the proliferation of capillaries in the host.

The pieces of healthy tissue taken from adult rats proved to be similarly incapable of stimulating the proliferation of capillaries. The preexisting blood vessels disintegrated without ever fusing with the vessels of the host, and the grafts became necrotic. One can therefore conclude that the vessels within a vascularized tumor graft are derived from the host, whereas the vessels within a graft of embryonic tissue are those of the graft itself. Hence only tumor grafts seem able to stimulate new blood vessels from the host. In sharp distinction, revascularization of normal tissue grafts, when it does occur, is predominantly the result of fusion of preexisting graft vessels with the host's circulation.

If tumors have the ability to stimulate the proliferation of host vessels and normal tissues do not, when during the transformation of a normal tissue to a cancerous tumor is this new property expressed? The question has been examined by my colleague Gimbrone and Pietro M. Gullino of the National Cancer Institute. They studied a strain of mice in which most of the adult females spontaneously develop cancer of the breast.

They found that normal breast tissue in these mice lacks the capacity for angiogenesis. A hyperplastic nodule often appears before the breast cancer itself. Even when the nodule is examined under a microscope, it looks benign. Yet more than a third of such nodules were found to be precancerous lesions, already capable of inducing the proliferation of capillaries. All the breast cancers that eventually arose were richly supplied with blood vessels. Evidently the capacity to induce angiogenesis may be an early event in the stepwise transformation of normal cells to the fully malignant state. The capacity can arise in a cell destined to become malignant even though the cell still looks benign morphologically.



TEN THOUSAND TUMOR CELLS can probably be supported for every millimeter of growth in the length of a vascular capillary. This hypothesis is based on the observation that oxygen, needed for cell respiration, can diffuse over a distance of about 150 microns. Occasionally the cylindrical clustering of tumor cells can be seen in histological sections. Most capillaries, however, follow such a tortuous course that the cylindrical configuration is not apparent.

The Normal Vascular Network

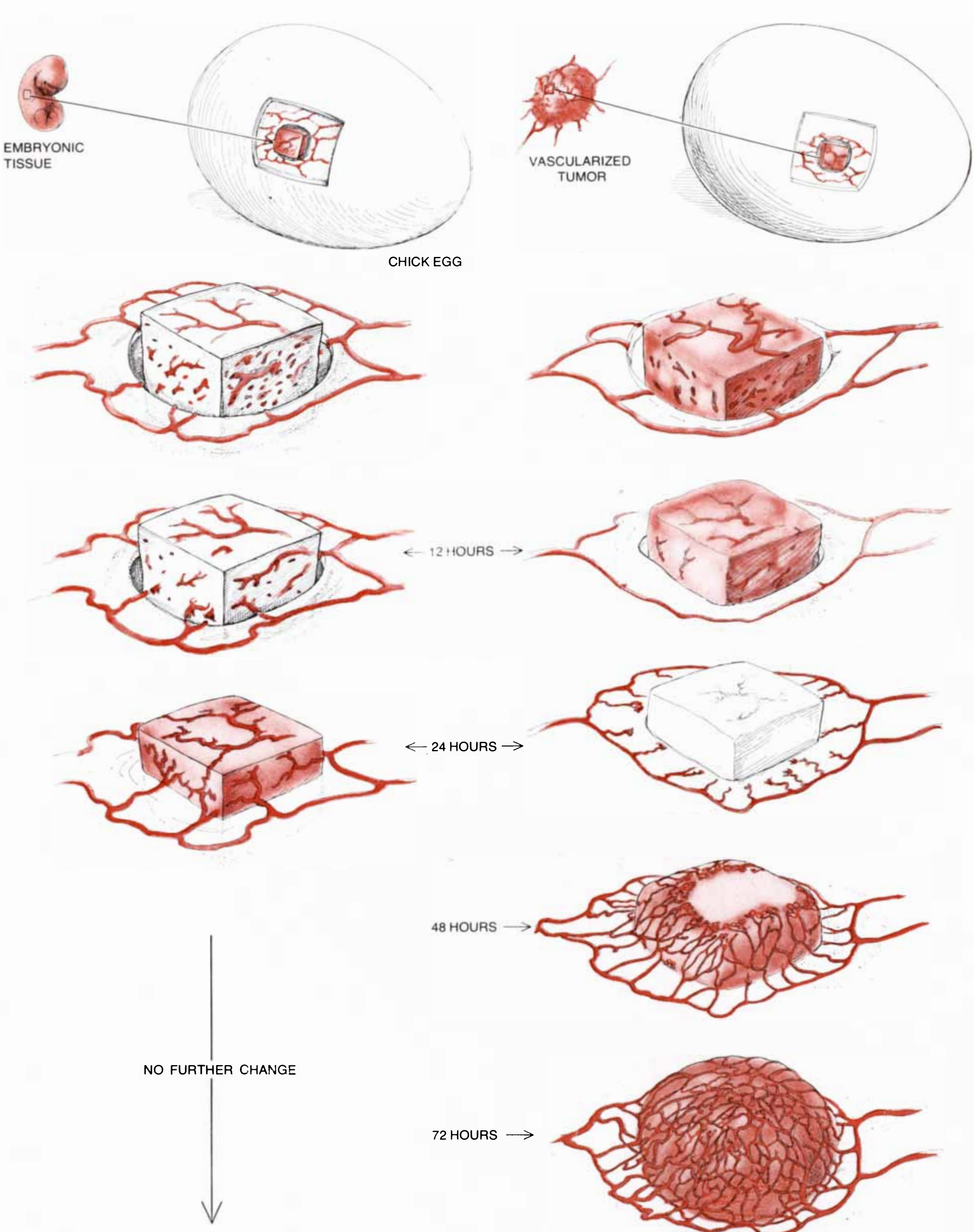
Let me briefly describe some of the properties of the normal vascular network. In the adult human being it accounts for about 3 percent of the total body weight. The endothelial cells that form the lining of the network renew themselves very slowly. Cells rarely divide in normal adult endothelium. At any one moment perhaps only one cell in 1,000 is undergoing division. Thus the vascular network is a quiet tissue compared, say, with the intestinal lining, the bone marrow and the skin, which have high-speed renewal systems. Occasionally there is a brief burst of proliferative activity in one part of the vascular system when such activity is needed to heal a wound or mount an immune response. The new vessels always regress after a short time, and regenerative activity subsides to its former low state.

In contrast, when a malignant tumor sends out its chemical message, the proliferation of endothelial cells rises steeply in the vicinity of the tumor. Up to 20 percent of the endothelial cells may synthesize DNA and divide. Capillaries bud from the side walls of venules and lengthen into thin tubes, converging on the tumor from all directions. Malignant tumor cells are dispersed among the actively proliferating endothelial cells. The call for new capillaries is continuous, relentless and steadily intensified. The tumor goes on recruiting new vessels. The process does not stop until the host is dead.

No one ever died of an avascular, *in situ* tumor. Only the vascularized tumor is lethal. In what ways does tumor angiogenesis contribute to lethality? One way is rapid growth. Neovascularization acts as a permissive switch enabling a tumor to attain its particular maximum growth rate. But how is the rapid growth facilitated? One explanation is that the cells in a vascularized tumor tend to cluster around each new capillary in a cylinder. Ian F. Tannock of the M. D. Anderson Hospital in Houston has shown that the most actively dividing tumor cells lie within about 100 microns of the nearest capillary. It is known that typical healthy tissues can be adequately supplied with oxygen by diffusion over distances of up to 150 microns. One can estimate that as many as 10,000 tumor cells could lie within a cylinder with a radius of 150 microns centered on a capillary only one millimeter long. A capillary of that length would contain somewhere between 20 and 100 endothelial cells. Hence whenever the capillary lengthens by just one endothelial cell, it could conceivably support 100 new tumor cells. This amplification factor may explain why each new capillary that penetrates a tumor is surrounded by a burst of new tumor growth.

Tumor Progression

Rapid tumor growth alone, however, does not explain the increasing malignancy of advanced cancers. The increase in malignancy arises in large part from changes collectively known as tumor progression. Whereas the progeny of healthy cells are usually faithful copies of their parent, the progeny of cancer cells exhibit increasingly malignant characteristics. For example, the early form of a spontaneous tumor rarely gives rise to cells that metastasize, or spread. Many cell divisions later a highly



EMBRYONIC TISSUES AND TUMOR TISSUES are vascularized by different mechanisms over different time spans. In the experiment depicted here one-millimeter samples of the two kinds of tissue are implanted on the richly vascularized chorioallantoic membrane of eight-day-old chick embryos, which readily accept foreign grafts. When embryonic tissue from a mouse or rabbit is implanted on the membrane (*left*), the vessels within the implant remain intact and fuse with the surrounding vascular bed within 24 hours. Thereafter there is no significant change in the vascular connection between the implant and the host. In contrast, if the implanted tissue is a tumor (*right*), the vessels within the tumor soon disintegrate and disappear. Within 48 hours, however, the tumor implant stimulates angiogenesis in the chorioallantoic membrane, with the result that the tumor is provided with a rich new blood supply within a period of 72 hours.

metastatic variant will appear. Its progeny may be even more dangerous.

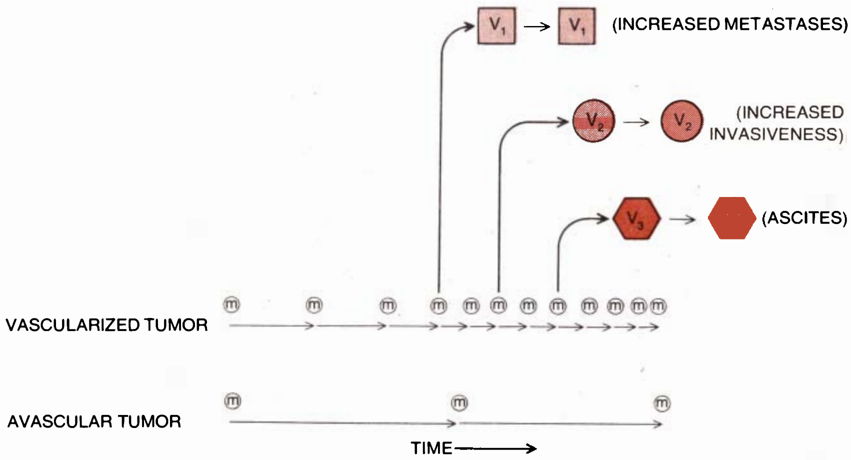
The concept of tumor progression was established in 1949 by Leslie Foulds of the Chester Beatty Research Institute in London. Its mechanism was later studied by George and Eva Klein of the Karolinska Institute in Stockholm. They showed that with repeated propagation from one animal to another experimental tumors gradually grow faster, lose signs of differentiation, become independent of certain growth regulators, are more readily transplanted to animals of a different strain and finally are able to grow in bone marrow or as ascites cells (free-floating cells in the abdominal fluid).

The time course of human cancer is similar. Although the mechanism of tumor progression is not known, it seems to be a function of the number of cell divisions. Since vascularization facilitates a high rate of cell division, it tends to accelerate tumor progression. In the avascular tumor the rate of cell division is so low that there is much less opportunity for more dangerous variants to arise. As one can imagine, vascularization also enables the tumor to consume glucose and amino acids from the host at a remarkable rate. Tumors that are vascularized do not have to be very large to cause the victim to lose weight rapidly. Gullino and Flora H. Grantham of the National Cancer Institute have documented this parasitic property of vascularized tumors in detail.

One can only speculate on the role that tumor angiogenesis plays in the malignant phenomena of invasiveness and metastasis. By invasiveness I do not mean the ease with which a normal white blood cell leaves the bloodstream and travels through tissues to reach an irritating foreign body. I am referring to the ability of an advanced tumor to encroach on and destroy normal tissues, to make holes in muscle and bone and to melt away tough planes of fibrous tissue.

Two observations hint at a possible link between angiogenesis and invasiveness. When *in situ* carcinomas in the skin and in the cervix are observed closely, invasion through the tough basement membrane seems to come almost simultaneously with neovascularization. Viewed in cross section under the microscope, the basement membrane runs like a filament through the skin, through the intestinal, genitourinary and respiratory tracts and through a variety of ducts that open into these tissues, such as ducts from the breast and the liver. Thus the basement membrane, consisting partly of collagen, lies just under the layers of epithelial cells that "see" the outside environment (including the environment represented by the internal passageways exposed to environmental substances). Normally the basement membrane separates the epithelial tissues from the vascular system.

Most pathologists believe invasion of the basement membrane is followed by neovascularization, but the two events come so close together that it could also be the other way around. We have found that avascular tumors in the rabbit cornea are incapable of breaking through the layers of collagen above and below them until they have become vascularized. On the other hand, the vessels converging on an avascular tumor readily penetrate the layers of the cornea to find the tumor.



TUMOR PROGRESSION is a term used to describe the steady increase in malignancy observed in vascularized tumors. As tumor cells proliferate, variants arise that possess increasingly harmful properties. Some of the variants are able to metastasize, or establish secondary sites. Other variants exhibit increased power to invade surrounding tissue. In the final stages of tumor progression variants of the original tumor appear as ascites, or free-floating tumor cells in the host's abdominal cavity. Tumor progression seems to be a direct function of the rapid increase in mitosis, or cell division, that is made possible by vascularization. In the avascular, or *in situ*, tumor many fewer mitoses of tumor cells (*m*) take place in a given period of time.

There has been little work relating the onset of angiogenesis to metastasis. There are, however, scattered reports that very superficial skin tumors, not yet vascularized, and some other *in situ* tumors are never associated with metastasis. One can speculate that the penetration of a tumor by rapidly growing capillary tubes, with their thin walls, open ends and gaps between endothelial cells, provides an ideal opportunity for tumor cells to escape into the bloodstream.

Other Vascular Proliferations

The studies of tumor angiogenesis I have recounted raise some fundamental questions about the nature of vascular proliferation itself. How is it controlled and what is its role under normal conditions and in certain noncancerous diseases?

For example, almost nothing is known about the role of neovascularization in the growth and development of the embryo. Might bone growth be controlled by the rate of vascular turnover at the ends of the bone, where it is attached to cartilage? Is an inhibitor such as the one we have isolated from the cartilage of newborn animals normally present in cartilage throughout adult life?

Furthermore, we have little understanding of the feedback mechanisms, if any, that control the turnover of capillaries in normal adult tissues. What limits the short burst of capillary proliferation in a wound or during a menstrual cycle? What is the function of the ubiquitous basement membrane that seems to be so effective in isolating epithelial compartments from vascular compartments throughout the body? Conceivably an important part of that function is to block capillaries from reaching the epithelium and stimulating the proliferation of epithelial cells.

Neovascularization also seems to be important in some diseases other than cancer. For example, one would like to know why capillaries invade the vitreous humor of the eye in diabetes and overrun the cornea in trachoma, leading in both cases to blindness. One would also like to know what enables newly proliferating capillaries to penetrate the cartilage of the joints in rheumatoid arthritis, eventually causing the cartilage to disintegrate. One would like to know why patients with psoriasis develop such intense neovascularization under their skin cells. Are the vessels proliferating because the epidermal cells are rapidly dividing, or is the reverse true? Perhaps, as in tumor angiogenesis, the excessive proliferation of epidermis is the result of neovascularization.

Finally, in the biology of tumor angiogenesis many areas remain to be explored. How does a capillary thinner than a hair make its way through tissues as tough as the cornea? Is the growing capillary itself invasive, or does it release an enzyme capable of dissolving collagen? Is it possible that a major difference between carcinoma (cancer of the epithelial cells) and sarcoma (cancer of the connective tissue) lies in the fact that although both kinds of cancer may require neovascularization for rapid growth, carcinoma is not invasive until after vascularization, whereas sarcoma may be invasive before vascularization? All these questions and many others have originated with the effort to perceive more clearly the role of angiogenesis in tumor growth.

Synchronous Fireflies

Whereas the flashing of the familiar fireflies of the Temperate zones is unsynchronized, certain species of Asia and the Pacific flash in unison. What is the evolutionary role of this behavior?

by John and Elisabeth Buck

The familiar fireflies that flit over our lawns and meadows in summer are beetles of the family Lampyridae. There are more than 2,000 lampyrid species, inhabiting most regions of the Temperate and Tropical zones of the earth except for deserts and high mountains. Many of the American species belong to a type we shall call roving fireflies because the males fly about singly, searching for females perched in low vegetation. The male flashes rhythmically, and when a female flashes in response, the two fireflies begin a courtship involving a series of alternating flashes that lead the male to the female. For 300 years explorers and naturalists have reported another kind of lampyrid behavior, seen in the region stretching from India east and southeast to the Philippines and New Guinea. In this behavior the fireflies gather in trees in dense swarms and the males flash on and off in the same rhythm.

Forty years ago the American biologist Hugh M. Smith, remembering displays he had seen in Thailand, wrote: "Imagine a tree thirty-five to forty feet high thickly covered with small ovate leaves, apparently with a firefly on every leaf and all the fireflies flashing in perfect unison at the rate of about three times in two seconds, the tree being in complete darkness between flashes.... Imagine a tenth of a mile of river front with an unbroken line of [mangrove] trees with fireflies on every leaf flashing in synchronism, the insects on the trees at the ends of the line acting in perfect unison with those between. Then, if one's imagination is sufficiently vivid, he may form some conception of this amazing spectacle."

Many observers have marveled at the beauty of the synchronous flashing—a beauty best appreciated, in our own experience, from a canoe slipping down a jungle river on a moonless night, when the steady, silent pulsing of the firefly trees has an almost hypnotic effect. Beauty alone, however, does not explain the persistent fascination of the displays and particularly the many comments by writers who have never seen them. What has been irresistible to naturalist and layman alike are the questions of how and why. How is it possible for thousands of fireflies to coordinate their flashing so exactly, cycle after cycle, and why do they do it? We hope to show that the questions are linked, in the sense that one cannot understand the why of synchronous flashing without understanding the how.

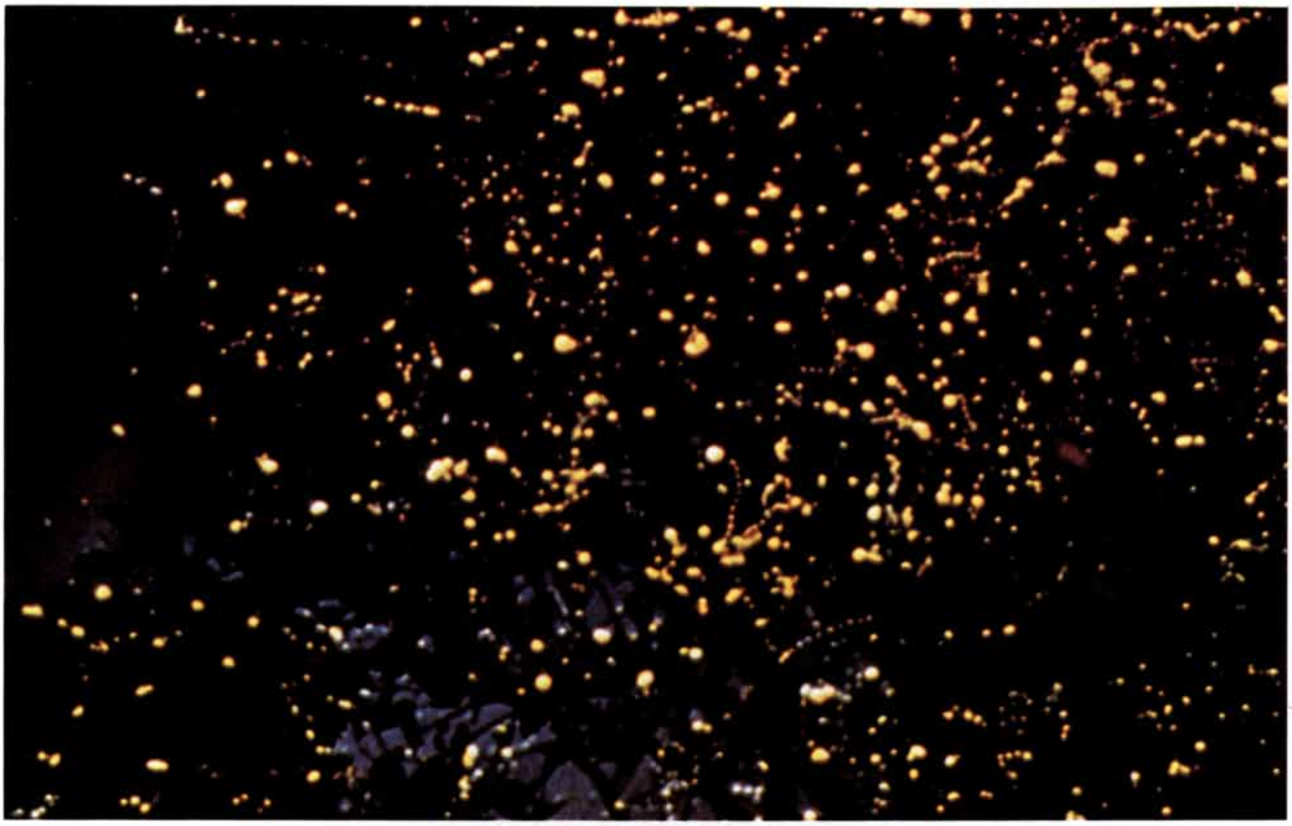
Just what capability communal synchrony demands is a question that does not come easily to us as human beings because we accept our own ability to dance or to march in unison as being second nature. To see thousands of synchronized flashes in the night, however, is to realize that analogous behavior is never seen in familiar animals. For example, although a circus horse appears to pace in time with band music, the effect is achieved by adjusting the music to the horse. One has only to watch a coach team to see that under normal conditions even a horse moving in harness is indifferent to the gait of its fellows. By the same token photographs of a flock of birds taking flight may show many of their wings beating in phase during the moments after takeoff, just as competing human runners may be in step for the first few strides after the starting gun. Yet even among birds that fly in formation, such as Canada geese or gray pelicans, synchrony of wingbeat occurs only as a transient chance event.

Other types of group behavior, such as the apparently simultaneous wheeling of flocks of pigeons or plovers or a change in direction by a school of fish, are sometimes mistakenly cited as examples of synchronous performance. They are only rapid mass responses to the movements of a leader. Much the same is true of the sometimes rhythmic chorusing of cicadas or frogs; all the individuals vocalize together but not in unison. Group activities such as these have little in common with rhythmic communal synchrony. That ability, requiring a group of organisms to repeat an action simultaneously and at regular intervals, seems to be confined to man, to a few kinds of katydids and crickets that chirp in synchrony and to certain fireflies of Asia and the Pacific.

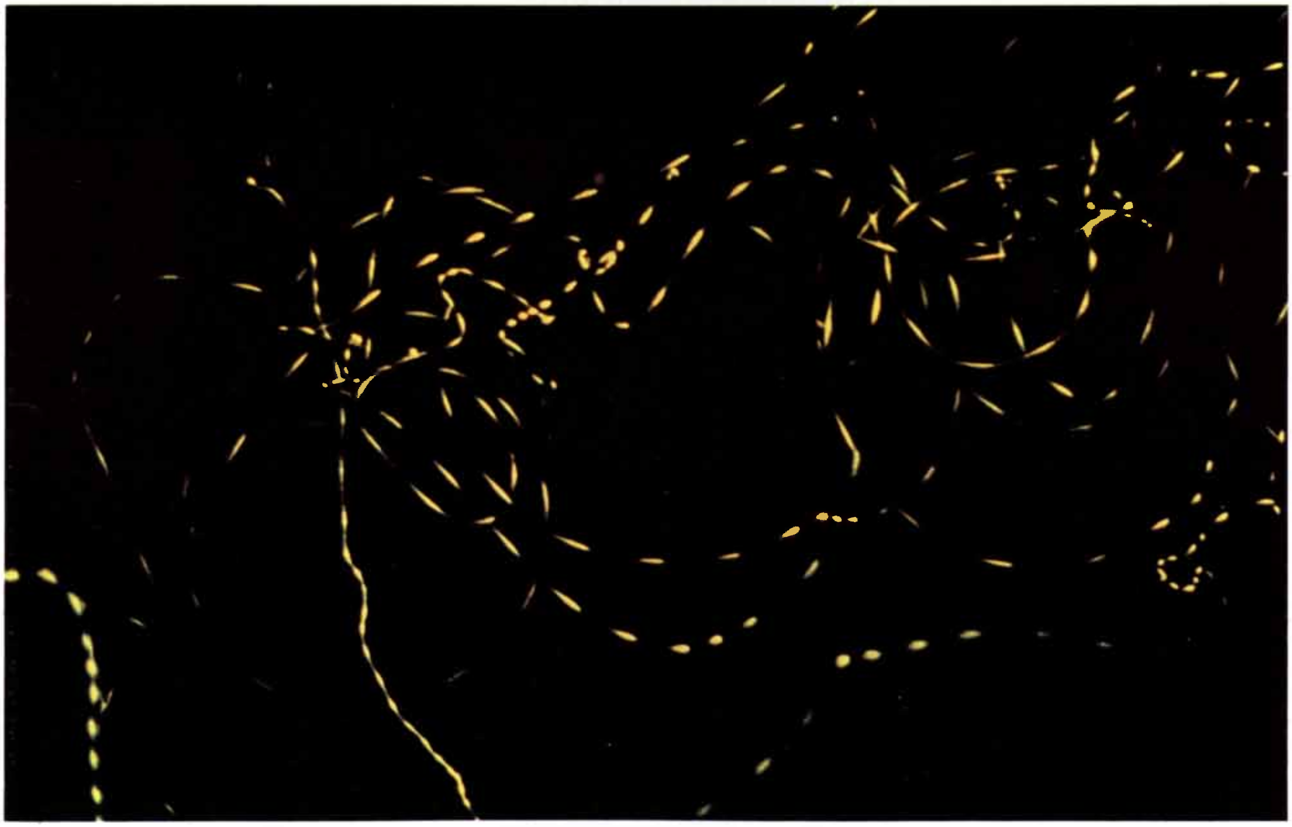
Until recently the remoteness of the areas where mass firefly synchrony occurs and the inadequacy of the field reports made it impossible to get a clear picture of the phenomenon. As a result a succession of inadequate hypotheses have been proposed to explain the displays. It has even been suggested that the rhythmic flashing is only an artifact of human perception. One psychologist, C. A. Ruckmick of the University of Illinois, actually tested this hypothesis by exposing subjects to an array of lights flashing at random. He concluded that accidental flash coincidences would "tend to set the mind of the observer in the direction of subsequent groupings of the flashes into patterns supplied, for the most part, by himself."

Self-deception is admittedly a hazard in behavioral work, but over the past 10 years, thanks to jet travel and portable electronic instruments, the reality of the synchronous firefly displays has been firmly established. In fact, in this decade more has been learned about synchronous flashing than everything that had been known before that time. For us the starting point was an international congress on bioluminescence held in Japan in 1965. After the meetings we went on to Borneo and Thailand, armed with a recording photometer and high-speed film that enabled us to prove that synchronous flashing is not an artifact of human perception and to measure the fireflies' flashing period and the degree of coincidence in their flashing.

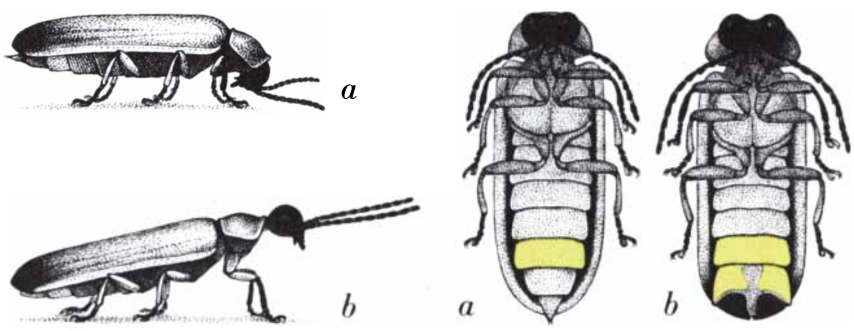
At the same time another participant in the Japan congress, the French authority on bioluminescence Jean-Marie Bassot, visited Singapore, where he joined Ivan Polunin of the University of Singapore in recording "constellations" of synchronously flashing fireflies. Bassot and Polunin did this by the ingenious stratagem of winding high-speed film through an open-shuttered camera. To the short list of biologists who have been fortunate enough to observe synchronous fireflies under natural conditions and to study them with modern laboratory techniques the National Science Foundation's 1969 Alpha Helix Expedition to New Guinea and several locations in Southeast Asia then added the neurophysiologists James F. Case, Frank Hanson and Anthony Barnes, the Japanese expert on bioluminescence Yata Haneda and James E. Lloyd, an authority on the field behavior of fireflies. We should like to convey our gratitude to all



SYNCHRONOUS DISPLAY of male fireflies in a "firefly tree" in Southeast Asia is recorded in a time-exposure photograph made by Ivan Polunin of the University of Singapore. Synchronizing fireflies, mostly of the genus *Pteroptyx,* are found from India to New Guinea.



RANDOM FLIGHT of *Pteroptyx* males, taken from firefly trees in Thailand by the authors and released in a darkened Bangkok hotel room, left the streaks visible in this time-exposure photograph. After the insects landed their rhythmic flashes soon became synchronized.



MALE AND FEMALE FIREFLIES of the species *Pteroptyx malaccae* are seen here in profile and in ventral view; the area of their light organs is colored. The female (*a*) is shown in a resting, retracted stance; the male (*b*) is shown in the alert position, with head and prothorax extended.

these workers and to our Thai colleague Boonsong Lekagul for making available previously unpublished data and observations for this progress report. Moreover, our work could not have been done without the help we received from colleagues in every country we visited.

The problem of how fireflies synchronize their flashes is a problem of how the nervous system meters time. The light organ of the firefly, located near the end of the abdomen, is activated by signals originating in the brain. Experiments have shown that stimulation of a firefly's eye by either light or electricity can trigger a flash from the light organ. The minimum delay between the stimulus and the response—the total time needed to process the stimulus in the eye and the brain, to generate motor-nerve impulses, to conduct the impulses down the nerve cord and out through peripheral nerves to the light organ and finally to excite the light-producing tissue—is usually from 150 to 200 milliseconds. That interval is much shorter than the usual time between successive flashes of the individual firefly in nature. *Pteroptyx malaccae,* the principal synchronously flashing firefly of Thailand, flashes every half second or so; the exact interval is 560 milliseconds when the ambient temperature is 25 degrees Celsius. *Pteroptyx cribellata* of New Guinea has a slower rhythm; its interflash period is about a second at the same ambient temperature. Other species have interflash periods ranging up to three seconds.

When two fireflies are flashing synchronously, they must be responding to each other's flashes, since light is the only medium of communication between them. Yet, depending on the species, they flash every three seconds, two seconds or 500 milliseconds rather than every 200 milliseconds, which is all a nerve impulse needs to travel from the eye to the light organ. Even more puzzling, when two fireflies that are originally out of phase with each other go through the process of getting into synchrony, they must obviously be responding at intervals that are neither the minimum neural delay (200 milliseconds) nor the normal species interflash period. How are all these different responses controlled?

Some understanding of the adjustment of neural delays can be gained from two simple experiments that we have conducted many times with another synchronizing animal: man. In the first experiment the members of an audience are asked to hold a coin in their fingers and close their eyes. Each person is then supposed to listen for the click of the experimenter's coin on a tabletop and rap his own coin on the arm of his chair as quickly as possible thereafter. This, of course, is a mass version of the familiar "reaction time" test of psychology. It shows that no matter how hard one tries, such a direct finger response cannot be accomplished in less than 150 milliseconds.

After several repetitions of the first test we would give the members of the audience, their eyes still closed, a second task: "Start tapping and get in step with one another. Just pick a comfortable rhythm and keep it regular." With no more than these simple instructions an audience of several hundred people will achieve a good mutual synchrony within a few cycles, usually at a frequency of two or three taps per second. The interval between the taps of the earliest and the latest response in any one volley is usually less than 130 milliseconds. That, of course, is a shorter interval than the reaction time. Therefore no participant in the experiment could have been waiting to hear a neighbor's tap before he himself tapped. Instead each participant's brain somehow measured the passage of time up to the instant when it was necessary to initiate the neural message that caused his fingers to move in synchrony with the fingers of all the other participants. There are thus two components to the overall delay interval between successive taps: the clocking time in the brain and the motor time between the brain and the finger. Clearly the clock triggers the motor processes, but what starts the clock? It is the sound of the *preceding* communal tap.

It may seem rather a long way from a lecture hall in America to a riverbank in Southeast Asia. Nonetheless, it was evident to us, as we recorded congregations of Thai fireflies flashing in unison every 500 milliseconds or so, with no member out of phase by more than 20 milliseconds, that a time-metering mechanism similar to the one involved in human synchrony must be responsible for the performance.

The pacemakers that control rhythmic activity in many animals have been found to be either single oscillatory nerve cells or networks of such spontaneously rhythmic cells. For example, the rate of the lobster's heartbeat is controlled by six pacemaker cells linked by various excitatory and inhibitory nerve fibers. In the firefly's tiny but complex brain no one has so far identified even the flash pacemaker region, let alone the ultimate oscillator. Fortunately it is possible to study the spontaneous behavior of a single firefly's pacemaker, and the interactions between the pacemakers of two or more fireflies, by indirect means. When the male firefly is flashing in its spontaneous rhythm, each flash-to-flash interval should equal the length of one pacemaker cycle. Therefore changes in a firefly's flash timing in response to stimulation by electric light allow one to infer properties of the pacemaker.

With Case and Hanson we made such tests in New Guinea. The principal species of firefly we worked with was *Pteroptyx cribellata,* which normally emits a single-peaked flash at about one-second intervals. The responses of this species are similar to those of *P. malaccae,* which was the subject of most of the behavioral studies that are described here.

In each experiment a male firefly was fastened on its back to a wax pallet. The firefly's head was masked to keep the insect from detecting its own light emission. A flash of electric light was directed to one of the firefly's eyes through a fiber-optics light guide. The light source used as a stimulus was controlled with respect to intensity, duration and the intervals between flashes. (To avoid confusion between this artificial flash and the firefly's own flash we shall call the artificial flash the stimulus or the signal.) A photomultiplier tube detected the firefly's response flashes, which were amplified and recorded on both magnetic tape and chart paper.

We found that the flashing of the male *Pteroptyx cribellata* firefly is readily entrained by, or synchronized with, artificial signals; full entrainment usually takes only one or two cycles. When the stimuli are delivered at intervals shorter than the firefly's normal flashing period, the insect shortens its period correspondingly. When the period of the driver lamp is longer than that of the firefly, the insect lengthens its period to match that of the stimulus. Unexpectedly the firefly flashes simultaneously with the driver lamp only when the period is the same as the firefly's normal spontaneous flashing period of 1,000 milliseconds. If the lamp is flashed every 1,300 milliseconds, say, the firefly flashes every 1,300 milliseconds, but each of its flashes precedes the corresponding lamp signal by 300 milliseconds. If the lamp period is 900 milliseconds, the firefly also flashes every 900 milliseconds, but always 100 milliseconds later than the corresponding lamp signal.

Pocket CB

Talk to the world with a new citizens band transceiver that fits in your pocket.

The PocketCom measures approximately ¾" x 1½" x 5½" and easily fits into your shirt pocket. The unit can be used as a personal communications link for business or pleasure.

The Dick Tracy wrist radio may no longer be a dream. Mega Corporation proudly introduces the PocketCom—a new tiny personal communications system that actually fits in your pocket.

MANY PERSONAL USES

An executive can now talk anywhere with anybody in his office, his factory or job site. The housewife can find her children at a busy shopping center. The motorist can signal for help in an emergency. The salesman, the construction foreman, the traveler, the sportsman, the hobbyist—everybody can use the PocketCom—as a pager, an intercom, a telephone or even a security device.

LONG RANGE COMMUNICATIONS

The PocketCom's range is limited only by its 100 milliwatt power and the number of metal objects between units or from a few blocks in the city to five miles on a lake. Its receiver is so sensitive, that signals several miles away can be picked up from stronger citizens band base stations.

VERY SIMPLE OPERATION

To use the PocketCom simply turn it on, extend the antenna, press a button to transmit, and release it to listen. And no FCC license is required to operate it. The PocketCom has two Channels—channel 14 and an optional second channel. To use the second channel, plug in one of the 22 other citizens band crystals and slide the channel selector to the second position. Crystals for the second channel cost $7.95 and can only be ordered after receipt of your unit.

BEEP-TONE PAGING SYSTEM

You can page another PocketCom user, within close range, by simply pressing the PocketCom's call button which produces a beep tone on the other unit if it has been left in the standby mode. In the standby mode the unit is silent and can be kept on for weeks without draining the batteries.

A MAJOR BREAKTHROUGH

The PocketCom's small size results from a breakthrough in the solid state device that made the pocket calculator a reality. Mega scientists took 112 transistors, integrated them on a micro silicon wafer and produced the world's first transceiver linear integrated circuit. This major breakthrough not only reduced the size of radio components but improved their dependability and performance. A large and expensive walkie talkie costing several hundred dollars might have only 12 transistors compared to 112 in the Mega PocketCom.

SUPERIOR FEATURES

Just check the advanced PocketCom features now possible through this new circuit breakthrough: 1) Incoming signals are amplified several million times compared to only 100,000 times on comparable conventional systems. 2) Even with a 60 decibel difference in signal strength, the unit's automatic gain control will bring up each incoming signal to a maximum uniform level. 3) A high squelch sensitivity (0.7 microvolts) permits noiseless operation without squelching weak signals. 4) Harmonic distortion is so low that it far exceeds EIA (Electronic Industries Association) standards whereas most comparable systems don't even meet EIA specification. 5) The receiver has better than one microvolt sensitivity.

EXTRA LONG BATTERY LIFE

The PocketCom has a light-emitting diode low-battery indicator that tells you when your 'N' cell batteries require replacement. The integrated circuit requires such low power that the two batteries, with average use, will last weeks without running down.

The PocketCom is used as a pager, an intercom, a telephone or even a security device.

MULTIPLEX INTERCOM

Many businesses can use the PocketCom as a multiplex intercom. Each employee carries a unit tuned to a different channel. A stronger citizens band base station with 23 channels is used to page each PocketCom. The results: an inexpensive and flexible multiplex intercom system for large construction sites, factories, offices, or farms.

NATIONAL SERVICE

The PocketCom is manufactured exclusively for JS&A by Mega Corporation. JS&A is America's largest supplier of space-age products and Mega Corporation is a leading manufacturer of innovative personal communication systems—further assurance that your modest investment is well protected. The PocketCom should give you years of trouble-free service, however, should service ever be required, simply slip your 5 ounce PocketCom into its handy mailer and send it to Mega's prompt national service-by-mail center. It is just that easy.

GIVE IT A REAL WORKOUT

Remember the first time you saw a pocket calculator? It probably seemed unbelieveable. The PocketCom may also seem unbelieveable so we give you the opportunity to personally examine one without obligation. Order only two units on a trial basis. Then really test them. Test the range, the sensitivity, the convenience. Test them under your everyday conditions and compare the PocketCom with larger units that sell for several hundred dollars.

After you are absolutely convinced that the PocketCom is indeed that advanced product breakthrough, order your additional units, crystals or accessories on a priority basis as one of our established customers. If, however, the PocketCom does not suit your particular requirements perfectly, then return your units within ten days after receipt for a prompt and courteous refund. You cannot lose. Here is your opportunity to test an advanced space-age product at absolutely no risk.

A COMPLETE PACKAGE

Each PocketCom comes complete with mercury batteries, high performance Channel 14 crystals for one channel, complete instructions, and a 90 day parts and labor warranty. To order by mail, simply mail your check for $39.95 per unit (or $79.90 for two) plus $2.50 per order for postage, insurance and handling to the address shown below. (Illinois residents add 5% sales tax). But don't delay. It took only four advertisements last year to sell out our entire production.

The era of personal communications is the future of communications. Join the revolution. Order your PocketComs at no obligation today.

$39.95 NATIONAL INTRODUCTORY PRICE

Allow at least six weeks for delivery.

JS&A NATIONAL SALES GROUP

Dept. SA JS&A Plaza
Northbrook, Illinois 60062

CALL TOLL-FREE . . 800 325-6400

In Missouri Call 800 323-6400


The world's most counterfeited pen.
SAUDI ARABIA
South Korea
INDIA
INDIA
IRAN
Japan
IRAN

Its many imitators suggest, quite logically, that your best buy in pens is a Parker 75. There are a lot of reasons it cannot be duplicated, but people keep trying.

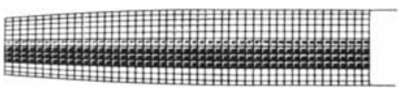
If imitation is the sincerest form of flattery, Parker is indeed flattered.

The confiscated pens in the photo at left are ample proof. All are phonies. Not one is a real Parker 75. Though fake Parker pens are almost unheard of in the United States, they are much in evidence where the genuine thing is scarce and hard to get.

Why? Because in many countries a Parker 75 pen is the mark of a cultured and educated person. And its clip attached to one's pocket becomes a visible character testimonial.

Small wonder then that in America, as in every literate nation of the world, a Parker 75 pen is a gift to be cherished from one generation to the next. At $7.50 to $40, or more, a Parker 75 pen is both an immediate and lasting value. Yes, Parker makes all types of pens—ball pen, soft tip, fountain pen. When you buy one for yourself or as a gift, buy it in one of the thousands of nice stores that carry and service them around the world.

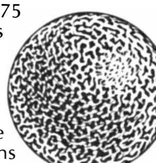
Ten common mistakes Parker 75 counterfeiters should avoid.



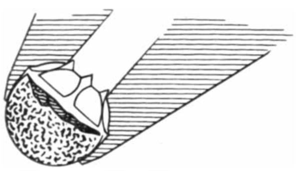
1. **GRID PATTERN IS SIMULATED CRUDELY.** Imitators make shallow stampings or simply lithograph pattern onto cases. Inspired by a London silversmith, the classic Parker grid on all sterling silver Parker 75 pens is carved deeply into the case by a precise sequence of cuts. The result is a metal sculpture that provides dozens of finger-fitting corners for easy, certain grip.

2. **FEEBLE SPRING ACTION IN COUNTERFEIT CLIP.** The real Parker 75 clip is made of beryllium copper, tested to 20,000 snap actions. Imitations often bend away from the pen body or snap off at the front end of the feathers.

3. **INFERIOR BALL DESIGN.** Imitators usually use ordinary smooth industrial ball bearings. The ball for a Parker 75 ball pen takes three weeks to make and is a small masterpiece of powder metallurgy—a tungsten-carbide cermet. For even ink delivery, it must be round within ten/millionths of an inch. The microscopic texture on its surface is formed by controlled "crater geometry." Result: an even line and good start-up.

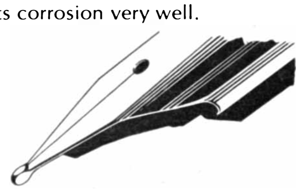


4. **IMPERFECT BALL SOCKET.** Phonies regularly use brass or bronze socket to seat the ball. The lip impacts against the ball, scrapes off ink, prevents its return to reservoir. Result: blobbing. These sockets are also subject to wear and corrosion, changing the flow rate drastically. The actual Parker ball seat is made of extremely tough



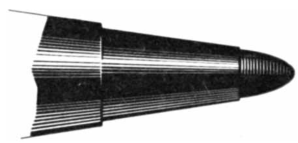
corrosion-resistant stainless steel. The Parker 75 socket *must* be especially long-wearing because the ink supply writes three times longer than the ordinary ballpoint.

5. **STIFF NIB WRITES LIKE NAIL.** Due to use of unyielding inferior material. For smooth feel and even ink flow, the nib must "give" some, but not too much. The Parker 75 fountain pen nib is solid 14K gold. This has the exact flex and resilience necessary and resists corrosion very well.



6. **NIB TINES CONTACT PAPER DIRECTLY.** Tines of many counterfeit fountain pen nibs wear quickly, causing a scratchy feel and erratic delivery of ink to paper. The Parker 75 nib rides on a tiny pellet welded to the tip of the point. The pellet is a tough, special alloy of ruthenium and platinum that wears *in*, not *out*. Counterfeiters are foiled here because ruthenium is a rare, precious metal. (Of the eight precious metals in the world, it takes four to make a Parker 75 fountain pen.)

7. **THE SOUND OF CLOSING A PHONY PARKER IS A DEAD GIVEAWAY.** It is mushy or, at best, a light click. When a Parker 75 cap snaps down on a 75 barrel, a positive clutch is engaged. The resulting sound is a solid "thunk" (not unlike the sound of a sports car door closing) that informs you audibly that the two parts are married firmly.

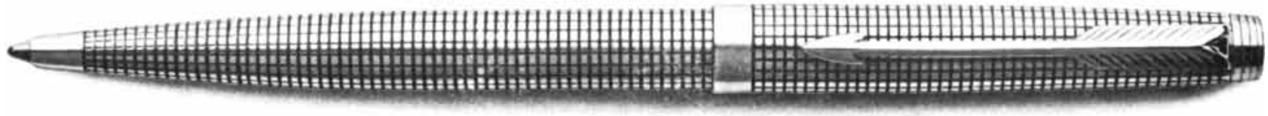


8. **SOFT TIP PEN POINT GOES LIMP OR SPLAYS.** A soft tip point is tricky to make right. The ink is very thin and actually flows by capillary action. The point must allow ink to flow but not excessively. The Parker point is very strong—the individual strands of nylon are bonded together by a critical trace of epoxy glue. Technically, the point can be duplicated but few counterfeiters are willing to pay the price.

9. **INKS NOT BACTERIA-RESISTANT.** In tropical climates, maverick mold growths in ink block the ink flow, causing writing failure. Parker makes separate and different inks for 75 ball pens, fountain pens and soft tip pens. Chemical makeup even varies from color to color.

10. **THEIR "STERLING SILVER" IS ACTUALLY BRASS.** Or less. That's because they use silver plate. All silver Parker 75 pens are made of solid sterling. That means they are sterling silver all the way through. Because of this intrinsic worth, plus the fact they are refillable and built to last, all Parker 75 pens are heirlooms in the making.

PARKER
World's most wanted pens




DAYTONA INTERNATIONAL SPEEDWAY
42
SCIROCCO. GERMAN SPORTSCAR, ITALIAN-STYLE.
We knew we had a winning combination. Because we were going to produce a true sportscar with absolutely impeccable credentials. German engineering and Italian styling. We gave this automobile a 1.6 liter overhead cam engine. And out on the track, it stormed from 0 to 50 in a mere 7.5 seconds. It knew its way around a corner, too. Front-wheel drive, rack-and-pinion steering, and front disc brakes for responsive stopping. The car was hot all right, but not too hot to handle. To match this kind of performance we wanted outstanding design. We went to Signor Giugiaro, the acknowledged master of automotive styling. And the results (as you can see for yourself) were simply stunning. So now there is Scirocco. Earning a reputation on the racetrack, turning heads on the street. Amazing what you can do with a little help from your friends.
The EPA estimates that with standard transmission Scirocco got 39 mpg highway, 25 city. (Actual mileage may vary, depending on how and where you drive, optional equipment, and the condition of your car.) ©Volkswagen of America.

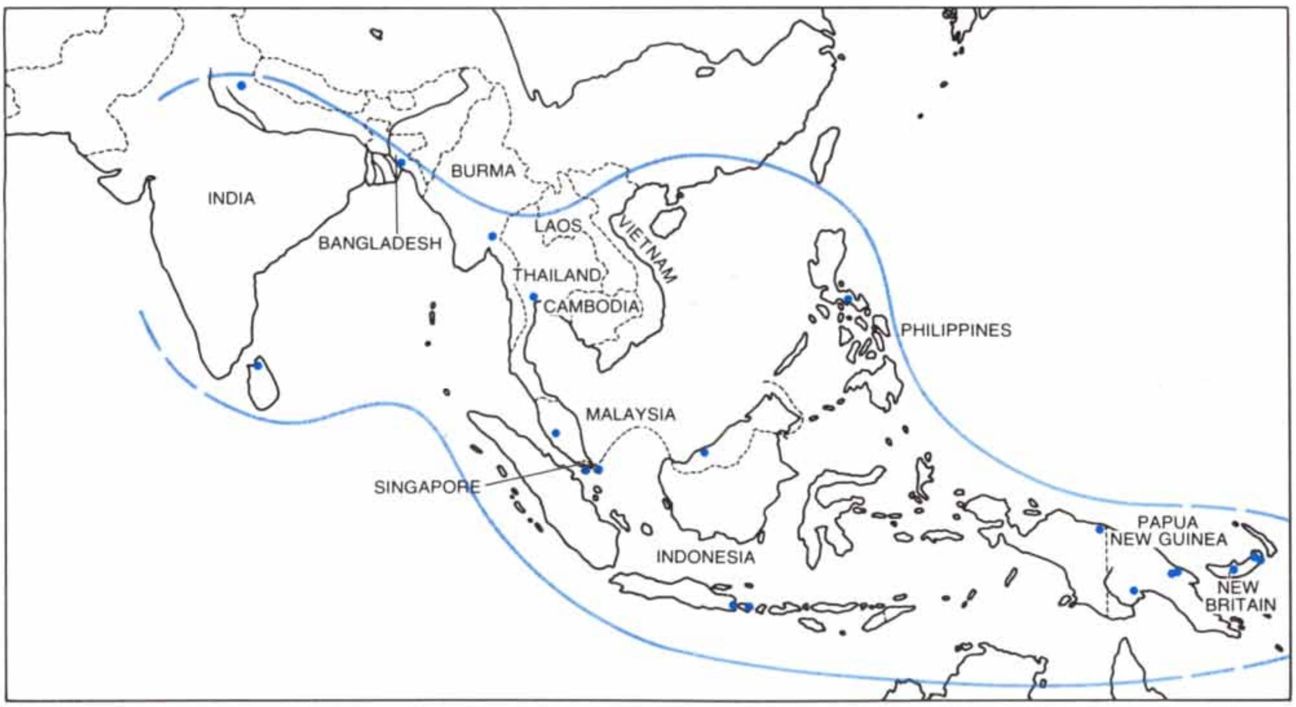
In more than 30 tests with five fireflies the insects were found to synchronize with series of stimuli as close together as 800 milliseconds and as far apart as 1,600 milliseconds, that is, from 20 percent shorter than the normal period to 60 percent longer. In all cases the fireflies promptly returned to their normal one-per-second flashing rhythm as soon as the rhythmic stimulation was stopped. We noticed that even when a firefly was entrained to a rhythm with a period very much longer than the normal one, the intervals between each of its flashes and that of the preceding lamp signal were fairly constant and in addition were not much different from 1,000 milliseconds. This suggested that the driver lamp produces its effect by an entirely automatic resetting of the firefly's flash pacemaker. Such a halting and immediate restarting of the pacemaker at the beginning of its cycle could explain the lengthening of the period observed during entrainment. For example, if the pacemaker were reset 300 milliseconds after it had started, the new normal period of 1,000 milliseconds would be added on to the aborted initial 300 milliseconds, producing the observed interflash period of 1,300 milliseconds. Resetting by the signal from the preceding cycle would also fit the human finger-synchronizing experiment, in which the preceding mass tap seems to be the stimulus.

The experiments with artificially driven fireflies have shown that flash synchronization is controlled by something that can be described as a resettable pacemaker. What kind of mechanism could account for the observations? We have been thinking in terms of a very tentative and diagrammatic model that makes some of the experimental results easier to visualize. Our basic postulate is that some internal property or state of the pacemaker cell or network, which we shall call excitation, changes with time. A normal change in excitation level would therefore be related to the passage of time. Since we know that the normal firefly flashes spontaneously at regular intervals, we imagine that pacemaker excitation normally follows a sawtooth course of successive 1,000-millisecond cycles. Excitation would start from a minimum, or resting, level and increase steadily for 800 milliseconds to a threshold level at which two events would occur. One is a spontaneous triggering of the motor message, which will give rise to a flash in the light organ about 200 milliseconds later. The other is a spontaneous decline in excitation, also lasting about 200 milliseconds, during which the pacemaker momentarily returns to its original state before the new cycle begins. We postulate further that a strong external light signal overrides the normal pacemaker control and resets excitation immediately to the resting level, after which a new cycle begins spontaneously.

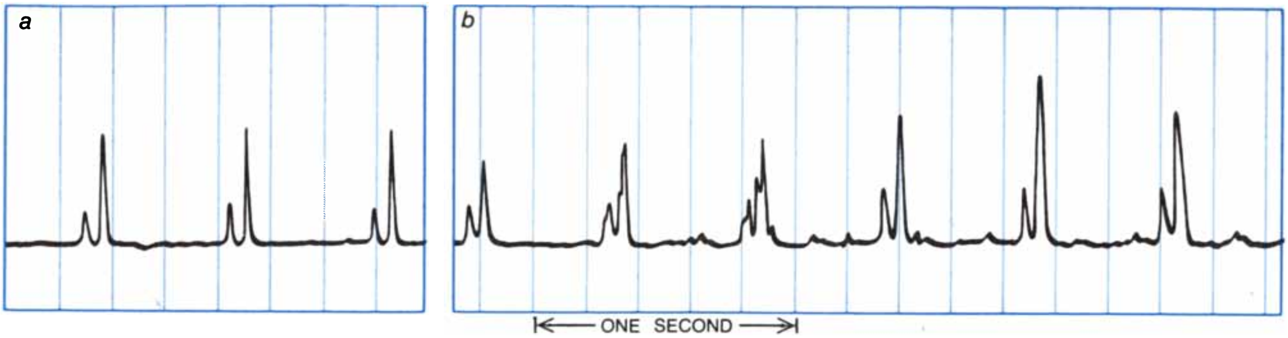
We have already suggested how a resetting signal 300 milliseconds after the flash could lengthen the interflash period to 1,300 milliseconds, and it is clear from the model that repeated signals 1,300 milliseconds apart would force the pacemaker to adopt the same period, cycle by cycle, for as long as the driving continues. The explanation of pacemaker shortening is more complex. When an external signal is applied perhaps 100 milliseconds before a flash is scheduled to occur, that flash occurs anyway and the response flash occurs only 900 milliseconds later. The motor message has already left the brain and is on its way to the light organ by the time the resetting stimulus is received. Thus the firefly can be induced to flash twice within an interval that is shorter than its normal period. One apparently contradictory observation is the failure of fireflies to synchronize with signals that are less than 800 milliseconds apart. The model shows that signals this close together would keep resetting the pacemaker before its state of excitation could rise to the threshold level and trigger a flash.

Lest the reader think that our model, which is only one of many possible models, necessarily mirrors the real pacemaker, it would be well for us to cite the aphorism "A model is an artifice that gives one the illusion of knowing more about a process than one actually does." Nevertheless, it is probably no accident that the hypothetical pacemaker cycle resembles the charge-discharge cycles of electrical capacitors (condensers) such as the ones that serve to time stroboscopes, warning flashers and other rhythmic devices. Work on animals from worms to man demonstrates that neural control systems all depend on the charging and discharging of the capacitative membranes of nerve cells. In fact, electrical driving of a single pacemaker cell from the sea slug *Aplysia* has been shown to yield a resettability diagram rather like the one obtained from the intact firefly.

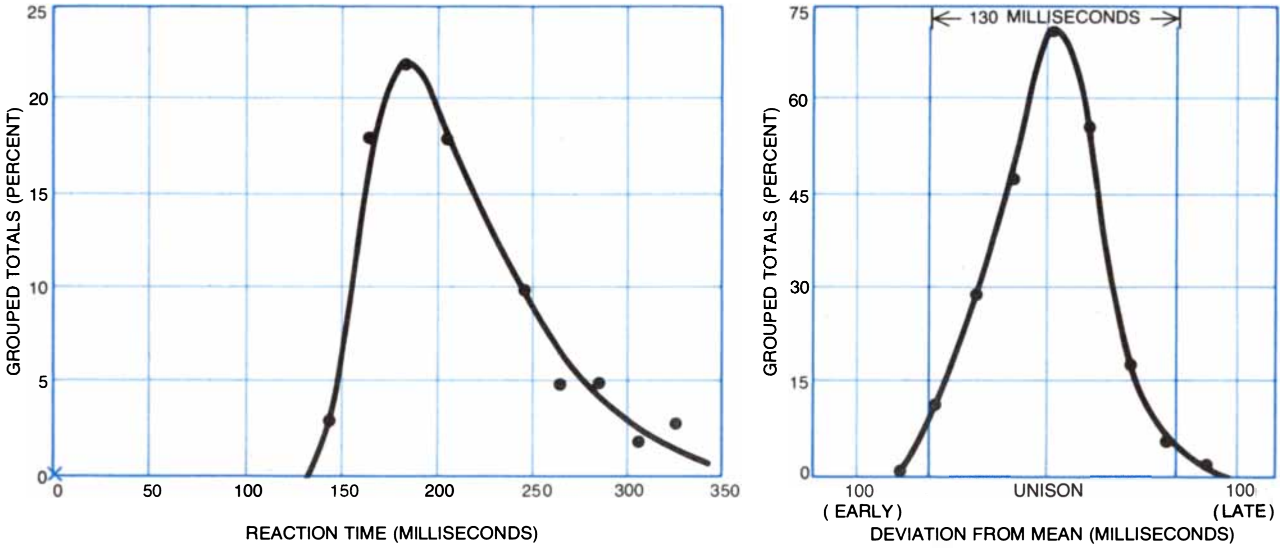
Experimental work on firefly mass syn-



DISTRIBUTION of synchronous fireflies in Asia and the western Pacific is indicated schematically on this map. Colored dots indicate locales where synchronous displays have been observed. The westernmost area, in India, is on the Ganges east of New Delhi; the easternmost is on the island of New Britain, a part of Papua New Guinea. The absence of reports from other points within the perimeter (*color*) tentatively defining the range of *Pteroptyx* species does not necessarily preclude the presence of these or other synchronous firefly species.



SOLO AND CHORUS FLASHING of *Pteroptyx malaccae* males are compared in these graphs; intervals are 200 milliseconds. The single firefly (*a*) emits a two-peaked flash every 500 milliseconds. Fireflies in synchrony (*b*) virtually duplicate the solo performance.



REACTION LAG AND AUTOSYNCHRONY in human subjects may be demonstrated by simple tests. When asked to tap with a coin (*left*) as soon as possible after hearing a guiding tap (*x, color*), few subjects can do so in less than 150 milliseconds. When subjects are instead asked to tap rhythmically in unison (*right*), synchrony soon develops, and most subjects tap within the same 100-millisecond interval. This interval is far too short to let any subject delay tapping until a tap is heard; the time cue instead is the previous chorus of taps.

chronization has scarcely begun, but there is every reason to believe the proposed pacemaker-resetting mechanism applies within large congregations. We have found that whereas the single male entrains to a driving lamp almost immediately, it may take 10 or 15 cycles to shift an out-of-phase but mutually synchronized group of males into synchrony with the lamp. This agrees with the field observation that synchrony builds up relatively slowly at dusk in the display trees, where each male is being stimulated by light from many sources. Increasing the number of fireflies does not, however, degrade either the precision or the grip of synchronization. The flash synchronization among individuals in a large swarm can be impressively close, both between near neighbors and between males in widely different locations in the tree. The force of mass entrainment is also well documented by the way in which males caught in spider webs continue to flash synchronously with their neighbors.

We come now to the second major question about synchronously flashing fireflies: Why do they synchronize? What advantage do males gain by flashing in unison, as Hugh Smith wrote, "hour after hour, night after night, for weeks or even months"? So far there are only very speculative answers to the question. A brief review of the principal hypotheses will, however, provide an occasion to describe the natural history of synchronized firefly swarms and to touch on some possible physiological requirements for synchrony in various kinds of firefly behavior.

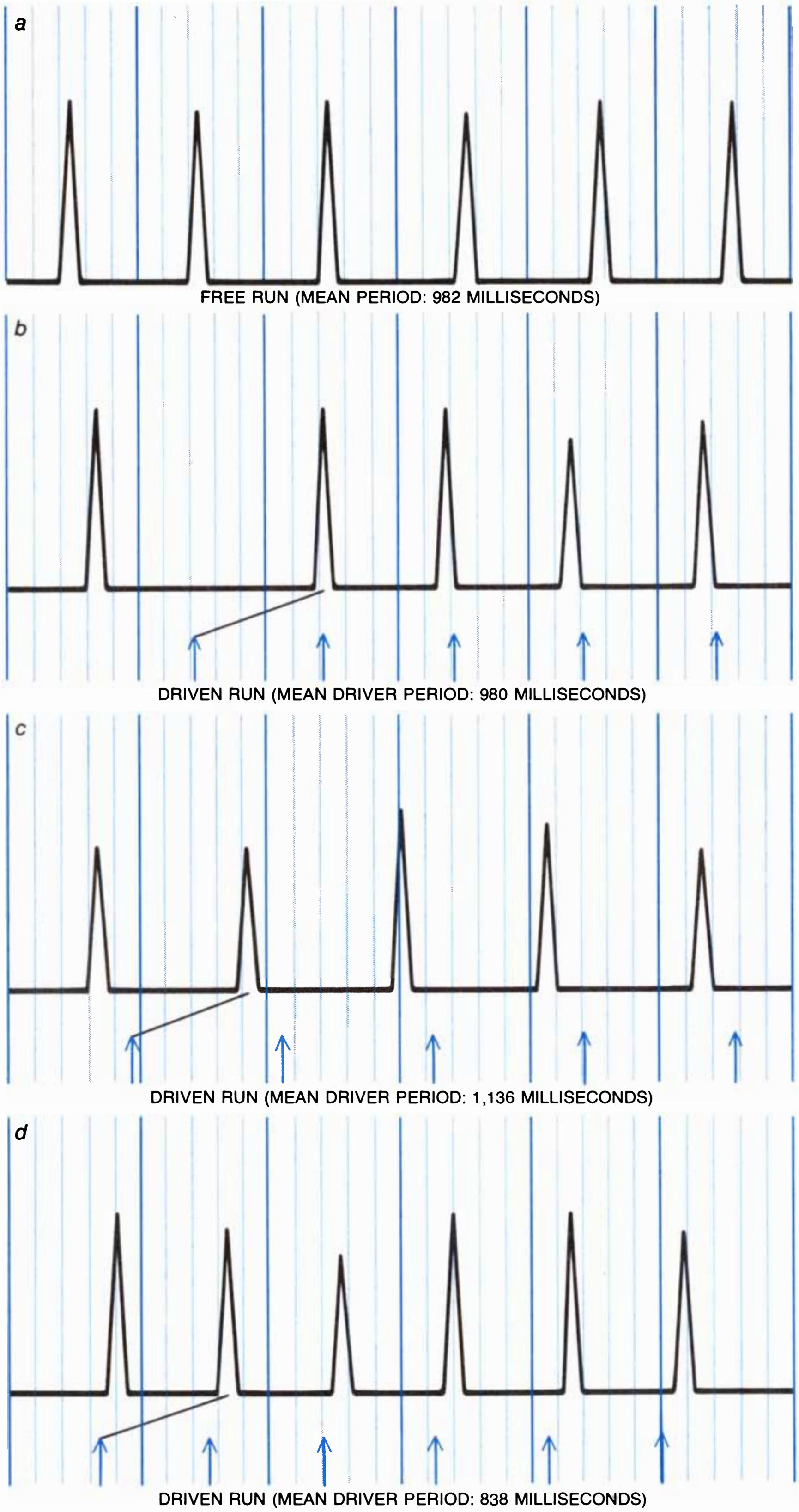
Because we had previously seen mating in nonsynchronized firefly tree swarms in Jamaica and because Haneda had found mating pairs under a synchronized-display tree in New Britain, we were prepared to look for sexual behavior before we encountered our first *Pteroptyx malaccae* swarm in the mangrove swamps of Thailand. It was therefore quite puzzling not to find any recognizable signaling or other interaction between males and females. If one can manage to disregard the overpowering luminous beat of the synchronized males, one can catch a glimpse of other modes of flashing during the intervals of darkness. One of them is a flicker of about 12 pulses per second, emitted by flying males as they occasionally shift their position in the tree. We identified other dim and leisurely luminescences, flashes and glows emitted by perched or flying females. We found copulating pairs among the fireflies that cascaded out of trees when we shook them, but there was no clue to how the individual firefly's reproduction was being aided either by the gathering in trees or by the synchronous flashing of the males.

In thinking back to our experiences with the courtship of roving fireflies, which sometimes requires the uninterrupted exchange of dozens of time-coded flashes alternately between the two sexes to successfully guide the male to the female, it occurred to us that such line-of-sight courting would be difficult or impossible in heavy tropical vegetation. Success in mating depends on the male's and female's being able to see each other almost continuously during the male's stepwise approach; if there is an obstruction, so that two or three successive signals are missed, the courtship is broken off. Accordingly we invented the hypothesis that the Southeast Asian tree displays had evolved as an adaptation to aid mating in jungle areas. Our notion was that the combined light from all the males would make a beacon sufficiently large and bright to attract males and females from all directions and from considerable distances. At this center males could find more females than they could by searching individually through a population dispersed in a tangle of trees, vines and bushes. Because large numbers of fireflies were attracted to the nonsynchronous tree displays we had seen in Jamaica, we concluded that the synchrony observed in Asia was a refinement to enhance the drawing power of the display still further by making the overall flashes brighter and making the light itself intermittent.

We found that both males and females remained in the trees during the day, indicating that each evening's display is begun by these residents rather than by fireflies gathering afresh. Another indication that individual tree displays may be relatively permanent is an old report that indigenous rivermen in Malaya use firefly trees as navigation markers when they are traveling at night. Moreover, Polunin tells us that he studied a particular tree display near Singapore over a period of five years. Because adult fireflies live for only about a month, at least in captivity, we visualize the fireflies in the display trees as communities breeding throughout the year. The number of males in a display tree is probably kept fairly constant by a balance between deaths and recruitment. Since fireflies develop from eggs and larvae living in the soil or in water, the female population in the tree should be a constantly changing one. Its numbers are presumably stabilized by a balance between those entering the tree and those returning to the surrounding environment, after mating, to lay their eggs.

In 1966 our beacon hypothesis, postulating that flash synchronization rewards the entire male firefly population, was in line with current beliefs about altruistic and cooperative behavior among animals. At that time biologists were just beginning to perceive flaws in such beliefs—flaws originating in a disregard of Darwin's concept of evolution by natural selection of the fittest. No matter how beneficial or altruistic an act is, Darwin argued, it will fail to persist as a behavioral characteristic of the species unless the individuals showing the behavior succeed in reproducing. "Survival of the fittest" does not mean the survival of the strongest, the noblest or the most cooperative; it means the survival of those that are best at reproducing. In societies of sexually reproducing organisms there is competition for mates; hence any unselfish behavior that puts the individual at a disadvantage can be expected to disappear because in each new generation there will arise selfish individuals who will take advantage of those who are unselfish.

In 1973 Lloyd published an extended analysis of synchronous flashing in fireflies. In these papers he pointed out that our beacon hypothesis was defective in assuming that indiscriminate mating in the display tree could perpetuate the synchronous



FLEXIBLE RESPONSE of a firefly to artificial stimuli is shown in these four traces. A male of the species *Pteroptyx cribellata,* its natural flashing frequency (*a*) is once per 980 milliseconds. Ordinate intervals are 200 milliseconds. When the insect was stimulated by a light that also flashed every 980 milliseconds (*b*) but first flashed 700 milliseconds into a natural cycle (*first arrow*), it "reset" and thereafter maintained the stimulus rhythm. When the stimuli were slowed to one per 1,140 milliseconds (*c*), the firefly matched the slower rhythm but flashed prematurely. When the stimulus was accelerated to one per 840 milliseconds (*d*), the firefly matched the faster rhythm but lagged behind. The responses suggest how the pacemakers work.

If you need help synthesizing a new product from catechol, send for a free CZ chemist.

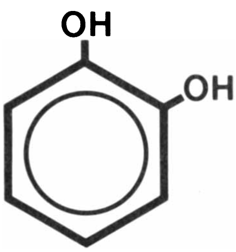
The pure crystals called catechol have a significant chemical future.

Because catechol is an important building block for many useful compounds, especially as a replacement for scarce and expensive natural materials.

What's more, it offers uniform quality and ready availability at a low price.

The versatility of catechol.

While its commercial synthesis is relatively new, we already see catechol used in adhesives, antioxidants and stabilizers, insecticides, photographic developers, medicinals, etchants and sensitized papers.



But beyond these existing uses, catechol is also one of nature's important building blocks.

Its structure is found in many naturally occurring compounds.

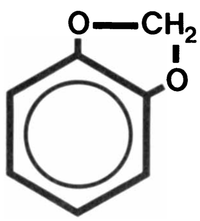
And many of these are useful as starting materials for pharmaceuticals, fragrances or insecticide synergists.

A few examples are dopamines (L-dopa), epinephrine, guaiacol, heliotropin, safrole, norepinephrine, papaverine, vanillin, and piperonyl butoxide.

Consider catechol as the *starting material* for these and similar products.

MDB, another step toward your products.

1,2-Methylenedioxybenzene (MDB) is a newly available derivative of catechol, taking you one giant step toward your synthesis of commercially useful compounds.



MDB is already being used as a starting material for new pharmaceuticals.

Its structure is found in most of the commonly used pesticide synergists.

And important new flavor and fragrance materials are being developed starting with MDB.

TBC—another derivative.

Our latest product is 4-tertiary butyl catechol (TBC), which is used extensively as an antioxidant and monomer stabilizer.

The free chemist?

We have many ways to assist you in developing applications for catechol and its derivatives.

We offer literature — "Reactions of Catechol," "Applications for Catechol," and our product information bulletins on MDB and TBC.

We have laboratory samples available.

We offer the immediacy and convenience of technical conference calls, to help solve your application or synthesis problems.

We would welcome a visit from you at our research center in Camas, Washington.

But, in the cases where on-the-spot help is deemed mutually beneficial, we *will* send a CZ chemist to you.

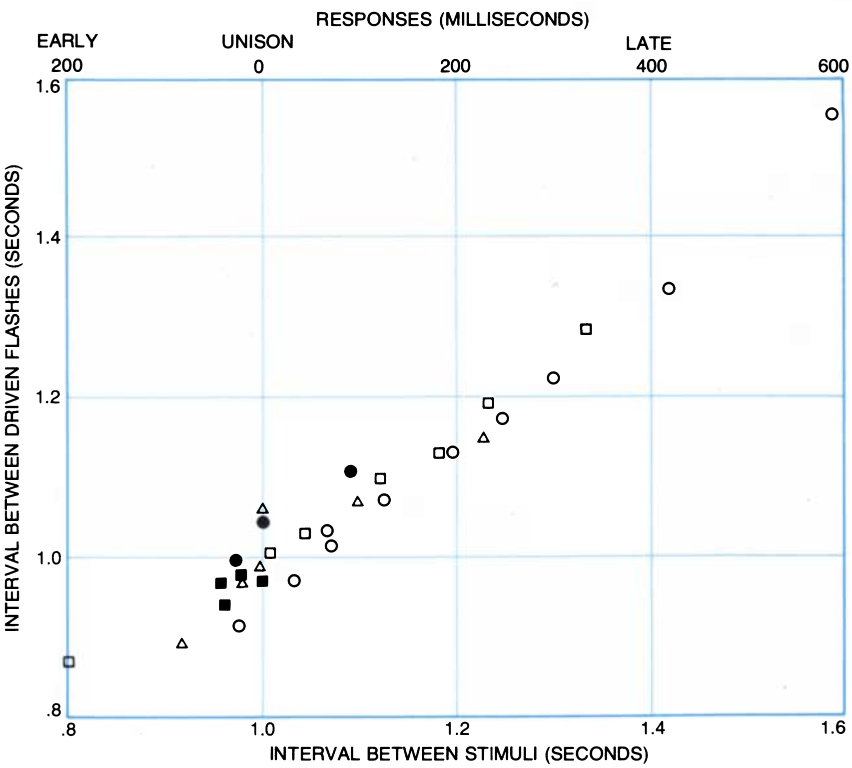
Call us on it.

CrownZellerbach
Chemical Products Division
Camas 107, Washington 98607
(206) 834-4444

flashing behavior. If a male firefly invested time and energy in helping to attract females for the common good, Lloyd argued, mutant "cheater" individuals in the congregation, not genetically burdened by this compulsion, would shortcut the cooperative behavior, get the lion's share of the matings and thus eventually eliminate the synchronizing behavior from the species.

Lloyd, who had studied several synchronizing species in New Guinea, was no more successful than we were in putting together a consistent picture of courting behavior from actual observations. He did, however, devise a detailed model of what ought to be going on in the display trees according to natural-selection theory. The basic requirement of his model is that synchronous flashing must be helping the individual male in his competition for a mate. Lloyd postulated that the males in the tree are in small, synchronized clusters, each associated with a single female. Within the cluster each male is competing with the other males in displaying to the female in an attempt to induce her to choose him as her mate. Lloyd considered local flash synchronization to be very important in accentuating the male flashing rhythm, which in turn is essential in attracting males and females to the tree and in enabling them to recognize and orient toward each other. He also suggested that the individual male may profit by synchronizing flashes with a close neighbor in his cluster because their combined luminescence may attract the female toward their cluster in preference to dimmer ones. In addition he proposed that flash synchronization would make it possible for an "interloping" male to join a courtship in progress between a female and another male and displace the other male. Lloyd regarded the mass synchrony of the entire congregation as being simply the incidental consequence of the presence of the small independent clusters.

Two series of our earlier laboratory observations may now be reexamined in relation to the male fireflies' small-scale distributions and interactions postulated by Lloyd. In the first series of experiments we brought to our hotel in Bangkok bags of fireflies from a riverbank outside the city, sorted out groups of 50 males and liberated them in our bedroom to observe how synchronous flashing develops. At first the insects flew about, flickering rapidly and sometimes darting at each other like moths at a candle. Gradually they settled down on the wall in small groups, but with the individual fireflies spaced no closer to one another than 10 to 15 centimeters, and began to flash independently at their normal frequency (every 560 milliseconds). Then the flashing within each group became mutually synchronous.



FIVE ENTRAINED FIREFLIES of the New Guinea species *Pteroptyx cribellata* flexibly adjusted their flashing rhythms to approximate the faster than normal and slower than normal rhythms of an artificial light source. As was found in earlier tests, the fireflies' rhythm remained in phase with the rhythm of the stimulus when this approximated the insects' natural frequency of about one flash per second (*zero on top scale*). When the driving stimulus was faster, however, the fireflies' response fell out of phase with the stimulus, lagging behind it. When the stimulus was slower, the response came early. In both instances the phase difference was equal to the difference between the stimulus interval and the fireflies' natural frequency of flashing.

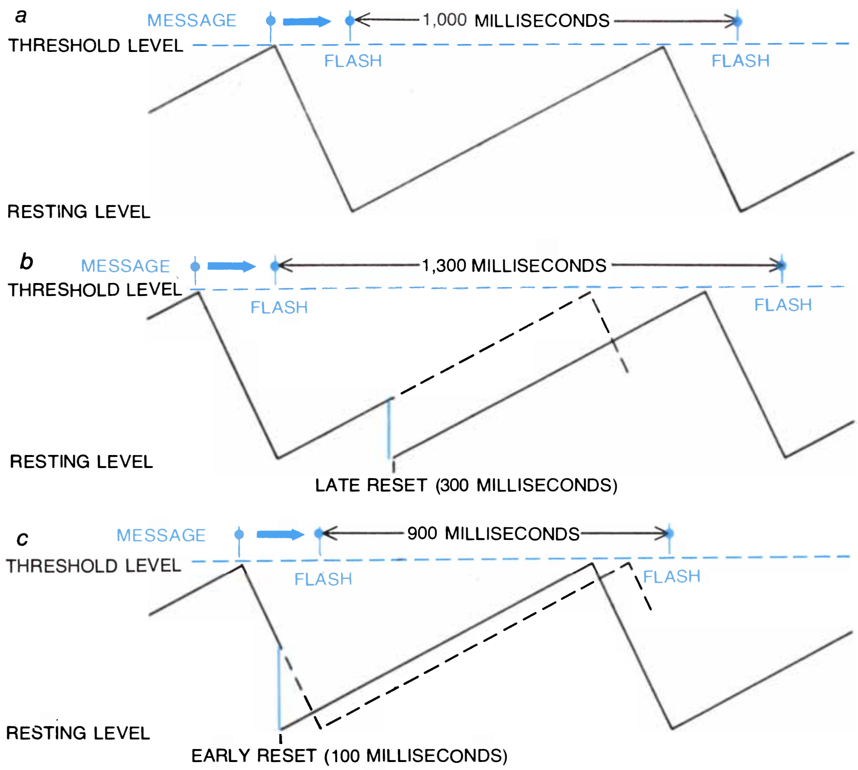
A noteworthy finding in these experiments was the definite limitation in proximity among the males after they had recovered from being disturbed and had begun their rhythmic display luminescence. This agrees well with the field observation that males in the mass-display congregations are not crowded together several to a leaf but are established on separate leaves. Laboratory studies of roving species have shown that a light input to the male's eye that is too intense inhibits the insect's flashing. It therefore seems possible that the males space themselves far enough apart to avoid mutual flash inhibition. In field tests in New Guinea with a string of small, rhythmically flashed lamps, each much brighter than an individual firefly, Hanson and we observed that male fireflies were first drawn to the lamps from a distance but then, when they came close to the lamps, veered off.

The second series of observations was made in collaboration with Bassot with fireflies brought from Thailand by courier. By confining pairs of males in a chamber that was too shallow to allow flight we were able to observe interactions and record individual phase-shifting as the two walking fireflies synchronized with each other. Some pairs flashed synchronously for hundreds of consecutive cycles. When the two males approached to within a centimeter or so of each other, there would be a sudden scuffle accompanied by much flickering, and one male would drive the other away.

We conclude from the two series of observations that flickering, which is the usual luminescence of the *Pteroptyx malaccae* male as it is approaching the display tree and as it is flying about within the tree, can also be a response to disturbance and, when the males are very close to each other, a sign of aggression. Similar complexities exist in the spatial relations among males. When a male is outside a tree display, it is strongly attracted to the synchronously flashing perched males in the congregation. When the male is a member of that group, it maintains a minimal distance from its neighbors. If it gets closer to one of its neighbors, one of the two is actively repelled. The behavior in these laboratory experiments was not inconsistent with Lloyd's predictions that the basic behavior in synchronized firefly swarms is local courting and that the males display synchronously in small groups (although our groups formed in the absence of females). With a denser population we would expect the males not to be clumped but to be distributed uniformly through the display area, as is in fact observed in the natural swarms.

The apparent aggressive territoriality involving pairs of males strengthens the resemblance of the overall behavior in the tree congregations to the behavior in the courting assemblies called leks, which are formed by the males of many different bird and mammal species. In a lek each male occupies a small personal territory that he defends against encroachment by other males. In it he engages in some special visual or vocal display in order to attract one of the females that are passing by, which are apparently comparing the individual displays before choosing one of the males.

Because of a new thought we have revised our view of the significance of synchronous flashing. We follow Lloyd in accepting the principle that behavior that is perpetuated genetically must ultimately promote the reproduction of the individual that engages in the behavior, but we believe true mutual synchrony is a kind of behavior that cannot serve as a direct competitive instrument. The reason, in retrospect, is rather obvious: it takes at least two to synchronize. Synchronous flashing is by definition cooperative or group behavior. The physiological work on the resettable flash pacemaker amplifies this point. Because the entrainment mechanism in firefly *A* is automatically reset by the flashes of firefly *B*, firefly *C* and so on, firefly *A* cannot control the time of its own flashing when it is synchronized with other fireflies. Neither can any firefly control the flashing of other fireflies that are synchronized with it. A male that was consistently out of phase with its cluster-mates could of course be excluded by the female, but the female seemingly has no way of choosing between males that are flashing in phase. This point is supported experimentally by long serial recordings from synchronized pairs that we made with Bassot. These separate, concurrent records from two males show that the entrainment is evenly reciprocal with regard to phase, with first one of the fireflies and then the other assuming the lead for one cycle or a few cycles.



AUTHORS' MODEL of resettable pacemaker is schematized in three graphs. First (*a*) is a normal one-second pacemaker cycle between flashes (*black*): the pacemaker charges for 800 milliseconds to reach threshold level. Two things now happen. Message (*colored arrow*) travels to light organ, causing a flash 200 milliseconds later. At the same time the pacemaker discharges, reaching resting level in the same interval. Next (*b*) is a late reset (*colored line*), 300 milliseconds after start of cycle; the next flash is delayed accordingly. Last (*c*) is an early reset. It cannot affect the first flash but reduces the time until the next flash to 900 milliseconds.

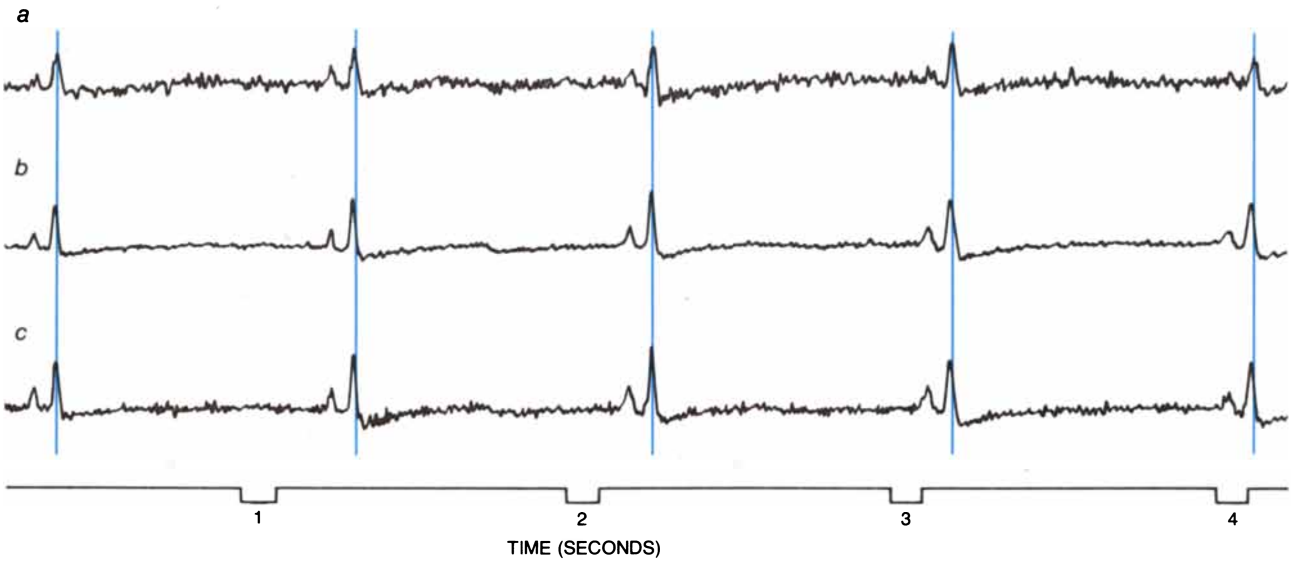
The indication that synchronous flashing cannot play a competitive role in the courtship of synchronizing firefly species raises new questions. What behavior plays a role in male competition if the synchronization of flashes does not, and what is synchrony doing if it is not playing a part in competition? There is also the paradox that synchronous flashing is clearly genetically perpetuated behavior and just as clearly group behavior, apparently unsuited for the promotion of the reproductive fitness of the individual male. We shall ignore the paradox for the moment and address ourselves to the problem of how the males are competing. This means that we must first identify a kind of behavior, presumably a kind connected with light emission, that can be used by the individual male in displaying. Then we have to show why that behavior needs to be synchronized in order to be effective.

Several observations suggest that the control of flash intensity may be the behavior that plays a role in competition. For example, males flying in from a distance to join a tree display brighten their flashes as they shift into synchrony with the tree swarm. Similarly, groups of initially asynchronous captive males brighten their individual flashes as synchrony develops. A dramatic demonstration was seen by Case and his colleagues when they set up a string of electric lights, flashed in the proper species rhythm, next to *Pteroptyx malaccae* display trees near Singapore. In these tests clouds of male fireflies flew out of the trees toward the lure, as if they were being drawn by a giant vacuum cleaner, brightening their flashes concurrently. Flash intensity seems well suited for competition because the individual male can modulate the light emitted by its light organ. Polunin, Case and Hanson have noted another apparent means of enhancing the effective flash intensity: a twisting of the male's abdomen to aim the light organ in a particular direction. Although this behavior has so far been observed only in males on the outside of the tree, with their abdomens aimed outward, we are suggesting that it might also be employed in displaying to females in the tree.

We can thus cite evidence that the control of light intensity might be used competitively by the males, but we have not shown why a male would have to be synchronized with others in order to have his flashing affect the female. Our speculative suggestion is that the female's need for a synchronized input is connected with the decrease in sensitivity that is often seen in response mechanisms immediately after stimulation. For example, in one American species of firefly we have found that the female cannot be restimulated for several hundred milliseconds after she has received a signal from a male. If the *Pteroptyx* female similarly becomes physiologically refractory after seeing one flash, two or more flashes would have to be perceived almost simultaneously for her to be able to compare their intensities. Incidentally, if the female were "programmed" in this way, it would provide physiological support for Lloyd's surmise that females may "not select males unless they are flashing in phase with neighbors."

The role tentatively proposed for the synchronization of the males' flashes, namely to make it possible for the female to select a mate from among competing males on the basis of the effective intensity of its flashing, has some curious implications. What flash synchronization gives the male is not a reproductive advantage over its cluster-mates because of its more intense flashing but simply an opportunity to compete for such an advantage. In a similar way synchronization aids Lloyd's "interloping" male not in physically displacing a competitor in courtship but only in gaining an opportunity to displace it. Nevertheless, the use of the male's primary competitive instrument, whether it is controlled flash intensity or something else, is essential to reproduction. Hence if the male cannot use that instrument without flashing synchronously with its competitors, synchronization is likewise essential for reproduction.

We therefore return to the paradox of

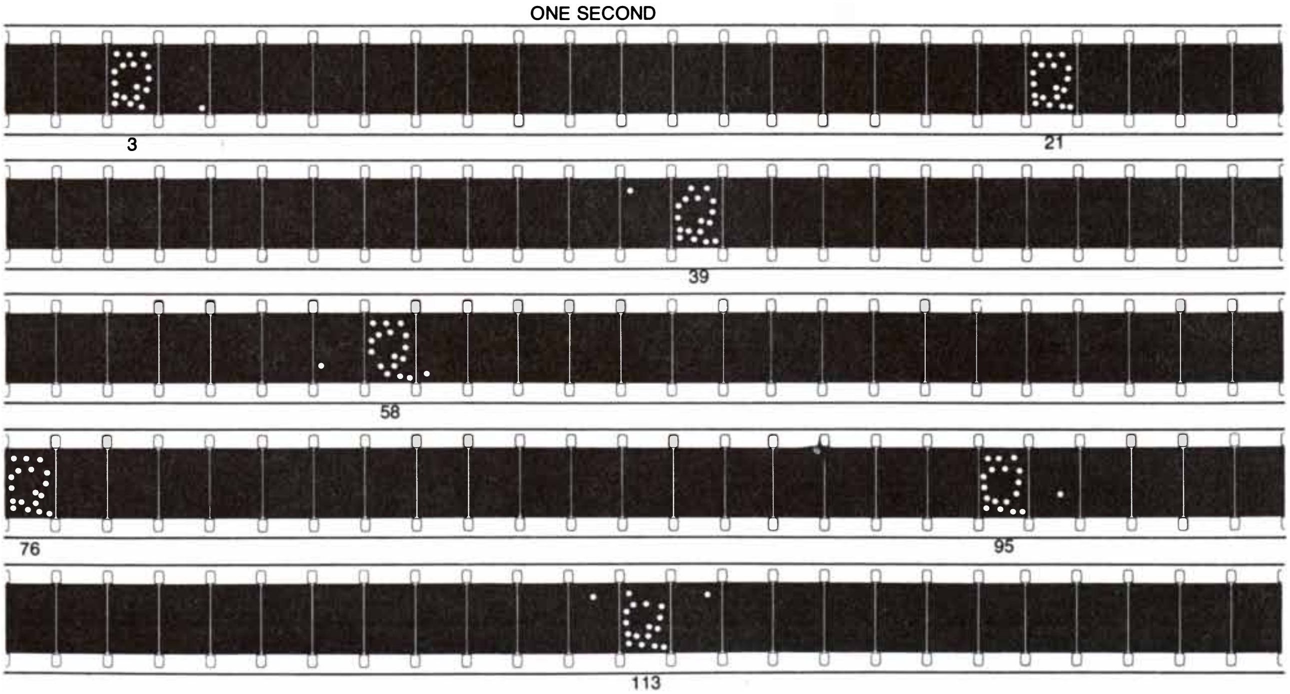


SYNCHRONOUS FLASHING by three males in a firefly tree is recorded on three photomultiplier traces. The fireflies were spaced in a straight line separated by intervals of about four meters. The maximum deviation from synchrony within any of the five groups (*color*) of three flashes was 20 milliseconds. James F. Case of the University of California at Santa Barbara made the recording in Malaya.

one's apparently being forced to attribute an essential reproductive role to a group behavior. How might this be reconciled with natural-selection theory? One possible solution would be offered if firefly synchrony belonged to one of the two special categories of apparently group-selective behavior that are compatible with natural-selection theory. One of these categories, "kin selection," may apply when members of the group are closely related. Then an act that handicaps the altruist can still persist if the altruist's close relatives benefit. For example, the mother quail can "afford," in the evolutionary sense, to sacrifice herself by decoying a fox away from her chicks because the action will preserve more sets of her genes than will be lost when the fox catches her. It seems extremely unlikely, however, that the thousands of males engaged in any firefly display are more than remotely related.

In the other acceptable kind of group behavior, "reciprocal altruism," the cost to the donor of some service must always be less than the anticipated repayment by the recipient of the service (that is, the behavior is not really altruistic). Clearly synchronous flashing does not fall in this category. Each male in a synchronizing group is maintaining its own eligibility to compete and is simultaneously and inadvertently helping to promote the eligibility of its neighbors. Statistically the total reproductive benefit dispensed by any one male is exactly balanced by the total reproductive benefit it gains.

We now return to the paradox for the third time. We are dealing with genetic



NEW GUINEA DISPLAY, reproduced here in a drawing, was originally recorded on motion-picture film exposed at a rate of about 18 frames per second. Some frames show slightly early or late firefly flashes; the synchronous pulses come at about one-second intervals.

perpetuation of behavior that is intimately concerned with courtship and that depends on a complex, highly organized neural oscillator specialized for automatic mutual stimulation. Surely this is not a trivial mechanism to have become established in the course of the synchronous fireflies' evolution. We observe that the behavior appears to occupy nearly all the time of every male during its entire adult life. Yet the behavior is unequivocally cooperative and so apparently cannot qualify for natural selection. The paradox exists quite independently of our explanation of why synchronous flashing is necessary. If, however, we are correct in our conjecture that the response of the female is inhibited during a substantial portion of the male's interflash period, a very important consequence would follow: the courtship would have built-in protection against mutant "cheaters." If the courting female were able to perceive only those flashes that arrive almost simultaneously, she could not react to signals that are out of phase.

We therefore propose as a working hypothesis that the courtship is protected against cheating. Then, assuming that enough of our other guesses are correct, synchronous flashing can be considered a reproductive adaptation with the following features:

First, every participating male has a reproductive advantage over males that are not in the congregation. Second, no cooperatively flashing male is at a disadvantage in relation to any other male in the synchronized group. Third, no "cheater" male can gain a competitive advantage by failing to flash synchronously. Fourth, if more than one male is competing for a female's attention, the behavior actually used in competitive display (for example modulation of light intensity) is acceptable to the female only if the males display synchronously. Finally, the same behavior (flashing) is thus modulated both in intensity (for competition) and in timing (for eligibility to compete).

We should like to end on a note of caution. Although the pacemaker studies with *Pteroptyx cribellata* and the field studies with *P. malaccae* have been confirmed with respect to several other species, it appears that there are quantitative and qualitative differences in synchronous flashing among the several genera and many species of fireflies in different parts of Southeast Asia. Some of these differences may be incompatible with the interpretations proposed here. For the future there remains not only the task of testing evolutionary hypotheses but also the prospect of further unraveling the physiological mechanisms by which fireflies are able to control their flashing. In addition there are many blank areas on the distribution map of synchronous flashing that appeal for investigation. We may even hope for more news about the rare wavelike synchronization among field-living fireflies that has been reported from time to time in various parts of the U.S.

The Mass of the Photon

The particle of electromagnetic radiation is often assumed to be massless, but the laws of physics do not require that assumption. If the photon has a mass, however, it must be exceedingly small

by Alfred Scharff Goldhaber and Michael Martin Nieto

The photon, the quantum of light and of other electromagnetic radiation, is generally assumed to be a massless particle. The photon can carry energy and momentum from place to place, and it is deflected by the gravitational effects of large masses, but in the usual formulations of modern physics it is assigned a "rest mass" of zero. The meaning of that assignment is simply that a photon cannot be brought to rest; light cannot stand still. If the rest mass were greater than zero, on the other hand, it would be possible (at least in principle) to "catch" a photon and to measure its mass.

On what basis is it assumed that the rest mass of the photon is exactly zero? One argument is that the theory of electromagnetism, as it is most commonly written, prescribes zero mass for the quantum of light. An equally consistent theory can be constructed, however, for a photon of any arbitrary mass. The possibility that the photon has a large mass (for example, one as large as that of the proton) can readily be excluded; if it did, the world would be a profoundly different place. Perhaps, though, it has a very small mass, much smaller than that of the proton, or even than that of the electron, but still greater than zero. In that case the universe would differ only subtly from one containing massless photons, and only by detecting those subtle differences could we discover the photon rest mass.

In this article we shall discuss several experiments whose results are equivalent to the catching and weighing of a photon. We can state at the outset that none of the experiments has proved the rest mass to be zero, and indeed such a proof may be impossible. An experiment that fails to find a photon mass does not prove the mass is zero; it merely shows that the mass is less than the limit of accuracy of the experiment. These limits have approached ever closer to zero, and the most recent values are exceedingly small; nevertheless, there can be no assurance that the next experiment will not reveal evidence of a definite, nonzero mass.

1. $\vec{\nabla} \cdot \vec{E} = 4\pi\rho - \left(\frac{Mc}{\hbar}\right)^2 V$

2. $\vec{\nabla} \cdot \vec{B} = 0$

3. $\vec{\nabla} \times \vec{E} = -\left(\frac{1}{c}\right)\frac{\partial \vec{B}}{\partial t}$

4. $\vec{\nabla} \times \vec{B} = \left(\frac{1}{c}\right)\frac{\partial \vec{E}}{\partial t} + \left(\frac{4\pi}{c}\right)\vec{j} - \left(\frac{Mc}{\hbar}\right)^2 \vec{A}$

$\vec{E}$ = VECTOR OF THE ELECTRIC FIELD
$\vec{B}$ = VECTOR OF THE MAGNETIC FIELD
ρ = CHARGE DENSITY
$\vec{j}$ = CURRENT DENSITY
$\vec{\nabla}$ = SPACE DERIVATIVE (RATE OF CHANGE WITH POSITION IN SPACE)
$\frac{\partial}{\partial t}$ = TIME DERIVATIVE (RATE OF CHANGE WITH TIME)
M = MASS OF THE PHOTON
c = FUNDAMENTAL CONSTANT (SPEED OF LIGHT IF M = 0)
$\hbar$ = PLANCK'S CONSTANT DIVIDED BY 2π
V = ELECTRIC POTENTIAL
$\vec{A}$ = MAGNETIC VECTOR POTENTIAL

MAXWELL'S EQUATIONS define the behavior of static electric and magnetic fields and predict the existence of electromagnetic waves. The original equations, as they were formulated by James Clerk Maxwell, are valid only if the photon is a massless particle. If the photon has mass, two additional terms (*colored boxes*) are required, and the equations become Proca's equations. The meaning of the equations is interpreted graphically in the illustrations on the opposite page.

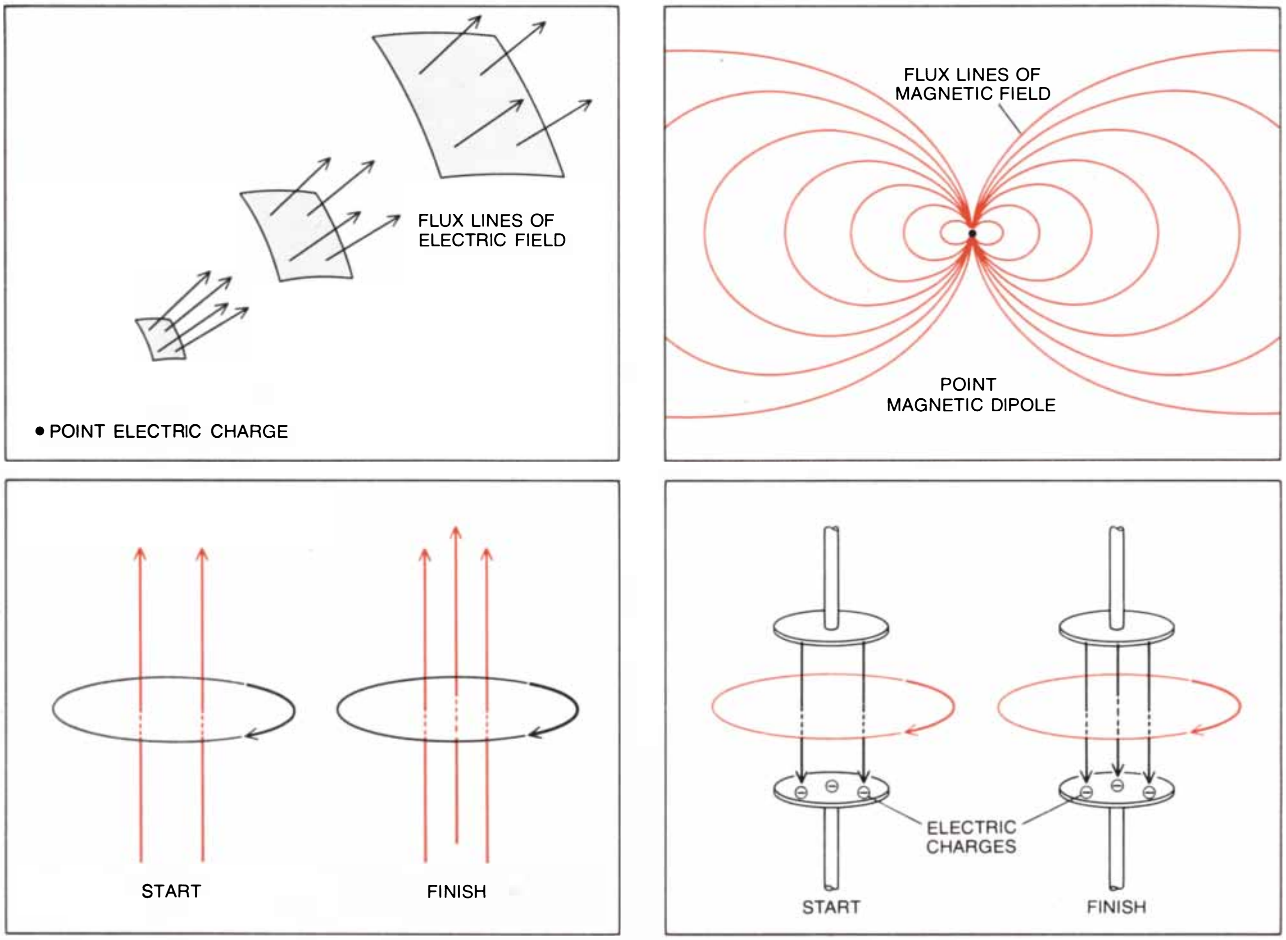
The endeavor to measure the rest mass of the photon began two centuries ago, when the concept of rest mass was unknown, in experiments that had nothing to do with photons. The first investigators, in the 18th century and the early 19th century, were concerned with the behavior of static and slowly changing electric and magnetic fields, and they formulated the first laws of electricity and magnetism. These laws describe the interactions of an electric charge or current with other charges and currents or with a magnetic field. Perhaps the most important law for our purposes is the principle that has come to be known as Coulomb's law; it states that the force between two electric charges is inversely proportional to the square of the distance between them and is directed along the line connecting them.

In 1861 James Clerk Maxwell completed a set of four differential equations that constituted a synthesis of a century of experimental and theoretical study of electromagnetism. The equations describe the electric and magnetic fields as vectors (quantities that have both a magnitude and a direction), which are in turn determined by the charge density, the current density and the rate at which these quantities change in space and time.

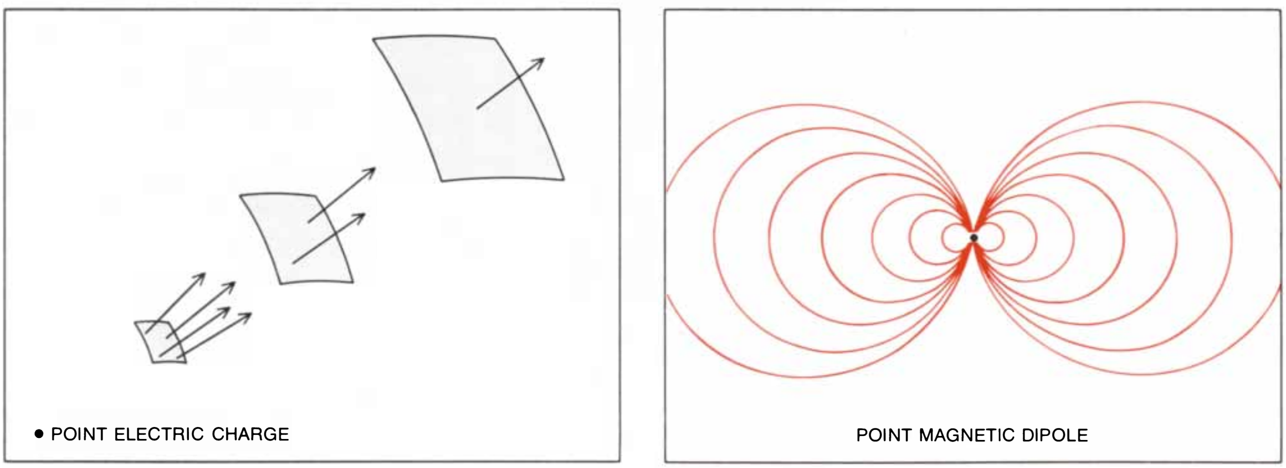
When Maxwell derived his equations, he realized that they allowed the existence, even in empty space, of waves composed of oscillating electric and magnetic fields. These electromagnetic waves have a fixed speed, defined by the Maxwell equations as a property of the vacuum. The speed is quite close to the directly measured value of the speed of light, a fact that inspired Maxwell's correct guess that light is an electromagnetic wave. (Today, of course, we know that visible light represents only a small portion of the complete spectrum of electromagnetic radiation.) Maxwell's theory thus provides an essential link between light and the phenomena of static electricity and magnetism. Any deviation from the theory must appear in a consistent way in both of these very different domains of physics.

It was Maxwell's theory, applied to the interpretation of new experimental results, that led to the greatest developments of physics in the 20th century: the theories of relativity and of quantum mechanics. Electromagnetism has since been interwoven with those theories to create the modern theory called quantum electrodynamics. If accuracy in predicting experimental results is to be a basis for judgment, quantum electrodynamics is an extraordinarily successful theory: it has predicted some experimentally measured quantities with a precision of one part in 10^8.

Quantum mechanics imposes on electromagnetism the requirement that light and other electromagnetic radiation be carried



FIELDS associated with a massless photon are described by Maxwell's equations. The first equation (*1*), which embodies Coulomb's law, states that the number of flux lines representing the electric field surrounding an isolated charged body is constant at all distances; as a result the number of lines per unit area, and hence the strength of the field, declines as the square of the distance. The second equation (*2*) states that the flux lines of a magnetic field always form closed loops; as a result there are no isolated magnetic charges. Maxwell's third equation (*3*), which incorporates the law of magnetic induction, states that for any period of observation the average electric field along a closed curve is proportional to the increase in the magnetic flux passing through the curve during that period. The fourth equation (*4*), which includes Ampère's law, states that the average magnetic field in a closed curve is proportional to the sum of two terms: the first term is determined by the increase in the electric flux and the second by the total electric charge passing through the curve, again during the period of observation. Here a voltage is applied to the plates of a capacitor; the magnetic field can be considered to arise from either the changing electric field between the plates (represented by the first term) or from the current in the wire (the second term).



MODIFIED FIELDS are predicted by Proca's equations if the photon has a mass greater than zero. The electric field (*left*) no longer diminishes as the square of the distance but falls off exponentially. Flux lines can now fade away even in empty space, and at great distances the field effectively vanishes. The magnetic field (*right*) declines exponentially with distance and also changes shape, being compressed at the magnetic equator. These modifications imply a characteristic length scale for electromagnetism determined by the photon mass.

in discrete units, represented by photons. The energy, E, of a photon is defined by the equation $E = h\nu$, where h is the quantum constant introduced by Max Planck and ν (the Greek letter nu) is the frequency of the radiation. Thus the wave description of light is complemented by a particle description. (At the same time quantum mechanics introduces a wave description of the massive particles of ordinary matter. It was only for practical reasons that the wave aspect of light was discovered first, whereas the particle description of all other substances was formulated before their wavelike properties were suspected.)

The photon hypothesis was suggested in 1905 by Einstein in order to explain the photoelectric effect. In the same year Einstein published the special theory of relativity, and that too was intimately related to electromagnetism. Einstein approached the theory of relativity from the postulate, implied by Maxwell's equations, that light always travels with the speed c, commonly called the velocity of light. Einstein found a relation between the velocity, v, of a particle, its rest mass, M, and its energy, E: $v^2 = c^2(1 - (Mc^2/E)^2)$. Inspection of this equation reveals that for an object with a finite rest mass the velocity depends entirely on the energy, since all the other quantities are constant. Moreover, it gives the unsurprising result that the velocity can be increased only by increasing the energy. The equation also implies, however, that for a massive particle the velocity of light is unattainable; if the particle is to attain the speed c, then the expression Mc^2/E must become zero (so that the overall equation becomes $v^2 = c^2(1 - (0)^2)$. Since that would require infinite energy, it is concluded that a particle with a finite rest mass can never attain the speed c.

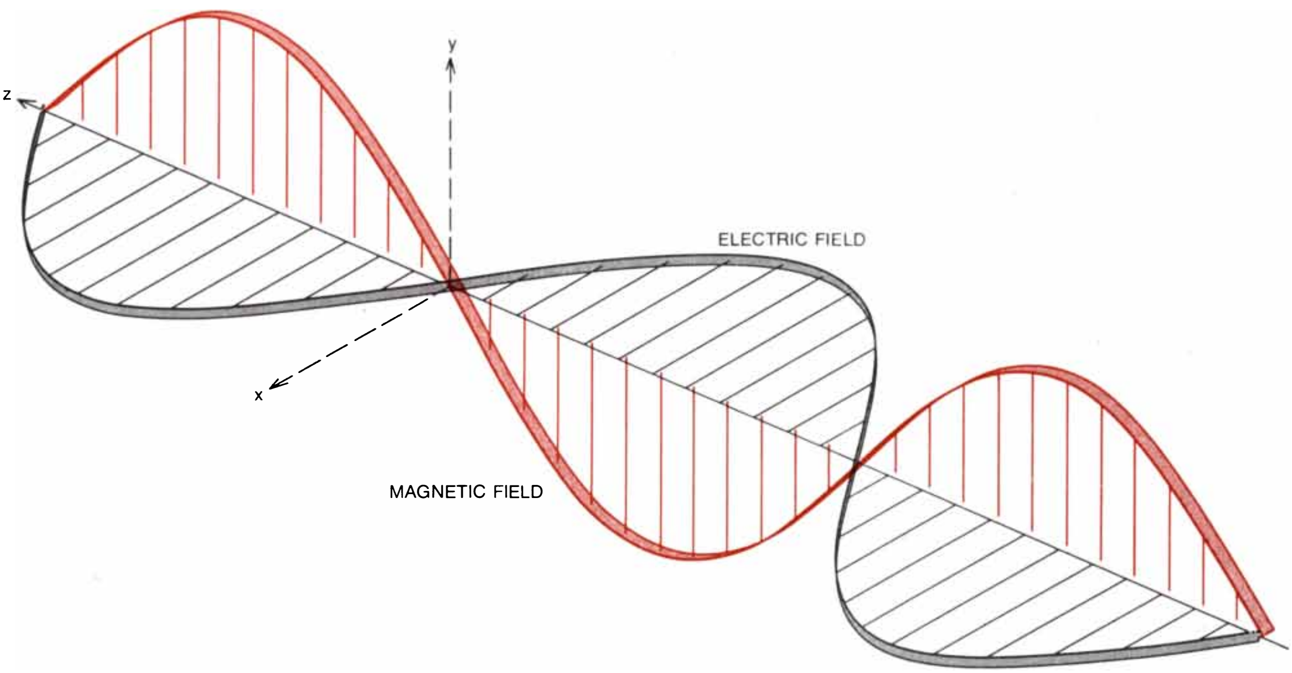
For a massless particle, however, the equation makes a quite different prediction. If M is zero, then Mc^2/E is always zero too, regardless of the energy. Hence the particle always travels with the speed c; it can neither slow down nor speed up, no matter what its energy. (It can, however, change its direction of motion.)

Einstein assumed that photons are such massless particles, but the theory of relativity does not require that assumption. It is sufficient that c be retained as a constant, the speed approached by any particle of finite mass as its energy increases without limit; c need not be the speed of light. If the photon has mass, then its velocity is dependent on its energy and is always less than c.

The possibility that the photon has a rest mass greater than zero was expressed in mathematical terms in the 1930's by Alexandre Proca. The Proca equations are identical with the Maxwell equations, except that an extra term has been appended to two of them. The new terms are proportional to the square of the photon mass, and they alter a number of important properties of both static electric and magnetic fields and electromagnetic radiation.

One direct effect of the massive photon is that electromagnetic waves of different frequencies propagate with different speeds. The effect can be understood as a consequence of the equations from quantum mechanics and the special theory of relativity cited above. One of those equations states that the velocity of a massive particle depends on its energy; the other states that the energy of a photon is proportional to the frequency of the corresponding electromagnetic wave. If the photon has mass, it follows that the velocity of a light wave is determined by its frequency: high-frequency electromagnetic waves move faster than low-frequency ones. Indeed, as the frequency is reduced a limit is eventually reached for any given photon mass at which the velocity falls to zero; in other words, the light stands still. This limit is attained when the wave has the frequency Mc^2/h; it is then no longer an oscillation in space but has the same amplitude everywhere. Its wavelength is infinite.

The possibility of observing light at a standstill would seem to offer an obvious and dramatic method of measuring the photon mass. In order to verify that the wave is stationary, however, we must observe it in a region whose dimensions are large compared with the wavelength the radiation would have if it moved with the speed c. That wavelength is equal to c divided by the

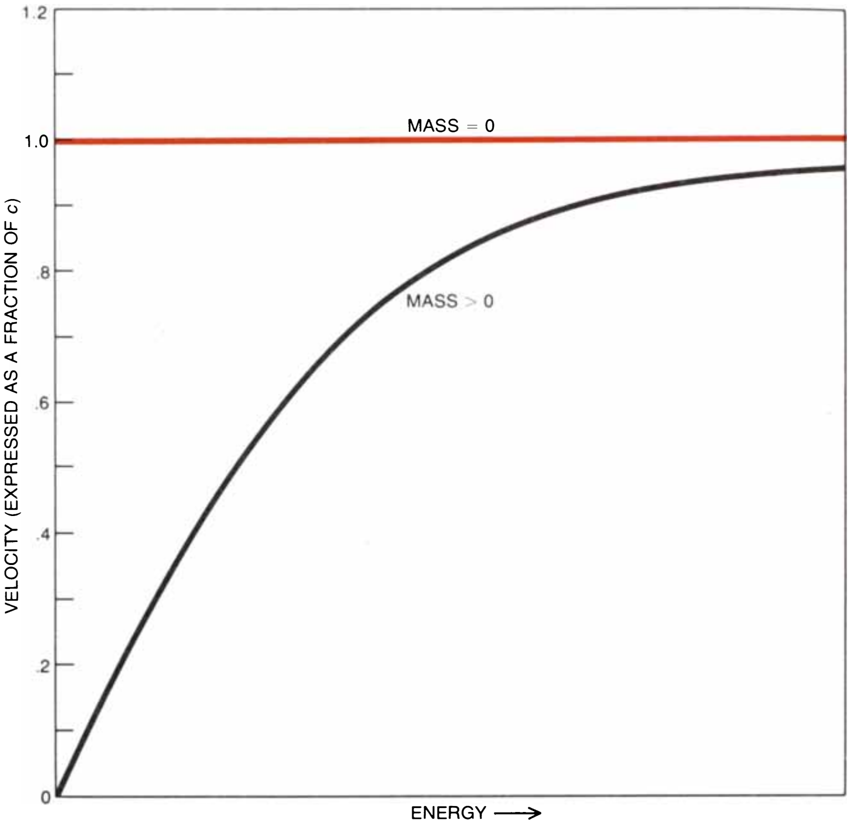


ELECTROMAGNETIC WAVES predicted by both the Maxwell and the Proca equations consist of oscillating electric and magnetic fields. The waves are described by the third and fourth equations, which state that a moving magnetic field generates an electric field and vice versa. The wave is moving along the *z* axis in the direction of increasing *z*. The strength of the fields is given by the length of the lines; their spacing has no significance. Electromagnetic radiation can also, of course, be represented as a stream of discrete particles: photons. If the mass of the photon is zero, the waves propagate with the speed *c*, often called the "speed of light." If the photon mass is greater than zero, the waves always move with some speed less than *c*, determined by their frequency. At some frequency the velocity must fall to zero and light must stand still; with the present limits on the photon mass, however, that frequency is too low to be detected by known techniques.

frequency of the radiation, or h/Mc. Present experimental limits on the photon mass give a "rest frequency" of less than about one oscillation every 10 seconds. A numerical calculation shows that the corresponding wavelength is more than 400 times the radius of the earth. Unfortunately it would be difficult to search for such slow oscillations over such large distances.

On the other hand, one can search for a small difference between the speeds of two waves of different frequencies. The measurement can be made most conveniently when the waves are emitted at the same instant and when they travel over a very long path, so that the difference between their times of arrival is large enough to be measurable. An almost ideal source of such waves is a pulsar, an astronomical object (thought to be a compact, rotating star) that emits sharply timed pulses of light and radio waves.

The arrival time of the radio waves from pulsars can be measured with great precision, and it has been found that low-frequency waves are delayed significantly with respect to high-frequency waves. The magnitude of the delay could be interpreted as implying that the photon has a finite rest mass, and indeed a rather large one: about 50,000 times greater than the limit given by other methods of measurement. The delay, however, is probably not caused by the photon rest mass. Interstellar space is not a perfect vacuum but contains diffuse matter, including free electrons, that acts to slow down electromagnetic waves of lower frequency. The smaller limit on the photon mass obtained by other techniques is consistent with the conclusion that the interstellar medium and not the photon mass accounts for the delay of the lower-frequency components of pulsar signals.



VELOCITY AND ENERGY are related by the special theory of relativity. For particles that have a rest mass greater than zero, velocity increases with energy, approaching *c* asymptotically; a massive particle could attain the speed *c* only if its energy were infinite. Massless particles, on the other hand, must always travel with a speed of exactly *c*, regardless of their energy. If the photon mass is zero, *c* is in fact the speed of light. If the photon is massive, the speed of an electromagnetic wave is determined by its energy, and quantum mechanics shows that energy in turn is proportional to frequency. Thus in a universe with massive photons visible light moves faster than radio waves, and X rays move faster still. Again, however, with present experimental limits on the mass of the photon the differences in velocity are too small to be detected.

A nonzero rest mass would also have an effect on the polarization of photons. The Maxwell equations imply that a photon can be polarized in either of two directions, both of them perpendicular to the photon's direction of motion. The Proca equations, on the other hand, allow three states of polarization; in the third one the vector of the electric field points along the line of motion and the particle is called a "longitudinal photon."

Polarization is readily detected, so that searching for longitudinal photons would seem to be another promising method of determining the photon rest mass. The Proca equations require, however, that the faster a longitudinal photon moves, the weaker its electric field becomes. As the velocity reaches *c* the electric field vanishes entirely. In this way the Maxwell and Proca equations are reconciled: in the Maxwell theory there are no longitudinal photons; in the Proca theory longitudinal photons of zero rest mass carry no electric or magnetic field and are therefore unobservable. Because of the attenuation of the electric field a longitudinal photon of plausible mass would interact only very weakly with matter; for example, the sun would be almost perfectly transparent to a longitudinal radio wave. It therefore seems unlikely that we could construct a detector sensitive to such waves.

What effects of a nonzero photon mass are actually observable, and how are the best limits on that mass obtained? It turns out that moving electromagnetic waves are less suitable for experimentation than the static fields with which the investigation began 200 years ago. The only practical way to test for the existence of a photon mass is to search for deviations from Coulomb's law and its magnetic analogue, Ampère's law. These laws, which were the first principles of electromagnetism to be stated formally, are embodied in the first and the fourth Maxwell equations, which are the same equations modified by Proca to reflect the effects of massive photons.

Coulomb's law was discovered by at least three investigators before Charles Augustin de Coulomb, and the reason Coulomb's name is now indelibly linked to it is an interesting story in the history of physics. The investigation that led to the statement of the law began in 1755 with Benjamin Franklin's observation that a cork ball placed inside an electrically charged metal cup is not attracted to the inside surface of the cup. Franklin communicated his discovery to Joseph Priestley, who repeated the experiment and reported his results in 1767 at the end of his classic treatise *The History and Present State of Electricity, with Original Experiments.* In suggesting an explanation for the phenomenon, Priestley recalled Newton's reasoning in deriving the inverse-square law of gravitation. Newton had shown that a uniform spherical shell of matter will exert no gravitational forces on objects inside it, provided that the gravitational force declines as the square of the distance. Priestley made the brilliant inference that the phenomenon he had observed was in some way similar and that therefore the electric force too should obey an inverse-square law.

The first quantitative test of Coulomb's law was made two years later by a Scot, John Robison. After discussing his experiment at some since forgotten scientific gathering, however, Robison did not publish an account of it until 1801. By then Coulomb had already published his work. Nevertheless, Robison's article was important in that it alerted British workers to the significance of studies of electricity. It is to be remembered that the theory of electromagnetism later reached its apex in the work of Robison's fellow Scot, Maxwell.

Robison's experiment was also inspired by the thinking of Franklin, although it reached him by a rather roundabout route. It was Franklin who proposed that there are two kinds of electric charge (plus and minus), and Franklin's idea led Franz Aepinus of Germany to speculate on the possibility of an inverse-square law in a book published in Latin in 1759 by the Russian Imperial Academy of Sciences. Robison, a classics scholar, came on the book, was fascinated by Aepinus' speculation and devised an experiment for testing it.

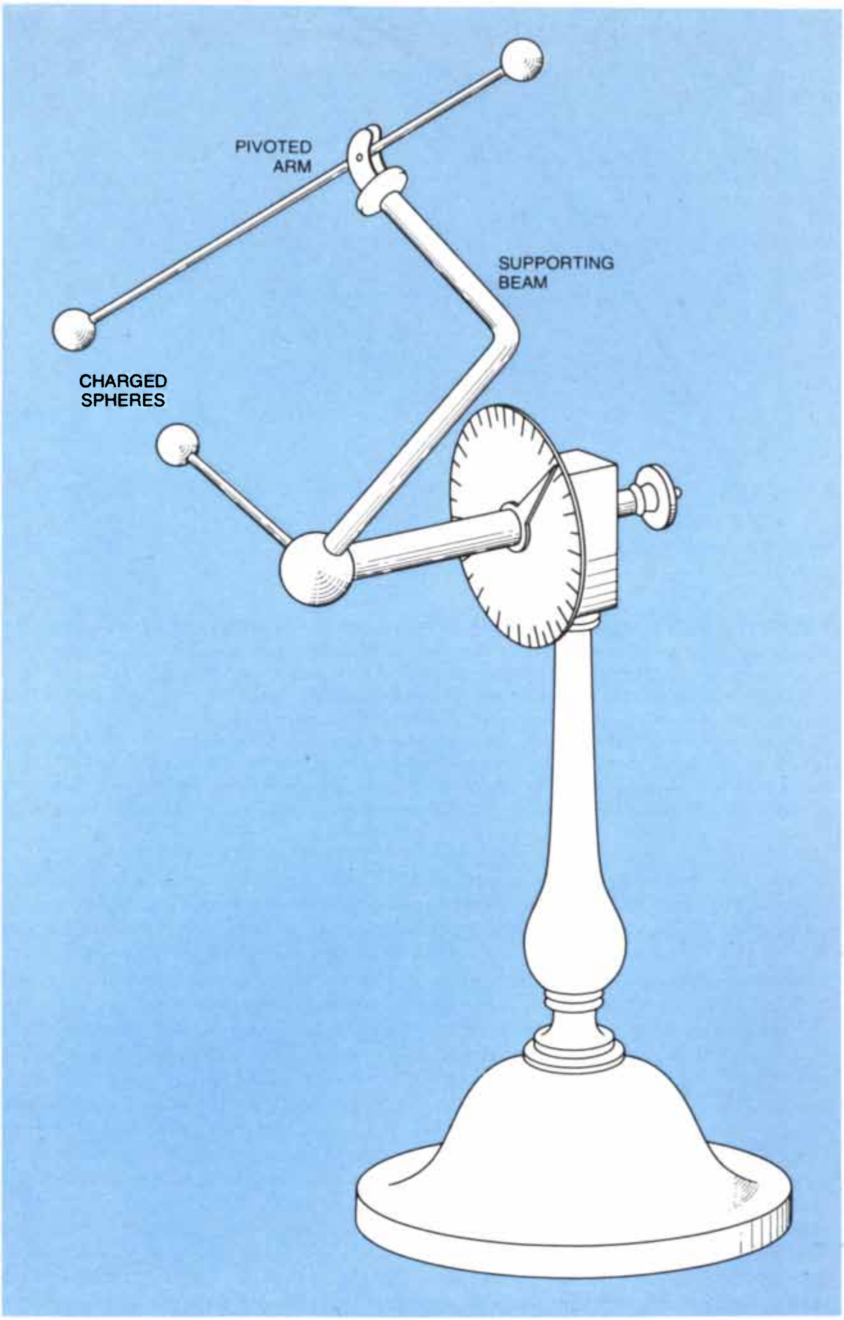
The experiment was ingeniously simple. The repulsive forces between two electrically charged spheres were balanced by the force of gravity acting on a pivoted rod. From the known weight of the rod the magnitude of the electric force could be calculated at various distances, and the agreement of the results with the inverse-square law could be tested. Coulomb's law is expressed mathematically by the equation $F = e_1e_2/r^2$, where F is the force between two electric charges, e_1 and e_2, and r is the distance between them. Robison expressed his results in the form of a modified equation, $F = e_1e_2/r^{2+q}$, so that if q were found to be zero, the inverse-square law would be exact. Robison obtained a value for q of .06; he ascribed the result to experimental error and concluded that the electric force does obey an inverse-square law.

The next man to precede Coulomb in discovering Coulomb's law was Henry Cavendish. In 1773 Cavendish conducted an experiment, also suggesting the influence of Newton's ideas about gravitation, with two concentric metal spheres connected by a conducting wire. The outer sphere was given an electric charge, then the connection between the spheres was broken and the inner sphere was tested for charge. If the inverse-square law were exact, there should be no charge in the interior of the larger, charged sphere; if the law were not exact, some charge could be expected to migrate through the wire to the smaller inner sphere. With this technique Cavendish placed a limit on the magnitude of q equal to .02, or 1/50. All subsequent improvements in the testing of the inverse-square law have been made through variations of Cavendish's method.

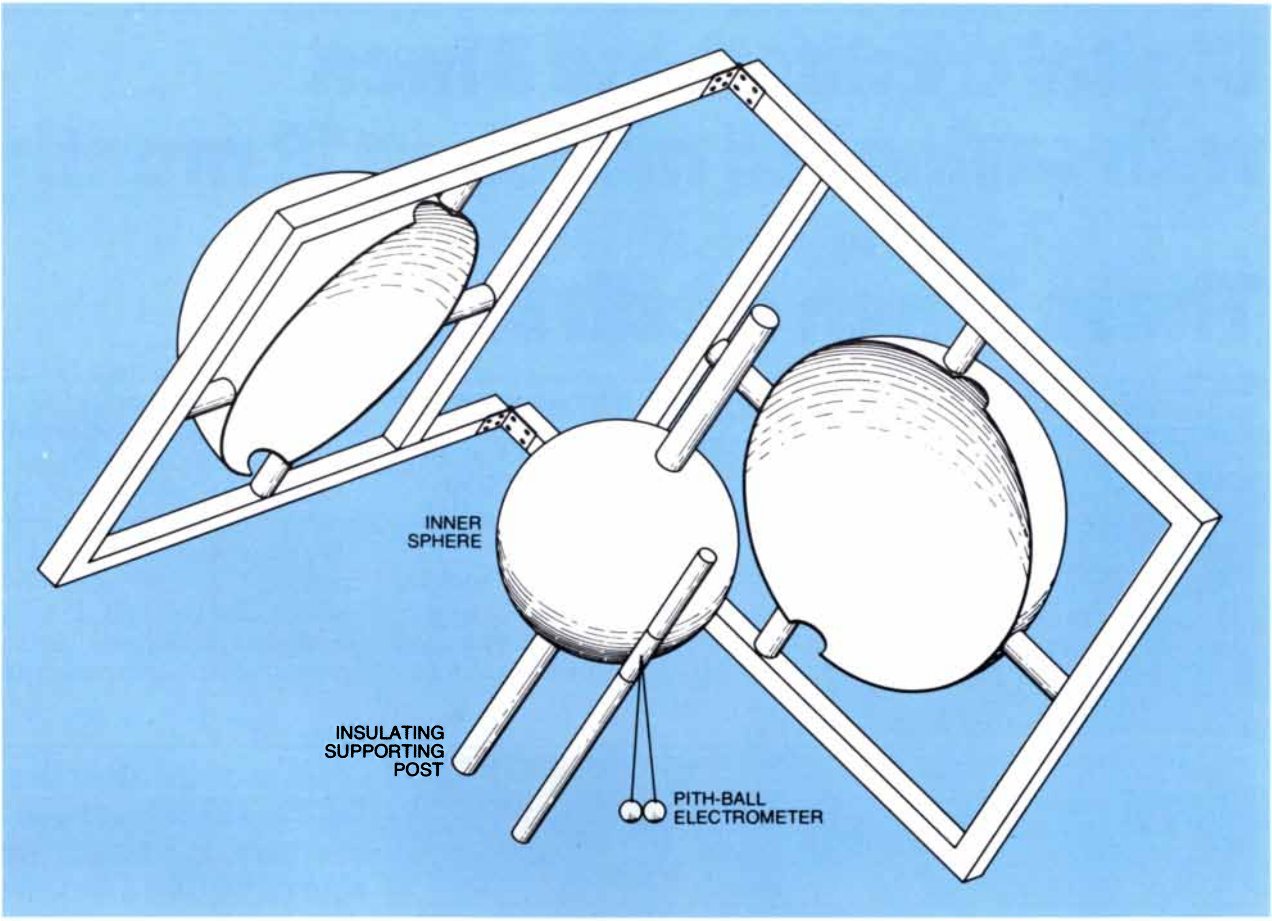
Why was Cavendish denied credit for his demonstration? Again the reason is dilatory publication; his results did not appear until 100 years later, when Maxwell mentioned the experiment in his *Treatise on Electricity and Magnetism.*

Finally we come to Coulomb himself. Coulomb measured both the repulsive and the attractive electric forces, employing a torsion balance in which the forces are compared with the torque required to twist a stiff fiber away from its equilibrium position. He also tested the force law for magnets, an inquiry that had been initiated by Johann Tobias Mayer in 1760 and was continued by Johann Heinrich Lambert from 1766 to 1777; the law was given its final form in 1826 by André Marie Ampère.

Coulomb completed his experiments in 1785 and published his results in 1788 in a memoir of the Royal Academy of Sciences in Paris. There are two reasons he received credit for the law, even though he clearly did not have priority. First, he measured all



FIRST MEASUREMENT OF THE PHOTON MASS was made by John Robison in 1769, more than a century before the existence of the photon was deduced. Robison's experiment was a test of Coulomb's law (although it also preceded Coulomb's work), the principle that the force between two charged bodies is inversely proportional to the square of the distance between them. His apparatus balanced the repulsive electric force between two charged spheres against the gravitational torque on a pivoted arm; by adjusting the angle of the supporting beam the force could be measured at several distances. Robison expressed his results in terms of a possible deviation from Coulomb's law, supposing that the exponent applied to distance is not exactly 2 but $2 + q$. He obtained a value for q of .06. The correct interpretation of this result was not understood until the 20th century; it implies a limit on the photon mass of 4×10^{-40} gram.



CONCENTRIC METAL SPHERES were employed by Henry Cavendish to test Coulomb's law in 1773. The small globe was enclosed in the assembled hemispheres and connected to them electrically by a wire that was passed through one of the hemispheres. A charge was placed on the outer sphere and the electrical connection was then broken by withdrawing the wire. Finally, the outer sphere was opened and the inner one was removed and tested for an electric charge with the electrometer. The experiment is based on the principle that a charged sphere can have no charge in its interior if the inverse-square law of the electric field is exact; if there is any deviation from that law, charge will migrate through the wire to the inner sphere. The fact that the pith balls of the electrometer do not separate indicates the absence of charge. Cavendish established that the correction, *q*, to the exponent in Coulomb's law cannot be greater than .02. Modern interpretation of Cavendish's result gives a limit on the mass of the photon that is a little greater than 1×10^{-40} gram.

the forces, both attractive and repulsive. More important, he published his findings promptly, which Robison and Cavendish had not done.

Cavendish's value for q of 1/50 was improved in 1873 by Maxwell, who showed that q is no greater than 1/21,600. The next refinement was made in 1936 by Samuel J. Plimpton and Willard E. Lawton of the Worcester Polytechnic Institute, who again employed apparatus consisting of two concentric spheres. With the more precise instruments available by then, they were able to determine that q is less than or equal to 2×10^{-9} over distances of about half a foot.

The experiments of Robison and Coulomb, in which forces were actually measured, seem to provide a direct and obvious test of Coulomb's law, but the Cavendish technique is the more powerful one. It is a "null experiment." A small deviation from the inverse-square law would have led to small fractional changes in the observations of Robison and Coulomb, but Cavendish needed only to find out whether a charge was present or absent. It is much easier to make a yes-or-no determination than it is to achieve high accuracy in each of a series of measurements of some nonzero quantity such as the electric field at various distances from a charged body.

The testing of Coulomb's law illuminates a philosophical question: How is a scientific hypothesis to be verified? Coulomb's method was straightforward: he measured the force between two charges at several distances of separation and reported his results. The accuracy of his measurements was about 10 percent, and they were compatible with the inverse-square law. He concluded that the law was verified to an accuracy of 10 percent for distances ranging from nine to 24 inches.

Robison and Cavendish independently devised a more elaborate and potentially more informative approach. They proposed that if the force between charges does not decrease as the square of the distance, then it must decrease as some other power of the distance, expressed as r^{2+q}. Thus they replaced the existing law with a hypothetical new one of greater generality, which could be adopted if the experimental results demanded it. Their conjecture was ingenious, but it has since become apparent that the form of their hypothetical law is incorrect.

Defining the photon mass by applying a correction, *q,* to the exponent in Coulomb's law is logically inconsistent, although the error could not have been detected by the early investigators; after all, they were concerned with the law itself and not with the photon, a particle whose existence was then unknown and unsuspected. Moreover, the inconsistency does not invalidate their experiments; it simply requires that we reinterpret the results before attempting to deduce the photon mass from them.

At the time of Robison and Cavendish there was no known fundamental unit of length (as opposed to arbitrary or conven-

bility at a total cost of only $10,000 a month. We estimate the same capability would cost us $50,000 a month at a service bureau."

Thanks to Digital's flexibility, Shawmut has been able to apply this timesharing computer power to portfolio pricing, five-year bank forecasting, personnel management, bank location analysis and corporate financial planning. To do this, data communications terminals are located throughout the bank for instantaneous information.

"Our experience has been that our Digital DATASYSTEMS handle all this workload without bogging down on the job. We get the information we need in seconds."

Hunt concludes, "Money management is Shawmut's business. Computers are Digital's. When Shawmut can save approximately $40,000 a month using Digital computers, it shows we both do our jobs well." ■

---

inventory is something he knows a lot about.

"We have over 140,000 different auto parts spread over three large distribution centers. The headaches used to be enormous. Then we got our Digital DATASYSTEM. Not only has it made us more efficient, it has made us more competitive.

"Our service is faster and more accurate than ever. Our jobbers, many of whom have their own terminals, can order their parts through our computer 24 hours a day. We can tell a customer that the part he needs is in the warehouse, or when it will be—even when the warehouse is over 100 miles away. And that's service he can't get anywhere else.

"Yes, we looked at other systems. But we chose Digital for capability, cost savings, and besides, everyone we talked to said that Digital made the most reliable equipment." ■

---

essing load. The hardware is extremely cost-effective. And the ease-of-use gives us great economy. In fact, we only use two operators to do all phases of our computer work.

"Currently, we handle 9 million transactions a year. But we have the ability to go over 60 million. Today we are using less than 20% of our DECsystem-10 capacity for reservations. We have plenty of room for the future."

Right now, Digital's interactive teleprocessing system lets guests obtain hotel reservations in seconds. While it does on-line systems and applications programs for home office business accounting simultaneously.

The cost for all this efficiency? "Our dual DECsystem-10's cost us 50% less than the nearest competitor. In fact, with the money we saved, we covered the cost of 3 new buildings." ■

---

need from a company with over 4000 field representatives in 25 countries around the world.

To find out how Digital can help you save money, send for your free copy of "50,000 Computers Saving Managers Millions." Fill out the coupon below, or call or write Digital Equipment Corporation, Maynard, Mass. (617) 897-5111. European headquarters: 81 route de l'Aire, 1211 Geneva 26. Tel: 42 79 50. Digital Equipment of Canada, Ltd.

Please send me your free book "50,000 Computers Saving Managers Millions" to show me how I can get more work done at lower cost.

My computer application is ____________________

Name ____________________ Title ____________________

Company ____________________ Address ____________________

City ____________________ State ____________________ Zip __________

digital

50,000 computers saving managers millions.

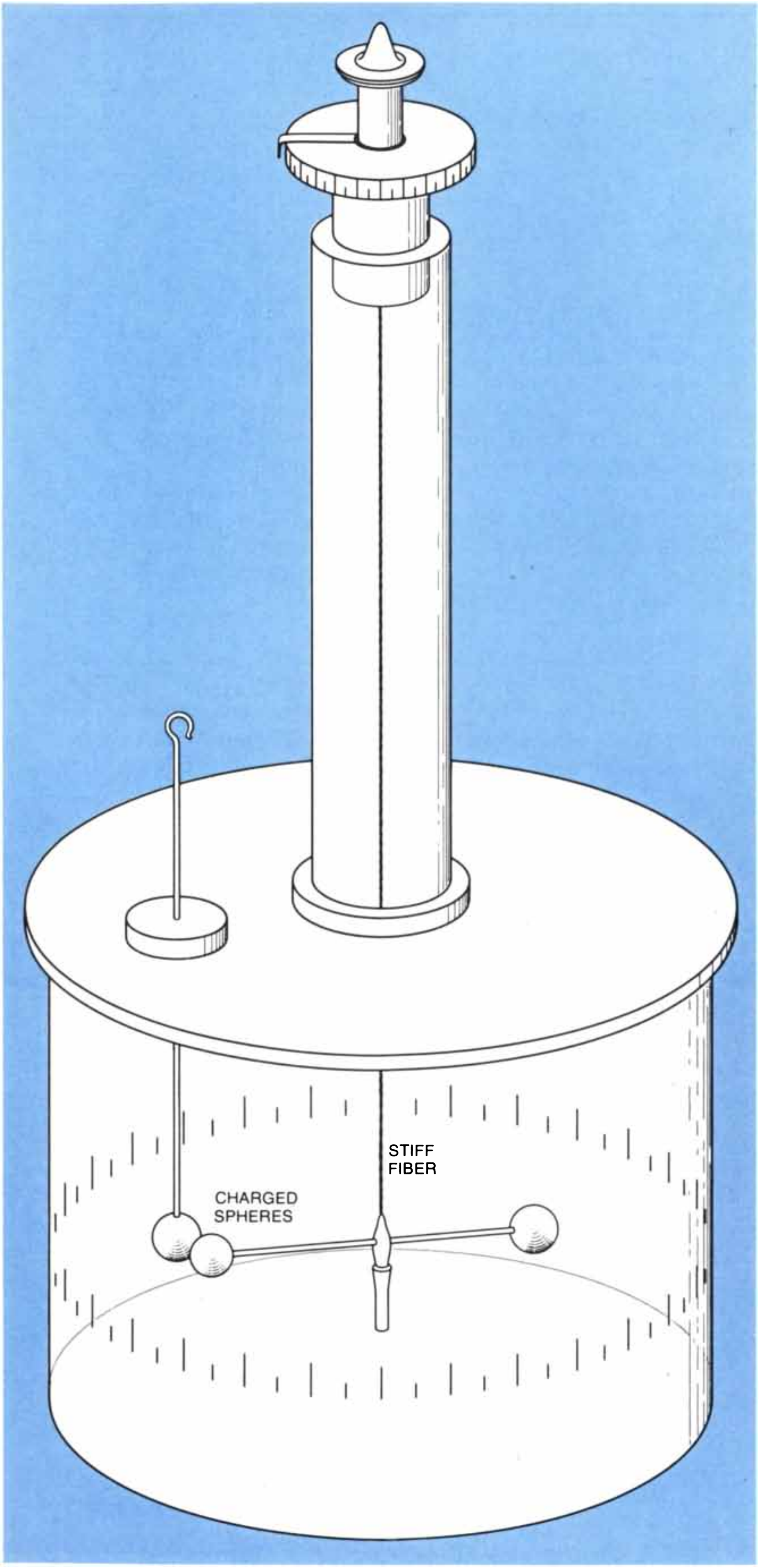
tional units such as the meter); similarly, there was no fundamental unit of force. Hence it was only reasonable to suppose the phenomena of electricity would be identical in form whether they were measured on the scale of meters or the scale of inches. The principle is called scale invariance, and if it is to be obeyed, then the ratio of the forces measured at two different distances must be determined by the ratio of the distances; moreover, if the force changes smoothly or continuously as the separation is increased, then the force must vary as some simple power of the distance. From this conclusion followed the justification for choosing the expression r^{2+q}.

About 40 years ago it became apparent from the work of Proca and of Hideki Yukawa that scale invariance would not apply to the behavior of a massive photon or to that of other particles analogous to it. It was shown that if Coulomb's law is not exact, then the deviation from the law does establish a fundamental unit of length, related to the photon's mass. In that case the relation of force to distance in electromagnetic phenomena cannot be described by any simple power law. If q were zero, then the law would be exact and correct; otherwise no value of q could accurately describe the forces. Clearly there is a contradiction; it can be resolved only by formulating laws for massive photons that take account of the intrinsic scale of length.

It should be pointed out that the principle of scale invariance has had many successful applications in physics. The fact that the first application (or the first we know of) turned out to be inappropriate does not detract from the achievement of Robison and Cavendish in their cleverly attempting to devise a generalization of Coulomb's law.

How are we to proceed from tests of Coulomb's law to the calculation of a limit on the rest mass of the photon? Although the change cannot be expressed as a modification of a power law, there is no question that the nature of a static electric field would be profoundly altered by the existence of a photon mass.

Coulomb's law can be interpreted geometrically by imagining an electric charge isolated in empty space, radiating lines of

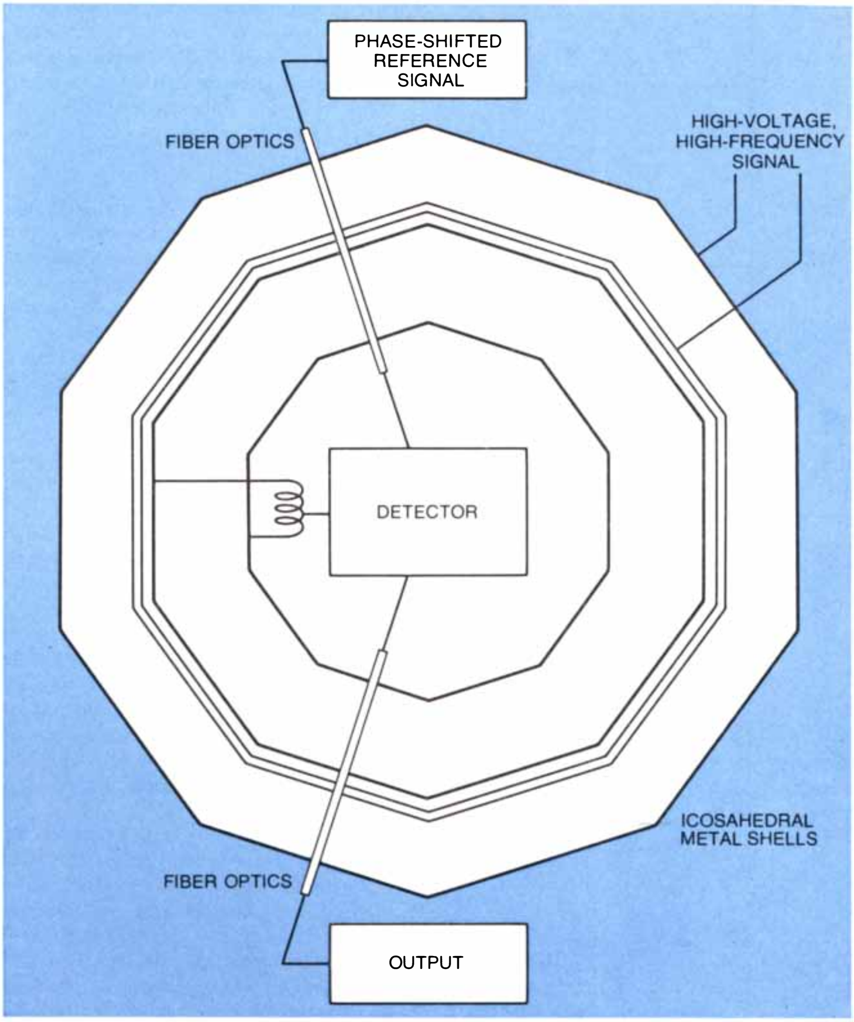


TORSION BALANCE was employed by Charles Augustin de Coulomb in his test of the inverse-square law. The repulsive force between two charged spheres was measured by the extent to which it twisted a stiff fiber away from its equilibrium position. By modifying the apparatus Coulomb tested the attractive force between spheres with opposite charges and also established an inverse-square law for magnetism. He published his results, which were less accurate than those of Robison or Cavendish, in 1788 and therefore had no claim to priority. The law is ascribed to Coulomb because he surveyed all the forces and because his predecessors failed to publish promptly.

flux in all directions. If the law is exact, the flux lines continue indefinitely, that is, the number of lines remains constant at all distances from the charge (although the number of lines per unit area decreases as the square of the distance, giving the law for the electric force). Given a massless photon, the flux lines cannot stop until they meet another charge. If the photon has mass, on the other hand, the lines of flux fade away in empty space. At large distances, therefore, the electric field is effectively extinguished.

The rate at which the field decays is determined by the characteristic scale of length associated with the mass of the photon. This length can be derived from the equations relating energy, frequency and velocity in quantum mechanics, and it is found to be equal to h/Mc; since h and c are constants, the scale is defined entirely by the mass. For an isolated electric charge the flux is reduced about 600-fold each time the distance from the charge is increased by an amount h/Mc. The relation of field intensity to distance is thus an exponential one.

This result is familiar in the wider context of particle physics, where a more general rule states that the range of a force is inversely proportional to the mass of the particle that transmits it. The strong, or nuclear, force that acts between protons and neutrons has a quite short range: about 10^{-13} centimeter. From that fact Yukawa predicted in the 1930's that the quantum of the strong force would have a mass roughly a tenth that of the proton; one such particle, the pion, was discovered in the following decade, and its mass is near the predicted value. The weak force responsible for certain radioactive decays has an even shorter range: probably no more than 10^{-15} centimeter. The particles thought to transmit the weak force have not been discovered, but their masses are supposed to be at least 50 times the mass of the proton. The same law of proportionality predicts that if the photon is massless, the range of the electromagnetic force must be infinite. If it should be found to have mass, however, the influence of a stationary charge or of a steady current would be effectively confined to a sphere of finite radius. (These conclusions, it should be emphasized, do not apply to the propagation of free electromagnetic waves.)



MODERN MEASUREMENT of the photon mass is a refinement of Cavendish's technique. Five concentric metal shells are used instead of two, and the shells are icosahedrons instead of spheres, but the method remains one of searching for electric charge communicated to the interior of a charged, closed shell. A high-voltage, high-frequency signal is applied across the outer two shells, and a sensitive detector is employed to search for any trace of this signal appearing across the inner two shells. The detector operates by amplifying the signal from the inner shells and comparing it with a reference signal that is identical with the one applied to the outer shells but that is shifted in phase at a rate of 360 degrees per half hour. Any signal in the output of the detector that has a period of a half hour is then evidence for a violation of Coulomb's law. To avoid introducing extraneous fields the reference signal and the output of the detector are transmitted through fiber optics. The experiment was conducted in 1971 by Edwin R. Williams, James E. Faller and Henry A. Hill, who were then at Wesleyan University. They obtained a limit on the photon mass of 2×10^{-47} gram, which remains the best laboratory measurement.

The Cavendish experiment is entirely capable of detecting the exponentially decreasing field that would be associated with a massive photon. The experiment is based on the notion that the interior of an electrically charged conducting sphere will be free of charge only if the electromagnetic force obeys an exact inverse-square law. A law of exponential decrease obviously departs from the inverse-square rule, so that the experiment should be a sensitive indicator of photon mass.

The Plimpton-Lawton experiment of 1936, reinterpreted according to these principles, yields a limit on the photon rest mass of 10^{-44} gram. In the past decade the measurement has been repeated several times by various groups of investigators, with ever increasing precision. The best limit yet obtained by the Cavendish method was reported in 1971 by Edwin R. Williams, James E. Faller and Henry A. Hill of Wesleyan University, who employed five concentric shells instead of two in order to improve the sensitivity and to help eliminate errors introduced by stray charges. The shells were icosahedral rather than spherical. Williams, Faller and Hill established a limit of 2×10^{-47} gram; in contrast, the electron, the lightest particle known to have a nonzero mass, weighs about 10^{-27} gram.

By studying magnetic instead of electric fields it has been possible to improve even on this result. Magnetic fields are superior indicators of the photon mass because they extend over large distances. In principle, of course, both electric and magnetic fields could have infinite extent (assuming that the photon is massless). In practice a large electric field attracts charges of opposite polarity on which flux lines stop; as a result the field is confined and sometimes neutralized. Magnetic flux lines have never been found to terminate but always form closed loops. The loops can be very large; some may be of galactic size. Magnetic fields can therefore be studied over vast distances and examined for alterations of form that could be attributed to a nonzero photon mass. The accuracy of the measurements in such experiments is not as great as it is in the laboratory, but the scale of the observations more than compensates for that disadvantage.

As in studies of electric fields, the essential clue that the photon is massive would consist of evidence that the field diminishes exponentially with distance. The scale of the magnetic experiments, however, makes them highly sensitive to the characteristic length associated with a nonzero rest mass. Erwin Schrödinger, one of the founders of quantum mechanics, was the first to exploit this fact. In 1943 he employed data on the earth's magnetic field to obtain a limit on the photon mass. In 1968 we analyzed improved measurements of the earth's magnetic field, including some made by artificial satellites, and set a new limit on the photon mass of 4×10^{-48} gram, which is five times smaller than the best laboratory value. Since then measurements of Jupiter's magnetic field have made possible a further improvement. The measurements were made by instruments on board the *Pioneer 10* spacecraft. We studied them in collaboration with Leverett Davis, Jr., of the California Institute of Technology. The new limit is 8×10^{-49} gram, and it is the smallest reliable one obtained so far. The measurements span a distance a billion times greater than that of laboratory experiments.

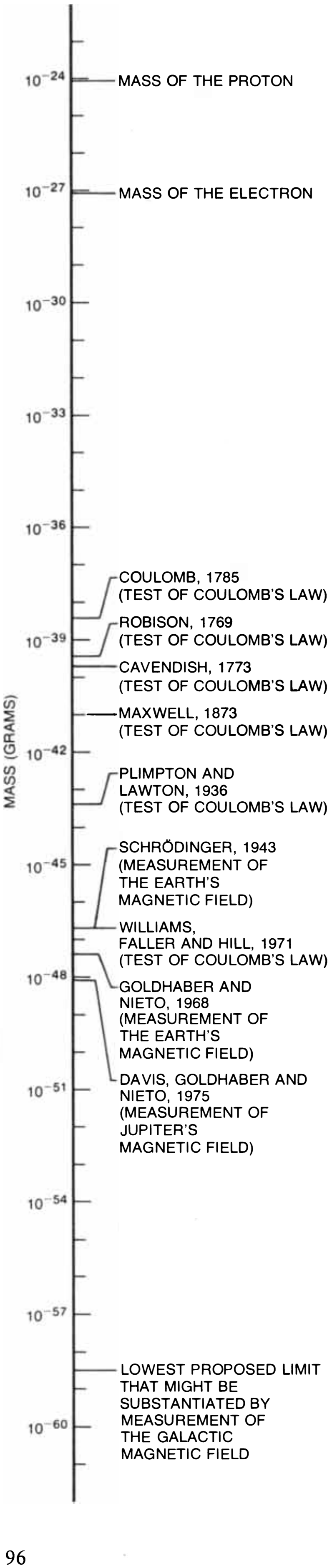
The upper bound on the photon mass derived from measurements of Jupiter's magnetic field is by no means the smallest that can be achieved. One possibility for improving on it is through observations of even larger magnetic fields, such as the field of the galaxy. Measurements of the galactic field are difficult, however, and they would have to be indirect, so that it is not certain how much of an improvement could be expected from this technique. On the basis of scale alone observations of the galactic magnetic field might improve the limit by a factor of a billion or more. Even a conservative treatment of such data could give a thousandfold improvement.

Another approach is through observations of magnetic waves in a highly conductive medium, such as an ionized gas, or plasma. The velocity of such waves is determined by the properties of the plasma, and if the photon is massless, the velocity is independent of frequency. If the photon is massive, on the other hand, low-frequency waves are retarded, and there is a limiting frequency below which the waves cannot propagate at all. The existence of low-frequency magnetic waves therefore implies an upper limit on the photon mass. Observations of such waves in interplanetary space have suggested a limit somewhat smaller than the one obtained from laboratory tests of Coulomb's law. Last year Aaron Barnes and Jeffrey D. Scargle of the Ames Research Center of the National Aeronautics and Space Administration employed evidence of magnetic waves in the Crab Nebula to deduce a plausible limit 10,000 times better than the one obtained from Jupiter's magnetic field. There are large uncertainties in the calculation, however, because we cannot be sure of what we are observing in an object as distant as the Crab.

Finally, we should mention a subtle quantum-mechanical argument, showing that a nonzero photon mass is inconsistent with the existence of the particles called magnetic monopoles, which possess a magnetic charge analogous to the electric charge of more commonplace particles. The singular distinction of this test of the photon mass is that it does not merely set an upper limit; it states that if monopoles exist, the mass of the photon must be exactly zero. In rebuttal it could be argued that quantum mechanics may not be valid over extremely long distances. Moreover, the existence of monopoles is by no means certain; evidence for the discovery of a monopole was reported last year, but alternative explanations of that event have been proposed, and the outcome remains undecided.

If we ignore the possibility of finding magnetic monopoles, then the present limits on the photon mass are small enough so that no consequences of a nonzero mass could be detected with known techniques, except perhaps in the behavior of static or slowly changing magnetic fields. This fact raises another philosophical question: Why bother to pursue the limit on the photon mass any further? Aside from the obvious answer that a nonzero value might be found at any time, the main motive lies in maintaining an anti-Aristotelian approach to science. We insist that insight into nature must be vindicated by experiment, and acknowledge that just beyond the frontiers of experiment may lie mysteries we have not even guessed at.

The studies surveyed here, together with a host of others conducted at microscopic scale, have verified electromagnetic theory at distances ranging from 50 billion centimeters to a quadrillionth part of a centimeter. This range is impressive, but it is still finite, and we must stay alert for opportunities to extend it. Perhaps we shall find a nonzero photon mass, or some other deviation that violates a physical principle even more sacred than the dictum that light cannot stand still.

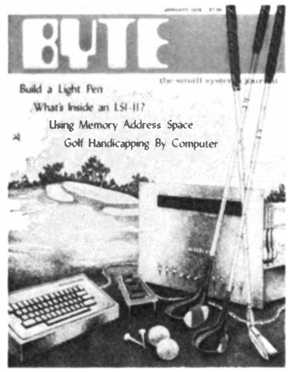


LIMITS on the mass of the photon have been improved by a factor of a billion since Robison's first test of Coulomb's law more than 200 years ago. The best limits based on direct measurements are deduced from the failure of experiments to detect any exponential decay in large magnetic fields. Measurements of Jupiter's magnetic field, obtained by the *Pioneer 10* spacecraft and studied by the authors in collaboration with Leverett Davis, Jr., of the California Institute of Technology, imply that the mass of the photon cannot exceed 8×10^{-49} gram. That limit might eventually be improved by a factor of a billion or more through indirect observations of the galactic magnetic field, but at present the interpretation of those observations is uncertain.

Have you considered the idea of a personal computing system?

The last few years have seen a remarkable quantum jump in the cost effectiveness of computing power brought about by the advent of inexpensive microcomputer systems. You've been reading about these machines for some time in the technical press. You've seen stories of applications ranging from specialized numerical control systems for machine tools to intelligent traffic light controllers.

One of the most exciting possibilities which has come about as a result of the inexpensive LSI computer is the fact that a general purpose computing system is within the budget range of you, the individual with an interest in the technology and an appreciation of both the intellectual challenge and fun of building and using a personal computing system. There is now a whole micro industry of companies which package and market microcomputer related items as kits, finished products and related items for personal use. The products range from complete system kits with hardware and software to peripherals, software and literature on the subject. But where do you go to find out about this personal involvement aspect of microcomputer technology?

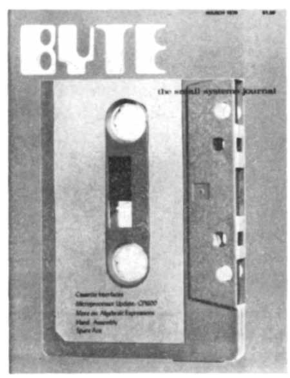


Turn to BYTE, The Small Systems Journal for a wealth of information on the personal use of computer systems. BYTE is a monthly compendium of information you need for personal use applications of microcomputers:

- Detailed hardware and software design articles authored by individuals who are experimenting in the field.
- Tutorial background articles on hardware, software and applications ideas for the home computer and general topics of computer science.
- Reviews of processors as candidates for small general purpose systems.
- An editorial bias toward the fun of using and applying computers toward personally interesting problems such as electronic music, video games, control of systems for hobbies from ham radio to model railroading, uses of computers from burglar alarms to private information systems.
- Advertisements of the firms who bring you products to help expedite your personal computing activities.
- Information on clubs, newsletters and other social activities of the individuals engaged in personal computing.

BYTE is professionally edited and packed with the information you need on this fast growing field of personal computer applications. Don't miss a single exciting issue. Order your subscription today, using the coupon below, or phone your request directly (call 603-924-7217 and ask for the subscription department).

Please allow six weeks for processing



Please enter my subscription to BYTE.

☐ $12 one year ☐ $22 two years ☐ $30 three years

☐ Check enclosed ☐ Bill me Exp. Date ________

☐ Bill BAC No. ________ ☐ Bill MC No. ________

Name ....

Address..........

City.......... State.......... Zip..........

BYTE • 70 Main St • Peterborough NH 03458

Stephen Hales

This 17th- and 18th-century clergyman was the first to measure the pressure of the blood. He also investigated the flow of water and sap in plants and thereby founded modern plant physiology

by I. Bernard Cohen

A central feature of Newtonian physical science during the Enlightenment of the 18th century was its demonstrations that the universe was orderly and perfectly balanced. For example, it was shown that if the speed of one of the planets in its orbit had been too high, the planet would have escaped from the solar system, and if the speed had been too low, the planet would have spiraled in toward the sun. The same was true of the satellites in orbit around the planets. The exact relation between the gravitational force and the inertial component of the motions of the planets and satellites in their orbits led Newton himself to conclude that such a "most beautiful system ... could only proceed from the counsel and dominion of an intelligent and powerful being."

Did the same considerations of order and balance pertain to the world of living things as well as to the world of celestial bodies? Newton was certain that the answer was affirmative. In the early 18th century, however, the life sciences had barely begun to be put on a quantitative basis, let alone codified into a deductive mathematical and experimental system on the model of Newton's *Philosophiae naturalis principia mathematica.* The first person to analyze the physiology of animals and plants quantitatively was one of Newton's disciples, Stephen Hales.

As a Newtonian scientist Hales sought to discover the harmonies of nature in the functions of animals and plants, just as Newton had discovered them in the universe of celestial objects. It was Hales's aim to identify and measure the forces that act in living systems. Specifically he was interested in the pressure of the fluids within such systems (blood in animals, water and sap in plants) and the speed with which these fluids course through the structures in animals and plants that seemed specially designed for the purpose. The result of his investigations was that he added considerably to knowledge of the dynamics of the circulatory system in animals and laid an entirely new foundation for the science of the physiology of plants.

In applying the principles of the physics of fluids to animals and plants Hales was consciously extending the boundaries of Newtonian science into the world of living matter. Furthermore, in so doing he was consciously glorifying the God of nature whose wisdom and power were manifest in all beings. He wrote: "Since we are assured that the all-wise Creator has observed the most exact proportions, *of number, weight and measure,* in the make of all things; the most likely way therefore, to get any insight into the nature of those parts of the creation, which come within our observation, must in all reason be to number, weigh and measure."

Stephen Hales was born on September 17, 1677, in the village of Bekesbourne in Kent. He was educated at private schools in Kensington and Orpington. In 1696, at the age of 19, he went to Cambridge, where he was admitted as a pensioner of Corpus Christi (then called Bene't College). Although his intention was to be ordained as an Anglican priest, he studied the classics, mathematics and the sciences as well as theology and philosophy. When Hales took his first degree as a bachelor of arts in 1699, Newton was just ending his service as Lucasian Professor of Mathematics at Cambridge and had gone to London to become Master of the Mint. (William Whiston was chosen as his successor.) Hales stayed on at Cambridge, becoming a fellow of Corpus Christi in 1703, the same year that he received his master of arts degree and was ordained deacon of the parish of Bugden.

It was only after Hales had become a fellow of his college that he developed a genuine interest in natural science, a subject he pursued with William Stukeley, a new undergraduate at the college. Together they studied anatomy, made dissections and anatomical preparations and collected plants in the Cambridge area. They also interested themselves in chemistry, repeating "many of Mr. *Boyle's* experiments," attending "the chymical lectures that were then read by the public Professor Signior Vigani" and going to see "the chymical operations which he performed in a room at Trinity College, which had been the laboratory of Sir *Isaac Newton.*" In addition they attended Whiston's lectures on hydrostatics and pneumatics (which repeated the classical experiments on water and air pressure) and the lectures on astronomy given by Roger Cotes, who later edited the second edition of Newton's *Principia.*

During that period of initiation into science Hales was no mere passive learner. Peter Collinson, a contemporary of Hales's and Stukeley's, has recorded that when the pair "proceeded also to the dissection of dogs, ... Hales contrived a method of obtaining a preparation of the lungs in lead." Stukeley later in life proudly exhibited his lead castings of the bronchial tree, which had been made according to Hales's suggestion. During this period Hales sufficiently mastered the principles of Newtonian astronomy to be able to design, and to have constructed, an orrery to illustrate the motions of the planets according to Newton's principles.

For some unknown reason Hales left Cambridge in August, 1709, to become curate of Teddington in Middlesex. There he remained until his death in January, 1761. It was at Teddington, where the parish duties were not heavy, that he conducted his many experiments and showed how biological science might become as quantitative and exact as the Newtonian physical sciences he had studied at Cambridge. His new results in animal and plant science immediately brought him the commendation of the Royal Society of London. In 1718 he was elected a Fellow of the Royal Society, with Newton in the chair.

Hales's first book, *Vegetable Staticks,* was devoted to his work in plant physiology and in chemistry. He had actually begun to conduct experiments with animals before he turned to plants. His contributions to animal physiology did not have as profound an effect on the course of science as his research on plants; nevertheless, those contributions were of the first rank.

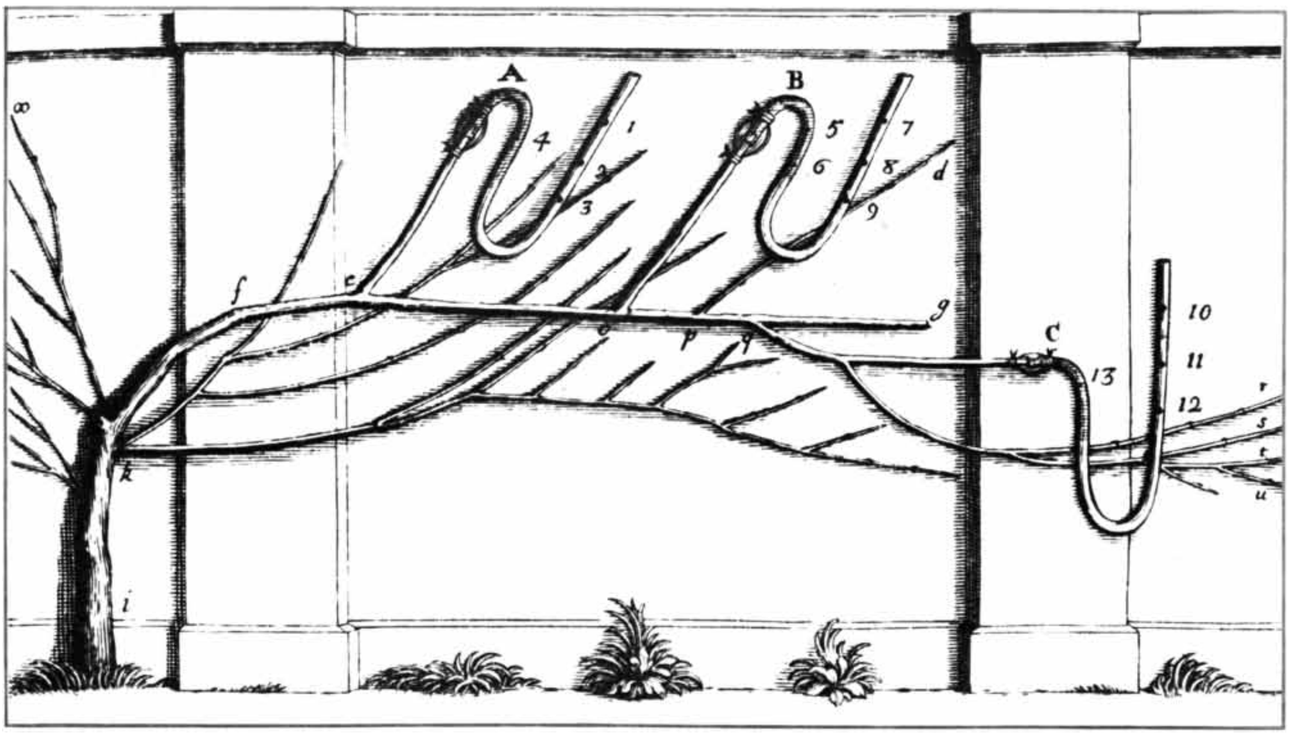
In Hales's studies in animal physiology he sought to elucidate the dynamics of the circulation of the blood by actual measurements and calculations. By Hales's time knowledge of the circulation of the blood had advanced considerably since William Harvey had discovered the circulation a century earlier. In particular, Marcello Malpighi of Italy had found that the capillary vessels are the link between the arteries that carry the blood away from the heart and the veins that bring the blood back to it. There was no secure knowledge, however, of the actual forces acting on the blood and exerted by it. An indication of the state of ignorance in those days is provided by the estimate, based largely on volumetric measurements, of the force generated by a single heartbeat. It was believed that the circulation of the blood was maintained at each heartbeat by a force of 100,000 pounds!

According to an account by Hales, he was led to study the forces of blood circulation by his interest in muscle. In the 18th century it was generally believed that muscle contraction was the result of the dilation of the muscle fibers by the blood flowing through them. Hales related that after he had "read the unsatisfactory Conjectures of several [writers], about the Cause of muscular Motion," it occurred to him "that by fixing Tubes to the Arteries of live Animals, I might find pretty nearly, whether the Blood by its meer hydraulick Energy, could have a sufficient Force, by dilating the Fibres of the acting Muscles, and thereby shortning their Lengths, to produce the great Effects of muscular Motion." Thus it was that Hales was "insensibly led on from time to time, into this large Field of statical and other Experiments."

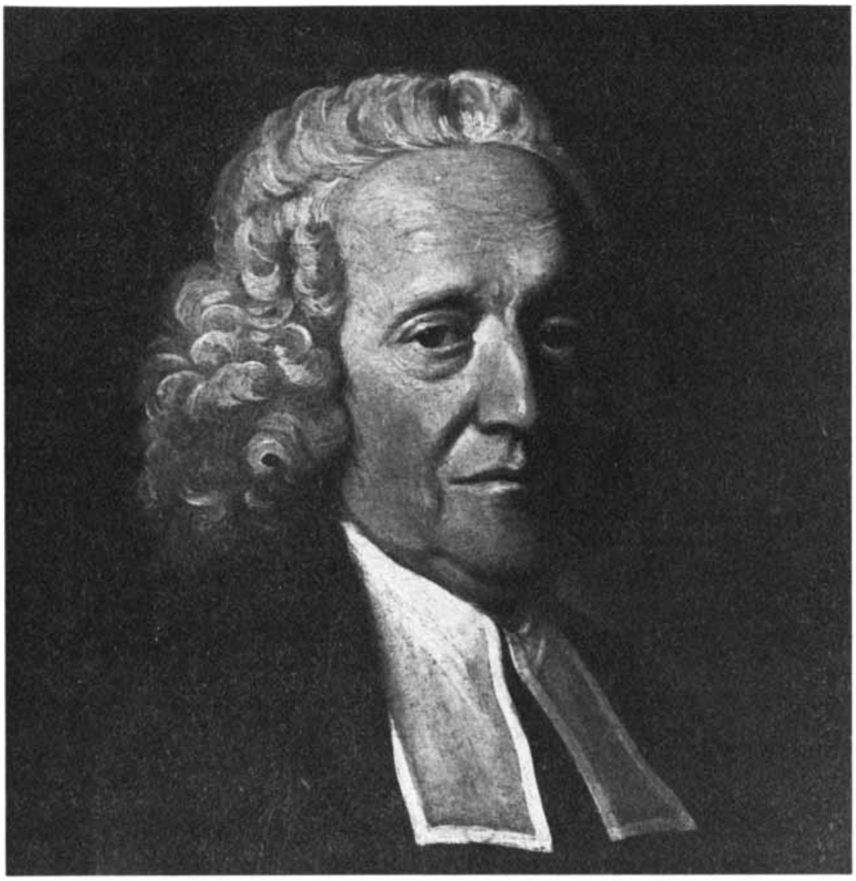
The result of Hales's experiments was the first direct measurement of the pressure of blood in the arteries and veins of an animal. Hales's method, however, was oriented toward the study of physiology rather than medicine, and it was painful and bloody. Indeed, when Hales was recounting his experiments in the preface to *Haemastaticks,* his book on animal physiology, he observed that the "disagreeableness of the Work did long discourage me from engaging in it." He was only "spurred on by the hope" of gaining "some further Insight into the animal Oeconomy." At that time, we must remember, the standards of acceptable pain and cruelty—to human beings as well as to animals—were very different from what they are today. Surgical operations were performed without benefit of anesthesia and brutal blood sports were normal gentlemanly pastimes. In the 18th century there were few men in public positions who condemned cruelty to animals.

Initially Hales had sought to measure the forces of the blood in order to test the contemporary theory of muscular action. In so doing he inserted a cannula, or flexible tube, into an artery or a vein and connected to it a long glass tube that acted as an open manometer. In the glass tube the blood would rise and fall with each heartbeat, yielding an exact measure of the changing pressure. Before long, however, Hales had left the problem of muscle and had become concerned directly with the "Weights and Measures" of the blood. He was not content simply to measure the hydrostatic pressure of the blood in the large arteries and veins of horses, dogs and other animals. He also sought to find the relative contribution of two components to the pressure he had measured in the arteries. (One component originated with the output of the heart and the other with the resistance to the flow of the blood by the vessels in the rest of the circulatory system.) Moreover, Hales's account shows that he was fully aware that both the output of the heart per beat and the pulse rate (the product of which gives the output per minute) are not constant but vary with physical exertion and emotional stress.

Hales was particularly interested in comparing certain aspects of the circulatory process in different animals. He found that since the blood has a longer course to flow in larger animals than it does in smaller ones, it meets with greater resistance in larger animals. Accordingly the blood pressure in the arteries of larger animals is higher than it is in smaller animals. On the other hand, the heart of a smaller animal beats faster than the heart of a larger one. Thus whereas the output of blood per heartbeat is approximately proportional to the size of the animal, the heart of a small animal pumps a weight of blood equal to the weight



SINGLE VINE BEARING THREE MANOMETERS, or open glass tubes partly filled with mercury, is one of many experiments described and illustrated in Hales's *Vegetable Staticks.* This particular experiment was designed to measure the pressure of the sap exuded by the vine during the "bleeding" season early in the spring. As the sap was exuded from or withdrawn back into the branch, the level of the mercury in each of the manometers rose or dropped, thus providing a visible measure of the pressure. The experiment demonstrated that the pressure of the sap was not equal throughout the different parts of the plant: one branch might be "in an imbibing state" at the same time that another branch was "in a state of pushing sap." Hales concluded from the experiment that the force drawing the sap upward through the plant did not originate solely in the roots "but must also proceed from some power, in the stem and branches" in addition.



PORTRAIT OF HALES was painted by Thomas Hudson when Hales was 81. Hales did most of his experiments during the quiet 52 years he spent as curate of Teddington in Middlesex.

Whereas ſome complain that they do not underſtand the ſignification of thoſe ſhort ſigns or characters, which are here made uſe of in many of the calculations, and which are uſual in Algebra; *this mark* + *ſignifies* more, *or* to be added to. *Thus page* 18, *line* 4, 6 ounces + 240 grains, *is as much as to ſay,* 6 ounces more *by, or* to be added to 240 grains. *And in line* 16, *of the ſame page, this mark* × *or croſs ſignifies* multiplied by; *the two ſhort parallel lines ſignify* equal to; *thus* 1820 × 4 = 7280 : 1, *is as much as to ſay,* 1820 multiplied by 4 equal to 7280 is to 1.

LAST PARAGRAPH of Hales's preface to *Vegetable Staticks* shows the reader how to interpret algebraic signs used in the book. The signs were still relatively new in the 18th century.

of its body in less time than the heart of a larger animal. In other words, Hales found that the output of the heart per minute is proportionately greater in smaller animals than it is in larger ones.

From studies of the cardiac output as a function of the blood pressure and the weight of an animal, Hales went on to examine the resistance to the passage of the blood by the small arteries, the capillaries and the veins. In a series of ingenious experiments he determined some of the factors (such as heat and various chemical substances) that influence the actual degree of constriction or dilation of the small blood vessels. To this subject he applied quantitative methods. One conclusion to which he was led by his calculations was that the blood must travel through the capillaries of the lungs of a frog 43 times faster than it travels through the capillaries of the animal's muscles. Having determined the actual magnitude of the "very small Force of the Arterial Blood among the muscular Fibres," he saw how inadequate it was to produce "so great an Effect, as that of muscular Motion."

Hales concluded that the contemporary theory of muscular action was wrong and that muscular action "must therefore be owing to some more vigorous and active Energy, whose Force is regulated by the Nerves." He continued: "But whether it be confined in Canals within the Nerves, or acts along their Surfaces like electrical Powers, is not easy to determine." His statement has been cited as a notable early suggestion that the neural control of muscular action is electrical. It is more likely that he was merely distinguishing between an "Energy" whose "Force" is transmitted through the interior of the vessels and one that acts along the outside of the vessels. The only example of such a surface force that he knew was the force of static electricity, which his contemporary Stephen Gray had shown to be a surface effect.

When Hales named the book containing his studies on the circulatory system *Haemastaticks,* he was using the word statics in a traditional sense to mean weighing or gravimetric analysis, and by implication to mean the study of other types of force as well, particularly the forces of fluids. The two volumes *Haemastaticks* and *Vegetable Staticks,* Hales's book on plants, were given the general title *Statical Essays.* He referred to his approach to science as "the Statical Way of Investigation." In John Harris' *Lexicon Technicum,* an English dictionary of arts and sciences first published in 1704, statics is defined as a "Species of *Mechanicks,* conversant about Weights, and shewing the Properties of the *Heaviness* and *Lightness,* or *Equilibria* of Bodies." A well-known example of "statical" physiological experiments had been those in which the 16th-century physician Santorio Santorio had placed a man in a cage attached to one arm of a balance, in order to be able to record the change in the subject's weight during a period in which his solid and liquid intake and his solid and liquid excreta were also measured. In Hales's day and throughout the 18th century the adjective statical was applied particularly to experiments that measured the amount of perspiration and other excretions of the human body. That sense of the word, deriving directly from Santorio's experiments, fits Hales's work on plants more aptly than his work on animals.

In *Vegetable Staticks* Hales began by explaining his particular application of the "statical method" to studies of animals and plants. His experiments on animals had involved "the statical examination of their fluids, *viz.* by enquiring what quantity of fluids, and solids dissolved into fluids, the animal daily takes in for its support and nourishment: And with what force and different rapidities those fluids are carried about in their proper channels, according to the different secretions that are to be made from them." Since Hales believed in the fundamental unity of the principles underlying natural phenomena, he insisted that "in vegetables, their growth and the preservation of their vegetable life is promoted and maintained, as in animals, by the very plentiful and regular motion of their fluids." He concluded that it is "reasonable to hope, that in them also, by the same method of inquiry, considerable discoveries may in time be made, there being, in many respects, a great analogy between plants and animals."

The assumed analogy between plants and animals had led other investigators besides Hales to look for a circulation of the sap in plants analogous to the circulation of the blood in animals. They believed that the sap ascends in trees through the older wood in the inner parts of the trunk and the branches and that it descends in the spaces between the wood and the bark and in the external layers of the newer wood. There was no heart or vessel valves in plants, however, and so it was not impossible for the supposed flow of sap in plants to reverse its direction.

How could one undertake statical experiments on the circulation of the sap in plants? In the preface to *Vegetable Staticks* Hales referred to "several haemastatical Experiments on Dogs" that he had made 20 years earlier and had subsequently repeated on horses and other animals "in order to find out the real force of the blood in the Arteries." How he had wished then that he "could have made the like Experiments, to discover the force of the Sap in Vegetables"! He confessed, however, that at the time he had "despaired of ever effecting it."

Then in about 1720 he came on just such a method of experiment by accident. He had cut an old stem of a vine "too near the bleeding season" in the late spring, and he wanted to stop the "bleeding" lest the vine die. After several efforts that proved ineffective, he finally "tied a piece of bladder over the transverse cut of the Stem" and found that "the force of the Sap did greatly extend the bladder." It immediately occurred to him that he might affix a long glass tube to the stem "in the same manner, as I had before done to the Arteries of several living Animals." He would thus be able to measure "the real ascending force of the Sap in that Stem."

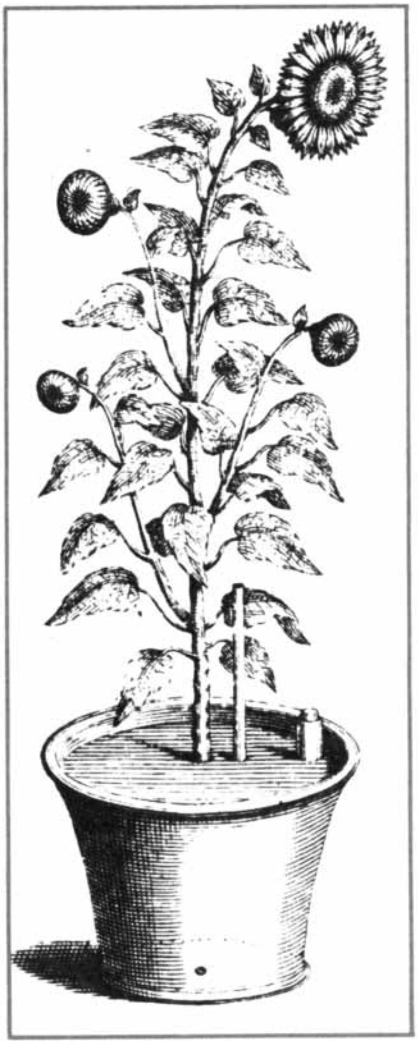
Hales's use of an open manometer succeeded according to his expectations and gradually led him to make "farther and farther researches by variety of Experiments." He described his experiments and conclusions in a manuscript he submitted to the Royal Society in January, 1725, where it was read in several installments at ensuing meetings. Later he sent a supplementary section, titled "Analysis of Air," consisting of 70 chemical experiments; this material eventually made up the long seventh chapter of *Vegetable Staticks,* which was published in London in 1727 with the imprimatur of Newton.

It is not possible in a brief compass to do justice to the many kinds of quantitative experiments Hales performed on plants. Hence I shall present only a few of his most significant investigations together with their implications for his general principles of plant science.

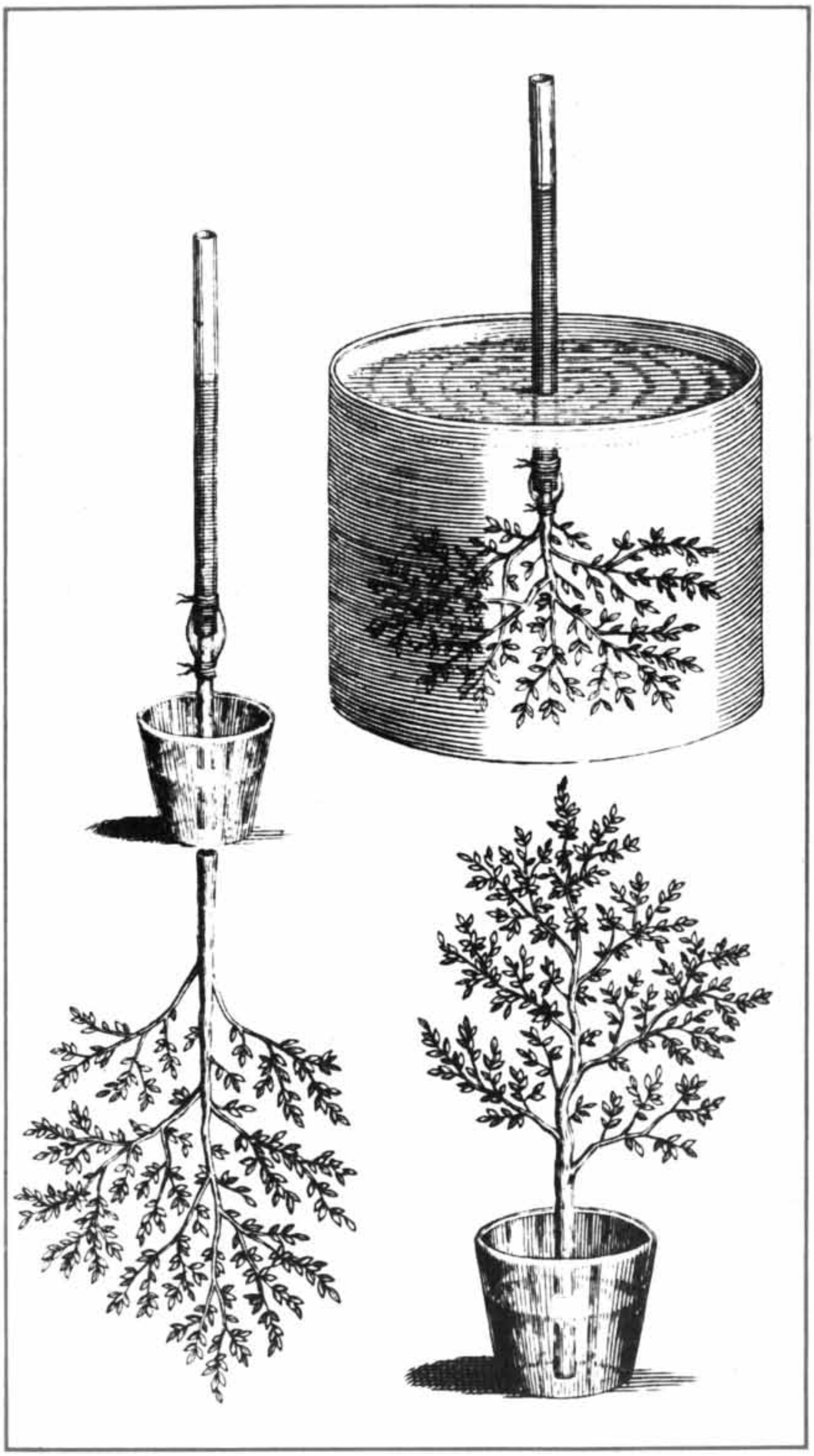
Hales conducted his first group of experiments in July and August of 1724. They were designed to determine the quantities of moisture "imbibed and perspired by Plants and Trees." He planted a sunflower three and a half feet high in an unglazed earthenware pot and covered the pot "with a plate of thin milled lead." The lead plate was cemented to the rim of the pot and fitted closely around the stem of the sunflower "so as no vapour could pass." Only a single thin glass tube penetrating the lead cover near the stem allowed air to pass to and from the root system and the soil. Another tube, farther from the stem, was fitted with a cork; through that tube Hales could pour measured quantities of water into the soil for the roots. Stoppers were fitted to the drainage holes at the bottom of the pot.

Over a period of 15 days Hales weighed the pot with the plant morning and evening. He realized that he had to make allowance for the fact that some of the water evaporated through the wall of the pot. Therefore at the end of the 15 days he cut off the plant close to the lead plate and covered the stump with cement. By weighing the plant as before he determined that "there perspired thro' the unglazed porous pot two ounces every twelve hours," a factor that had to be entered into the main measurement. He found from the experiment that on a very warm, dry day the "greatest perspiration" rate was one pound 14 ounces (avoirdupois) of water in 12 hours; the "middle rate of perspiration" over the entire 15 days was one pound four ounces in 12 hours. On "a dry warm night, without any sensible dew," the "perspiration . . . was about three ounces." With any dew whatsoever there was no "perspiration," and when there was a heavy dew or a light rain, the pot and the plant increased in weight by two or three ounces.

Hales's next step was to estimate the surface area of the leaves and of the roots. He cut the leaves off the sunflower and sorted them into five piles according to their size. He measured the area of a representative leaf in each pile by placing it over "a large lattice made with threads, in which the little squares were $\frac{1}{4}$ of an inch each." He now multiplied the area by the number of leaves in the pile. With this method he found "the surface of the whole plant, above ground, to be equal to 5616 square inches, or 39 square feet." He then estimated the length of all the



A SUNFLOWER planted in an unglazed earthenware pot was used by Hales in the summer of 1724 to determine the quantities of moisture "imbibed and perspired by Plants and Trees." Hales covered the top of the pot with a lead plate sealed to the pot around the edges so that no moisture could escape. One tube allowed air to pass to and from the roots. Through another tube, fitted with a cork, Hales poured measured quantities of water. By weighing the pot twice a day he monitored the loss of the water. He concluded that the water was imbibed by the roots and was "perspired," or transpired by way of the leaves.



BRANCHES OF FRUIT TREES were the subjects of Hales's next experiments to determine exactly what forces caused water to flow in plants. He attached a glass tube to an apple-tree branch "full of leaves," filled the tube with water and compared the rate at which the branch imbibed the water when its leaves were exposed to the air with the rate at which it imbibed the water when the leaves were immersed in a tank of water (*top right*). He found that when the leaves were exposed to the air, the rate was significantly higher. That observation led him to conclude that the water was not merely pushed up by the roots but was drawn up through the plant by the exhalation of moisture through the leaves. In a further experiment he found that very little water could be driven through a 13-inch portion of the branch's stem without the leaves (*left*) simply by the hydrostatic pressure of water in a glass tube above it. Yet when the rest of the branch with its leaves was stood upright in a vessel of water (*bottom right*), it imbibed much more water in the same length of time, showing the great "power of perspiration."

roots and multiplied that length by the average circumference of the roots, which he took to be about 10/76 inch. In this way he found that the roots had a surface area of "2286 square inches, or 15.8 square feet; that is, equal to $^3/_8$ of the surface of the plant above ground."

Next Hales set out to compute the velocity with which the water flowed in different parts of the plant, using the same method he had developed for finding the speed with which the blood flowed in the arteries, veins and capillaries of animals. He calculated that the average rate of the plant's transpiration of 20 ounces of water in 12 hours corresponded to a volume of 34 cubic inches of water in 12 hours. That is, 34 cubic inches of water entered through an area of 2,286 square inches of root surface in 12 hours. Therefore the water must have entered the roots at a rate of 34/2,286 cubic inches of water per square inch in 12 hours, or 1/67 cubic inch of water per square inch of root system in 12 hours. The rate at which the water was transpired through the leaves came out to 34/5,516 cubic inches of water per square inch in 12 hours, or a speed of 1/165 cubic inch of water per square inch of leaf surface in 12 hours. Since the main stem of the sunflower proved to be one square inch in cross section, Hales concluded that the water must have risen in the stem at a speed of 34 inches in 12 hours, on the supposition that the stem was hollow. He then investigated what factors, if any, were needed to correct for the fact that the stem consists of solid structures.

Those three speeds were in the ratio of 1/2,286 : 1/5,616 : 1, or nearly 5 : 2 : 10,000. An error arose, however, from the fact, discovered much after Hales's time, that only a part of the root imbibes fluid. And Hales also did not know that only part of the stem, composed of the dead xylem cells, is involved in the upward transport of water. Furthermore, his method of calculating the surface area of the root took no account of the system of fine root hairs; if it had, the area of the root in his calculations would have been greatly increased.

Having proved that water is imbibed by the roots of the sunflower and is transpired through the leaves, and having determined the rates of imbibition and transpiration and the speed with which the fluid moves in these processes, Hales set out to determine the same rates for other plants, among them the cabbage, certain vines, several varieties of apple tree, a lemon tree, a "*Musa Arbor,* or *Plantain-tree* of the *West-Indies,*" a Carolina aloe, a spearmint bush and various other fruit trees and evergreens. He also compared and contrasted the perspiration rate in man and the transpiration rate in plants with respect to their weight, surface area and temperature. One of his conclusions shows how he saw a plan in all the phenomena of life: "And since, compared bulk for bulk, the plant perspires seventeen times more than the man, it was therefore very necessary, by giving it an extensive surface, to make a large provision for a plentiful perspiration in the plant, which has no other way of discharging superfluities; whereas there is provision made in man, to carry off above half of what he takes in, by other evacuations."

Hales next set out to find the forces that cause the water and the sap to flow. Malpighi and the 17th-century English botanist Nehemiah Grew, among others, had suggested that capillary action, the attraction of a liquid by a solid surface, is what causes sap to rise, at least to a certain height. Could capillary action, however, explain the continuous motion of water and sap that Hales had observed? And would it also be affected by humidity and temperature?

Hales conducted several experiments to answer those questions. In one experiment he cut off similar pairs of branches from four different fruit trees. Each branch was between three and six feet long. He stripped the leaves from one branch of each pair. Then he set the lower end of each branch in a separate vessel filled with a known quantity of water. The branches with the leaves on them in each case imbibed more water than those without leaves, "more or less in proportion to the quantity of leaves they had." Evidently it was the action of the leaves and not solely that of the capillaries in the branches that determined the rate at which the fluid flowed.

To further test this hypothesis Hales attached a glass tube, seven feet long and five-eighths of an inch in diameter, to the base of an apple-tree branch "full of leaves." He hung the tube with the branch at the bottom, filled the tube with water and immersed the branch in a tank of water so that the junction of the branch and the tube was well below the surface. He found that the water in the tube "subsided 6 inches the first two hours, (being the first filling of the sap vessels) and 6 inches the following night, 4 inches the next day; and 2 + 1/4 the following night." On the morning of the third day he took the branch out of the water "and hung it with the Tube [still] affixed to it in the open air; it imbibed this day 27 + 1/2 inches in 12 hours." He correctly concluded that the experiment "shews the great power of perspiration; since when the branch was immersed in the vessel of water, the 7 feet column of water in the tube, above the surface of the water, could drive very little thro' the leaves, till the branch was exposed to the open air." He also concluded that since trees "perspired" more in warmer weather, what causes the leaves to perspire is not merely the force of the rising sap. On the contrary, a major cause of the water being drawn up through the plant must be the exhalation of moisture through the leaves.

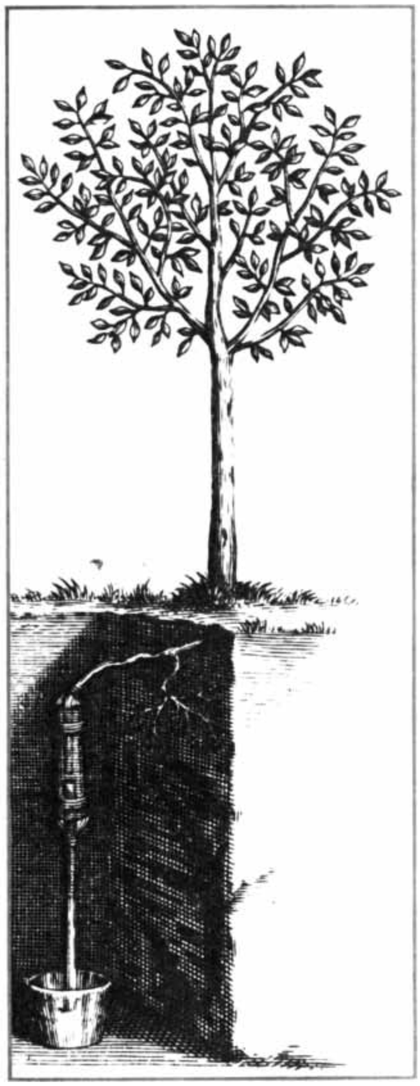
To quantitatively determine the "power of perspiration" in drawing the water upward through the plant Hales now cemented a nine-foot glass tube to a five-foot apple-tree branch full of leaves. He hung the tube and the branch as he had before, but he did not immerse the branch in water. When he poured water into the tube, he found it to be "imbibed plentifully, at the rate of 3 feet length of the tube in an hour." Next he cut off the branch at a point 13 inches below the glass tube and put a glass vessel around the stump, covering the space between the sides of the branch and the rim of the vessel with stretched ox gut to prevent the evaporation of any water that might pass through the branch into the vessel. Again he filled the tube with water. In this way he found that the hydrostatic pressure of seven feet of water in the tube could force only six ounces of water through the 13-inch stem in 18 hours by day or 12 hours by night. Yet if the rest of the branch with its leaves was stood upright in a vessel of water, a full 18 ounces of water would be imbibed and drawn upward in the same length of time, which again showed "the great power of perspiration."

There was no longer any question that transpiration through the surface of leaves is a major agent in promoting the flow of sap and water in plants. Nevertheless, Hales thought it was necessary to conduct a series of three additional experiments "to try whether the capillary sap-vessels had any power to protrude sap out at their extremities, and in what quantity." From that series of experiments he concluded: "Tho' the capillary sap vessels imbibe moisture plentifully; yet they have little power to protrude it farther, without the assistance of the perspiring leaves, which do greatly promote its progress."

Hales now devised still another series of experiments to measure the force with which trees imbibe moisture. Here he studied the imbibing force in the same way that he had studied transpiration. For this purpose he used what he called "aqueo-mercurial" gauges, which could be applied to a root, a main stem or a branch of the plant he was studying. For example, he "dug down 2 + 1/2 feet deep to the root of a thriving baking *Pear-tree,* and laid bare a root 1/2 inch diameter." He cut the root and joined to its upper end, which was still attached to the tree, a glass tube eight inches long and an inch in diameter. The other end of the tube was joined to a second tube 18 inches long and a quarter of an inch in diameter. He turned the combination of tubes upward, filled both tubes with water, placed his finger over the open end of the smaller tube and inverted the tubes in a pit beside the tree, with the larger tube still joined to the root. He now placed the end of the smaller tube, still stoppered by his finger, in a vessel filled with mercury. When he removed his finger, the air pressure acting on the surface of the mercury prevented the water in the tubes from running out. As the root imbibed the water from the upper tube the mercury rising in the lower tube acted as a gauge.

In warm air or in direct sunshine the mercury began to rise rapidly in the small tube as the water in the large tube was imbibed. The rate of imbibition diminished in cool air or in the absence of sunshine. At night the mercury in the tube fell. Hales writes that the height of the mercury "did in some measure shew the force with which the sap was imbibed." He conducted many variations on this experiment to test the effect of such factors as removing the bark of the tree or leaving the fruit as well as the leaves on the branches. He explained the results he obtained in Newtonian terms as "many instances of the great efficacy of attraction; that universal principle which is so operative in all the very different works of nature; and is most eminently so in vegetables."

Hales had thus answered some fundamental questions about the nature of green plants. By measuring the intake of water, the loss of water by transpiration and the variation in both with changing conditions,

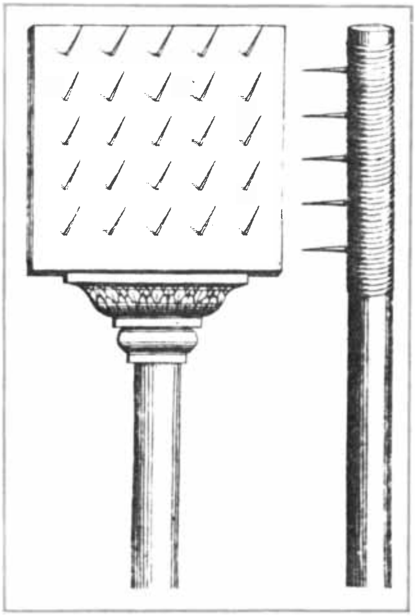


"IMBIBING FORCE" of the root of a tree drawing water was measured by Hales with what he called an aqueo-mercurial gauge. He laid bare the root of a pear tree and attached the upper end of the root to a wide glass tube filled with water. To the wide tube he then fastened a narrow tube, the lower end of which he placed in a vessel of mercury. As the root imbibed the water in the wide tube the mercury was drawn upward in the narrow tube, and its height thus acted as a measure of the force with which the water was imbibed.

he had shown the special function of the leaves in transpiration and of the roots in imbibition. He did not know how the leaves act to produce transpiration, and he was not aware that there are special structures in the leaves (the stomata) through which water is transpired. And after having discovered the existence of root pressure he had no clue to the fact that it is caused primarily by the osmosis of water through the root hairs and the root cells. He had nonetheless proved that capillary action alone could not account for the rise of sap through the stem of the plant, and he had shown how additional forces moving the sap upward came from the roots and the leaves.

In Hales's writings he does not exhibit much interest in the architecture of plants or in the distinguishing details of different plant structures. If he had been interested in such matters, he might have made an even greater contribution. He may have believed, however, that careful studies of both the macroscopic and the microscopic features of plants would not yield clues to the causes of the phenomena he observed involving the flow of fluids. In any event his temperament led him in different paths of investigation. He sought the immediate cause of the movement of water and sap in the combined effects of root pressure and transpiration, and he did not concern himself with ultimate causes, which he believed were to be found in the omniscience and omnipotence of God.

The work on plants I have described so far is found in the first two chapters of *Vegetable Staticks.* Hales summarized his results by stating that first he had shown "the great quantities imbibed, and perspired by trees," and then he had measured "the force with which they do imbibe moisture." He now turned to the force that causes "bleeding" in plants, a phenomenon indicating that there must be great pressure behind the sap that makes it flow copiously from a wound even before the leaves make their appearance. That running of the sap in the spring is a familiar sight in New England, where sugar maples are tapped to collect the sap that is then boiled down to maple syrup. (In trees such as maples, however, the phenomenon is far more complex than it is in the vines Hales studied.)

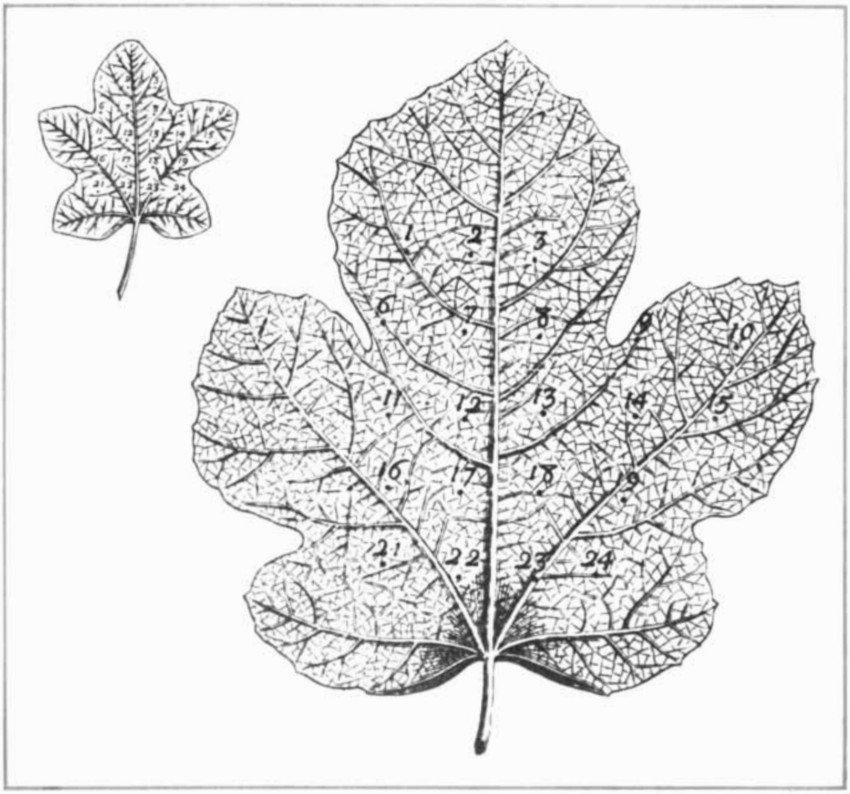


TWO INSTRUMENTS to measure growth of plants were devised by Hales. He marked the stem of a plant by pricking it with five pins attached to a pole, each pin spaced a quarter of an inch from its nearest neighbor (*right*). He marked the leaves of a plant with an inch-square array of 25 pins attached to a spatula (*left*). To make lasting marks he first dipped the points of the pins into red lead.

Hales measured the springtime sap pressure by placing open mercury manometers on a cut vine, sometimes even putting three manometers on different branches of the same vine. He was thus able to observe the force of the sap flowing out of a branch in terms of the height of the column of mercury. Furthermore, he could actually watch when the sap flowed, when it was imbibed again and when it was neither flowing nor being imbibed. With this technique he established that there is "a considerable energy in the root to push up sap in the bleeding season." He found that the force of the rising sap in the morning was sufficient to raise the mercury to 38 inches, a force equal to the pressure exerted by a column of water 43 feet 3.3 inches high. Such a tremendous force, Hales noted, "is near five times greater than the force of the blood in the great crural artery of a Horse."

Although Hales had discovered the existence of root pressure, he concluded that the roots are not solely responsible for the pressure of the sap in the branches. The experiment with three manometers showed that the three branches did not all imbibe and exude sap at the same time. For example, one branch might be "in an imbibing state" while another was "in a state of pushing sap." Hence the experiment showed that the force "is not from the root only, but must proceed from some power, in the stem and branches" as well.

In further experiments Hales was able to demonstrate that there is a lateral flow of sap across a stem. He also looked into the question of a possible descent of sap. He did find some evidence of downward flow, but he pointed out that such flow was likely to occur only at night, when a drop in temperature would cause the ascending sap to fall in the same way that mercury or alcohol falls in a thermometer. He did not believe that the sap might descend through the bark or that there might be a circulation of fluid in plants analogous to the circulation of blood in animals. That defect, as he called it, was in some measure compensated for by "the much greater quantity of liquor, which the vegetable takes in." Hales had found by experiment that "the Sunflower, bulk for bulk, imbibes and perspires seven-



GROWTH OF A FIG LEAF is clearly shown with Hales's technique. An illustration of a young leaf just marked with the points of red lead (*left*) is compared with an illustration of the same leaf fully grown (*right*). Irregular spacing of numbered points on larger leaf shows that all portions of a leaf do not grow uniformly. Hales found the same to be true of stems of plants.

teen times more fresh liquor than a man, every 24 hours." In any event, he concluded, "nature's great aim in vegetables being only that the vegetable life be carried on and maintained, there was no occasion to give its sap the rapid motion which was necessary for the blood of animals."

Hales's methods of investigation were not developed to the point where he could distinguish between the force arising from normal root pressure and the force arising from the special conditions that exist in the plant in the early spring before the leaves appear. It was actually this second force that he measured with his experiments on vines.

Hales was also concerned with quantitative aspects of the growth of plants. He monitored the growth rates of plants by two techniques. In one technique he made a spatula with 25 pins in it forming a square array with five pins on a side. The 25 pins divided one square inch into 16 square boxes, with each box having a pin in each of its four corners. In the early spring, when the leaves of the plants were young, Hales pricked several leaves "with the points of all these pins, dipping them first in the red lead, which made lasting marks." Thus he was able to observe and to measure the different rates of growth in the various parts of a leaf.

In the other technique Hales made marks a quarter of an inch apart along the stem or young shoot of a vine. He found that the plant grew at the highest rate in the region between the nodes where leaves branch out from the main stem, and not in the region close to the nodes themselves. That result was in marked contrast to the growth of bones in animals, as Hales observed when he conducted a similar experiment on the two-inch leg bone of a "half grown Chick": "With a sharp pointed Iron at half an inch distance I pierced two small holes through the middle of the scaly covering of the leg, and shin-bone; two months after I killed the Chick, and upon laying the bone bare, I found on it obscure remains of the two marks I had made at the same distance of half an inch: So that that part of the bone had not at all distended lengthwise, since the time that I marked it: Notwithstanding the bone was in that time grown an inch more in length, which growth was mostly at the upper end of the bone, where a wonderful provision is made for its growth at the joining of its head to the shank, called by Anatomists *Symphysis*."

Having dealt at length with fluids in plants, Hales turned to the role of the circumambient air. Here he was inspired by the well-known fact that, as he said, "air is a fine elastick fluid [that is, a compressible gas], with particles of very different natures floating in it." Those properties made air "admirably fitted by the great Author of nature, to be the breath of life, of vegetables, as well as of animals, without which they can no more live nor thrive than animals can." He proved that air nourishes the plant and even provides some of the matter that makes up its substance. With a vacuum pump and a bell jar he demonstrated that "it is very probable, that the air freely enters plants, not only with the principal fund of nourishment by the roots, but also through the surface of their trunks and leaves, especially at night." That led him naturally to a discussion of air itself: to how it enters in so "great a proportion . . . into the composition of animal, vegetable, and mineral Substances," and how it might be released from such substances by chemical action to resume its former gaseous state.

Hales's chemical analysis of air occupies almost half of *Vegetable Staticks.* Interesting as his investigations are for specialists in the history of chemistry and physics, they do not have the general importance for science at the fundamental level that characterizes his work in biology, notably in plant physiology. Hales was essentially a Newtonian chemist; his approach to the subject of air has been characterized by the historian of science Henry Guerlac as "more physical than chemical." Hales tended to think of air as a unitary substance characterized by its physical property of elasticity, and so he failed to note the different chemical properties of the various kinds of air he produced.

Guerlac has nonetheless shown the wide influence on other investigators of one aspect of Hales's work on airs: his concept of "fixed air," or carbon dioxide. He called it fixed air because it was fixed in many different kinds of substance (animal, vegetable and mineral) and was released and absorbed by natural and artificial processes. In particular his work was of real importance in the development of the chemistry of Antoine Laurent Lavoisier. Guerlac has demonstrated that one key concept Lavoisier drew from his reading of Hales was that the effervescence observed in various chemical reactions was not merely the result of fermentation or of the thermal agitation accompanying the reaction; it was produced by the sudden release of fixed air. Hales also pioneered in the development of chemical techniques; his most important innovation was the pneumatic trough for collecting gases as they displaced water.

Hales was interested in practical devices, and after the publication of *Vegetable Staticks* he turned his attention to such problems as converting salt water into fresh water fit for human consumption. He also succeeded in having mechanical ventilators of his own invention introduced into prisons, where the crowded conditions and foul air had been a principal cause of bad health, and into ships to force fresh air into the holds. As he grew older he turned from pure science to practical problems of applied chemistry and physiology, particularly in connection with the common affliction then known as distemper of the stone. He hoped to find a solvent that might dissolve stones in the bladder, and he experimented in vain on numerous human stones supplied to him, chiefly by the Surgeon to the Royal Household. Although it was no problem to find solvents that would work on such stones in vitro, they were all too strong for human consumption. Hales thereupon turned his inventive energies to designing a new form of catheter combining the features of a cannula and a miniature set of forceps, which was actually used by a number of surgeons. We are reminded of Benjamin Franklin, whose career has many features in common with Hales's and who also invented a new kind of catheter for kidney stones.

When Hales was 43, he married. His wife died about a year later. His life as a clergyman was not very eventful. He performed the customary duties and seems to have been able to make both men and women do "Public Penance" (which he faithfully entered in the parish records) for adultery, fornication or bearing an illegitimate child. According to Collinson, he sought no preferment in the church, lest "his time and attention might thereby be diverted from his other favorite and useful occupations."

In May, 1733, Hales was recommended for a degree of Doctor of Divinity at Oxford "on account of his excellent performances so justly esteemed in the learned world, and the virtues which adorn the character of a clergyman." The degree was conferred a few months later. A greater honor was his election in 1753 as one of the eight foreign associates of the French Academy of Sciences.

In 1732 Hales became one of the trustees for the American colony of Georgia, and he seems to have played a prominent part in the colony's affairs as a member of both the Trustee Board and the Common Council. The primary aim was to relieve pauperism, and accordingly emigrants were granted 50 acres of land free of rent for the first 10 years, together with tools and arms. Many of those who went to Georgia were debtors, freed from prison according to a recently enacted law.

Hales died in 1761 at the age of 83. According to his last will and testament, he left all his books that the executor should think proper to "a public parochial Library to such Town or Parish in Georgia in America [as] the Governor shall think fit to appoint." Hales even made a provision that the transportation of those books to Georgia was "to be at the expense of my Executor and Executrix." To this day there is no record that the books ever came to Georgia, although it is difficult to believe that such an express wish was totally ignored.

There are, however, two continuing memorials to Hales and his American connections. A lovely flowering tree native to the region of Georgia was named *Halesia* in his honor by John Ellis, an American botanist of Colonial times. And the American Society of Plant Physiologists today recognizes outstanding contributions to botany by conferring the Stephen Hales Award.

The Galilean Satellites of Jupiter

First observed by Galileo in 1610, these four largest of Jupiter's moons have begun to be explored by passing spacecraft. What is being revealed is unlike anything seen so far in the solar system

by Dale P. Cruikshank and David Morrison

"On the 7th day of January in the present year, 1610, the first hour of the following night, when I was viewing the constellations of the heavens through a telescope, the planet Jupiter presented itself to my view, and . . . I noticed . . . that three little stars, small but very bright, were near the planet; and although I believed them to belong to the number of the fixed stars, yet they made me somewhat wonder, because they seemed to be arranged exactly in a straight line, parallel to the ecliptic, and to be brighter than the rest of the stars."

Thus did Galileo Galilei recount his discovery of the first three "Medicean stars" in his epoch-making book *The Sidereal Messenger.* Over several nights his observations showed not just three objects attendant on Jupiter but four, and from their motions he correctly deduced that they travel in orbit around the planet. The discovery of this miniature solar system did much to establish the Copernican picture of a heliocentric planetary system and to set the stage for the development of a universal theory of celestial mechanics by Johannes Kepler and Isaac Newton. Although the Bavarian astronomer Simon Mayer appears to have found the four satellites of Jupiter independently and may even have observed some of them a month before Galileo did, he did not recognize their significance, and he did not communicate his findings to Kepler and other scholars of the period until after Galileo's announcement was published.

Later, in his *Dialogue concerning the Two Chief World Systems,* finished in 1629, Galileo's interlocutors Salviati and Sagredo discuss the importance of Jupiter's four satellites:

Salviati: "We see Jupiter, like another earth, going around the sun in 12 years accompanied not by one but by four moons, together with everything that may be contained within the orbits of its four satellites."

Sagredo: "And what is the reason for your calling the four Jovian planets 'moons'?"

Salviati: "That is what they would appear to be to anyone who saw them from Jupiter. For they are dark in themselves, and receive their light from the sun; that is obvious from their being eclipsed when they enter into the cone of Jupiter's shadow. And since only that hemisphere of theirs is illuminated which faces the sun, they always look entirely illuminated to us who are outside their orbit and closer to the sun, but to anyone on Jupiter they would look completely lighted only when they were at the highest points of their circles. In the lowest part—that is, when between Jupiter and the sun—they would appear horned from Jupiter. In a word, they would make for Jovians the same changes of shape that the moon makes for us Terrestrials."

For most of the three and a half centuries that followed Galileo's discovery the four bright satellites of Jupiter, aptly named the Galilean satellites, attracted little attention among astronomers. Since the 1960's, however, as the interests of planetary scientists have progressed outward in the solar system to the planets that have large numbers of satellites, the entire retinue of 33 natural satellites has come under close scrutiny. Attention has naturally focused on the Galilean satellites, which are the brightest and easiest to study of all the planetary satellites except the earth's own moon.

The Galilean satellites are known by the names first suggested by Mayer, which are those of Jupiter's lovers in Greco-Roman mythology. Proceeding outward from the planet, they are Io, Europa, Ganymede and Callisto. Jupiter has at least nine other satellites (including one discovered in 1974), but they are all so small and faint that virtually nothing is known of their physical properties. The big four, in contrast, are practically planet-sized spheres, and observations made with ground-based telescopes and with the spacecraft *Pioneer 10* and *Pioneer 11* reveal them as being unique and fascinating places: worlds in their own right, yet worlds strikingly different from Mercury, Mars and the moon, bodies of similar size in the inner solar system.

Our understanding of the surfaces of the Galilean satellites has evolved from a variety of ground-based observations. The first physical studies of the satellites consisted of precision measurements of their brightness at the Lick Observatory in the mid-1920's. Those photometric observations showed that the brightness of each satellite varies by as much as 40 percent, with a periodicity equal to the orbital period. It was therefore concluded that the satellites vary in reflectivity across their surfaces and that they are locked in synchronous rotation around Jupiter, keeping the same face toward the planet at all times. There are sound dynamical reasons for satellites fairly close to their planet being locked into synchronous rotation; indeed, our moon and all the satellites of Mars, Jupiter and Saturn for which periodic variations in brightness can be measured show this property.

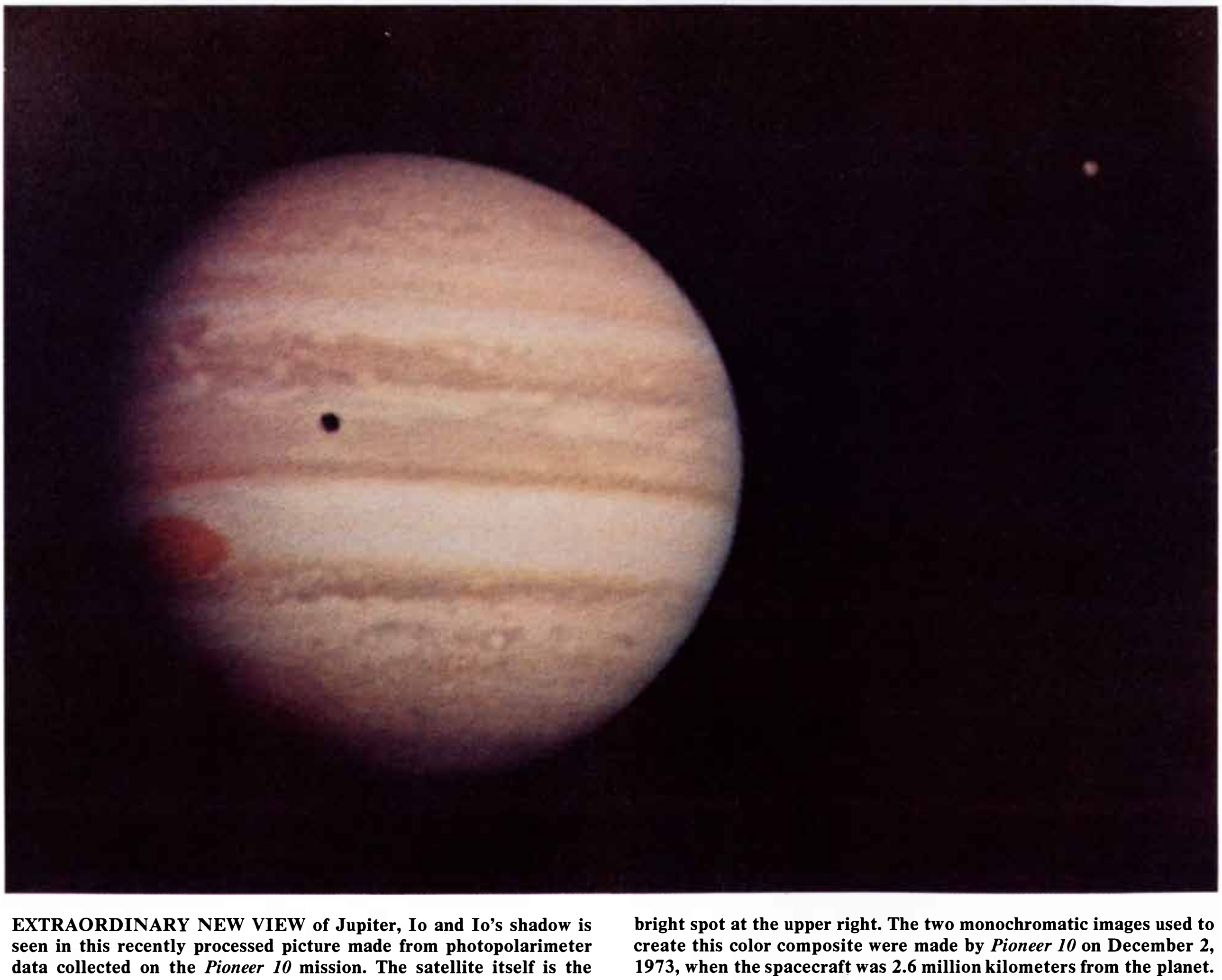
Early photometric studies revealed not only that the Galilean satellites rotate but also that their surfaces differ greatly from one another in both reflectivity and color. Io is particularly red, and its color, together with its high reflectivity (about 62 percent, roughly equivalent to white sand), make it a unique object in the solar system. Europa is equally reflective but is more neutral in color. Ganymede's surface has a reflectivity of about 44 percent, comparable to dirty snow or to finely pulverized rock. Callisto's reflectivity is only 19 percent, similar to that of many common terrestrial rocks and of the very brightest areas on our moon. From photometry alone one can conclude that these four objects have different surface compositions, but identifying the chemical constituents of the surfaces is a more difficult task.

For each satellite the variation of brightness with rotation is related to orbital motion. Io is brightest on its leading side and darkest (and reddest) on its trailing side. The same is approximately true of Europa and Ganymede. Callisto is the exception, keeping its dark face forward and its lighter hemisphere behind. The meaning of the leading-trailing asymmetry is not understood. As the satellites move in their orbits there is a statistical tendency for them to encounter more meteoritic debris on their leading side, and over the aeons this statistical difference may have resulted in the accumulation of meteoritic material on their surface. Some investigators have speculated, however, that because of the sandblasting effect of meteoritic impacts the original surface layer on the leading hemisphere would be preferentially worn away, exposing materials at levels lower than those on the trailing hemisphere.

Additional information on the structure and composition of the surfaces of the Galilean satellites can be derived from measurements of their temperature. For the illuminated hemisphere an average temperature can be measured by recording the thermal infrared radiation. The first such measurements were made 14 years ago at the Hale Observatories and the University of Arizona. The data showed that the four satellites had temperatures essentially in equilibrium with the incident sunlight. At their distance from the sun (five times greater than that of the earth), however, even the noonday temperatures are quite low, ranging from −106 degrees Celsius for dark Callisto to −133 degrees C. for Io and Europa, which reflect most of the sunlight away. These temperatures are extremely interesting from a compositional point of view, since it is precisely in this range that one expects to see the

BEST VIEW obtained to date of one of the moons of an outer planet in the solar system is this color composite picture of Ganymede, the largest of the Galilean satellites. The composite was made by combining two images recorded simultaneously through red and blue filters by the photopolarimeter system on board the *Pioneer 10* spacecraft. At the time the images were made (on December 3, 1973) the spacecraft was approaching Jupiter and was more than 750,000 kilometers from the surface of the satellite. The surface resolution of the imaging system at that distance is approximately 400 kilometers. When one of two forthcoming Mariner missions to Jupiter and Saturn reaches the vicinity of Ganymede in 1979, it is expected to reveal structures on the surface of the satellite as small as a few hundred meters across, a resolution comparable to that of the detailed television pictures of Mercury returned by *Mariner 10* in 1974. Ganymede, a comparatively low-density body slightly larger than Mercury, is believed to be covered by a rocky ice crust some 100 kilometers thick.

RED POLAR CAPS of Io, the innermost of the Galilean satellites, were discovered by R. B. Minton of the University of Arizona in the photograph at the left, made with the 1.5-meter telescope at the Catalina Observatory on the night of August 9, 1973. The satellite itself is the faint image seen slightly to the right of the conspicuous black shadow it casts on the Jovian surface. The red caps are visible only when they are viewed against one of the light-colored bands of Jupiter. In the photograph at right, made 16 minutes later, the caps can no longer be distinguished because of the darkening of the band near Jupiter's limb. The Great Red Spot moves into view at the lower left.



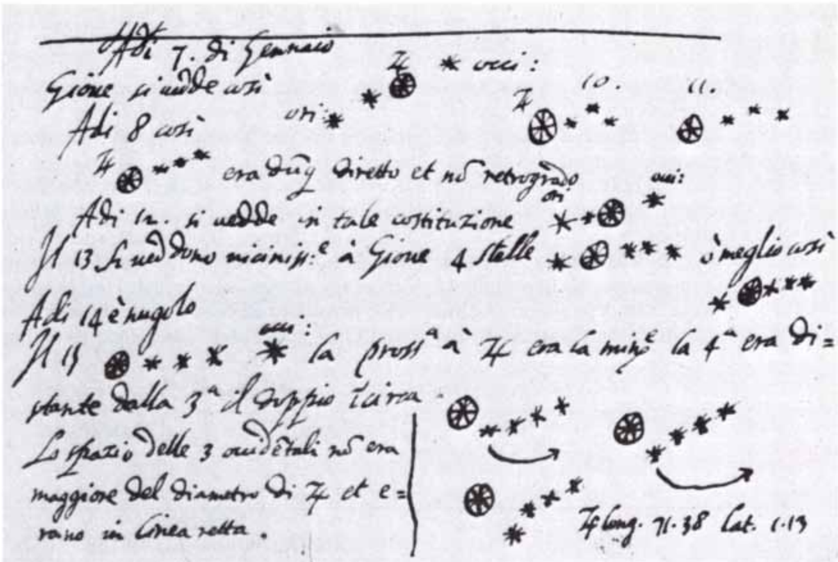
EXTRAORDINARY NEW VIEW of Jupiter, Io and Io's shadow is seen in this recently processed picture made from photopolarimeter data collected on the *Pioneer 10* mission. The satellite itself is the bright spot at the upper right. The two monochromatic images used to create this color composite were made by *Pioneer 10* on December 2, 1973, when the spacecraft was 2.6 million kilometers from the planet.

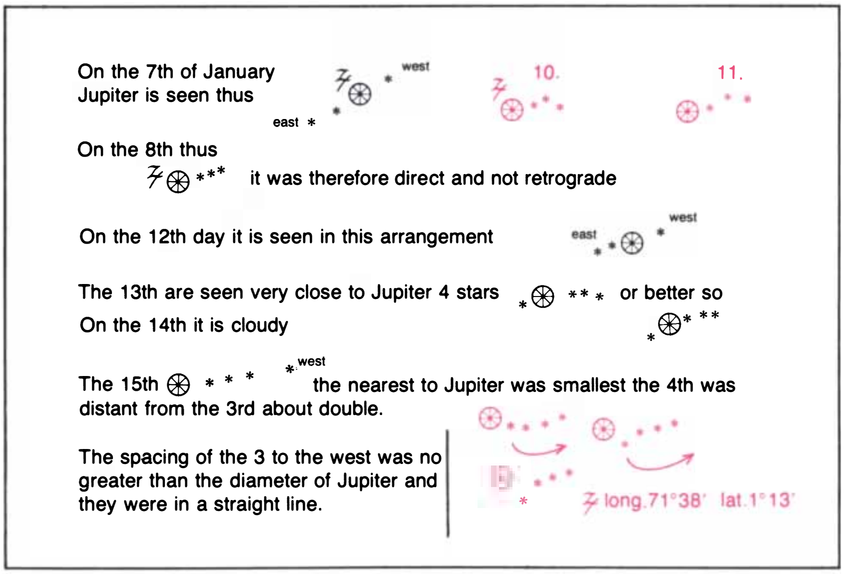
transition from a regime in which ordinary water ice evaporates so slowly that it is stable over the 4.5-billion-year history of the solar system to a regime in which exposed ice would have a lifetime of no more than a few million years.

On each orbit the satellites pass through the shadow of Jupiter and are eclipsed. During the two or three hours when the sunlight is effectively cut off, the temperature of a satellite's surface must drop several tens of degrees. A measurement of the steepness of the temperature decrease as the satellite enters the shadow or of the temperature increase as it returns into the sunlight can yield information on the thermal-insulating properties of the uppermost surface layers. Working with the 2.2-meter telescope on 14,000-foot Mauna Kea in Hawaii, we have measured the change in infrared radiation from all four satellites as they enter and emerge from the shadow of Jupiter. The results of these studies show that the thermal conductivity of the surfaces of the Galilean satellites is exceedingly low, comparable to that of commercial insulating materials on the earth. Either fine rock powder or loosely packed frost crystals could have these thermal properties. The eclipse observations also enable us to calculate that the otherwise unobservable temperatures on the night side of the satellites drop as low as −193 degrees C., about the temperature of liquid air.

Although such studies tell much about the structure of a satellite's surface, a more direct line of evidence on its chemical composition is provided by low-resolution spectroscopy. Particularly at wavelengths in the near-infrared region of the spectrum many common minerals and frosts can reveal their presence by their characteristic absorption of certain wavelengths in the incident sunlight. In the mid-1950's Gerard P. Kuiper of the University of Arizona first measured the reflectivity of Europa and Ganymede at wavelengths of between one micrometer and three micrometers and pointed out similarities with laboratory spectra of water frost. It was not until 1971, however, that infrared instruments had become sensitive enough to make it possible to obtain higher-resolution spectra of all four satellites. Cal B. Pilcher and his colleagues obtained interferometric spectra at the Kitt Peak National Observatory while, working independently but simultaneously, Uwe Fink and his colleagues were acquiring similar data just 80 miles away at the Catalina Observatory of the University of Arizona. The results agreed: broad and distinct absorption features attributable uniquely to water frost at low temperature (consistent with the temperatures of the satellites) were found in the spectra of both Europa and Ganymede but not in those of Io and Callisto. From an analysis of the depth of the frost bands in the spectra Pilcher concluded that for Europa between 50 and 100 percent of the surface is exposed frost and for Ganymede the figure is between 20 and 65 percent. If it is assumed that the rest of the surface is covered with dark rocky material, probably mixed in with the frost, these estimates of the quantities of frost present are consistent with the measured reflectivities. According to this picture Callisto is presumed to have an entirely rocky surface, but the available reflection spectra do not indicate the mineralogical composition of the surface material.

The reflection spectrum of Io is unique. We have mentioned the satellite's red color, which is indicative of a reflectivity that declines sharply toward the blue end of the spectrum. From the yellow all the way out through the infrared, however, the reflectivity of Io is uniformly high. The absence of infrared-absorption features apparently precludes the presence of significant quan-


Adi 7. di Gennaio Giove si vedde così
10. 11.
Adi 8 così era dunq diretto et no retrogrado
Adi 12. si vedde in tale costituzione
Il 13 si veddono vicinissime à Giove 4 stelle o meglio così
Adi 14 è nugolo
Il 15 così la prossima à Giove era la minore la 4a era distante dalla 3a il doppio in circa.
Lo spatio delle 3 occidentali no era maggiore del diametro di Giove et erano in linea retta.
Giove long. 71.38 lat. 1.13



GALILEO'S NOTES summarizing his first observations of the moons of Jupiter in January, 1610, were entered on a piece of "scratch paper" that had previously served as the first draft of a letter he had written several months earlier presenting a telescope to the Doge in Venice. The original manuscript page on which the notes were found is reproduced in part at the top through the courtesy of the University of Michigan Library, Department of Rare Books and Special Collections. A translation from the original Italian, made by Stillman Drake of the University of Toronto, appears at the bottom. According to Drake, the sketches marked *10* and *11* (*shown in the transcription in color*) are not observations for those two days; instead they probably represent two further sketches of the three western satellites made on the night of January 13 and subsequently mislabeled by Galileo in reviewing his notes. In addition, the three sketches that appear at the bottom right (*also in color*) are probably not observations but rather diagrams sketched by Galileo in his search for a theory to account for all observations. The idea that the objects were in simple rotation around Jupiter occurred to Galileo after he made the sketches.

tities of ice or frost, and the overall high reflectivity is not consistent with ordinary rocky minerals. Among the few substances that seem compatible with the observations are sulfur (finely divided and of course at low temperature) and any of several common salts (such as sodium chloride, Epsom salts or sodium sulfate). We shall discuss below whether such materials seem plausible on other grounds. First, however, we must examine the probable interior structure and past history of the satellites.

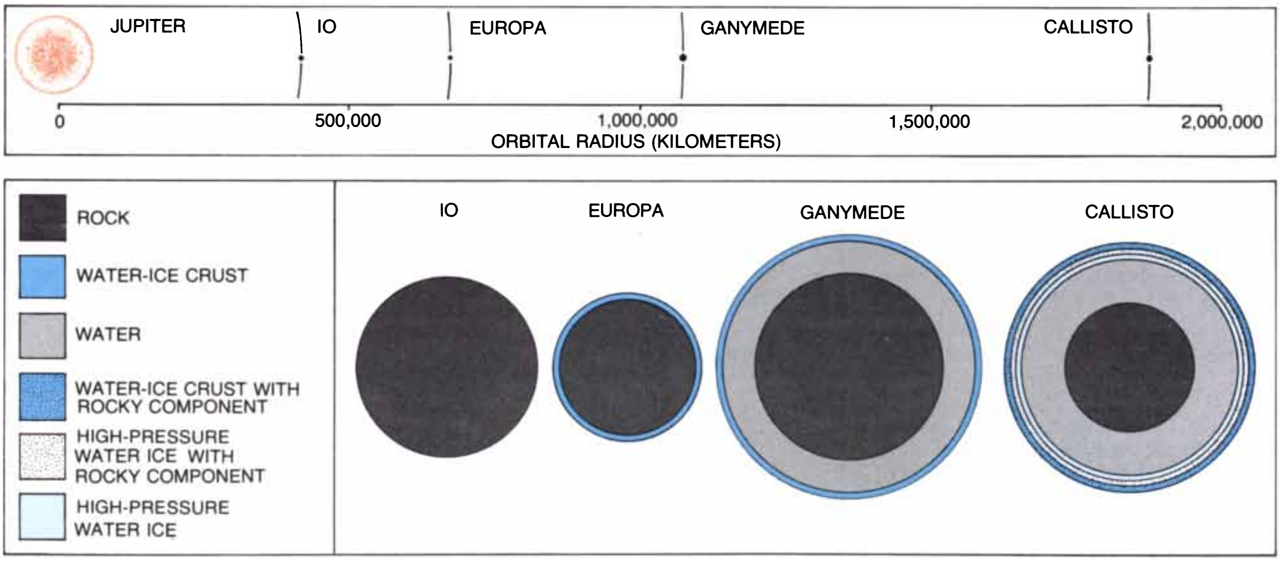
Just as the Galilean satellites have widely differing surfaces, so do they also appear to have a variety of internal structures. The latter differences are best illustrated by the objects' differing densities. The average density of a planet or a satellite is the simplest measure of its bulk composition and hence of the cosmochemical conditions under which it formed.

In order to calculate density one must know both size and mass. All four Galilean satellites are large enough to appear as disks even in telescopes of moderate size, and their approximate sizes have been known from visual observations for about a century. Recently much more precise diameters, accurate to within about 1 percent, have been derived for Io and Ganymede by timing the period required for the satellite to pass in front of, and so to occult the light from, a bright star. Stellar occultations provide a powerful tool for the study of satellites, and we shall return to this topic when we consider atmospheres. Suitable occultations are rare, however, and none has been observed for Europa or Callisto, whose sizes may be uncertain by as much as 15 percent.

The masses of the Galilean satellites were determined decades ago with a precision of between 10 and 20 percent from their mutual gravitational attractions, as revealed by earth-based studies of their motions. New data obtained from *Pioneer 10* and *Pioneer 11* have improved those values, and masses are now known for all four satellites to an accuracy of within 2 percent. Highly accurate densities can thus be calculated for Io and Ganymede, and values good to within perhaps 10 percent can be found for Europa and Callisto.

The most striking trend in the densities is their decrease outward from Jupiter. The densities of Io and Europa, between 3.3 and 3.6 times the density of water, are similar to that of the earth's moon and suggest a composition of rocky minerals throughout, with no more than 25 percent of volatile substances such as water or ice. At the opposite extreme, Callisto has one of the lowest densities measured for any solid body in the solar system, and Ganymede has a density nearly as low as Callisto's. These two satellites must be composed primarily of volatile substances and lightweight minerals.

How can one explain this great range in properties among objects of about the same size that presumably formed together out of the same preexisting nebular material? A clue to the mystery is provided by the similar trend in the planets from high to low densities at progressively greater distances from the sun. That variation is thought to be a result of heating of the early solar nebula by the proto-sun, a process that evapo-



	IO	EUROPA	GANYMEDE	CALLISTO
DIAMETER (KILOMETERS)	3,640±20	3,050±100	5,270±50	4,900±200
MEAN DENSITY (WATER = 1)	3.52	3.3	1.95	1.6
RADIUS OF ORBIT (KILOMETERS)	421,600	670,900	1,070,000	1,880,000
PERIOD OF ORBIT (DAYS)	1.769	3.551	7.115	16.689
MEAN REFLECTIVITY OF SURFACE (PERCENT)	63	64	43	17
MAXIMUM TEMPERATURE AT SURFACE (DEGREES CELSIUS)	−133	−133	−119	−106

MAIN PROPERTIES of the Galilean satellites are presented in the diagrams at the top, which are drawn roughly to scale, and in the table at the bottom. The earth's moon has a diameter of 3,476 kilometers, a mean density 3.3 times that of water, an orbital radius of 384,400 kilometers, an orbital period of 27.3 days, a reflectivity of 12 percent and a maximum surface temperature of 125 degrees Celsius.

The world's finest portable typewriter and the ribbon that's stealing the show.

The Smith-Corona Cartridge Ribbon Typewriter.

The introduction of our Smith-Corona® cartridge ribbons has caused quite a stir.

Understandably.

Snap! Now a worn ribbon can be replaced by a fresh ribbon in just 3 seconds.

And with the development of a variety of color cartridges, film cartridges (for the look of executive typewriting), and correction cartridges that correct errors in a snap, our cartridge ribbons have ushered in a far more flexible system of typing.

But while everyone is making a fuss over our cartridge, you should know that we spent a great deal of time fussing over our cartridge typewriter.

In fact, purchase this number-one-selling electric portable and you'll receive a typewriter engineered to the same standards that helped Smith-Corona steal the show...long before cartridges came along.

SCM® SMITH-CORONA
SCM CORPORATION

Number One Rated!

CORVUS 500

TK Enterprises Reporting to Consumers

With MOSTEK single chip technology, the new Corvus 500 is the first non-Hewlett-Packard calculator with Reverse Polish Notation, 10 addressable memories, 4 level roll down stack to be introduced. If you compare the Corvus 500 feature by feature with the HP-45, you will find striking similarities. There are also some important differences:

	Corvus 500	HP-45
RPN (Reverse Polish Notation)	Yes	Yes
Memory Store and Recall 10 Registers	Yes	Yes
4 Level Stack, Rotate Stack	Yes	Yes
10 MEMORY EXCHANGE WITH X	Yes	No
Log, LN	Yes	Yes
Trig (Sine, Cosine, Tangent, INV)	Yes	Yes
HYPERBOLIC (SINH, COSINH, TANH, INV)	Yes	No
HYPERBOLIC RECTANGULAR ⟷	Yes	No
y^x, e^x, 10^x, $\sqrt{x}$, $1/x$, $x!$, $x \leftarrow y$, π,CHS	Yes	Yes
$\sqrt[x]{y}$ through INVERSE	Yes	No
GRADIANS	No	Yes
DEGREE-RADIAN CONVERSION	Yes	No
Degree-Radian Mode Selection	Yes	Yes
DEC-DEG-MIN-SEC	No	Yes
Polar to Rectangular Conversion	Yes	Yes
Recall Last ×	Yes	Yes
Scientific Notation, Fixed and Floating	Yes	Yes
Fixed Decimal Point Option (0-9)	Yes	Yes
DIGIT ACCURACY	12	10
DISPLAY OF DIGITS	12	10
%, Δ %	Yes	Yes
GROSS PROFIT MARGIN %	Yes	No
Mean and Standard Deviation	Yes	Yes
Σ+, Σ−	Yes	Yes
Product—Memories	Yes	Yes
C.F. DIRECT CONVERSION	Yes	No
F.C. DIRECT CONVERSION	Yes	No
LIT-GAL, DIRECT CONVERSION	Yes	No
KIL-LBS, DIRECT CONVERSION	Yes	No
GAL-LIT, DIRECT CONVERSION	Yes	No
LBS-KIL, DIRECT CONVERSION	Yes	No
CM-INCH DIRECT CONVERSION	Yes	No
INCH-CM DIRECT CONVERSION	Yes	No

As you can see, the Corvus 500 IS a lot more calculator for $69.95.

We have listed some of the many features, but let's amplify on some highlights:

1. RPN (Reverse Polish Notation) "COMPUTER LOGIC" and 4 LEVEL STACK. Your problem is solved the way it is written, left to right sequence, eliminating restructuring, unnecessary keystrokes, and the handicap of having to write down intermediate solutions. And all information is at your disposal—just roll the stack (R↓) to any intermediate information desired. You arrive at your solution faster, more simply and therefore more accurately.

Perhaps at this point we should address ourselves to the controversy between algebraic entry and RPN. One question we must ask is why proponents of algebraic entry *always* use an example of sum of products and *never* an example of product of sums:

(2+3) × (4+5)=

Algebraic: 2+3=MS 5+4=×MR=
TOTAL 12 keystrokes (SR51, add 2 more keystrokes)

RPN: 2 Enter 3+4 Enter 5+×
TOTAL 9 keystrokes

2. THE CORVUS 500 and HP-45 HAVE 10 ADDRESSABLE MEMORY REGISTERS, 4 LEVEL OPERATIONAL STACK, and a "LAST X" REGISTER (10th Mem. Reg.) With 10 addressable memories, you have access to more entries, or intermediate solutions; less remembering, or writing down, YOU have to do. And less chance for error.

The stack design also permits X and Y register exchange, and roll-down to any entry to the display for review or other operation.

The "last x" register permits error correction or multiple operations when a function is performed, the last input argument of the calculation is automatically stored in the "last x" register, which can be quickly recalled to correct an error, or to perform another operation using the same number.

3. DIRECT HYPERBOLIC and HYPERBOLIC RECTANGULAR to POLAR, and INVERSE. For those of you electronic and computer science engineers who require access to this specialized application, the Corvus 500 solves "your" problems.

4. A WORD ABOUT CORVUS 500 12 DIGIT DISPLAY AND ACCURACY. Finally you have displayed 12 digit accuracy in business format and 10 + 12 in scientific notation. LED is manufactured by Hewlett-Packard.

FOR THE FIRST TIME you can raise the number 10 to 199th power or calculate Factorial (x!) of up to 120. Unbelievable!

5. The CORVUS 500 CONVERTS METRIC/U.S. and INVERSE UNITS DIRECTLY. These preprogrammed functions act not just as constants, eliminating unnecessary keystrokes.

WHAT ABOUT CONSTRUCTION? With so many features, the next most obvious question must be in regard to the quality of the unit itself. We are proud to report the Corvus 500 to be double injected molded, with "tactile" feedback keyboard. The compact, contoured case is 5½" long by 3" wide by 1¼" high, and weighs just 8 oz.

The COMPLETE CORVUS 500 for $69.95 includes:

- **Rechargeable and replaceable Nickel Cadmium batteries. Optional 3 AA batteries.**
- **Adaptor/Charger**
- **Owner's handbook**
- **Soft carrying case**

The Corvus 500 is warranted by the manufacturer against defects in materials and workmanship for one year from date of delivery.

For those of you who have the HP-21 or 45 or any other advanced calculator on order, aren't you glad you still have the opportunity to take advantage of the release of the Corvus 500 for $69.95? Hurry! Order yours today.

***AN INVITATION:** TK Enterprises is proud that we are able to introduce the MOSTEK chip Corvus 500 to you, our discerning readers. (Incidentally, we have received orders for Corvus 500 from almost every major company in the USA, in every state in the Union (including HP & TI people). Many are already taking advantage of this incomparable price performance ratio instrument. We invite you to experience the new Corvus 500 by mailing in the coupon today, or by calling our order desk COLLECT at (213) 370-5795. From the tremendous initial response, please allow 3 days for delivery. We are sure you will agree that the CORVUS 500 is the calculator of the year, and the one you have been waiting for. However, you may return the remarkable Corvus 500 within 7 days without obligation, for any reason whatsoever. So, please mail or phone today . . . before the news of Corvus 500's demand exceeds supply!*

To order your Corvus 500 Scientific Calculator, phone: (213) 370-5795 or mail coupon today!

tkenterprises
BETTER BUSINESS PRODUCTS

16611 Hawthorne Blvd.
Lawndale, Ca. 90260
(213) 370-5795

Yes . . . I'd like to try the Corvus 500 for 7 days.
Please ship me the Corvus 500 Advanced Scientific Calculator, complete with accessories, at $69.95, plus $2.50 for shipping and insurance. I understand that if I'm not completely satisfied, I may return the unit and accessories within 7 days for full refund (or, at my option, receive full credit toward the purchase of any other calculator carried by T.K. Enterprises).

NAME ______
ADDRESS ______
COMPANY ______
PHONE ______

☐ **Cash Payment:** Check or money order enclosed. (Please be sure to add any applicable state and local taxes.) To speed-up delivery send money order.
☐ **Bill My Credit Card:** ☐ BankAmericard
☐ Master Charge Bank No. ☐☐☐☐
Account No. ☐☐☐☐ ☐☐☐☐ ☐☐☐ ☐☐☐
Expiration Date______
Signature: ______

SA #5-75

Other Values from TK:

Texas Instruments

PC-100	$239.00
SR50A	$ 59.95
SR51A	$ 89.95
SR52	$299.95
SR56	$139.00

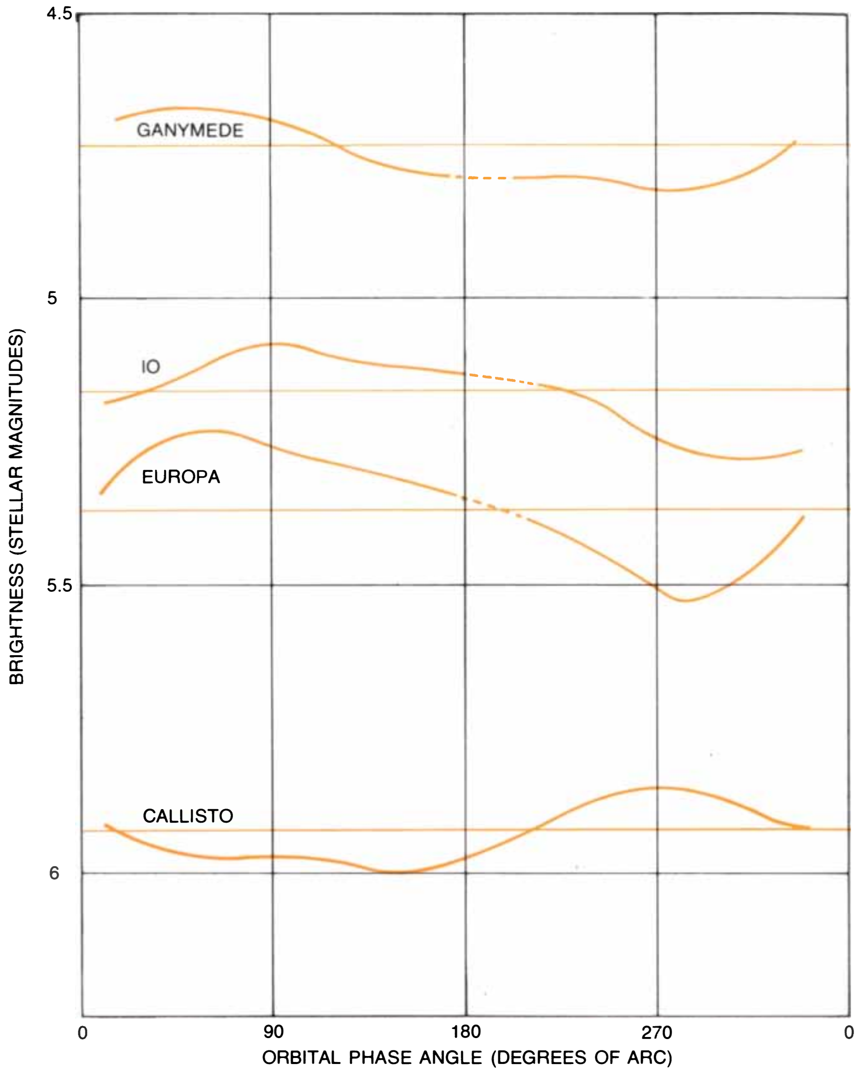
NOVUS Consumer Products from National Semiconductor

Mathematician #4510	$24.95
Scientist #4520	$32.00
Scientist PR #4525	$64.95
NS #4615	$54.95
NS #4640	$64.95
Financier	$28.45
Statistician	$28.45

rated the lighter and more volatile materials from the inner solar system to leave the dense terrestrial planets of today. James B. Pollack and his co-workers at the Ames Research Center of the National Aeronautics and Space Administration suggest that exactly the same process would have taken place within the miniature solar system of the Jovian satellites, with the proto-Jupiter the source of the heat. Even today Jupiter radiates more than twice as much heat as it absorbs from the sun, making up the energy deficit from internal sources. Calculations show that during the first few million years of its existence Jupiter must have radiated about a ten-thousandth as much energy as the sun does today. Pollack concludes that there would have been enough heat to melt Io and Europa and drive off most of their volatile components, leaving Callisto and perhaps Ganymede little influenced by the primordial heat wave.

If Europa lost most of its water during the first few million years of its existence, why does it now seem to be the one satellite with a surface nearly covered with water frost? The answer may be that only if there is a core of heavy material will there be a sufficient concentration of radioactivity in the interior to heat up the satellite and release water to the surface. Europa may be the only satellite with both a hot interior and enough water for periodic eruptions of vapor to provide a source to keep its surface frost-covered. On Io water released from the interior in the past may have carried dissolved salts to the surface and subsequently evaporated, leaving a coating reminiscent of salt flats or dry salt lakes on the earth. Presumably Ganymede and Callisto, although they contain a great deal of water in their interior, lack the radioactive heat sources required to produce water "volcanoes" in sufficient quantity to maintain a coating of pure ice.

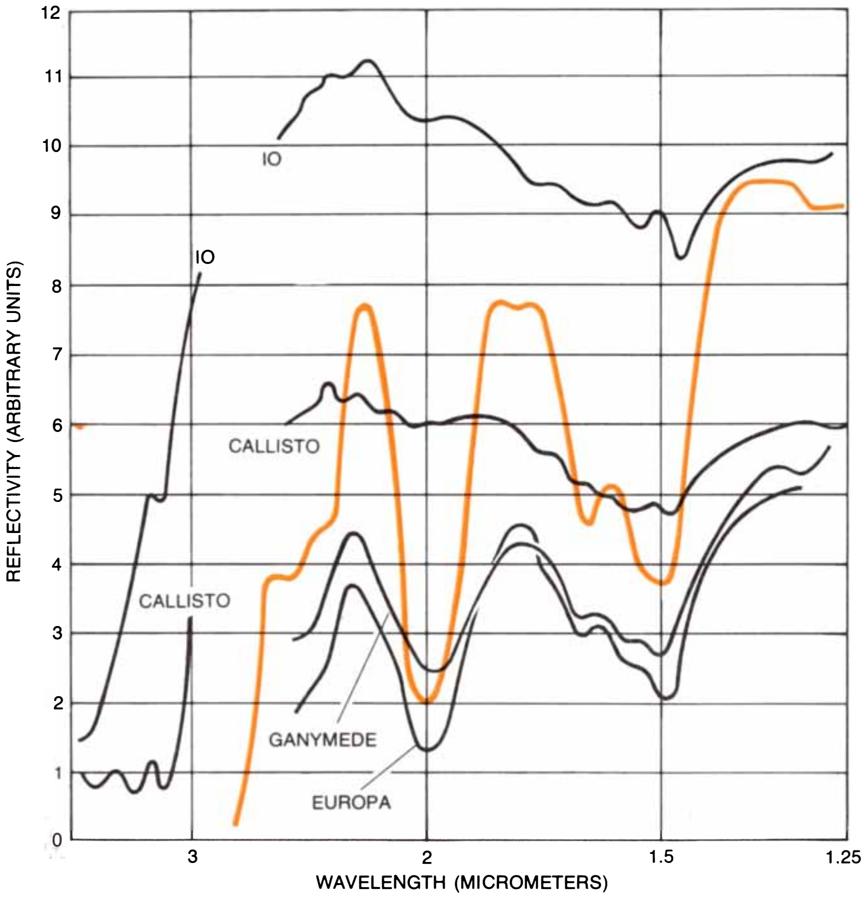
The interior structure that a satellite with such a history might assume has been studied by John S. Lewis of the Massachusetts Institute of Technology [see "The Chemistry of the Solar System," by John S. Lewis; SCIENTIFIC AMERICAN, March, 1974]. Lewis concludes from the density of Ganymede and Callisto that these satellites contain no more than about 15 percent by mass of rocky or silicate minerals, with most of the rest of their bulk made up of frozen water, ammonia and methane. Initially these ice forms may have been well mixed, but early in the history of the satellite either internal radioactivity or the intense radiation and gravitational effects of the proto-Jupiter would probably have heated the interior above the melting temperature of some of the ices. Once melting began, the release of energy from the phase changes themselves would have rapidly melted the entire interior. The heavy rocky materials would have sunk under their own weight to the center to form a core of rock and mud slush, whereas most of the satellite would have consisted of liquid water with admixtures of methane and ammonia.



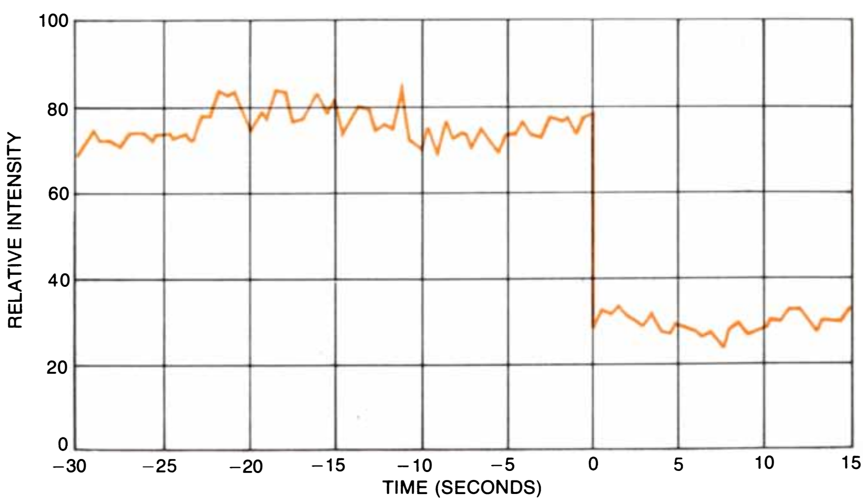
BRIGHTNESS of the Galilean satellites has been found to vary significantly as each rotates on its axis and at the same time revolves around Jupiter in a nearly circular orbit. As these four curves indicate, the leading hemispheres of Io, Europa and Ganymede are brighter than their trailing hemispheres, whereas the reverse is true for Callisto, the outermost of the "big four." Each curve was compiled from a large number of photometric measurements of brightness made through a yellow filter. An orbital phase angle of 0 degrees corresponds to the point of geocentric superior conjunction (that is, the point where the satellite is directly behind the planet as viewed from the earth). An orbital angle of 180 degrees corresponds to the point of inferior conjunction (where the satellite is between the planet and the earth). A phase angle of 90 degrees corresponds to the satellite's leading hemisphere (in the sense of its revolution around Jupiter), and a phase angle of 270 degrees corresponds to the trailing hemisphere. The horizontal lines associated with each curve indicate the mean brightness of that body. The broken segments of the curves denote the part of an orbit where the satellite is not visible from the earth.

The primordial crust of mixed rock and ice might have survived that stage or it might have melted; at present there is no way to tell which was the case. Alternatively, even if the crust had survived the initial melting of the interior, it might subsequently have been breached by a meteoritic impact, which could have resulted in its breakup and sinking into the molten interior in one cataclysm. In more recent times the interior may have cooled somewhat and the crust may have become more stable, but according to these models most of Ganymede and Callisto, starting from several hundred kilometers below their surface, are still liquid. Whether there would be observable consequences of this interior structure depends in part on whether the solid crust is thick enough to keep the liquid and vapors trapped inside. If there is outgassing from the interior, it might be identified by searching for faint traces of atmospheres on these satellites.

The first concerted search for possible atmospheres on the Galilean satellites was made in the 1940's by Kuiper. In the course of a spectroscopic survey of the satellites he discovered the dense methane atmosphere of Titan (a large satellite of Saturn),



PRESENCE OF ICE on the surfaces of Europa and Ganymede, but not on those of Io and Callisto, was proved by an analysis of the way each of the surfaces reflects sunlight at wavelengths in the near-infrared region of the spectrum. As these spectroscopic measurements show, the reflection spectra of Europa and Ganymede at wavelengths of between one micrometer and five micrometers strongly resemble a typical laboratory spectrum of water frost (*colored curve*). Comparable curves for Io and Callisto reveal broad indistinct features in their spectra, but the evidence for water frost is not strong. The spectroscopic data for these curves were obtained at the Kitt Peak National Observatory by Cal B. Pilcher, S. T. Ridgeway and Thomas B. McCord.



OCCULTATION of the star Beta Scorpii C by Io on May 14, 1971, afforded an opportunity to test for the presence of an atmosphere on the satellite by gauging the rapidity with which the star's light was cut off as the satellite passed in front of it. The left side of this record shows the combined brightness of the star and the satellite, as measured with a high-speed photometer attached to a small telescope. The right side of the record shows the brightness of the satellite seen alone, the star having been occulted. The occultation of the star was found to be essentially instantaneous, indicating that any tenuous atmosphere that might exist on the satellite would have a surface pressure less than a ten-millionth the earth's atmospheric pressure at sea level.

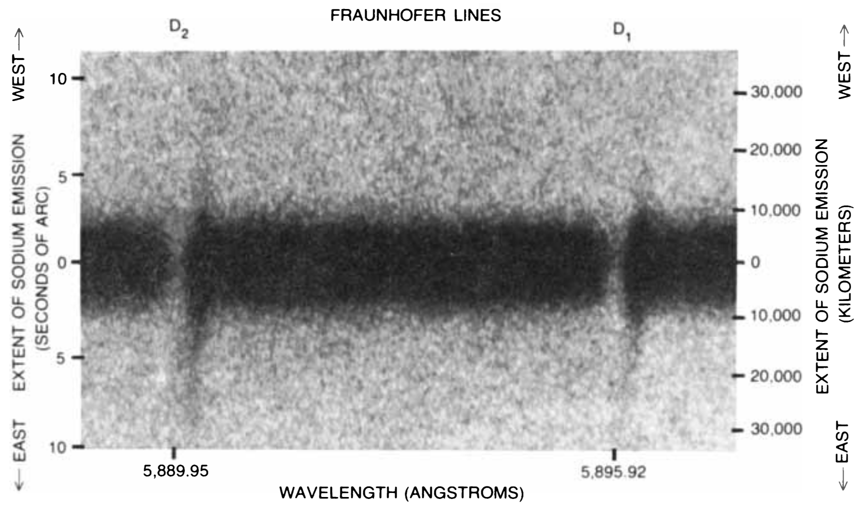
but he was unable to detect either methane or ammonia on the Galilean satellites, indicating that any gaseous envelope of this composition must be quite tenuous, with a surface pressure less than about a hundred-thousandth of the pressure of the earth's atmosphere at sea level. Then in the early 1970's it was recognized that a highly sensitive probe for tenuous atmospheres on satellites and other small bodies in the solar system can be made on the rare occasions when these objects occult bright stars. If there is no atmosphere surrounding the satellite, the light is cut off instantaneously when the satellite passes in front of the star, but the presence of even a tenuous atmosphere causes the light to be extinguished gradually. The rate of extinction is an index of the nature and refracting properties of the atmospheric gas.

On May 14, 1971, Io occulted the bright star Beta Scorpii C. The occultation had been predicted with precision just three weeks earlier and was visible from only a small area of the earth's surface, owing to the small size of the "shadow" cast by the satellite. The occultation was observed from several locations by different teams of observers; all found that the intensity of the starlight changed abruptly as the satellite passed in front of the star, indicating that if Io has an atmosphere at all, its surface pressure must be less than a ten-millionth of that on the earth. In 1972 there was another occultation, this time by Ganymede, and photometric measurements were made by teams of observers in India and Indonesia. Although the results for Ganymede were less conclusive than those for Io, they allowed the possibility of an atmosphere on Ganymede with a surface pressure a few millionths of the surface pressure of the earth's atmosphere.

Although planetary scientists have come to expect the unexpected as they explore the solar system, they were caught by surprise when Robert A. Brown of Harvard University announced in 1973 that he had observed the spectral lines of sodium gas in the emission spectrum of Io. Other observers quickly verified this evidence of a metallic atmosphere, and they also discovered that the glowing sodium was not confined to the proximity of Io; it extended far out into space, much farther than is possible for a normal atmosphere that is gravitationally bound to a planet. Apparently Io is the source of an enormous quantity of sodium that flows from the satellite into a great toroidal cloud surrounding Jupiter and filling the orbit of the satellite. This cloud is estimated to contain some 10^{29} atoms of sodium, a number implying that Io releases on the average 10 million sodium atoms per second from each square centimeter of its surface.

Once the sodium escapes from Io, it emits no light of its own but scatters solar radiation. The scattering mechanism has been verified by the observation that the cloud ceases to glow when it is in the shadow of Jupiter. The dimensions of the cloud are so great that its glow could be seen by a hypothetical observer on the surface of the satellite, where the intensity would be similar to that of a terrestrial aurora. Unlike an aurora, however, the sodium glow would be yellow in color and probably would show no rapid variation.

Just when ground-based observers were mapping the extent of the sodium cloud of Io, new information on the extended atmosphere of the satellite was provided by *Pioneer 10* as it plunged through the Jovian system on its historic first reconnaissance of Jupiter and its satellites. A sensitive ultraviolet photometer on board detected radiation characteristic of excited hydrogen gas not only in the atmosphere of Jupiter, where it had been expected, but also throughout a vast region in the vicinity of the orbit of Io. The number of hydrogen atoms in this cloud appears to be about 10,000 times greater than the number of sodium atoms. The brightness of the Io orbital "doughnut" suggests that the hydrogen atoms are excited in part by auroralike activity caused by high-energy electrons streaming between Jupiter and Io and to scattered sunlight. Late last year two additional gases—potassium and ionized sulfur—were tentatively identified in the vicinity of Io. The potassium apparently has a distribution similar to that of the sodium, whereas the faint emission from the ionized sulfur permeates a very large region around the orbit of the satellite.



TWO PROMINENT SPECTRAL LINES characteristic of glowing sodium gas were discovered in the spectrum of Io by Robert A. Brown of Harvard University in 1972. In this spectrogram, obtained with the 1.5-meter telescope of the Smithsonian Institution's Mount Hopkins Observatory in southern Arizona, the continuous spectrum of the sunlight reflected from the satellite's surface appears as a dark horizontal strip with the superposed solar Fraunhofer lines (labeled D_1 and D_2), both well identified with sodium in the sun's atmosphere, flanked by red-shifted emission features that originate in a cloud of sodium gas surrounding Io. The spectrogram shows that the zone of sodium emission extends far beyond the surface of the satellite, reaching to some 30,000 kilometers in the easterly direction. Similar spectrograms made with a north-south orientation also indicate that the cloud extends well beyond the satellite. By obtaining spectrograms of this kind for several positions of Io in its orbit around Jupiter, the size and shape of a huge, toroidal cloud of sodium gas that fills the orbit has been mapped.

The trajectory of *Pioneer 10* was adjusted by a carefully executed maneuver to produce an occultation of the spacecraft by Io of about a minute's duration on December 4, 1974, shortly after the spacecraft's closest approach to Jupiter. Since the spacecraft was transmitting radio signals of known frequency at the time it passed behind the satellite, it was possible to sound the space around Io for the presence of even small quantities of electrically conducting gas, which would distort the radio frequency. In this way A. J. Kliore and his colleagues at the Jet Propulsion Laboratory of the California Institute of Technology discovered that Io has an ionosphere on the daylight side so extensive that it can be compared to the ionospheres of Venus and Mars. Such a layer of electrically charged atoms is expected at the top of a planetary atmosphere, where ultraviolet light from the sun ionizes the atoms by stripping them of their outer electrons. It had not been known previously, however, whether Io had enough atmosphere to support the existence of such a layer.

This experiment dramatically verified a hypothesis put forward a few years ago to explain another of Io's strange properties: its ability to influence the radio emission of Jupiter. Giant radio-noise "storms" are generated at several points in the atmosphere of Jupiter, but it had been found that the apparent strength of these bursts as observed on the earth depended on the orbital position of Io. One possible explanation was that if Io had an electrically conducting atmosphere or surface, it could be connected by means of an electric current with the polar regions of Jupiter and in this way give rise to the observed modulation of the radio-noise storms. The ionosphere discovered by *Pioneer 10* is easily big enough to provide the necessary electrical conductivity.

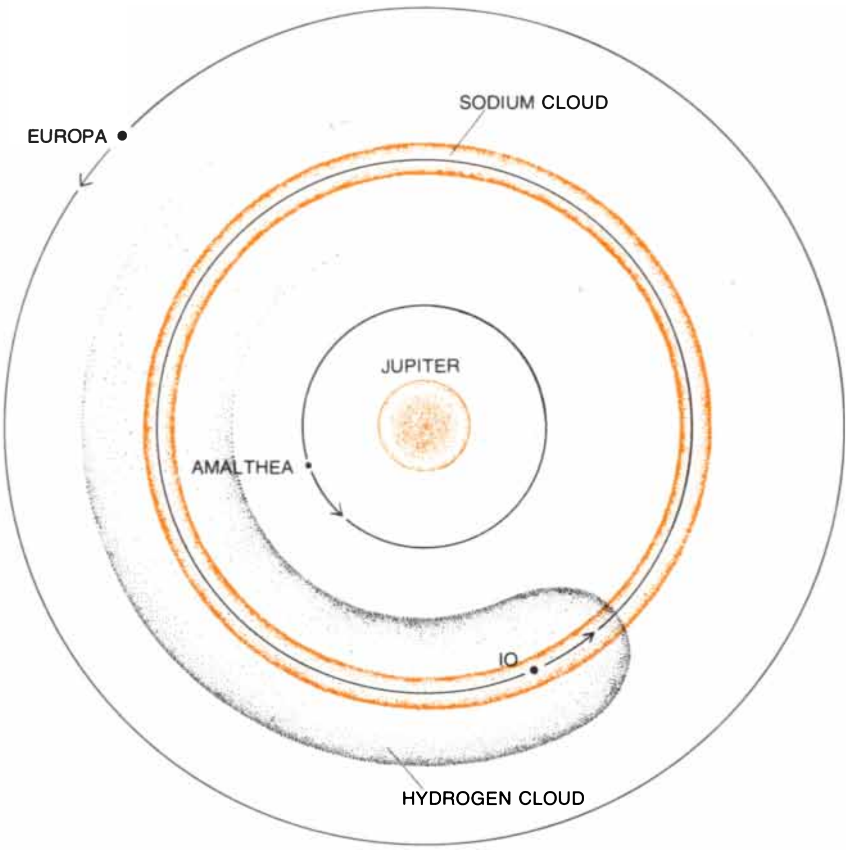
The existence of an ionosphere surrounding Io implies that some neutral gas is present in an atmosphere near the surface. This atmosphere needs a surface pressure only about a billionth that of the terrestrial atmosphere, however, to provide the atoms ionized by the sunlight. Such a low surface pressure is far below the limit of detection by either the stellar-occultation technique or spectroscopic observations.

Confronted with Io's clouds of hydrogen, sodium and potassium and its extensive ionosphere, planetary scientists have begun to search for the origin of these components of the environment of this remarkable satellite. The most tenable hypotheses point to Io's surface as the source for atoms of sodium and potassium that, once liberated from the surface, quickly attain the energy necessary to escape the satellite's weak gravitational field and spread out in space. Although light atoms can escape from Io quite easily, the strong gravitational field of nearby Jupiter is a restraining force. The result is a cloud of atoms held in "Jupiter space" but concentrated in the vicinity of Io whence they came. None of the gases observed can remain indefinitely in the form of a cloud in Io's orbit, and there must be a high flux of these atoms from the satellite's surface in order to balance their loss by various mechanisms.

Can the surface of Io possibly produce the large outflows of matter indicated by the observations? Sodium and potassium are normally only trace constituents of minerals. In the salt-flat model, which was initially proposed by Fraser P. Fanale and his colleagues at the Jet Propulsion Laboratory to account for the high reflectivity and absence of infrared spectral features on Io, a great concentration of sodium- and potassium-rich materials is expected on the surface. In addition it is known that Io is subject to a continuous bombardment by high-energy particles from the Jovian analogue of the terrestrial Van Allen belts, a radiation environment so extreme that it would be lethal to an unshielded man in just a few minutes. By the process known as sputtering, the impact of electrons and protons on the surface could chip away atoms and release them into the atmosphere, from which they would quickly escape. Quantitatively the sputtering process seems able to explain the observed flux of sodium and probably of potassium, but it does not account for the hydrogen, which probably does not originate on the satellite itself. Alternative hypotheses are being examined by several groups of workers, but so far it appears that the extended atmosphere of Io may have arisen in part from the satellite's unique surface material, which in turn may have arisen from the evaporation of its primordial oceans.

We have dwelled on Io and its atmosphere because in spite of the questions remaining, planetary scientists believe more is known about this satellite than about the other three Galilean satellites considered together, mostly on the basis of data gathered over the past two or three years.

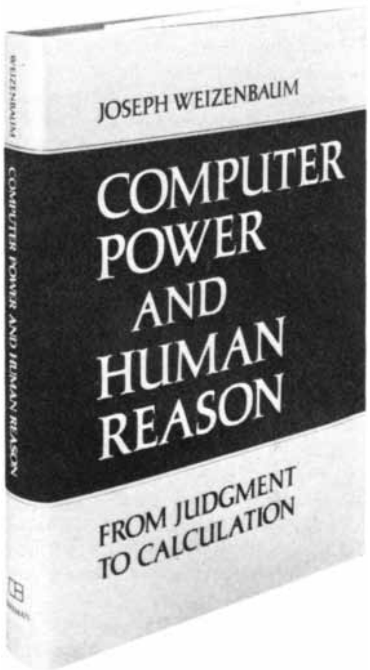
Until recently all that had been learned about the Galilean satellites had come from painstaking observations carried out with earth-based astronomical telescopes. Now the study of the solar system is rapidly passing from the era of telescopic astronomy to that of closeup observation and direct experimentation with space probes. The *Pioneer 10* and *Pioneer 11* spacecraft were only forerunners of a series of increasingly sophisticated flyby and orbiter vehicles planned for the exploration of the Jovian system over the next decade. The first will be a pair of Mariner missions to Jupiter and Saturn; these two spacecraft are scheduled to be launched in 1977 and to swing by Jupiter in 1979. They will be similar in capability to the *Mariner 9* and *Mariner 10* spacecraft that spectacularly advanced man's knowledge of Mars, Venus and Mercury in 1972 and 1974. Several hundred high-resolution television pictures of each of the Galilean satellites will be returned from each of the new Mariner missions. At its best the photographic coverage will be comparable to that of Mercury obtained by *Mariner 10,* with about half of the surface observed with a resolution of a few kilometers and selected areas with a resolution of a few hundred meters. We can hardly guess what kind of geology will be revealed by these pictures; we have no experience with planets consisting substantially of ice. The television cameras and other experiments on the new Mariner missions can be expected to open up for study four new worlds with a total surface area as great as that of Mars, Mercury and the moon combined, but differing fundamentally from all bodies in the solar system explored so far.



SODIUM CLOUD surrounding Io and occupying most of its orbit is indicated in color in this idealized north-polar view of Jupiter and its three innermost satellites. The sodium cloud is now known to be embedded in an even larger hydrogen cloud, observed for the first time by *Pioneer 10* in 1973. Although both the sodium cloud and the hydrogen cloud form toroidal rings completely encircling Jupiter, both gases are strongly concentrated near the satellite. The sodium torus is detectable all around the orbit, but the hydrogen cloud, shown here in black, was detected by *Pioneer 10* extending over only about a third of the orbit, stretching behind Io in a long cometlike tail. Two additional gases, potassium and ionized sulfur, have recently been discovered in the vicinity of Io. The potassium probably has a distribution similar to that of the sodium, whereas the ionized sulfur may be even more widely distributed than the hydrogen. For both of these gases, however, the observational data are insufficient to define the extent or the density of the clouds. The satellites Amalthea and Europa are also shown circling Jupiter in this view. So far no detectable clouds of gas have been associated with either of these bodies.

"A landmark in the integration of scientific and humanistic thinking"

—Lewis Mumford



1976, 300 pages, 13 illustrations, ISBN 0-7167-0464-1, $9.95

Computer Power and Human Reason is a distinguished computer scientist's searching probe of the limits of computer power and of scientific rationality itself. It is, above all, an eloquent defense of the uniqueness and the sanctity of the human spirit.

"Weizenbaum's deep social and ethical concerns, backed by his competence in exact science, give his work an appeal to a much wider audience than his immediate academic colleagues. . . . It will still be read half a century from now, as a landmark in the integration of scientific and humanistic thinking." —Lewis Mumford

"I found the book to be a very impressive and important one. Weizenbaum writes from a deep understanding of the promise and the limits of computer science, and he gives a very thoughtful and illuminating appraisal of what can realistically be expected, and a very cogent and telling critical commentary on some widespread illusions. . . . I know of no comparable work, and, given the considerable importance of the issues, I hope . . . for the widest possible distribution of this book." —Noam Chomsky

"I found it to be most stimulating, full of new and original ideas. I am convinced that this book will be a great success and will be read by a wide public. It deals with the societal problems with computers and their applications. These are problems which every thinking person today is interested in. Professor Weizenbaum deals with these problems in a profound way and also in a way that can be followed by those who are not experts in the computer sciences. I am convinced that this book will be widely read." —Victor F. Weisskopf

COMPUTER POWER AND HUMAN REASON

FROM JUDGMENT TO CALCULATION

JOSEPH WEIZENBAUM

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

15-DAY FREE EXAMINATION. To order, use the adjacent card. If card is missing, send order with payment to:

W. H. FREEMAN AND COMPANY
Dept. SA, 660 Market Street, San Francisco, CA 94104

MATHEMATICAL GAMES

A few words about everything there was, is and ever will be

by Martin Gardner

"A curious thing about the ontological problem is its simplicity. It can be put in three Anglo-Saxon monosyllables: 'What is there?' It can be answered, moreover, in a word—'Everything.'"

So begins Willard Van Orman Quine's famous essay "On What There Is." Last year a topic of this department was "nothing." I have nothing more to say about nothing, or about "something," since everything I know about something was said when I wrote about nothing. But "everything" is something altogether different.

Let us begin by noting the curious fact that some things, namely ourselves, are such complicated patterns of waves and particles that they are capable of wondering about everything. "What is man in nature?" asked Pascal. "A nothing in comparison with the infinite, an all in comparison with the nothing, a mean between nothing and everything."

In logic and set theory "things" are conveniently diagrammed with Venn circles. In the top illustration on the opposite page the points inside circle *a* represent humans. The points inside circle *b* stand for feathered animals. The overlap, or intersection set, has been darkened to show that it has no members. It is none other than our old friend the empty set.

So far, so clear. What about the points on the plane outside the two circles? Obviously they represent things that are not *a* and not *b*, not human and not feathered, but how far-ranging is this set? To clarify the question Augustus De Morgan invented the phrase "universe of discourse." It is the range of all the variables with which we are concerned. Sometimes it is explicitly defined, sometimes tacitly assumed, sometimes left fuzzy. In set theory it is made precise by defining what is called the universal set, or, for short, the universe. This is the set with a range that coincides with the universe of discourse. And that range can be whatever we want it to be.

With the Venn circles *a* and *b* we are perhaps concerned only with living things on the earth. If this is so, that is our universe. Suppose, however, we expand the universe by adding a third set, the set of all typewriters, and changing *b* to all feathered objects. As the bottom illustration on the opposite page shows, all three intersection sets are empty. It is the same empty set, but the range of the null set has also been expanded. There is only one "nothing," but a hole in the ground is not the same as a hole in a piece of cheese. The complement of a set *k* is the set of all elements in the universal set that are not in *k*. It follows that the universe and the empty set are complements of each other.

How far can we extend the universal set without losing our ability to reason about it? It depends on our concern. If we expand the universe of the top illustration on the opposite page to include all concepts, the intersection set is no longer empty because it is easy to imagine a person growing feathers. The proofs of Euclid are valid only if the universe of discourse is confined to points in a Euclidean plane or 3-space. If we reason that a dozen eggs can be equally divided only between one, two, three, four, six or 12 people, we are reasoning about a universal set that ranges over the integers. John Venn (who invented the Venn diagram) likened the universe of discourse to our field of vision. It is what we are looking at. We ignore everything behind our head.

Nevertheless, we can extend the universe of discourse amazingly far. We certainly can include abstractions such as the number 2, π, complex numbers, perfect geometric figures, even things we cannot visualize such as hypercubes and non-Euclidean spaces. We can include universals such as redness and cowness. We can include things from the past or in the future and things real or imaginary, and can still reason effectively about them. Every dinosaur had a mother. If it rains next week in Chicago, the Water Tower will get wet. If Sherlock Holmes had actually fallen off that cliff at Reichenbach Falls, he would have been killed.

Suppose we extend our universe to include every entity that can be defined without logical contradiction. Every statement we can make about that universe, if it is not contradictory, is (in a sense) true. The contradictory objects and statements are not allowed to "exist" or be "true" for the simple reason that contradiction introduces meaninglessness. When a philosopher such as Leibniz talks about "all possible worlds," he means worlds that can be talked about. You can talk about a world in which humans and typewriters have feathers. You cannot say anything sensible about a square triangle or an odd integer that is a multiple of 2.

Is it possible to expand our universe of discourse to the ultimate and call it the set of all possible sets? No, it is a step we cannot take without contradiction. Georg Cantor proved that the cardinal number of any set (the number of its elements) is always lower than the cardinal number of the set of all its subsets. This is obvious for any finite set (if it has n elements, it must have 2^n subsets), but Cantor was able to show that it also applies to infinite sets. When we try to apply this theorem to everything, however, we get into deep trouble. The set of all sets must have the highest aleph (infinite number) for its cardinality; otherwise it would not be everything. On the other hand, it cannot have the highest aleph because the cardinality of its subsets is higher.

It is amusing to learn that when Bertrand Russell first came across Cantor's proof that there is no highest aleph, and hence no "set of all sets," he did not believe it. He wrote in 1901 that Cantor had been "guilty of a very subtle fallacy, which I hope to explain in some future work," and that it was "obvious" there had to be a greatest aleph because "if everything has been taken, there is nothing left to add." When the essay was reprinted in *Mysticism and Logic* 16 years later, Russell added a footnote apologizing for his mistake. ("Obvious" is obviously a dangerous word to use in writing about everything.) It was Russell's meditation on his error that led him to discover his famous paradox about the set of all sets that are not members of themselves.

To sum up, when the mathematician tries to make the final jump from lots of things to everything, he finds he cannot make it. "Everything" is self-contradictory and therefore does not exist!

The fact that the set of all sets cannot be defined in set theory, however, does not inhibit philosophers and theologians from talking about everything, although their synonyms for it vary: being, ens, what is, existence, the absolute, God, reality, the Tao, Brahman, dharmakaya and so on. It must, of course, include everything that was, is and will be, everything that can be imagined and everything totally beyond human comprehension. Nothing is also part of everything. When the universe gets this broad, it is difficult to think of anything meaningful (not contradictory) that does not in some sense exist. The logician Raymond Smullyan, in one of his several hundred marvelous unpublished essays, retells an incident he found in Oscar Mandel's book *Chi Po and the Sorcerer: A Chinese Tale for Children and Philosophers.* The sorcerer Bu Fu is giving a painting lesson to Chi Po. "No, no!" says Bu Fu. "You have merely painted what *is.* Anybody can paint what is! The real secret is to paint what isn't!" Chi Po, puzzled, replies: "But what is there that isn't?"

This is a good place to come down from the heights and consider a smaller, tidier universe, the universe of contemporary cosmology. Modern cosmology started with Einstein's model of a closed but unbounded universe. If there is sufficient mass in the cosmos, our 3-space curves back on itself like the surface of a sphere. (Indeed, it becomes the 3-space hypersurface of a 4-space hypersphere.) We now know that the universe is expanding from a primordial fireball, but there does not seem to be enough mass for it to be closed. The steady-state theory generated much discussion and stimulated much valuable scientific work, but it now seems to have been eliminated as a viable theory by such discoveries as that of the universal background radiation (which has no reasonable explanation except that it is radiation left over from the primordial fireball, or "big bang").

The large unanswered question is whether there is enough mass hidden somewhere in the cosmos (in black holes?) to halt the expansion and start the universe shrinking. If that is destined to happen, the contraction will become runaway collapse, and theorists see no way to prevent the universe from entering the "naked singularity" at the core of a black hole, that dreadful spot where matter is crushed out of existence and no known laws of physics apply. Will the universe disappear like the fabled Poof Bird, which flies backward in ever decreasing circles until—poof!—it vanishes into its own anus? Will everything go through the black hole to emerge from a white hole in some other part of our space-time or in some completely different space-time? Or will it manage to avoid the singularity and give rise to another fireball? If reprocessing is possible, we have a model of an oscillating universe that periodically explodes, expands, contracts and explodes again.

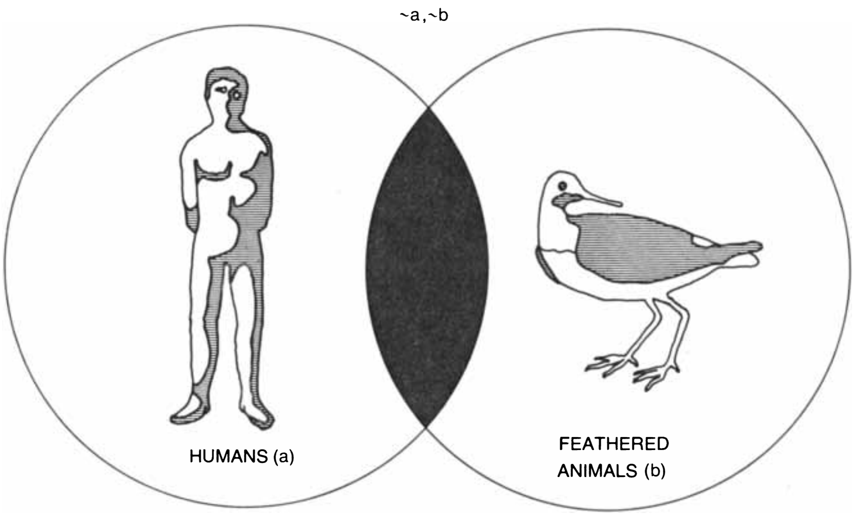
Among physicists who have been building models of the universe John Archibald Wheeler of Princeton University has gone further than anyone in the direction of everything. In Wheeler's wild vision our universe is one of an infinity of universes that can be regarded as embedded in a strange kind of space called superspace.

In order to understand (dimly) what Wheeler means by superspace let us start with a simplified universe consisting of a line segment occupied by two particles, one black and one colored [*see top illustration on next page*]. The line is one-dimensional, but the particles move back and forth (we allow them to pass through each other) to create a space-time of two dimensions: one of space and one of time.

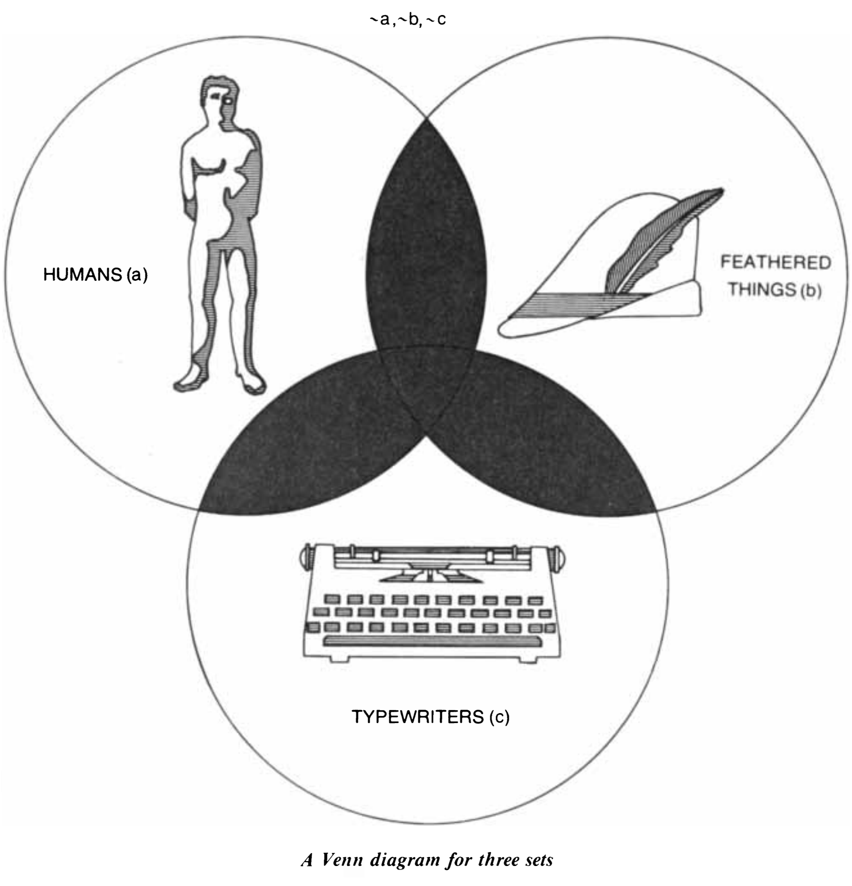
There are many ways to graph the life histories of the two particles. One way is to represent them as wavy lines, called world lines in relativity theory, on a two-dimensional space-time graph [*see bottom illustration on next page*]. Where was the black particle at time *k?* Find *k* on the time axis, move horizontally to the black particle's world line, then move down to read off the particle's position on the space axis.

To see how beautifully the two world lines record the history of our infant universe, cut a slot in a file card. The slot should be as long as the line segment and as wide as a particle. Place the card at the bottom of the graph where you can see the universe through it. Move the card upward slowly. Through the slot you will see a motion picture of the two particles. They are born at the center of their space, dance back and forth until they have expanded to the limits and then dance back to the center, where they disappear into a black hole.

In kinematics it is sometimes useful to graph the changes of a system of particles as the motion of a single point in a higher space called configuration space. Let us see how to do this with our two particles. Our configuration space again is two-dimensional, but now both coordinates are spatial. One coordinate is assigned to the black particle and the other to the colored particle [*see illustration on page 123*]. The positions of both particles can now be represented by a single point called the configuration point. As the point moves, its coordinate values change on both axes. One axis locates one

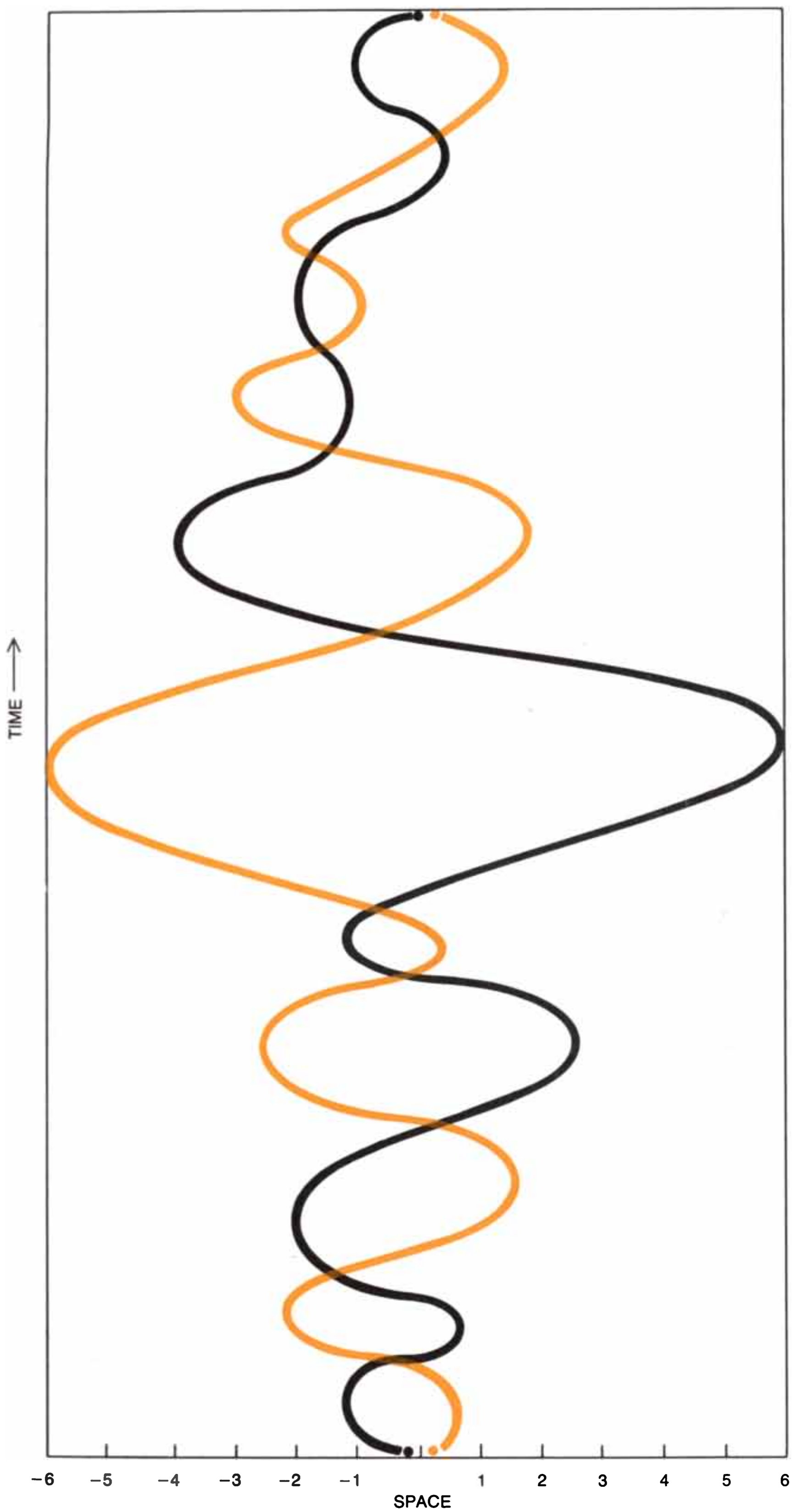


A Venn diagram for "No humans have feathers"



A Venn diagram for three sets

A one-dimensional universe with two particles



A space-time graph of a two-particle cosmos from birth to death

particle and the other axis the other particle. The trajectory traced by the moving point corresponds to the changing pattern of the system of particles; conversely, the history of the system determines a unique trajectory. It is not a space-time graph. (Time enters later as an added parameter.) The line cannot form branches because that would split each particle in two. It may, however, intersect itself. If a system is periodic, the line will be a closed curve. To transform the graph into a space-time graph we can, if we like, add a time coordinate and allow the point to trace a curve in three dimensions.

The technique generalizes to a system of N particles in a space with any number of dimensions. Suppose we have 100 particles in our little line-segment cosmos. Each particle has one degree of freedom, so that our configuration point must move in a space of 100 dimensions. If our universe is a system of N particles on a plane, each particle has two degrees of freedom, and so our configuration space must be a hyperspace of $2N$ dimensions. In 3-space a particle has three degrees of freedom, so that the configuration space must have $3N$ dimensions. In general the hyperspace has an order equal to the total degrees of freedom in the system. Add another coordinate for time and the space becomes a space-time graph.

Unfortunately the position of a configuration point at any instant does not enable us to reconstruct the system's past or predict its future. Josiah Willard Gibbs, working on the thermodynamics of molecules, found a slightly more complicated space in which he could graph a system of molecules so that the record was completely deterministic. This is done by assigning six coordinates to each molecule: three to determine position and three to specify momentums. The movement of a single phase point in what Gibbs called a "phase space" of $6N$ dimensions will record the life history of N particles. Now, however, the position of the phase point provides enough information to reconstruct (in principle) the entire previous history of the system and to predict its future. As before, the trajectory cannot branch, but now it also cannot intersect itself. An intersection would mean that a state could be reached from two different states, and could lead to two different states, but both possibilities are ruled out by the assumption that position and momentums (which include a vector direction) fully determine the next state. The curve may still loop, however, indicating that the system is periodic. (On phase space see "The Arrow of Time," by David Layzer; SCIENTIFIC AMERICAN, December, 1975.)

Our universe, with its non-Euclidean space-time and its quantum uncertainties, cannot be graphed in anything as simple as phase space, but Wheeler has found a way to do it in superspace. Like configuration space, superspace is timeless, but it has an infinity of dimensions. A single point in superspace has an infinite set of coordinates that specify completely the structure of our non-Euclidean 3-space: its size, the location

Vivitar Series 1 35-85mm f2.8 variable focusing lens.

For many photographers a lens of this focal length range is an "ideal" lens covering wide angle, through normal, to medium telephoto. But for professional and scientific photographers the requirements of an "ideal" lens include more than a versatile range of focal lengths

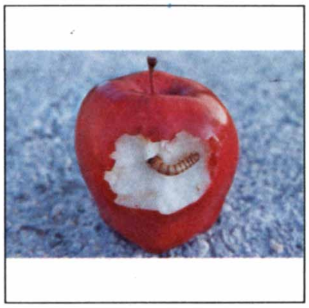
The assignment given by Vivitar to the Series 1 Research and Development Team included many complex design specifications, some conflicting, such as the need for a relatively high-speed lens and the insistence on compactness.

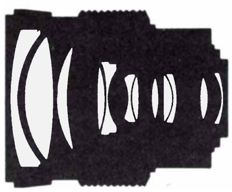
The specifications included the following: (1) A focal length range from 35 to 85mm. (2) Close focusing capability. (3) An f2.8 maximum aperture, so the lens could be used in place of a normal lens in low-light areas. (4) Length under 4 inches. (5) Weight under 30 ounces. (6) Contrast and resolution equal to or superior to comparable lenses. (7) Smooth but rugged mechanical operation. (8) Multicoating.

To accomplish all these requirements in one lens the team spent two years working with some of the world's largest computer banks. And instead of using the customary zoom lens configuration, which entailed some sacrifices in resolution at wide angle close focusing, the designers chose a variable focus solution. Changing the focal length is accomplished by movement of three independent floating groups in the lens, thus allowing close focusing to 4.3" from the front element (in the 35mm position), without sacrificing resolution. All done with a single-touch control.

The mechanical motion of these three groups is controlled by cams milled into sleeves. In order to achieve the extremely close tolerances specified by the Japanese mechanical designers. the cams had to be machined on specially-made, numerically-controlled lathes designed and built in Germany and Switzerland.

The extreme compactness of the lens itself necessitated the use of a nested series of cams and operating sleeves. Again, extremely close tolerances had to be maintained on the five concentric sleeves to eliminate centration errors. Even with the use of the most advanced optical equipment available today, to comply with the specifications each lens is individually adjusted by an engineer to ensure optimum optical alignment. The result is a valuable example of international cooperation, representing the combined efforts of Japanese, German and American specialists.





Optical Specifications

Construction:	12 elements 9 groups
Angle of view:	28° to 63°
Minimum focus distance	
From film plane:	10.2in. (25.9cm)
From front element:	4.3 in. (10.9 cm)
Maximum reproduction ratio:	1:3.5
Focal length ratio:	2.4:1

Mechanical Specifications

Filter size:	72mm
Weight:	27 oz. (770 gr.)
Length:	3.6 in. (9.1cm)
Max. diameter:	3.19 in. (81mm)
F/number range:	f2.8 to 16

Slip-on lens hood included. Available in mounts to fit Nikon, Canon, Minolta, Konica, Olympus OM, and Universal Thread Mount cameras.

Vivitar Series 1 Program

In recent years, remarkable progress has been made in solving some of the classic problems of optical design. Intensive work in the field was spurred on by the demands of space exploration and military applications and vastly aided by the growing sophistication of computer technology.

Vivitar optical designers, working with programs devised for highly specialized optical tasks, have used computer-generated designs to develop for Vivitar a new series of lenses capable of performance unreachable until now.

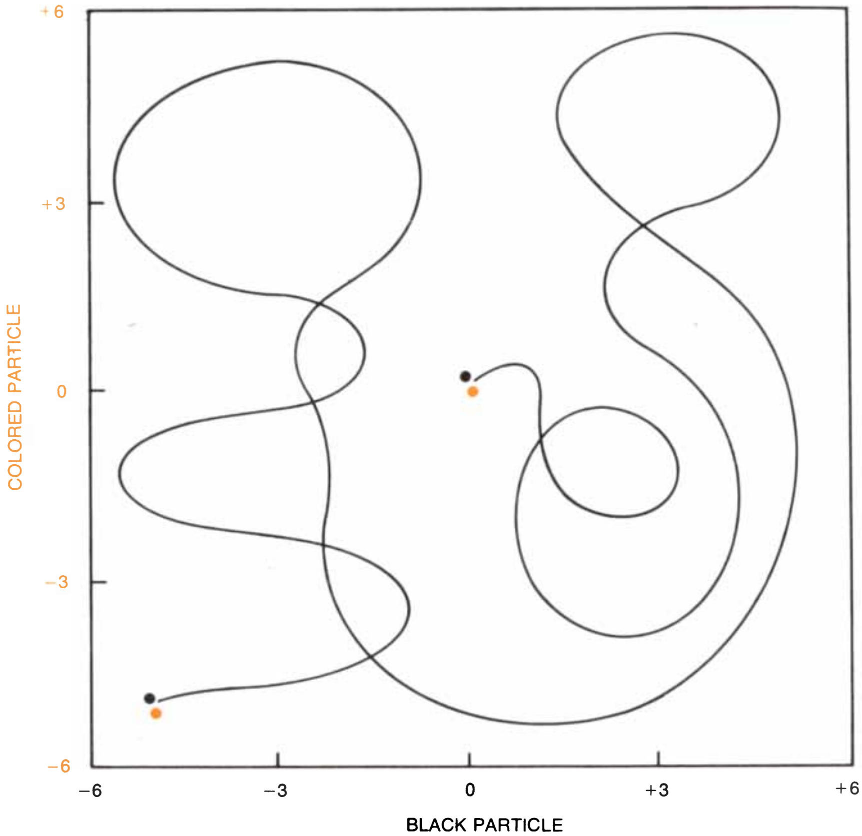
Each Vivitar Series 1 lens so far introduced represents a breakthrough in optical design. The 200mm f3 and the 135mm f2.3 are among the fastest automatic telephoto lenses in their respective focal lengths. They are unusually light and compact. Each has a uniquely positioned rear compensating element that automatically corrects aberrations at all points from the closest focusing point to infinity.

The 70-210 f3.5 automatic zoom lens and the 35-85mm f2.8 auto variable focusing lens are likewise definite advances in lens design, both offering extremely close focusing capability and remarkable compact configuration.

Most recently introduced are a 90mm f2.5 macro, a 28mm f1.9, and a 600mm f8 solid catadioptric lens. To come, 800mm f11 solid catadioptric and 1200mm f11 solid catadioptric telephoto lenses. There eventually will be a complete optical system of more than twenty Vivitar Series 1 lenses, each representative of advanced technology and demonstrably superior to other lenses currently available.

Vivitar®

Marketed in the U.S.A. by
Ponder&Best, Inc.
Corporate Offices: 1630 Stewart Street, Santa Monica, CA 90406.
In Canada: Precision Cameras of Canada, Ltd., Quebec.



A configuration-space graph of the history of two particles in a one-dimensional universe

of every particle and the structure of every field (including the curvature of space itself) at every point. As the superpoint moves, its changing coordinate numbers describe how our universe changes, not failing to take into account the role of observers' frames of reference in relativity and the probability parameters of quantum mechanics. The motion of the superpoint gives the entire history of our universe.

At the same time (whatever that means!) that the present drama of our cosmos is being acted on the stage of superspace countless other superpoints, representing other 3-space universes, are going through their cycles. Superpoints close to one another describe universes that most resemble one another, like the parallel worlds that H. G. Wells introduced into science fiction with his *Men like Gods*. These parallel universes, cut off from one another because they occupy different slices of superspace, are continually bursting into space-time through a singularity, flourishing for a moment of eternity, then vanishing back through a singularity into the pure and timeless "pregeometry" from whence they came.

Whenever such a cosmos explodes into being, random factors generate a specific combination of logically consistent (Leibniz called them compossible) particles, constants and laws. The resulting structure has to be tuned exceedingly fine to allow life. Alter the fine-structure constant a trifle either way and a sun such as ours becomes impossible. Why are we here? Because random factors generated a cosmic structure that allowed us to evolve. An infinity of other universes, not so finely tuned, are living and dying without there being anyone in them capable of observing them.

These "meaningless" universes, meaningless because they contain no participator-observers, do not even "exist" except in the weak sense of being logically possible. Bishop Berkeley said that to exist is to be perceived, and Charles Sanders Peirce maintained that existence is a matter of degree. Taking cues from both philosophers, Wheeler argues that only when a universe develops a kind of self-reference, with the universe and its observers reinforcing one another, does it exist in a strong sense. "All the choir of heaven and furniture of earth have no substance without a mind" was how Berkeley put it.

As far as I can tell, Wheeler does not take Berkeley's final step: the grounding of material reality in God's perception. Indeed, the fact that a tree seems to exist in a strong sense, even when no one is looking at it, is the key to Berkeley's way of proving God's existence. And what about the possibility of universes tuned to allow observers radically different from ourselves? And why should a universe be limited to 3-space, and what if the order of space is an irrational or complex number?

Here is an uncanny footnote. Shortly before Edgar Allan Poe died he wrote a small book called *Eureka*, which contains a vision astonishingly like Wheeler's. A universe begins, said Poe, when God creates a "primordial particle" out of nothing. From it matter is "irradiated" spherically in all directions, in the form of an "inexpressibly great yet limited number of unimaginably yet not infinitely minute atoms." As the universe expands, gravity slowly gains the upper hand and the matter condenses to form stars and planets. Eventually gravity halts the expansion and the universe begins to contract until it returns again to nothingness. The final "globe of globes will instantaneously disappear" (how Poe would have exulted in today's black holes!) and the God of our universe will remain "all in all."

In Poe's vision each universe is being observed by its own deity, the way your eye watched the two particles dance in our created world of 1-space. But there are other deities whose eyes watch other universes. These universes are "unspeakably distant" from one another. No communication between them is possible. Each of them, said Poe, has "a new and perhaps totally different series of conditions." By introducing gods Poe implies that these conditions are not randomly selected. The fine-structure constant is what it is in our universe because our deity wanted it that way. In Poe's superspace the cyclical birth and death of an infinity of universes is a process that goes on "for ever, and for ever, and for ever; a novel Universe swelling into existence, and then subsiding into nothingness at every throb of the Heart Divine."

Did Poe mean by "Heart Divine" the God of our universe or a higher deity whose eye watches all the lesser gods from some abode in supersuperspace? Behind Brahma the creator, goes Hindu mythology, is Brahman the inscrutable, so transcendent that all we can say about Brahman is *Neti neti* (not that, not that). And is Brahman being observed by a supersupersupereye? And can we posit a final order of superspace, with its Ultimate Eye, or is that ruled out by the contradiction in the concept of a greatest aleph?

It is here that we seem to touch—or perhaps we are still infinitely far from touching—the hem of Everything. Let C. S. Lewis (I quote from Chapter 2 of his *Studies in Words*) make the final comment: "'Everything' is a subject on which there is not much to be said."

Magic-square buffs will welcome an excellent book just published by Dover: *New Recreations with Magic Squares*, by William H. Benson and Oswald Jacoby. The book is filled with original material that appears in print for the first time. All 880 magic squares of order 4 are listed in an appendix, and the book gives the fantastic tri-magic square of order 32 constructed by Captain Benson in 1949. This is a square that retains its magic not only when every number is squared but also when every number is cubed. The simplest-known square of that type was of order 64 before Captain Benson found a way to halve the order.

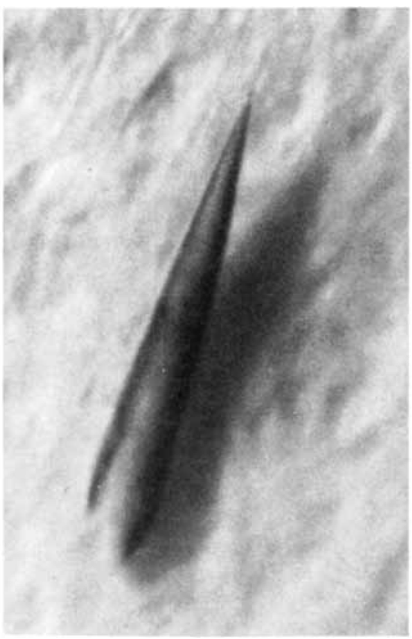
BOOKS

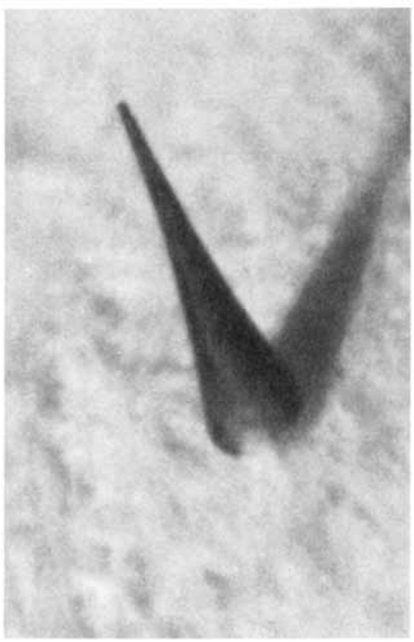
Among other things, the useful tracks made in solids by energetic particles

by Philip Morrison

NUCLEAR TRACKS IN SOLIDS: PRINCIPLES & APPLICATIONS, by Robert L. Fleischer, P. Buford Price and Robert M. Walker. University of California Press ($31.50). When a heavily ionizing nuclear particle traverses matter, it leaves behind a faint track of disturbed atoms. If the material is an insulating solid, whether a mineral crystal, a natural or an artificial glass or a high-polymer organic plastic, the track is a permanent feature of the solid (barring certain healing processes at high temperature). There endures a core of disturbed atoms perhaps up to a dozen atomic lattice spaces in diameter. With the electron microscope this minute trace can often be just made out by elegant technique. That is wonderful enough, but about 15 years ago the three authors of this book made a happy discovery (anticipated some four years by a Harwell physicist, D. A. Young, whose publication went unnoticed). That subtle atomic trace can be made to grow indefinitely by simple chemical etching. The etchant attacks the track along its length at an increased rate, and outward as well, if somewhat more slowly. The trace rapidly becomes a conical pit, easy to see with a light microscope. A surface fission trace in an ordinary glass microscope slide etched with dilute hydrofluoric acid will grow into a pit 10 microns deep and about the same diameter in a couple of minutes, a 10-millionfold amplification. Any glass surface or mineral inclusion becomes for nuclear events the equivalent of a sensitive photographic emulsion.

Bombardment by electrons does not leave any lasting trace; only heavy ionizing particles make a developable track. It is not the total energy lost that does the damage. Most of the energy goes into electrons, which diffuse many lattice spaces outward from the path of the particle. The track appears to begin as a local column of a few nearby atoms left electrostatically charged. They are mutually pushed into interstitial positions; this column of displaced sites is then slowly relieved by elastic relaxation, so that finally a large volume is occupied by a strained lattice, which is now able to react with the etching reagent more rapidly than the undisturbed material can. If the substance is a conductor, carriers or holes flow quickly to heal the electrical imbalance long before the ions can move out into the strained surrounding. Such substances do not etch. But the weaker the insulating material is, the closer its atoms are, the less its dielectric screening is and the more sensitive it is to etched tracks. Acetate will show up even relatively thin alpha-particle tracks; harder dielectrics such as mica reveal only the dense traces of slow-moving multiply charged ions.





Etched cosmic-ray tracks in an Apollo space helmet, from **Nuclear Tracks in Solids**

This treatise, with some 1,200 references, summarizes the whole of a versatile and surprising nuclear branch of solid-state physics. The applications have been so diverse that they strain neat ordering. They range from the authentication of art objects to the making of cheap one-gram altimeters for homing pigeons, through dating, cosmic-ray studies and radiation dosimetry. Since the protean authors want to motivate for us each of the many areas of research their ingenuity has assisted, they have created a diffuse volume with interesting introductory accounts of cosmic-ray origins, lunar-soil history, heavy-ion radiography and even a miscellany of uses for etched-track microsieves, commercially available with neat rounded holes measuring from a micron or two on up. The book is even typographically diffuse and bulky.

The power achieved by this kind of instrumentation is remarkable. If it is tedious to search microscopically for pits (a couple of hours per square centimeter is common), there are swifter means. One ingenious group floated their aluminized plastic detector films on the surface of the bath of alkali etchant. Below the solution they put a bright light source; they viewed the opaque floating sheet from above with a time-lapse motion-picture camera, watching for the appearance of bright points of light as the lye etched through and dissolved the thin acetate.

The Skylab heavy-cosmic-ray work and the fossil solar flares marked in moon dust are interesting. But it is uniquely the etched track that makes possible the proud graph shown on one page: dating by a single method, fully confirmed, extending from samples of synthetic glass a decade old to mineral inclusions from the earliest days of the solar system. One needs some natural uranium impurity (there is .4 part per million of uranium in a microscope slide) that always decays at a constant rate, leaving the heavy tracks of spontaneous fission. Count tracks after etching a surface. Expose the material to a neutron flux in your neighborhood reactor. Count the new pits induced, developed the same way in the same etching bath. Prudently include a standard dosimeter (the microscope slide again will do), so that its count will calibrate your neutron flux against known uranium content. The three counts date the material: an obsidian knife, a meteorite, Olduvai pumice or the zircons in the baked-clay core of a disputed bronze horse at the Metropolitan.

Wormholes of the fissioning impurities slowly grow in almost every crystal of our

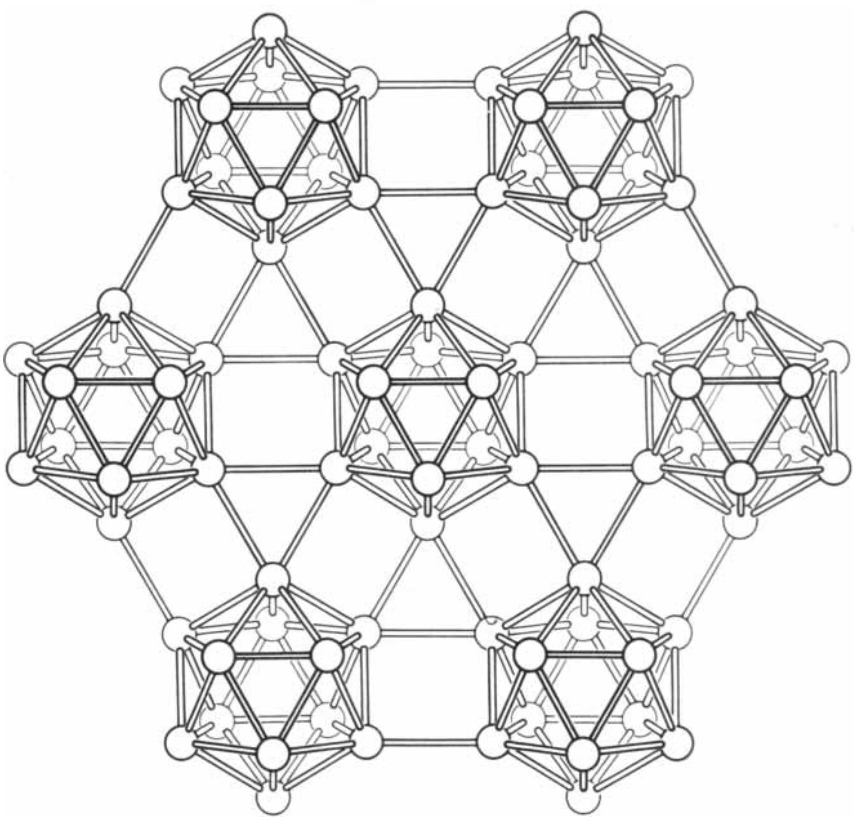
world, inexorably marking its age in every part. Given one part per million of uranium, "considerable labor" will fix ages from 8,000 years on back. If the sample is uranium-rich or too old, the pits may overlap. Bubbles and various inclusions also can confuse the count, as cautionary photographs make clear. There are many tricks to this trade, which like the tracks themselves is still growing.

THE STRUCTURES OF THE ELEMENTS, by Jerry Donohue. John Wiley & Sons ($23.75). The crystalline world of neatly packaged atomic modules is ubiquitous, whether in the visible facets of table salt or the hidden grains of the hammered knife blade. Today the diffraction experts—with their choice of X-ray photons or the de Broglie waves of electrons and neutrons—have winkled that elegant atomic geometry out of enough substances to crowd half a dozen thick volumes with diagrams and data. Here Professor Donohue, a veteran structure sleuth who played an important supporting part in the drama of the double helix, provides the chemically simplest sample: the elements themselves, all assemblages of identical atoms, from hydrogen right up to berkelium. (No structures of those half-dozen radioactive elements beyond berkelium, element 97, have yet been reported.)

We all know that identical atoms have the cunning to pack in different ways, each packing displaying some local minimum in the free energy. The Grand Duke's burning glass first made clear how the costly and invincible diamond burned to carbon dioxide no different from the product of glowing charcoal. In the section here on carbon one comes at last to the famous phase diagram, now some 15 years old, where fields of stability for graphite, diamond and liquid carbon occupy their ranges of pressure and temperature from room conditions to those 200 kilometers deep in the earth's mantle, where diamond must be the commonplace form of carbon. From the work behind that diagram the modern synthetic-diamond industry grew.

The plot does not tell the whole story. There are seven crystalline forms of pure carbon known. The diamond of the mines is an array with cubic symmetry, each carbon atom bonded to a tetrahedron of its fellows. But in some meteors, and in the laboratory press since 1967, a less stable hexagonal diamond is also known. Graphite also has two forms: in the normal one layers of similar atomic hexagons are put down in an alternating two-layer fashion, with certain atoms stacked above holes in the layer below. In the less common form, found in natural and artificial graphite in appreciable quantity, the repeat requires three layers instead of two.

There is a new cubic form of carbon reported at high pressure. The mineral chaoite, first found in shock-fused graphite from the great Ries meteor crater in Bavaria, is a complex hexagonal allotrope, packed almost as densely as diamond. In 1972 "yet another hexagonal form of carbon was reported," but beyond a strong sign of hexagonal symmetry its structure is uncertain. There is good reason to accept a ninth high-pressure phase, by analogy with the tinlike metallic phases of silicon and germanium.



The structure of rhombohedral-12 boron, from **The Structures of the Elements**

So does this insider's volume read, element by element arranged by chemical families. The author summarizes structures more or less chronologically, with an eye for the errors of the past. These are plentiful, and they are by no means absent in the latest work. What looks like a new phase is sometimes a mixture of several phases, or even a gross impurity.

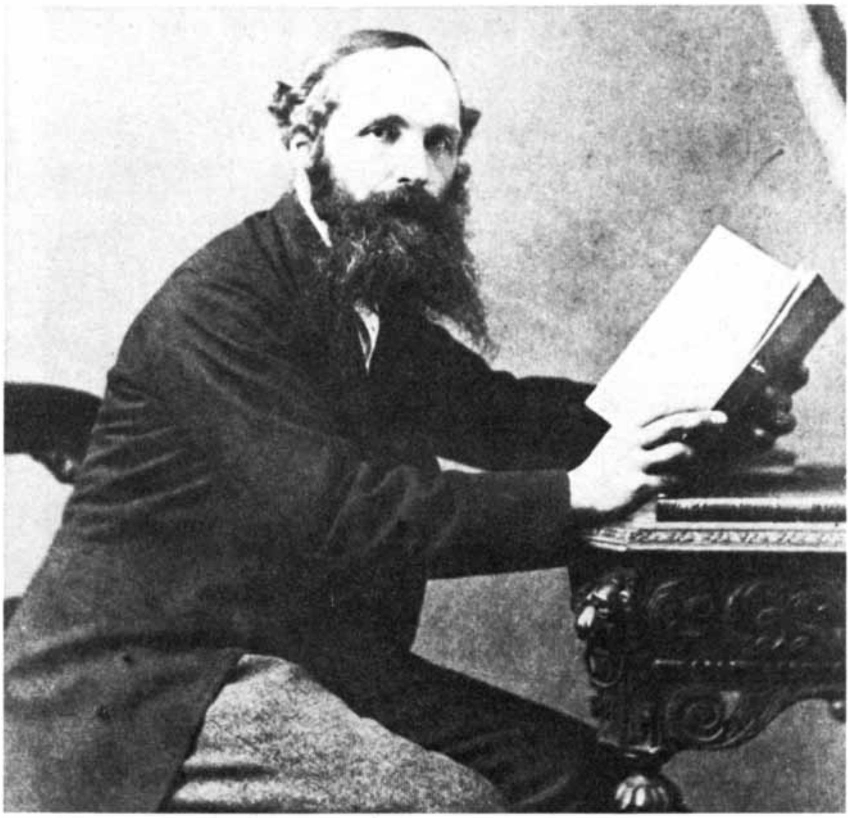
The chief data presented are pictorial structures of the element lattices, their lattice constants as a function of temperature and the phase diagrams. Few other properties are given. The text is a skeptic's account, which is much needed. Take sulfur. With its wide options for molecular grouping, it is a peculiarly confused example. Some results are clear: orange rhombohedral sulfur is a neat packing of sixfold molecules, each molecule very much like a pan of hearth rolls in the pleasant stippled drawing. Some are as mysterious as the green, purple and violet sulfurs published by a variety of workers, who condensed vapor from molecular beams or allowed solutions in odd solvents to stand overnight between glass plates ("when the laboratory temperature fell to 8°C.," as one Finnish winter chemist reported).

"The structural chemistry of elemental phosphorus is a Comedy of Errors on which the final curtain has not yet descended." Match tips are of amorphous red phosphorus, but nine X-ray-diffraction diagrams, all different and not one like any other well-characterized form of the element, are reported for crystalline "red phosphorus," depending on the method of preparation. Even if the Great Red Spot of Jupiter turns out to be a dust of red phosphorus, we would not be sure what that is. Oxygen has four cold crystal forms, all packings of O_2. The O_3 form is without diffraction data, since "solid ozone is capriciously explosive." Its density was first found in 1959.

Elemental boron has forms of "enormously complicated framework" with some "simple and beautiful features which would have made Kepler leap with joy." The ball-and-stick drawings here, with their linked icosahedrons, resemble sketches of splendid geodesic domes, some nearly regular, some with concave faces. It is a kind of relief to encounter elements as bland as gold or platinum, silver or zinc: close-packed lattices of one form or another, with no clear structural changes from the lowest temperature up to just below the melting point. For even a few of these, novel thin-film structures with different packing are claimed.

The moral is certainly made clear: even the simplest crystals are by no means simple. The book is clear, comprehensive and well written, but it implies that the range of techniques generally applied has been rather limited. Structural research so far is nearly all based on diffraction; it is a good guess that future work will come increasingly to employ such exploratory techniques as differential microcalorimetry and various electrical, magnetic or microwave measurements. There is plenty to do, even without attempting such exotica as radon and astatine.

JAMES CLERK MAXWELL: PHYSICIST AND NATURAL PHILOSOPHER, by C. W. F. Everitt. Charles Scribner's Sons ($2.95). Maxwell died too young, from abdominal cancer at 48, at the height of his rising powers. His reputation has soared until it transcends that of all other Victorian physicist worthies. It is the Maxwell equations, whose content was upheld first by Hertzian waves and then by the special theory of relativity (as it is now by quantum electrodynamics), that remain unchanged where Newton is amended. This "preliminary scientific *éloge*" should help to bring the man himself—slight of stature, modest, humorous, loving and profound—back into view. The famed equations are here, not in the compact form (due mainly to Heaviside and Hertz) now stenciled on students' T-shirts but as they appeared in *Treatise on Electricity and Magnetism,* Maxwell's big, rambling but locally elegant 1873 summary of many years' work. He wrote it in semiretirement on his (and his father's) country estate before he took up his last academic post: planner and first professor of the new Cavendish Laboratory at Cambridge. He was not only a mathematical physicist of powerful originality but also a first-rate experimenter. He wrote to Rayleigh (who succeeded him at the Cavendish): "It will need a good deal of effort to make Exp Physics bite into our university system.... If we succeed too well and corrupt the minds of youth till they observe vibrations and deflections... we may bring the whole university and all the parents about our ears."



Maxwell in about 1870, from **James Clerk Maxwell**

Maxwell shares with Helmholtz the honor of founding, on the three-receptor ideas of Thomas Young, the quantitative science of colorimetry, both in theory and in experiment. In this illustrated paperback we see a spectrum locus plotted in the modern style; the results of Maxwell and his wife Katherine ("Observer K") lie on the modern data rather better than those of specialists working 60 years later. The couple were childless; Mrs. Maxwell was not always emotionally well, but the two were close. The important experiments on the viscosity of gases were in large measure her work. "My better 1/2, who did all the real work of the kinetic theory, is at present engaged in other researches. When she is done, I will let you know her answer to your enquiry [about the data]," Maxwell wrote to his friend Peter Guthrie Tait in 1877.

Maxwell gave us the first mathematical treatment of servomechanisms, the first account of Gaussian units in electricity and magnetism (with a modern notation for dimensional analysis), the concept of relaxation times, the entire subject of the dynamics of rarefied gases and the best early treatments of kinetic transport theory as a whole. His remarkable 1860 approach to the statistical distribution of velocities among gas molecules, writes Professor Everitt, "marks the beginning of a new epoch in physics." That first paper "conveys a strange impression of having nothing to do with molecules or their collisions." Maxwell must forever share with Rudolf Clausius and Ludwig Boltzmann the founding of kinetic theory, but his insight was in a way more general, more akin to that of Josiah Willard Gibbs 40 years later. He was an early admirer and a "powerful advocate" of the thermodynamics of Gibbs, the brilliant outsider in far-off New England. Everyone knows of the "sorting demon," named by Lord Kelvin but imagined by Maxwell. Maxwell's demon, "small BUT lively," first appeared in his *Theory of Heat* (1870). That not so simple text was one of those he hoped would be useful to workingmen; active as a student in the Christian Socialist movement at Trinity College, Maxwell taught "evening classes for artisans" regularly.

Professor Everitt, a Stanford historian-physicist, clarifies a good deal of Maxwell's work. It becomes hard to doubt that the overly mechanical concepts of the ether, the little idler wheels rolling between vortexes, were mainly tentative models, not stern metaphysical stances. The ether was no neat account of anything. Maxwell seems to have shared William Whewell's more up-to-date metaphysics, that "reality is ordered in a series of tiers," and the key is to find the "appropriate idea" for each tier. Maxwell's views on charge itself, in an era before electrons, remain stubbornly hard to understand, even after a manful effort by Professor Everitt, complete with two drawings.

If Faraday "worked by gradually collecting arrays of facts," accumulating understanding a little at a time, Lord Kelvin "was a man of violent enthusiasms." "His best papers would have made perfect contributions to *Physical Review Letters;* their two or three pages... might be a clue to the trickiest problem in physics" or the start of a wild-goose chase. Maxwell, however, had the "goal of completeness." He wrote repeatedly on the same high topics after years of prolonged thought, and his great papers are 70 or 80 pages compact with ideas and their formal consequences.

It is a delight to see the photographs of the boy and the man and his family, the watercolors made by his first cousin, the apparatus of many kinds, the old laboratory of the Cavendish, the postcards Maxwell exchanged over the years with William Thomson (later Lord Kelvin) and Tait ("T and T′") once the halfpenny postcard was introduced. These enriching details distinguish this book from its less accessible source, the authoritative 14-volume *Dictionary of Scientific Biography,* approaching the end of its years of issue. The text is mainly a line-by-line reprint of the *Dictionary* article, in larger type on smaller pages, together with a welcome index and the portfolio of pictures. A few other major articles are being given the same form; they can be recommended unseen.

The tartan ribbon, the subject of the first trichromatic color photograph, projected in

Physics of the earth... astronomy...chemistry... the double helix... probability theory... electrodynamics...

To keep up with everything that's happening in every scientific area that interests you...Take any 3 books (values to $60.90) all for only $3.95– as a member of

The Library of Science.

if you will join now for the trial period and agree to accept only 3 more books—at members' discount prices—over the next 12 months.

The Library of Science 2-1AE
Riverside, New Jersey 08075

Please accept my application for membership and send me the three volumes indicated, billing me only $3.95. I agree to purchase at least three additional Selections or Alternates during the first year I am a member, under the club plan described in this ad. Savings range up to 30% and occasionally even more. My membership is cancelable any time after I buy these three books. A shipping and handling charge is added to all shipments. **Send no money. Members are billed when books arrive.**

3 books for $3.95
Indicate by number the 3 books you want.

[ ] [ ] [ ]

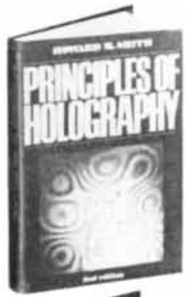
A few expensive books (noted in book descriptions) count as 2 choices.

Name ______________________

Address ______________________

City ____________ State ____________ Zip ____________

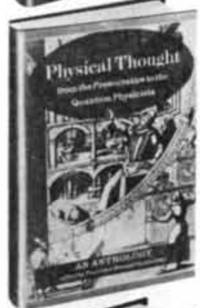
(Offer good in Continental U.S. and Canada only. Prices slightly higher in Canada.) Book selections purchased for professional purposes may be a tax deductible expense.



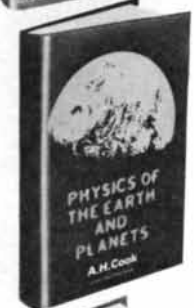
(Publishers' Prices shown)

70170. PRINCIPLES OF HOLOGRAPHY. Second Edition. *Howard M. Smith.* Covers every aspect of holography from fundamentals to rigorous theory, from chemical formulas to applications. **$16.50**

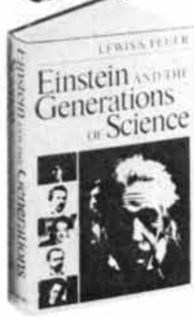
34140. APPLIED ANALYTICAL MATHEMATICS FOR PHYSICAL SCIENTISTS. *James T. Cushing.* Strikes a balance between rigorous theory and simple applications. Ranges from spectral analysis of linear operators to complex variables, to group therapy. **$19.95**



68750. PHYSICAL THOUGHT FROM THE PRESOCRATICS TO THE QUANTUM PHYSICISTS. *Samuel Sambursky.* Impressive history of the most important events in the development of the physical sciences. Includes excerpts of great scientists from Aristotle to Pauli. **$20.00**

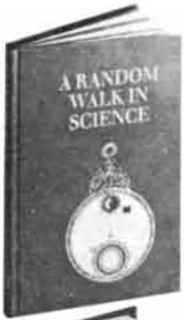


68735. PHYSICS OF THE EARTH AND PLANETS. *Alan H. Cook.* What forces shaped the earth? What is the mechanism that prompts continental drift? These questions—and dozens more—are answered by one of the world's leading authorities on physical meteorology. *Counts as 2 of your 3 books.* **$24.75**



44000. EINSTEIN AND THE GENERATIONS OF SCIENCE. *Lewis S. Feuer.* What really accounts for the shattering insights of Einstein, Bohr, de Broglie, Heisenberg, and other great scientists? A bold and controversial explanation. **$12.95**

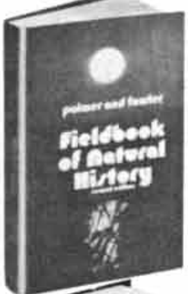
How the Club Operates • The Book Club News, describing the coming Main Selection and Alternate Selections, will be sent to you 15 times a year at 3-4 week intervals. • If you wish to purchase the Main Selection, do nothing and it will be shipped to you automatically. • If you prefer one of the Alternates, or no books at all, simply indicate your decision on the reply form always enclosed with the News and mail it so that we receive it by the date specified. • The **News** is mailed in time to allow you at least 10 days to decide if you want the coming Main Selection. If, because of late mail delivery of the **News,** you should ever receive a Main Selection without having had the 10 day consideration period, that Selection may be returned at Club expense. • Continued membership past the trial period brings you the added benefits of our Bonus Book Plan—an important way to save even more, at least 70% off publishers' prices.



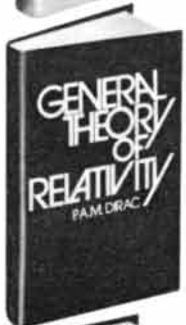
73330. A RANDOM WALK IN SCIENCE. *Compiled by Robert L. Weber and Eric Mendoza.* A collection of jokes, short essays and poems on humor and humanity in physics and related sciences. ". . . it is the best anthology of its kind I have seen." —Martin Gardner. **$12.50**

52650. THE HERITAGE OF COPERNICUS. *Edited by Jerzy Neyman.* 25 highly readable essays on the quasi-Copernican revolutions that have occurred in the past five centuries. Contributions by Bart J. Bok, Stanley L. Miller, Glenn T. Seaborg, and two dozen other scientists. *Counts as 2 of your 3 books.* **$30.00**

86540. THE WAY THINGS WORK BOOK OF THE COMPUTER. This well-illustrated volume is a veritable encyclopedia of information science, cybernetics, and data processing. Written in terms the non-specialist can easily understand. $8.95

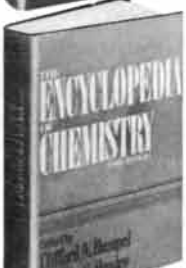


48470. FIELDBOOK OF NATURAL HISTORY. *E. Laurence Palmer and H. Seymour Fowler.* Most authoritative and comprehensive guide to natural history available. Over 2,000 illustrations. **$19.95**



50270. GENERAL THEORY OF RELATIVITY. *P.A.M. Dirac.* Nobel laureate explains as simply and as concisely as possible the basic mathematical principles and techniques involved in general relativity. A "must" for anyone who wants to really understand modern gravitational theory. **$10.95**

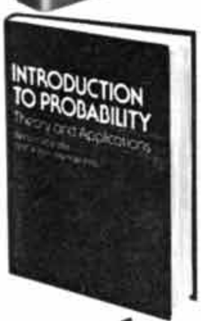
69990. PRELUDE TO SCIENCE. *Richard Smith.* A detached and witty excursion into the origin, history, vagaries, and intentions of such pseudosciences as magic, divination, astrology, Tarot, and I Ching. Offers enlightening descriptions of their methods and techniques. **$7.95**



44861. THE ENCYCLOPEDIA OF CHEMISTRY. Third Edition. *Edited by Clifford A. Hampel and Gessner G. Hawley.* 600 leading chemists thoroughly explore over 800 theoretical and applied aspects of chemistry and chemical technology. Over 1200 pages, hundreds of invaluable charts, diagrams, and illustrations. *Counts as 2 of your 3 books.* **$39.50**

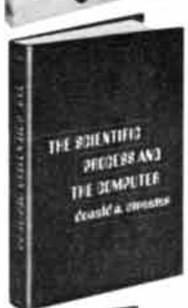
62900. MONUMENTS OF CIVILIZATION: Egypt. *Claudio Barocas.* Sumptuously illustrated portrait of the ancient pyramids and temples of Egypt and the culture that built them. Offers a richly detailed account of history's most alluring civilization—its sun-god pharaohs and fallahs, architects and slaves, religion and mythology, rise and fall. **$19.95**

32990. THE AMERICAN MUSEUM OF NATURAL HISTORY GUIDE TO SHELLS. *William K. Emerson and Morris K. Jacobson.* The first definitive guide for identifying and collecting Atlantic coast marine shells, *and* freshwater and land shells of the east and midwest. Includes 80 pages of photographs. **$15.00**



56380. INTRODUCTION TO PROBABILITY. *Richard L. Scheaffer and William Mendenhall.* For scientists using probability theory. Covers everything from Markov chains to the arrival times for the Poisson process. **$13.50**

36395. BLACK HOLES, QUASARS AND THE UNIVERSE. *Henry L. Shipman.* Where do black holes come from? Where do quasars get their fantastic energy from? What are white dwarfs, neutron stars, supernovae, and Seyfert galaxies? They're all in this absorbing exploration of the frontiers of astronomy. **$12.95**



76910. THE SCIENTIFIC PROCESS AND THE COMPUTER. *Donald N. Streeter.* A readable, comprehensive guide to the use of the entire range of computer-based systems and services currently available for scientific and technological activities. **$18.50**

61350. MATHEMATICAL TECHNIQUES IN CHEMISTRY. *Joseph B. Dence.* All of the mathematics commonly required by chemists—from elementary algebra through calculus to tensors, matrices, Bessel functions, and much more. **$14.50**

67190. THE PATH TO THE DOUBLE HELIX. *Robert Olby.* ". . . The first full scholarly account of how the structure of DNA was discovered . . . absorbing reading." —Francis Crick. *Counts as 2 of your 3 books.* **$23.50**

52190. HANDBOOK OF APPLIED MATHEMATICS. *Edited by Carl Pearson.* Over 20 contributing author-specialists provide over 1,000 pages of vital and practical techniques for use of mathematics as a tool. *Counts as 2 of your 3 books.* **$37.50**

70240. PRE-COLUMBIAN CITIES. *Jorge E. Hardoy.* A highly acclaimed synthesis of the urban civilization of the New World before Columbus. ". . . first-class reading" —*Scientific American.* **$19.95**

70190. PRINCIPLES OF OPERATIONS RESEARCH. Second Edition. *Harvey M. Wagner.* Based on the author's twenty years of experience applying operations research to a wide variety of problems, this 1039-page book offers a complete overview of all the fundamental concepts. **$19.95**

38305. CLASSICAL ELECTRODYNAMICS. *John D. Jackson.* Revised, updated, and expanded. A remarkably thorough review of all aspects of electrodynamics—from elementary topics to such advanced topics as Kirchhoff theory and Cerenkov radiation. **$20.95**

1861 by Maxwell before an audience that included Faraday, is not here. (It was reproduced in *Scientific American* for November, 1961.) The big copper beech at the Maxwell estate in Galloway ("even today one of the . . . least-known parts of Scotland") flourishes still; it is from a cutting of a copper-beech mutant that had arisen at Kew Gardens and was planted by Maxwell's father "amid huge festivities" to celebrate the safe return of his wife and the new infant James from Edinburgh, nearer the doctors. (Their firstborn, a daughter, had lived for only a few months.) That tree deserves visitors even more than did the old apple tree in Trinity Great Court, doubtful scion of the Woolthorpe gravitational apparatus.

OCEANOGRAPHY AND SEAMANSHIP, by William G. Van Dorn. Dodd, Mead & Company ($22.50). The hard school of experience has trained skippers and crewmen for millenniums. In this large volume the new science of physical oceanography is brought for the first time explicitly and convincingly to the aid of the expert yachtsman. The author is a veteran research worker at the Scripps Institution of Oceanography, a man who has gone to sea in "everything from two barrels lashed together to an aircraft carrier." He has dived for a lost anchor in the pass at Bora Bora and has spent two months trying to start without capsizing a Gilbertese sailing canoe in the choppy lagoon at Canton Island. He is a patient and cheerful expositor of simple mathematical and physical processes for serious use (the book plainly aims to save lives), and he salts the compendious and entertaining work with forthright opinion.

The keel of the book is laid in dynamics: the motions of wind, current, wave and the craft obedient to them all. Structure is not forgotten: a safe ocean-racing yacht ought to have shrouds and cleats "strong enough to lift the boat out of the water by." The author rails at builders who sacrifice strengthening members for performance until you are "left with a Dixie Cup that pants, hogs and twists [and] may cross the line first a few times before she breaks in two!"

Van Dorn explains waves—capillary waves, shallow-water waves and deep-water gravity waves—from first principles. He goes further to bring to an attentive reader, who need know nothing of Fourier analysis, the essence of the wave spectrum at sea. That spectrum is sketched, from the ill-defined high-frequency end, where waves are capillary ripples that arise at every puff of wind, with frequencies of a few cycles per second, through the high peak intensity of waves with periods of many seconds, fed by fair wind and foul, up to the sharp cutoff at about 20 seconds. Beyond that the expected height falls sharply as the very long waves feel the bottom even in mid-ocean. (Here the dread tsunami peak is dotted in.) Finally, that continuous spectrum of random wind-driven waves gives way to the sharp resonant lines of the 12- and 24-hour true tides.

On this up-to-date foundation Van Dorn builds a careful scheme for wave forecasting at sea: the expected sea state and its changes (depending on fetch, wind speed and duration) and the chances that state implies for the big wave that can pitchpole any boat. The strategy and tactics of sea-keeping—or sea-fleeing—in heavy weather flow from this kind of analysis, which is combined with a clear account of the response of ships to the sea, with emphasis on seaworthy yachts. Here is a photograph of the 68-foot schooner *Curlew* running toward Bermuda under bare poles before a wind gusting to 80 knots. The big waves are grimly there, pretty much as the book's charts predict, and they break heavily. The *Curlew* was abandoned, flooded to a depth of three feet over the cabin sole. That nonlinear and dangerous big wave is the one that is the least well understood; the author has estimated the breaking probabilities from his own photographic studies of wild seas. A careful account of the theory and practice of anchors and a chapter of virtuoso operations analysis about how to rescue a shipmate who goes overboard in the open ocean close the work.

There are plenty of examples, and the luminous good sense that goes with serious sailing, to round out a usable and fascinating analysis of circumstances seemingly so haphazard and capricious as a stormy sea. The book is excellent reading for landlubbers with an interest in the nature of the watery world, and it is an essential work for ocean sailors who want to convert chance-taking into a carefully calculated risk.

The weather at sea is made very understandable, with a voyage in prose right down a meridian from pole to pole. One comes almost to see the "meteorological equator," the wall of clouds at the Intertropical Convergence, which fixes the doldrums and dries the Line Islands. That structure is always displaced northward from the Equator, because the watery Southern Hemisphere is cooler than the Northern. There is then not enough room south of the convergence for hurricanes to feed on enough spin before they cross the Equator to encounter opposing rotations. "Therefore hurricanes are unknown in the South Atlantic," and it is generally safe to sail near the Equator but opposite any sector where the Intertropical Convergence is well established. It is just such links between knowledge and the prudent use of it that distinguish this work of devotion and reason. The general scientific reader easily profits from it all, but the sailor must take heed.

Can your boat roll clear over "without losing watertight integrity . . . and without emptying the contents of all drawers and lockers in a hopeless jumble . . . to slosh back and forth in a mixture of seawater, fuel oil and battery acid?" That is Van Dorn's "first test of seamanship"; if your answer is no, and you rest content, you are "forever committed to fair weather sailing, or to courting disaster."

BIBLIOGRAPHY

Readers interested in further reading on the subjects covered by articles in this issue may find the lists below helpful.

OIL AND GAS FROM COAL

CLEAN FUELS FROM COAL: SYMPOSIUM PAPERS, PRESENTED SEPTEMBER 10–14, 1973, CHICAGO, ILLINOIS. Institute of Gas Technology, December, 1973.

PROCEEDINGS OF SIXTH SYNTHETIC PIPELINE GAS SYMPOSIUM: CHICAGO, ILLINOIS, OCTOBER 28–30,1974. American Gas Association, 1974.

FEDERAL ENERGY ADMINISTRATION PROJECT INDEPENDENCE BLUEPRINT FINAL TASK FORCE REPORT. Prepared by the Interagency Task Force on Synthetic Fuels from Coal, under the direction of the U.S. Department of the Interior. U.S. Government Printing Office, November, 1974.

FISCHER-TROPSCH PLANT DESIGN CRITERIA: PRESENTED AT 68TH ANNUAL MEETING OF AMERICAN INSTITUTE OF CHEMICAL ENGINEERS, LOS ANGELES, NOVEMBER 19, 1975. J. B. O'Hara, A. Bela, N. E. Jentz and S. K. Khaderi. The Ralph M. Parsons Company, 1975.

OIL/GAS PLANT DESIGN CRITERIA: PRESENTED AT 68TH ANNUAL MEETING OF AMERICAN INSTITUTE OF CHEMICAL ENGINEERS, LOS ANGELES, NOVEMBER 19, 1975. J. B. O'Hara, G. H. Hervey, S. M. Fass and E. A. Mills. The Ralph M. Parsons Company, 1975.

CELL-SURFACE IMMUNOLOGY

SOME ASPECTS OF NORMAL AND ABNORMAL CELL SURFACE GENETICS. Edward Boyse and Lloyd J. Old in *Annual Review of Genetics,* Vol. 3, pages 269–290; 1969.

SURFACE ANTIGENIC MARKERS FOR DISTINGUISHING T AND B LYMPHOCYTES IN MICE. Martin C. Raff in *Transplantation Reviews,* Vol. 6, pages 52–80; 1971.

REDISTRIBUTION AND PINOCYTOSIS OF LYMPHOCYTE SURFACE IMMUNOGLOBULIN MOLECULES INDUCED BY ANTI-IMMUNOGLOBULIN ANTIBODY. Roger B. Taylor, W. Philip H. Duffus, Martin C. Raff and Stefanello de Petris in *Nature New Biology,* Vol. 233, No. 42, pages 225–229; October 20, 1971.

THE FLUID MOSAIC MODEL OF THE STRUCTURE OF CELL MEMBRANES. S. J. Singer and Garth L. Nicolson in *Science,* Vol. 175, No. 4023, pages 720–731; February 18, 1972.

T AND B LYMPHOCYTES AND IMMUNE RESPONSES. Martin C. Raff in *Nature,* Vol. 242, No. 5392, pages 19–23; March 2, 1973.

MECHANICAL ALLOYING

STRUCTURE AND PROPERTIES OF ALLOYS. Robert M. Brick, Robert B. Gordon and Arthur Phillips. McGraw-Hill Book Company, 1965.

DISPERSION STRENGTHENED SUPERALLOYS BY MECHANICAL ALLOYING. John S. Benjamin in *Metallurgical Transactions,* Vol. 1, No. 10, pages 2943–2951; October, 1970.

THE SUPERALLOYS. Edited by Chester T. Sims and William C. Hagel. John Wiley & Sons, Inc., 1972.

THE MECHANISM OF MECHANICAL ALLOYING. J. S. Benjamin and T. E. Volin in *Metallurgical Transactions,* Vol. 5, No. 8, pages 1929–1934; August, 1974.

THE VASCULARIZATION OF TUMORS

ISOLATION OF A TUMOR FACTOR RESPONSIBLE FOR ANGIOGENESIS. Judah Folkman, Ezio Merler, Charles Abernathy and Gretchen Williams in *The Journal of Experimental Medicine,* Vol. 133, No. 2, pages 275–288; February 1, 1971.

TUMOR DORMANCY IN VIVO BY PREVENTION OF NEOVASCULARIZATION. Michael A. Gimbrone, Jr., Stephen B. Leapman, Ramzi S. Cotran and Judah Folkman in *The Journal of Experimental Medicine,* Vol. 136, No. 2, pages 261–276; August 1, 1972.

SELF-REGULATION OF GROWTH IN THREE DIMENSIONS. Judah Folkman and Mark Hochberg in *The Journal of Experimental Medicine,* Vol. 138, No. 4, pages 745–753; October 1, 1973.

TUMOR GROWTH AND NEOVASCULARIZATION: AN EXPERIMENTAL MODEL USING THE RABBIT CORNEA. Michael A. Gimbrone, Jr., Ramzi S. Cotran, Stephen B. Leapman and Judah Folkman in *Journal of the National Cancer Institute,* Vol. 52, No. 2, pages 413–427; February, 1974.

RELATION OF ENDOTHELIAL PROLIFERATION TO TUMOR GROWTH. Judah Folkman and Ramzi Cotran in *International Review of Experimental Pathology: Vol. XVI,* edited by G. W. Richter and N. A. Epstein. Academic Press, 1976.

SYNCHRONOUS FIREFLIES

SYNCHRONOUS RHYTHMIC FLASHING OF FIREFLIES. John Bonner Buck in *The Quarterly Review of Biology,* Vol. 13, No. 3, pages 301–314; September, 1938.

PACEMAKER NEURONS: EFFECTS OF REGULARLY SPACED SYNAPTIC INPUT. Donald H. Perkel, Joseph H. Schulman, Theodore H. Bullock, George P. Moore and José P. Segundo in *Science,* Vol. 145, No. 3627, pages 61–63; July 3, 1964.

MECHANISM OF RHYTHMIC SYNCHRONOUS FLASHING OF FIREFLIES. John Buck and Elisabeth Buck in *Science,* Vol. 159, No. 3821, pages 1319–1327; March 22, 1968.

SYNCHRONY AND FLASH ENTRAINMENT IN A NEW GUINEA FIREFLY. Frank E. Hanson, James F. Case, Elisabeth Buck and John Buck in *Science,* Vol. 174, No. 4005, pages 161–164; October 8, 1971.

MODEL FOR THE MATING PROTOCOL OF SYNCHRONOUSLY FLASHING FIREFLIES. J. E. Lloyd in *Nature,* Vol. 245, No. 5423, pages 268–270; October 5, 1973.

THE MASS OF THE PHOTON

TERRESTRIAL AND EXTRATERRESTRIAL LIMITS ON THE PHOTON MASS. Alfred S. Goldhaber and Michael Martin Nieto in *Reviews of Modern Physics,* Vol. 43, No. 3, pages 277–296; July, 1971.

ON THE HISTORY OF THE DISCOVERY OF THE MAXWELL EQUATIONS. I. S. Shapiro in *Soviet Physics Uspekhi,* Vol. 15, No. 5, pages 651–659; March–April, 1973.

IMPROVED UPPER LIMIT ON THE PHOTON REST MASS. Aaron Barnes and Jeffrey D. Scargle in *Physical Review Letters,* Vol. 35, No. 17, pages 1117–1120; October 27, 1975.

LIMIT ON THE PHOTON MASS DEDUCED FROM PIONEER-10 OBSERVATIONS OF JUPITER'S MAGNETIC FIELD. Leverett Davis, Jr., Alfred S. Goldhaber and Michael Martin Nieto in *Physical Review Letters,* Vol. 35, No. 21, pages 1402–1405; November 24, 1975.

STEPHEN HALES

STEPHEN HALES, D.D., F.R.S.: AN EIGHTEENTH CENTURY BIOGRAPHY. A. E. Clark-Kennedy. Cambridge University Press, 1929.

STEPHEN HALES. Henry Guerlac in *Dictionary of Scientific Biography: Vol. VI,* edited by Charles C. Gillispie. Charles Scribner's Sons, 1972.

THE GALILEAN SATELLITES OF JUPITER

THE CHEMISTRY OF THE SOLAR SYSTEM. John S. Lewis in *Scientific American,* Vol. 230, No. 3, pages 50–65; March, 1974.

PHYSICAL PROPERTIES OF THE NATURAL SATELLITES. David Morrison and Dale P. Cruikshank in *Space Science Reviews,* Vol. 15, No. 5, pages 641–739; March, 1974.

MATHEMATICAL GAMES

SUPERSPACE. John Archibald Wheeler in *Analytic Methods in Mathematical Physics,* edited by Robert P. Gilbert and Roger G. Newton. Gordon and Breach Science Publishers, 1970.

GRAVITATION. Charles W. Misner, Kip S. Thorne and John Archibald Wheeler. W. H. Freeman and Company, 1973.

IS PHYSICS LEGISLATED BY COSMOGONY? Charles M. Patton and John Archibald Wheeler in *Quantum Gravity: An Oxford Symposium,* edited by C. J. Isham, R. Penrose and D. W. Sciama. Clarendon Press, 1975.

It takes more than a busy bee to give you luscious oranges.

The bee is a genius. It starts a blossom on its way to becoming an orange. But once it flies away, the destiny of the orange passes into the hands of man.

FMC helps the world's citrus producers complete the cycle. It helps growers plan and manage their groves, provides them with irrigation pumps, pesticides, sprayers, even automatic harvesters.

Citrus processing. Here, FMC engineered systems automatically perform a multitude of intricate steps required for fruit to end up fresh in the market, as juices or concentrates, or peeled and segmented, then sealed in jars or cans.

Tell us your needs. FMC serves worldwide markets for food and agricultural machinery, environmental equipment, material handling, power transmission, industrial and agricultural chemicals. FMC Corporation, 200 East Randolph Drive, Chicago 60601.

FMC

DEWAR'S® PROFILES

(Pronounced Do-ers "White Label")

BLENDED SCOTCH WHISKY • 86.8 PROOF • ©SCHENLEY IMPORTS CO., N. Y., N. Y.

RAQUEL RAMATI

HOME: New York City

AGE: 34

PROFESSION: Architect/Urban Designer

HOBBIES: Graphic art, tennis, people.

MOST MEMORABLE BOOK: Tolstoy's "Anna Karenina"

LAST ACCOMPLISHMENT: Headed the urban design group which devised a plan to preserve and revitalize New York's Little Italy.

QUOTE: "The built environment is a reflection of our culture. A cityscape reveals where we are at, how we feel about our community and how much we respect ourselves. To an urban designer, a good urban environment is one which gives us a sense of place, joy, and freedom of choice."

PROFILE: Sophisticated. Persuasive. Concerned about how the urban environment affects the people who live in it.

SCOTCH: Dewar's "White Label®"

Authentic. There are more than a thousand ways to blend whiskies in Scotland, but few are authentic enough for Dewar's "White Label." The quality standards established in 1846 have never varied. Into each drop go only the finest whiskies from the Highlands, the Lowlands, the Hebrides. ***Dewar's never varies.***