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PROTEIN CLUES TO ALZHEIMER'S

CONTROLLING URBAN SPRAWL

RULERS OF THE JURASSIC SEAS

THE REIGN OF ICHTHYOSAURS

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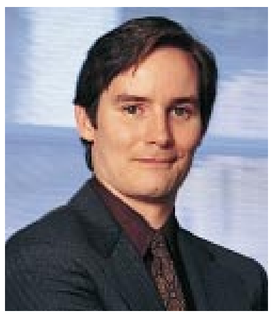
EDITOR_JOHN RENNIE

The Dragon in the Sea

Canst thou draw out leviathan with a hook? or his tongue
with a cord which thou lettest down?...
Canst thou fill his skin with barbed irons? or his head
with fish spears?...
Who can open the doors of his face? His teeth are terrible
round about....
By his neesings a light doth shine, and his eyes are like
the eyelids of the morning....
He maketh the deep to boil like a pot....
Upon earth there is not his like, who is made without fear.
—Job 41:1–33

Not a bad commentary, really, on those Jurassic sea monsters known as the ichthyosaurs (I've cooked the results slightly by deleting the verses that refer to the leviathan breathing fire, but you take my point). The biblical leviathan is usually identified with a whale, in keeping with John Milton's description from *Paradise Lost:* "There Leviathan/Hugest of living creatures, on the deep/Stretched like a promontory sleeps or swims,/And seems a moving land...." With the whole paleontological record at our disposal, though, why not consider ichthyosaurs instead? Certainly some of these Muppet-eyed prehistoric monsters were closer in form than whales to "Leviathan the piercing serpent... the dragon that is in the sea" (Isaiah 27:1).


ERICA LANSNER

For paleontologists the ichthyosaurs embody the fascinating principle of convergent evolution. Over millions of years, reptiles that paddled in the shallows evolved into deep-diving masters of the open ocean. Evolution remade them for a marine life by molding their lizardlike features into a more fishy form. Yet their evolutionary path back to the seas was different from that eventually followed by whales, seals and other animals that gave up life on land. Paleontologist Ryosuke Motani describes all these matters beginning on page 52.

As he observes, evolution does not follow a straight line. Natural selection sifts through the physical variations in a given population, favoring some, opening the trapdoor on others. It is a peculiar process that can give rise to exquisitely elegant anatomical structures but also to weird assemblies like the "corncob" bones found inside some ichthyosaurs' flippers.

For me, the fossil whose photograph appears on page 55 is a transporting piece of evidence. It shows a female ichthyosaur that died late in pregnancy or perhaps while giving birth; the baby was entombed with its mother in the mud. The preserved detail of the bones is so extraordinary and the pose so lifelike that this picture is the next best thing to a snapshot of these creatures as they were. Thou canst not draw out this leviathan with a hook, but you can with such a fossil, out of its prehistoric seas and 100 million years of lost time.

editors@sciam.com

EDITORS@SCIAM.COM

PENNYWISE BIOPLASTICS?

Tillman U. Gerngross and Steven C. Slater ["How Green Are Green Plastics?"] assert that policymakers should discourage the development of plant-derived plastics and instead promote plant material as a fuel for making plastics from petrochemicals. Such a recommendation is shortsighted. It is natural to expect dramatic improvements in the operational efficiencies of bioplastics factories in the future. Manufacturing facilities are already coming online that will convert plant material to higher-value products such as ethanol. Why ask farmers to compete with coal's cost of a penny per pound when they can compete with petrochemical products valued at 15 to 70 cents per pound or more?

DAVID MORRIS
Vice President,
Institute for Local Self-Reliance
Minneapolis, Minn.

Gerngross and Slater reply:

It's true that farmers will send their plant material where it can bring the most money. Whether that means selling it as a fuel or as raw material will depend on changes in technology and energy infrastructure. Our point is that we must consider sustainability alongside economics. No matter how efficient a bioplastics factory becomes, it is not sustainable in the long term if it runs on fossil fuels. Using plant material as an alternative would free up oil and gas reserves to be used instead as raw materials for plastics and other petrochemical products. This shift in fossil-fuel usage could extend reserves by 1,000 years.

FROM AGUE TO WEST NILE

During Shakespeare's day (1564–1616)—dubbed by climatologists the "Little Ice Age"—England's climate was significantly colder, but malaria ("ague") caused misery and death in many parts of the land. Today the disease has disappeared from England, but nobody attributes that to the weather; indeed, in most parts of the world, climate is not the dominant factor in malaria's prevalence or its distribution. Nearly all of Paul R. Epstein's inferences in "Is Global Warming Harmful to Health?"—about the causes of the recent spread of *Aedes aegypti* and dengue, the increasing prevalence of malaria at altitude, future "dramatic" increases in the disease throughout the world, the risk of yellow fever in the Andes, the outbreak of West Nile virus in New York, and so on—are based on intuition, not science. Serious public health problems cry out to be addressed seriously. Epstein's reveries amount to a comedy of errors.

PAUL REITER
Chief, Entomology Section
Centers for Disease Control and
Prevention, Dengue Branch

The real killer, the world over, is not climate change but poverty. And vastly increased poverty will result if we institute the draconian measures to cut CO_2 emissions that Epstein appears to favor.

AARON OAKLEY
Shenton Park, Western Australia

JEAN-MARC BOUJU *AP Photo*

IN MOZAMBIQUE malaria may have struck again.

Epstein replies:

Mosquitoes and other insects and plants have been moving to higher altitudes, and mainstream scientists believe the range changes are the result of warming, especially in wintertime. The intensity of extreme weather accompanying warming is, however, the primary concern. Prolonged droughts and heavy precipitation events are destabilizing predator/prey relationships and food availability, often boosting populations of opportunistic, disease-carrying organisms.

Infectious-disease epidemics occur cyclically throughout history. The present resurgence among animals and plants may be seen as an indicator of global change that includes social, ecological and climatic factors. Public health–related decisions must be precautionary—discerning emerging patterns and taking preventive measures when the stakes are high. We have apparently underestimated the rate of climate change and may have failed to appreciate the sensitivity of biological systems to small changes in average temperatures and the accompanying shifts in weather patterns.

Poverty is certainly the leading cause of disease, but climate instability is adding to that burden. Manufacturing energy-efficient and clean-energy technologies can be a boon to the international economy and can power development in poor nations while decreasing the direct health impact of pollution.

GRAVITY, REVISED

Nima Arkani-Hamed, Savas Dimopoulos and Georgi Dvali ["The Universe's Unseen Dimensions"] report that additional dimensions in space would

THE_MAIL

"MEASURE FOR MEASURE" [Antigravity, by Steve Mirsky] reminded readers of their own favorite obscure measurements, both real and imagined (and a few unprintable). Writes John H. Twist of Ada, Mich.: "I service and restore MG sports cars and older British vehicles, all of which use a complex conglomeration of obsolete units, from measuring the capacity of the sump (imperial gallons), to determining the "kerbside" weight of the vehicle (cwts or hundredweights), to the purchase price (£sd). So perplexing are these overlapped measurements, together with American, British and French metric thread forms, that a novice is quickly humbled. I love to zap our new employees with the question 'Approximately how many hundredweights in a moon unit?' " A clue to the (nonautomotive) answer: word four in the preceding sentence.

Comments on other topics from the August issue can be found above.

lead to a revision of Newton's law of gravitation (the force of gravity falling with the square of distance between masses). At close distances, gravitational force would fall at a higher power, depending on the number of added dimensions.

Suppose we discover gravity falling at higher powers of distance for bodies extremely close to one another. This is necessary for the higher dimensions postulated by the authors. Is it sufficient? If gravity weakens at powers greater than two at close distances, can there be reasonable explanations other than the existence of higher dimensions of space?

DAVID JONES
St. Paul, Minn.

Arkani-Hamed replies:

A number of theoretical possibilities would modify gravity at shorter distances by changing the coefficient that multiplies the inverse square law, but we don't know of any way to change the exponent in the inverse square law except by invoking extra dimensions. Seeing such a deviation from Newtonian gravity in tabletop experiments would lend strong support to the presence of large spatial dimensions but would not completely prove it. An airtight case could come from collisions at particle accelerators, by studies of the properties of gravitons escaping into the extra dimensions.

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017. Letters may be edited for length and clarity. Because of the considerable volume of mail received, we cannot answer all correspondence.

ERRATA

Lacewings and ladybugs are predators not of mosquitoes, as was stated in "Is Global Warming Harmful to Health?," but of aphids. Also in that article, in the chart entitled "El Niño's Message," Brazil was incorrectly depicted as having had outbreaks of malaria in 1997–98. Some malaria has been seen in Paraguay, next to the Brazilian border.

"The Killing Lakes," by Marguerite Holloway [July], stated that the release of tilapia into Lake Nyos was unauthorized. It was in fact conducted by the Cameroonian Institute for Zoological and Veterinary Research, which is now part of the Institute for Research on Agronomy and Development.

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Denise Anderman
PUBLISHER
danderman@sciam.com

NEW YORK ADVERTISING OFFICES
415 Madison Avenue
New York, NY 10017
212-451-8893 fax 212-754-1138

David Tirpack
Sales Development Manager
dtirpack@sciam.com

Wanda R. Knox
wknox@sciam.com

Darren Palmieri
dpalmieri@sciam.com

DETROIT
Edward A. Bartley
Midwest Manager
248-353-4411 fax 248-353-4360
ebartley@sciam.com

LOS ANGELES
Lisa K. Carden
West Coast Manager
310-234-2699 fax 310-234-2670
lcarden@sciam.com

SAN FRANCISCO
Debra Silver
San Francisco Manager
415-403-9030 fax 415-403-9033
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CHICAGO
ROCHA & ZOELLER MEDIA SALES
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DALLAS
THE GRIFFITH GROUP
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lowcpm@onramp.net

CANADA
FENN COMPANY, INC.
905-833-6200 fax 905-833-2116
dfenn@canadads.com

U.K.
Anthony Turner
Simon Taylor
THE POWERS TURNER GROUP
100 Rochester Row
London SW1P 1JP, England
+44 207 592-8323 fax +44 207 592-8324
aturner@publicitas.com

FRANCE AND SWITZERLAND
Patricia Goupy
33, rue de l'abbé Grégoire
75006 Paris, France
+33-1-4548-7175
pgoupy@compuserve.com

GERMANY
Rupert Tonn
John Orchard
PUBLICITAS GERMANY GMBH
Oederweg 52-54
D-60318 Frankfurt am Main, Germany
+49 69 71 91 49 0 fax +49 69 71 91 49 30
rtonn@publicitas.com
jorchard@publicitas.com

MIDDLE EAST AND INDIA
PETER SMITH MEDIA & MARKETING
+44 140 484-1321 fax +44 140 484-1320

JAPAN
PACIFIC BUSINESS, INC.
+813-3661-6138 fax +813-3661-6139

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HUTTON MEDIA LIMITED
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SPEKTRUM DER WISSENSCHAFT
Verlagsgesellschaft mbH
Vangerowstrasse 20
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tel: +49-6221-50460
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Éditions Belin
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75006 Paris, FRANCE
tel: +33-1-55-42-84-00

LE SCIENZE
Piazza della Repubblica, 8
20121 Milano, ITALY
tel: +39-2-29001753
redazione@lescienze.it

INVESTIGACION Y CIENCIA
Prensa Científica, S.A.
Muntaner, 339 pral. 1.ª
08021 Barcelona, SPAIN
tel: +34-93-4143344
precisa@abaforum.es

MAJALLAT AL-OLOOM
Kuwait Foundation for the Advancement of Sciences
P.O. Box 20856
Safat 13069, KUWAIT
tel: +965-2428186

SWIAT NAUKI
Proszynski i Ska S.A.
ul. Garazowa 7
02-651 Warszawa, POLAND
tel: +48-022-607-76-40
swiatnauki@proszynski.com.pl

NIKKEI SCIENCE, INC.
1-9-5 Otemachi, Chiyoda-ku
Tokyo 100-8066, JAPAN
tel: +813-5255-2821

SVIT NAUKY
Lviv State Medical University
69 Pekarska Street
290010, Lviv, UKRAINE
tel: +380-322-755856
zavadka@meduniv.lviv.ua

ΕΛΛΗΝΙΚΗ ΕΚΔΟΣΗ
SCIENTIFIC AMERICAN HELLAS SA
35–37 Sp. Mercouri Street
Gr 116 34 Athens, GREECE
tel: +301-72-94-354
sciam@otenet.gr

KE XUE
Institute of Scientific and Technical Information of China
P.O. Box 2104
Chongqing, Sichuan
PEOPLE'S REPUBLIC OF CHINA
tel: +86-236-3863170

Color Television, 1950

Why Good Sausages Go Bad

DECEMBER 1950

COLOR TELEVISION—"The Federal Communications Commission has finally adopted the color-television system advanced by the Columbia Broadcasting System. The 'field-sequential' system has color filters mounted in a rotating wheel in front of the cameras, which separate the image into its three primary colors. At the receiving end images are reproduced on a screen of a single tube and are translated back into color by another filter wheel synchronized with the camera wheel. The CBS image cannot be received in black-and-white on the estimated eight million existing TV sets unless they are equipped with an 'adapter.'" [*Editors' note: Lack of public interest in this system halted color broadcast within a few months.*]

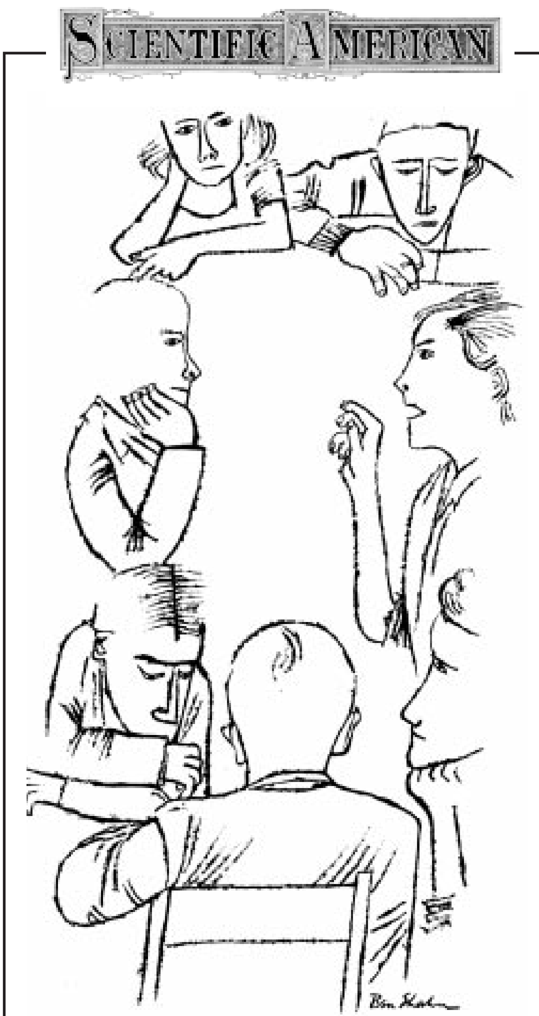
THE HAZARDOUS STRATOSPHERE—"When intercontinental flight through the stratosphere becomes a reality, the hazard of cosmic radiation must be considered, the intensity of which increases with altitude. Hermann J. Schaefer of the U.S. Naval School of Aviation Medicine in Pensacola, Fla., estimates cosmic radiation at 70,000 feet as 15 milliroentgens per day, in excess of the radiation safety standard set by the Atomic Energy Commission. Such doses will not cause appreciable physiological damage. 'But,' says Schaefer, 'the prospect that future commercial air traffic will be at those altitudes and an increasing percentage of the population will be exposed to those dosages is bad from a genetic viewpoint.'"

GROUP THERAPY—"From the parent trunk of psychoanalysis have come a number of different methods of treatment. One of them is group psychotherapy, with the group itself constituting an important element in the therapeutic process. In one form of treatment, analytic group therapy [*see illustration at right*], the emphasis is on interviews and discussion. Each group consists of patients who have the same general psychological syndromes. Once the patients' ego and super-ego defenses are lowered, they readily reveal their most intimate problems and seem to be almost entirely free of what is commonly referred to as 'self-consciousness.' The method is now being used in many parts of this country and abroad."

DECEMBER 1900

POPULATION IN A.D. 3000—"The equation that fits the growth of U.S. population between 1790 and 1890 forms the most probable basis for predicting the population of the future, depending, of course, upon the continuance of the same general conditions which have held in the past. A decided change in the birth-rate, or a widespread famine, would bring out large discrepancies. By the year 2000 the population of the United States (exclusive of Alaska and of Indians on reservations) will have swelled to 385,000,000; while, should the same law of growth continue for a thousand years, the number will reach the enormous total of 41,000,000,000. —H. S. Pritchett, president of the Massachusetts Institute of Technology"

DANGEROUS TIRES—"Many accidents have occurred on account of the tires becoming detached from the steering wheels of automobiles, and too much attention cannot be paid to this matter."



ANALYTIC GROUP THERAPY, 1950

DECEMBER 1850

POISON SAUSAGES—"German sausages are formed of blood, brains, liver, pork, flour, &c. [etc.], and, with spice, are forced into an intestine, boiled and smoked. If smoking is not efficiently performed, the sausages ferment, grow soft and slightly pale in the middle; and in this state they cause, in the bodies of those who eat them, a series of remarkable changes, followed by death. The poisonous power of fermenting sausages depends, first, on the atoms of their organic matter being in a state of chemical movement or transposition and, second, that these moving molecules can impart their motion to the elements of the blood and tissues of those who eat them, a state of dissolution analogous to their own. Organic matter becomes innocuous when fermentation ceases; boiling, therefore, restores poisonous sausages, or being steeped in alcohol."

INDIAN SHELL MOUNDS—"Shell banks are very common in the neighborhood of Mobile, Ala., and most remarkable. Just above the city is a huge bank of clam shells, some twenty-five feet in depth, in which remnants of cooking utensils, evidently of Indian origin, have been found. The southern people make excellent roads with these shells. In Bonne Secour Bay is a huge hill of oyster shells, over thirty feet high, from which vast quantities of lime have been already made."

FROM SCIENTIFIC AMERICAN

HEALTH POLICY_DRUG APPROVAL

The Second Abortion Pill

Mifepristone—a.k.a. RU 486—is anticipated to boost access to abortion. Based on the history of an older pill, it might not

When the U.S. Food and Drug Administration approved the French drug RU 486 in late September, advocates for women's health hailed the action as the long-awaited breakthrough that would increase access to abortion nationwide. Thanks to this pale yellow pill, women would be able to have abortions without having to visit abortion clinics—which are few and far between in the U.S. and often surrounded by haranguing protesters.

As it turns out, however, RU 486, or mifepristone, as it is known in this country, isn't so novel after all. Women seeking to end their pregnancies have had the option of choosing medication over surgery for close to a decade. But a variety of factors—ranging from state laws specifying the width of clinic halls to the verbal and physical harassment abortion providers can face—have made finding someone to prescribe such drugs exceedingly difficult. And there are few signs that obtaining mifepristone will be any easier.

Mifepristone made headlines in the U.S. back in 1993, when a French research group published its findings in the *New England Journal of Medicine:* that a two-drug regimen—mifepristone followed by misoprostol (approved as an antiulcer medication)—would safely induce miscarriages during the first seven weeks of pregnancy. That same year, in a much quieter development, another team of investigators announced that it had also identified a drug that could be used for medical abortions in the early weeks of pregnancy. Furthermore, the compound in question—the anticancer drug methotrexate—was already approved by the FDA and available in every pharmacy.

Mitchell Creinin of the University of Pittsburgh School of Medicine conducted the early studies of methotrexate (also used in combination with misoprostol) as an abortifacient. "Methotrexate is a real alternative" to mifepristone, Creinin says. His studies have concluded that the two drugs have similar efficacy rates, although the abortion process may take longer with methotrexate. "This shows the ridiculousness of the whole thing," he says, referring to the political climate surrounding mifepristone. "Medical abortions have been available for the past seven years," Creinin notes, and thousands of women have taken advantage of methotrexate for this purpose.

Over the past several years, doctors such as Creinin have learned a great deal about medical abortions and are now better able to prepare women on what to expect in terms of nausea, bleeding and pain. Creinin also points out that giving women a choice of medication over surgery hasn't led to a rise in the total number of the procedures and only "slightly increases access" to abortion—despite hopes to the contrary.

So why didn't medical abortion catch on? The answer lies in part with the fact that the methotrexate procedure requires a so-called off-label use. The practice of prescribing drugs in a manner not specifically approved by the FDA—but supported by studies in medical journals—is perfectly legal and quite common. According to women's health expert Diana Dell of Duke University Medical Center, however, practitioners who do not routinely provide abortions are often uncomfortable starting with the off-label approach.

That may mean that mifepristone, even now with the FDA's blessing, won't be prescribed as often as anticipated, because the second drug required to complete the abortion, misoprostol, still must be used off-label: it has been officially approved only to prevent ulcers. In late August, Searle, the company that makes the drug, issued a warning letter to doctors stating its position that the drug should not be given to women who are pregnant, "because it can cause abortion." (Perhaps ironically, mifepristone itself has shown some promising off-label uses: as emergency contraception to be taken within 72 hours of unprotected sex, and as possible treatment for prostate cancer, fibroid tumors and certain brain cancers.)

Carole Joffe, a sociologist at the University of California at Davis who has studied the history of both illegal and legal abortions, says the letter from Searle "was received with alarm by some physicians." Nevertheless, she feels that the

THREE TABLETS of mifepristone followed by the drug misoprostol will safely induce abortion. The FDA approved mifepristone in September.

NINA BERMAN *Sipa Press*

physicians who do medical abortions won't be scared off: "Those who wish to use misoprostol for medical abortion will continue to do so."

Yet the question remains of how many additional practitioners will, in the end, wish to offer medical abortions. And where and how will drugs like mifepristone, methotrexate or any newly discovered drugs be dispensed? At the end of the congressional session in October, Senator Tim Hutchinson of Arkansas and Representative Tom Coburn of Oklahoma introduced legislation that would essentially restrict the use of mifepristone to surgical abortion clinics. At press time, however, Congress had not discussed the bill. Joffe suggests that in the short term, few doctors will step forward because of all the political and legal complexities—not to mention the very real dangers—of treating women who wish to terminate their pregnancies.

But Joffe argues that the medical community should be more proactive, taking steps right now such as training more physicians in how to administer medical abortions and integrating abortion into mainstream medical institutions. "If all 40,000 of practicing ob-gyns in the U.S. were presumed to be familiar with mifepristone, then targeting those who are 'abortion providers' would become meaningless." *—Sasha Nemecek*

ARCHAEOLOGY_PALEOLITHIC CULTURE

Paleolithic Pit Stop

A French site suggests Neandertals and early modern humans behaved similarly

DORDOGNE, FRANCE—With thousands of caves and rockshelters peppering an area only slightly larger than New Jersey, southern France's Dordogne region is a mecca to archaeologists who study Stone Age ways of life. For more than 300,000 years humans have occupied this territory, and for 35 years University of Bordeaux archaeologist Jean-Philippe Rigaud has been unearthing the remnants of their past in hopes of determining how modern human behavior emerged.

As we drive past the cornfields and grazing horses and the stone farmhouses with their red tile roofs, Rigaud calls my attention to a hill in the distance, rising from the flat floor of the Dordogne River Valley like a giant green turtle. Grotte XVI, a site that he is currently excavating, is one of 23 caves that line a 1.5-kilometer-long cliff running along that hill, he explains. The locality has proved exceptionally rich. Over the past 17 years the field team has documented upward of 50,000 artifacts from at least 11 different archaeological levels dating back as far as 75,000 years ago, when Neandertals inhabited the cave. As such, Grotte XVI provides a rare opportunity for scientists to compare how Neandertals and early modern humans used the same living space—a comparison that is indicating that the two groups were more similar than previously thought.

EXCAVATION AT GROTTE XVI, a cave in southern France, involves a hanging grid system that enables three-dimensional mapping of each collected item.

KATE WONG

The cave entrance faces west, gaping 10 meters wide and nine meters high. Inside, Rigaud's colleague, University of Tennessee archaeologist Jan F. Simek, supervises the French and American graduate students excavating the chamber, which extends 20 meters deep. Weighted cords hang from a metal frame above, forming a grid system of one-meter squares that, with the help of a surveying instrument, allows the workers to map the original position of every collected item in three dimensions. Each student controls a meter-square plot and is responsible for all of the related digging, mapping, sifting and washing, Simek explains. All of the collected materials—including animal remains and bits and pieces from tool manufacture—are then shipped to the University of Bordeaux for later examination.

Excitement erupts as team member Maureen Hays announces that she has just uncovered a Mousterian hand ax—a pear-shaped, multipurpose tool from the so-called Middle Paleolithic period, made in a style that in Europe is associated with Neandertals. Simek grins as Hays places the putty-colored rock in his palm for inspection. Not the finest example of Neandertal handiwork, he proclaims, but a hand ax nonetheless. According to team tradition, Hays will buy the champagne.

Comparisons between the Mousterian and the Aurignacian—an Upper Paleolithic cultural tradition associated with anatomically modern humans—at Grotte XVI have led Simek and Rigaud to an intriguing conclusion. Whereas a number of researchers have argued that the transition from the Middle Paleolithic to the Upper Paleolithic was rapid, corresponding to a replacement of Neandertals by moderns, the Grotte XVI assemblages fail to support that idea. The Upper Paleolithic does represent a shift toward specialized hunting, Simek observes, but the change is gradual.

Indeed, preliminary analysis suggests that the Neandertal and early modern human inhabitants of Grotte XVI behaved in much the same way: in both cases, small groups of hunters seem to have used the cave for only short periods before moving on, and both hunted the same kinds of animals. In fact, both groups appear to have fished extensively, judging from the abundant remains of trout and pike, among other species. This finding is particularly interesting because Neandertals are not generally assumed to have made use of aquatic resources. Furthermore, Simek reports, Neandertals may have even smoked their catch, based on evidence of lichen and grass in the Mousterian fireplaces. Such plants don't burn particularly well, Simek says, but they do produce a lot of smoke. "People don't tend to think of Neandertals as using fire in very complex ways," he remarks, "and they did." (The fireplaces, which date to between 54,000 and 66,000 years ago, are themselves noteworthy as the best-preserved early hearths known, according to Simek. Striking bands of black, red, pink, orange, yellow and white reveal carbon and various stages of chemically decomposed ash that indicate short, hot fires.)

KATE WONG

NEANDERTAL FIREPLACES at Grotte XVI suggest that, based on the pattern of colored bands, fires were short and hot.

Although a radical shift did not occur between the Middle and Upper Paleolithic, Simek notes that significant change did come later with the so-called Magdalenian period, perhaps because population size was increasing. Remains from sediments toward the back of the cave reveal that around 12,500 years ago the Magdalenians used Grotte XVI specifically as a hunting site, leaving behind characteristic harpoons and other implements. The team has also unearthed engraved art objects in the Magdalenian deposits. That they brought artwork with them into mundane activities, Simek says, is important. "Like we might carry a cross, they carried their religious iconography, too."

Lunchtime approaches, and the crew prepares to head up to Rigaud's house. As the cave empties out, I comment that working here seems like a wonderful way to spend the summer. Yes, Simek agrees, leaning on the scaffolding and surveying the site contentedly, "It's a great privilege to do this." —*Kate Wong*

COMPUTERS_SECURITY

Red Team versus the Agents

At a nuclear weapons lab, a team of elite hackers matches wits with undefeated autonomous defenders

ALBUQUERQUE, N.M.—By the time my escort steers me past the armed guards, key-coded doors, and bags of shredded paper into the heart of Sandia National Laboratories, the rematch has already begun. Inside the Advanced Information Systems Lab, six men sit around a large table loaded with laptops and network cables, which snake over to a rack of high-powered machines labeled BORG SERVER CLUSTER. These men are the defense—the Blue Team in this high-tech version of capture the flag—and they lean back in their chairs confidently. This past March, they claim, their "agents"—computer programs that autonomously cooperate to protect a networked system—became the first defenders ever to thwart Sandia's esteemed Red Team of professional hackers. But that was in a two-day skirmish. Now Steven Y. Goldsmith, the research group's lead scientist, has invited the Red Team to spend this entire week in September trying to dodge, destroy or confuse the agent programs.

Sandia began recruiting some of its most highly skilled computer-security experts for Red Team missions four years ago, as attempts by crackers—malicious hackers—to break into corporate, government and military computer systems appeared to be growing rapidly. In March an annual survey conducted by the Computer Security Institute and the Federal Bureau of Investigation found that 70 percent of such large organizations had detected serious computer-security breaches during the past 12 months—the fourth straight increase. The main aim of Red Team exercises is to find security holes that crackers could exploit, before the crackers do.

"Our general method is to ask system owners: 'What's your worst nightmare?' and then we set about to make that happen," explains Ruth A. Duggan, the Red Team leader. Each nightmare scenario becomes a "flag" to be captured in the mission. "Most often we model a cyberterrorist organization that has mercenary hackers and the resources of a small nation-state," Duggan says. "That means they can buy all the skills they need, information about the design" and even the help of corrupt insiders. In the past two years Sandia's team has been asked to test three dozen supposedly secure systems, including those of military installations, oil companies, banks, electric utilities and e-commerce firms. The team brought home undisputed flags from each encounter, until the one against the agent-protected system in March.

The agents are a new kind of opponent, however. Three years in development, these programs are designed to act as artificial organisms. Their code is arranged into "genes," and the agents adapt in response to stimuli and communicate with one another to identify suspicious activity, such as unusual network traffic and unauthorized probes. As a result, the agents can detect and foil many kinds of insider attacks by bought or blackmailed operatives. Combining these capabilities is a new approach in computer security, Goldsmith says.

In this test, the agents are striving to prevent both outsiders and corrupt insiders from tampering with a security system for extremely sensitive facilities—Goldsmith won't say what kind of facilities exactly, but I imagine underground vaults with big red buttons marked DO NOT PUSH. A scattered group of high-level officials uses Web browsers to approve or reject the names of those who request access to the areas. The list of approved names then has to be transmitted across a far-flung network to a guard's desk at each facility.

Four members of the offense now huddle over their own laptops in a closet-size room connected to the lab. On one wall Julie F. Bouchard has hung the "attack tree," a poster-size diagram of the devious steps that the Red Team believes will allow it to capture six distinct flags.

Ray C. Parks, head hacker for this mission, swigs coffee from a thermos and pops Atomic Fireball candies as he watches a commercial program called Net X-Ray probe the Blue Team's security system for holes. A laptop computer next to him runs Snort, a free Linux program, recording all the information zipping around the network. Robert L. Hutchinson looks over Parks's shoulder. "Okay, here's the connection request," he says, pointing at the screen. "There's the acknowledgment ... and there's the name: Charles Carpenter ... ID number 3178633466," he reads, scribbling notes.

Realizing they can steal ID numbers, the team members ask an agent programmer, playing an inside collaborator, to deliberately insert a "bug" into the system. The new code watches for a name to be approved and then immediately transmits a different name—representing an infiltrator—that has the same ID number. They also try it vice versa: bad name followed by good.

In the Blue Team's room, Goldsmith now leans forward, sullen. "The first case crashed a machine, although it did set off alarms," he says. "But in the second case, you achieved one of the major flags—tricking [the guard's computer] into displaying an untrusted name. And it went completely undetected by the agents. Very well done," he concedes. But it is only day two of the seven-day mission, and the Red Team has 13 attack routes remaining on its tree.

Over the next three days the agents put up a noble fight against a variety of network attacks, including so-called SYN floods of the kind that disabled Yahoo, Amazon, CNN and other Web sites in February. But one by one, the Red Team captures every flag save the last: deceive the central server into adding an invalid name to the list.

It is late on day five when Stephen G. Kaufman bursts into the Red Team room and in a near shout announces: "The agents are communicating in plaintext—we can run files!" Kaufman is the team's expert in LISP, the language in which the system was written, and he has been scouring the system's source code for ways to exploit known weaknesses in the way LISP works on networks.

"Oh, goodie," Parks chuckles as Kaufman shows him how the agent will accept malformed input sent by a utility called NetCat. In the first test the agent gets confused and shuts down. At last Kaufman finds the right syntax, and the agent evaluates—that is, executes—almost any Linux command the Red Team cares to transmit. "Send it 'rm –rf'!" Bouchard exclaims. The team erupts in laughter. That command would delete everything on the Blue Team's hard disks.

But that would be too easy. "The golden egg is to steal the cryptographic keys" from three of the high-level officials' machines, Parks says. "Then we can approve any names we want," thus capturing the last flag. While Parks works on that, Kaufman informs the Blue Team that the Red Team can co-opt the agents.

Shannon V. Spires, one of the agents' developers, squints at the news. "So they can get outside code evaluated?" he asks teammate Hamilton E. Link. "So they say," Link responds. "Well, if that's true, it's a huge problem," Spires growls, his face reddening. After more discussion, Spires rises from the table. "This is the master key to the system!" he says as he strides into the Red Team's room.

He looks over Kaufman's shoulder and peppers him with questions, walks back over to Link, and, after a few moments of low conversation, starts swearing and marches back to the Red Team. "Okay, guys, let me sit down here," Spires says. Before long, seven people are craning to watch as he attacks his own system.

After the dust has settled on the final day of the test, the teams compare notes. This last attack, Goldsmith says, "turned out to be the most devastating. We did develop an agent-specific virus that swipes the cryptographic keys. Had you done this attack first, you could have gained control of almost any part of the system—without relying on an insider. However," he adds, pausing for a beat, "adding one line of code—'setf *read-eval* nil'—fixes the problem. And we guarantee that we will never forget to set read-eval to nil again."

That lesson and a number of others are why regular Red Team trials are part of the design process. "This certainly isn't the last time we'll do this," Goldsmith says. And as a reward for the hackers' efforts, he promises with a smile, "we hope to figure out how to make evil agents that can assist you in making mischief." —*W. Wayt Gibbs*

GOVERNMENT-PAID HACKERS (*left to right*) Ray C. Parks, Richard A. Sarfaty, Julie F. Bouchard and Stephen G. Kaufman faced a new kind of opponent in September.

CARY HERZ *Liaison*

The Amazing Acenes

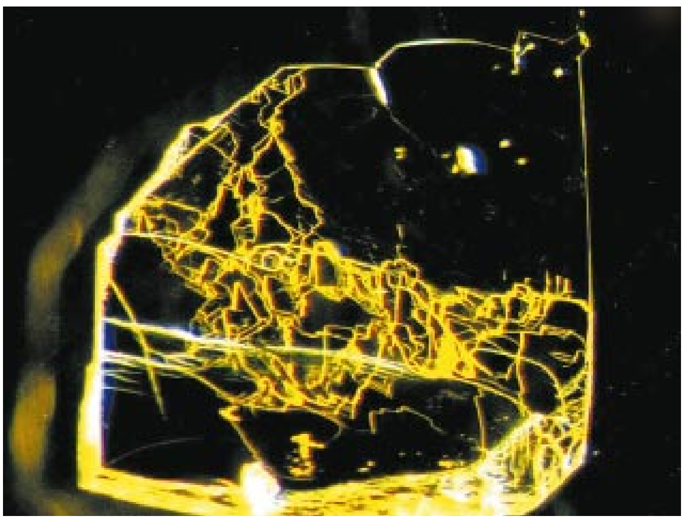
Organic crystals show siliconlike abilities and may elucidate fundamental physics

Silicon is the poster child of the microelectronics revolution—an inorganic crystal, carefully doped with the right ingredients and fashioned into myriad devices such as transistors on integrated circuits. Silicon's many siblings—germanium, gallium arsenide, indium phosphide and so on—are variations on the same inorganic theme and play profound roles in fundamental research, enabling physicists to study the odd behavior of electrons in strong magnetic fields and extremely low temperatures. Researchers have coaxed some siliconlike properties out of organic substances—polymers and carbon-based crystals—and hence created a new breed of semiconductor components, including flexible transistors and a prototype computer display. But success has been limited: organic semiconductors fill only niche markets, where the full power of the inorganics isn't needed, and haven't drawn as much attention for basic physics research.

That has begun to change over the past year, however. Bertram Batlogg, Hendrik Schön and their co-workers at Lucent Technologies's Bell Laboratories have demonstrated a series of stunning properties and achievements in a class of organic crystals called acenes. Among the first devices created were important types of lasers and transistors never before made from organics; the acenes have also exhibited superconductivity and the so-called fractional quantum Hall effect (FQHE), seen previously only in inorganic semiconductors. Other groups have built components out of acenes before but without uncovering this remarkable menu of features. Researchers who first synthesized conducting organics won this year's Nobel Prize for Chemistry [*see page 36*].

As Batlogg explains, the group's research "was not driven by having a particular application in mind." Rather it was "motivated originally by trying to understand the ultimate capabilities of organic semiconductors," he says. And they were amazed by the extent of those capabilities.

The acene molecules (more formally called polyacenes) consist of a short chain of benzene rings, the three of most interest being anthracene (three rings), tetracene (four) and pentacene (five). In crystals and thin films, those molecules pile up like bricks or paving stones. The usual techniques for making crystals of these molecules result in many defects and impurities compared with typical inorganic semiconductors. Such defects lower the material's all-important carrier mobility, which indicates how rapidly electrons or holes (absences of electrons) can move about. The very high switching speeds of modern computer chips, for example, rely on the semiconductor's high carrier mobility.



ULTRAPURE TETRACENE CRYSTAL, about four millimeters across, can be used to build transistors, lasers and superconductors.

CHRISTIAN KLOC *Lucent Technologies*

To eliminate the impurities, Christian Kloc, a materials scientist in Batlogg's group, produced the crystals with a "vapor transport" technique: a furnace vaporizes the polyacene, and hot gas such as hydrogen carries the vapor along in a quartz tube. Each particular polyacene condenses and forms crystals at a specific location along the tube. Immediately the group had its first surprise: at low temperatures, these exceptionally pure polyacene crystals had carrier mobilities that are surpassed only by the very best gallium arsenide, according to Batlogg.

Next the group set out to build from these crystals the workhorse of microelectronics: the field-effect transistor, or FET. Two types of FET exist, characterized by whether the active region is *n* type (current carried by electrons) or *p* type (carried by holes). In so-called complementary logic circuits, pairs of *n*- and *p*-type FETs work side by side, an arrangement whose advantages include low power consumption, robustness and simple circuit designs. Until now, no organic material had demonstrated both *n* and *p* types, so two different organic materials would be needed in a complementary device, which complicates its fabrication. The Lucent group made ambipolar FETs (that is, both *n* and *p* types) built from their extremely pure tetracene and pentacene crystals, apparently confirming that the obstacle in organics has been holes or electrons being trapped by defects. Furthermore, the behavior of the group's ambipolar FETs in circuits seems to follow all the usual laws of operation that apply to inorganic transistors.

Batlogg's group teamed up with Ananth Dodabalapur, whose group at Lucent is one of the leaders in organic integrated circuitry, to build the world's first organic solid-state "injection" laser out of a pair of their ambipolar FETs. Such a laser generates its beam by injecting electric current to excite the region that produces the light. All prior solid-state organic lasers have relied on a separate pump laser to excite the organic material, which defeats the goal and advantages of an all-organic device. The Lucent laser has two ambipolar FETs built back-to-back on a common piece of tetracene. One FET injects electrons, and the other injects holes; in the middle they annihilate and produce yellow-green light (it should be easy to modify the design to produce a full range of wavelengths). Cleaved edges of tetracene crystal served as rudimentary mirrors, which are required for lasing.

The group has also used its FETs to demonstrate superconductivity in pentacene, tetracene and anthracene, albeit down near absolute zero. The superconductivity occurred because the FET injected electric charges into the acene crystal, converting a layer of it from insulator to metal. Thanks to this new type of doping (highly controllable charge injection instead of built-in chemical impurities), the result may lead to profound advances in physicists' understanding of superconductivity. Inorganic semiconductors with many electronic properties comparable to the ultrapure polyacenes do not become superconducting.

Batlogg's group was surprised to see another low-temperature phenomenon: the FQHE in pentacene and tetracene at temperatures up to about two kelvins. The FQHE happens when the electrons in a two-dimensional layer in a strong magnetic field interact with one another and behave collectively in ways that look as if they have formed particles that have a fraction—most commonly a third or a fifth—of an electron's charge. Usually two kelvins is considered cold. But for the FQHE, it's hot—in inorganic materials such as gallium arsenide the FQHE occurs at about 0.5 kelvin. The higher temperature signifies that the relevant interactions are stronger in the polyacene systems, giving physicists an extraordinary new testing ground for their theories of the FQHE and related phenomena.

Richard Friend, who studies polymer electronics at the University of Cambridge, calls the Lucent work "absolutely beautiful physics" that confounded his expectations: "The limitations nature imposes on what you can do with organics are far fewer than people used to think." But he cautions that for commercial applications the work "doesn't present an appealing manufacturing process at the moment. The challenge is to see how that can be advanced."

—Graham P. Collins

ASTRONOMY_SOLAR PHYSICS

A Trace of the Corona

New images help to explain why the sun's atmosphere is hotter than its surface

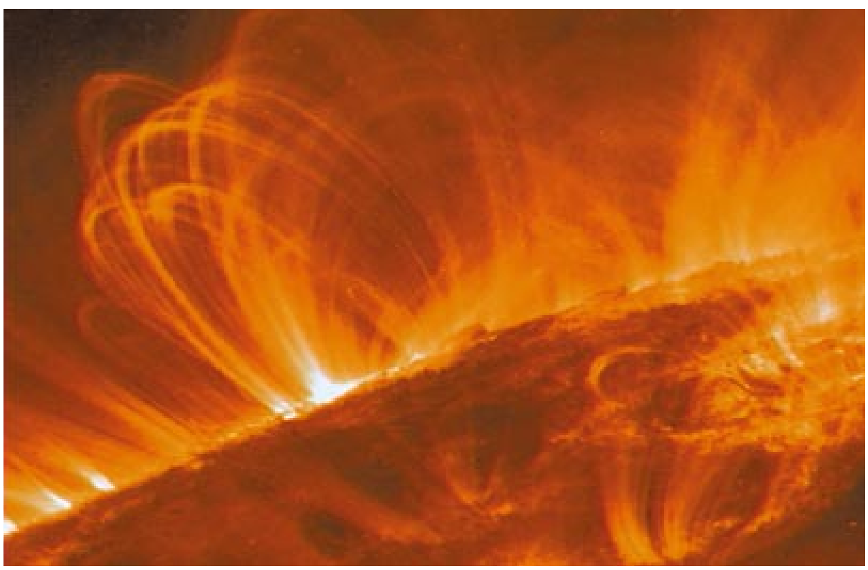
Astronomers have known since the 1940s that the sun's outer atmosphere, or corona, is hundreds of times hotter than the surface, but how the corona is heated has been a mystery. Researchers are now closer to an answer, thanks to the sharpest images ever taken of the corona, by the Transition Region and Coronal Explorer (TRACE) spacecraft. In September the National Aeronautics and Space Administration released the images of coronal loops—fountains of erupting gas that follow magnetic fields and heat the corona (as well as disrupt satellites and communications systems on Earth).

The images show that a single loop consists of several finer loops. More important, the loops are not uniformly heated, as earlier theories proposed. According to a new model developed by Markus J. Aschwanden of Lockheed Martin Advanced Technology Center and his colleagues, which is described in the October 1 *Astrophysical Journal*, the loops are instead cooked only at the base, near the sun-corona interface, where the temperature shifts from 5,800 degrees Celsius to several million degrees. The gas, consisting primarily of highly ionized iron, rises up a quarter-million miles at 60 miles per second and cools as it comes crashing down, says George L. Withbroe, director of NASA's Sun/Earth Connection program.

This model contrasts sharply with the old theory of uniform heating, which predicts that the tops of the loops, where the gas is thinnest and radiates heat poorly, should be the hottest. (The bulk of the corona is at about one million degrees.) What causes the heating at the loops' starting "footprint" is still unknown, although Withbroe and others hypothesize that the heating events are connected to the sun's shuffling magnetic fields.

TRACE's new data will also have to be reconciled with the information gathered by Yohkoh, a previously launched satellite. It found uniform heating in higher-temperature loops, an indication perhaps that coronal loops have different causes or consist of different types of material. Go to http://vestige.1msal.com/TRACE/ for more images and information.

—Naomi Lubick



TRACE/LOCKHEED MARTIN SOLAR AND ASTROPHYSICS LABORATORY

LOOPY: False-color ultraviolet image reveals the sun's corona-heating gas loops, which can span 30 Earths.

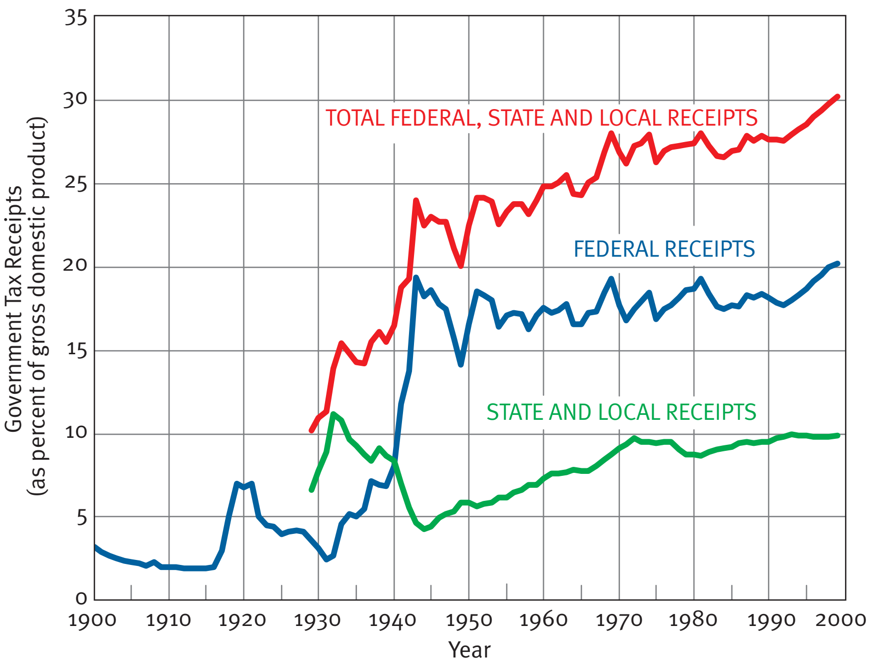
ECONOMICS_POLICY

Taxes: No Major Change in Sight

Significant alterations to U.S. taxation are driven by crisis, such as social turmoil or war, a point brought home long ago by the Whiskey Rebellion of 1794, when the federal government learned the hard way that heavy excise taxes were politically explosive. As a result, the government came to depend mostly on import tariffs set low enough to avoid vehement opposition from domestic interests.

This system shifted abruptly during the Civil War, when the Union raised federal spending from 2 to 15 percent of the gross domestic product, close to the current level of 20 percent. It did this by boosting tariffs and excise taxes and by imposing a limited income tax. After the war, the U.S. dropped the income tax and lowered excise taxes but maintained tariffs at fairly high levels because of their popularity with the politically potent manufacturers of the North.

As a means of financing U.S. participation in World War I, consumption taxes such as the tariff on imports proved inadequate, and so the federal government relied on corporate and personal income taxes, particularly the latter. The modern income tax was in place by 1916, the result of long-standing populist pressures, but the top rate, which was only 6 percent, was levied on incomes of more than $20,000, equivalent in spending power to $300,000-plus today. When the U.S. entered the war in 1917, the Democratic administration raised income tax rates sharply but, in keeping with its egalitarian philosophy, did not extend them to middle- and low-income workers.



SOURCE: Data for 1929 onward from U.S. Bureau of Economic Analysis. Pre-1929 data from U.S. Bureau of the Census, Historical Statistics of the United States, 1975.

The depression of the 1930s ushered in a new tax regime, which included greater federal taxing powers and the introduction of the Social Security tax. Employee contributions for Social Security, initially set at 1 percent of wages, are now 7.65 percent, including the Medicare tax. Because of this increase, 45 percent of Americans now pay more in Social Security than in personal income tax. (The figure rises to 80 percent if the employer share of Social Security is included.)

The most profound change in the system occurred during World War II, when everyone whose income exceeded a certain low minimum was obliged to pay the personal income tax. By war's end, more than 35 percent of the population was paying the tax, compared with about 5 percent in the late 1930s. Although tax rates declined after the war, the system of progressive, mass-based, relatively high taxes initiated then persists essentially intact to this day: an estimated 46 percent of Americans filed a return in 2000.

Democrats largely fashioned the American system, which has substantially lower rates than those of Europe, but Republicans have not made fundamental modifications. The increase in the proportion of GDP going to federal taxes during the 1990s reflects the bipartisan effort to pay off the national debt by accumulating a surplus: if fiscal budgets had been balanced during this period, federal tax receipts would have taken a declining share of the gross domestic product since 1991. In line with the recent rise in the share of GDP going to the federal government, all income groups experienced higher effective tax rates, except for families in the bottom 20 percent income bracket, who benefited from newly increased rebates under the earned income tax credit program.

History suggests that major changes in the tax system are extraordinarily difficult to implement in the absence of an overwhelming consensus, such as that which happens in wartime. Americans may accept large changes like the Tax Reform Act of 1986, which substituted two rates for 14 and greatly reduced the top rates, but in the absence of crisis, will they accept a radical alteration, such as replacing the progressive income tax with a flat tax? According to this line of reasoning, modifications that do not affect the basic tax regime—for example, more favorable treatment of capital gains, the imposition of a national (or perhaps international) Internet tax, and even the elimination of estate and gift taxes—have a better chance of becoming law.

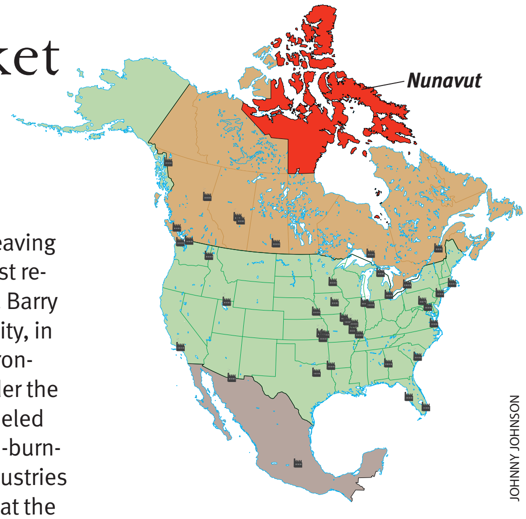
—Rodger Doyle (rdoyle2@aol.com)

RODGER DOYLE

Muscling DNA

For the first time, scientists have seen what it takes to move the long stretches of DNA through the enzyme factories that translate the genetic code into messages made of RNA: a muscle inside the nucleus of the cell. The molecular motor, called myosin I β, is a slightly altered version of the common myosin I protein, previously found only in the cytoplasm, where it helps to traffic organelles and other structures there. Physiologist Primal de Lanerolle of the University of Illinois discovered that myosin I β has a unique sequence that allows the motor to attach to the enzyme factories in the nucleus and to power the DNA strands. The work appears in the October 13 *Nature*. —*D.M.*

A One-Way Ticket to Nunavut



JOHNNY JOHNSON

Major dioxin sources, mostly in the U.S., have contaminated Nunavut.

The toxic fallout of heavy industries is leaving America's backyard and traveling to the most remote and pristine regions in North America. Barry Commoner of Queens College in New York City, in collaboration with the Commission for Environmental Cooperation, an agency created under the North American Free Trade Agreement, modeled the movement of dioxin released from trash-burning incinerators, cement kilns and other industries in Canada, Mexico and the U.S. He found that the cancer-causing dioxin could travel thousands of miles from its source, poisoning the land and eventually entering the food chain, where it accumulates in animal fat. Humans are exposed when they eat contaminated fat.

Commoner's findings help to explain why the Inuit people of Nunavut, a territory in the Canadian Arctic, have high levels of dioxin in their bodies, even though there are no sources of the chemical anywhere close by. Up to 82 percent of Nunavut's dioxin, the report says, originates from U.S. smokestacks. Canada's northern indigenous people may use the document to pressure governments to prevent or reduce dioxin emissions or even take legal actions against specific companies. —*Diane Martindale*

Gotcha!

Wanted for arboricide: Asian longhorned beetle

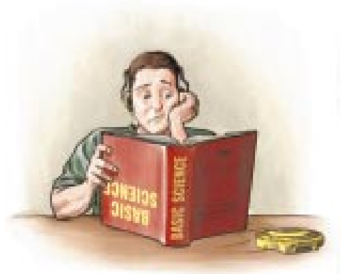
MARK MOFFETT *Minden Pictures*

The tiny larvae of the Asian longhorned beetle burrow inside maple trees. When they chew on the delicious wood meal, their jaws make a unique clicking sound. Glenn Allgood, Cyrus Smith and Dale Treece of Oak Ridge National Laboratory have recorded those sounds to develop a handheld acoustic sensor that can hear the larvae as they munch. "It's like matching fingerprints. If the sound frequency matches, then—bingo!—you've caught a beetle," Allgood says. Inspectors with the U.S. Department of Agriculture will soon use the device to spot infected wooden cargo crates arriving at New York City and Chicago ports from China, where the beetle is indigenous. Since the beetle arrived in the U.S. in 1996, more than 6,000 infected trees have been destroyed. The team is now fine-tuning the frequency-recognition program to increase accuracy, and inspectors should be equipped with the beetle catchers within nine months, the researchers predict. Work to broaden the sensor's abilities to detect other tree-boring bugs, such as the southern pine beetle, are under way. —*D.M.*

"It says, 'You may already be a Nobel Prize winner.'"

DATA POINTS

The (Somewhat) Scientific American



MATT COLLINS

Percentage of U.S. adults who say:

- Most entry-level jobs will require basic science literacy — 83%
- Science should be given the same priority as reading, writing and arithmetic — 64%
- It is important the U.S. maintain global leadership in science and technology — 93%
- They are aware that U.S. 12th graders rank near the bottom on international science tests — 7%

Percentage of U.S. adults who hope science will cure or solve:

- Diseases (cancer 30%; AIDS 6%) — 61%
- Environmental problems — 9%
- Hunger — 3%
- Space travel — 1%
- Poverty — <1%
- Nothing or don't know — 12%

Percentage of bachelor's degrees conferred in natural, health and computer science and engineering:
1986: 28.2% 1996: 24.0%

Graduate enrollment in science and engineering:
1993: 435,886 1998: 405,280

SOURCES: Bayer Corp./National Science Foundation Gallup survey; National Center for Education Statistics; National Science Foundation

The Nobel Prizes for 2000

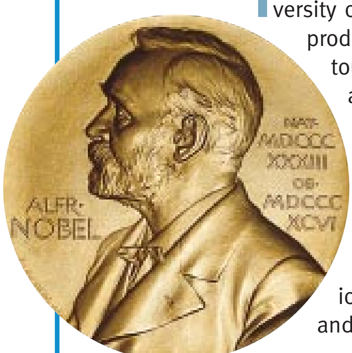
In October the Royal Swedish Academy awarded the most prestigious honors in science. The nine million Swedish kronor, or about $914,000, awarded to each field was divided up among the field's winners (not necessarily equally). See www.nobel.se for details.

PHYSIOLOGY OR MEDICINE

If the three winners are long remembered, they can thank their own discoveries. Starting in the 1960s, **Eric Kandel** of Columbia University studied and eventually deduced the molecular events that occur between neurons during memory formation. Working with sea slugs, Kandel saw that short-term memory depended on the alteration of specific proteins, whereas long-term memory was a function of genes being turned on to express whole proteins.

Arvid Carlsson of the University of Gothenburg in Sweden found in the late 1950s that dopamine was a crucial brain neurotransmitter and that its absence caused conditions such as Parkinson's disease. **Paul Greengard** of the Rockefeller University then determined how dopamine and other neurotransmitters worked, now known as slow synaptic transmission. The neurotransmitter encounters a receptor on the surface of a nerve cell, which triggers a cascade of reactions that structurally alter proteins and thereby regulate nerve cell functions.

CHEMISTRY

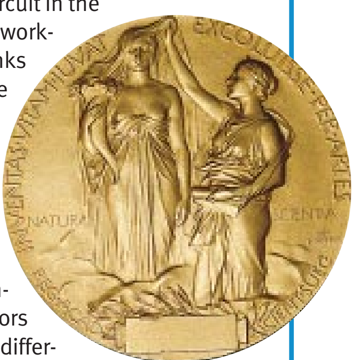


In the late 1970s **Hideki Shirakawa** of the University of Tsukuba in Japan was studying the production of polyacetylene; in a serendipitous error, 1,000 times more catalyst was added. Shirakawa told **Alan G. MacDiarmid** of the University of Pennsylvania of the product that resulted—a shiny, silvery film; soon Shirakawa, MacDiarmid and **Alan J. Heeger**, then also at Penn and now at the University of California at Santa Barbara, diffused iodine into the new polyacetylene films and measured the films' properties. The resulting product began carrying electricity at a capacity some 10 million times greater than the normally insulating plastic could.

Researchers have since crafted various plastic electronic devices from conducting polymers and greatly improved them—the polymers can also be made to emit light. Although they will not replace silicon semiconductors, they are lightweight, flexible, and easy to make and are beginning to find abundant uses, such as in antistatic films and in light-emitting diodes for displays.

PHYSICS

In a break from the past, the prize went to applied rather than basic physics. **Jack S. Kilby** of Texas Instruments was cited for being one of the inventors of the integrated circuit in the 1950s. (The late Robert Noyce of Intel, working independently, was the other.) Thanks to Kilby and Noyce, engineers can carve millions of transistors and other components onto a single chip. **Zhores I. Alferov** of the A. F. Ioffe Physico-Technical Institute in St. Petersburg, Russia, and **Herbert Kroemer** of the University of California at Santa Barbara were winners for their separate inventions of heterostructures—semiconductors that consist of different layers and have different electronic properties. Such heterostructures, which can produce laser light, enabled modern fiber-optic communications, data storage and the laser inside compact-disc players.



ECONOMICS

The Bank of Sweden's economics Nobel went to **James J. Heckman** of the University of Chicago and **Daniel L. McFadden** of the University of California at Berkeley for their separate studies of the individual and household behavior in consumption, job choice and other kinds of so-called microdata. Heckman found how economic models of such microdata can be biased because of selective sampling—models that drew conclusions about, say, wage data without considering other, more slippery variables, such as motivation. He came up with statistical methods to compensate. McFadden devised statistical methods to analyze people's discrete choices, quantifying, for example, how public opinion polls and subsidies determine a new highway route or the likelihood of electric-car usage.

AP/WIDE WORLD PHOTO

COMPUTER SCIENTIST_LYNN CONWAY

Completing the Circuit

Her research on integrated circuits advanced the Internet age by years. Now she finds herself revisiting her earliest, groundbreaking work in computers, which she long kept secret because, back then, she existed as a man

SHAKING THINGS UP **comes naturally to VLSI pioneer Lynn Conway, now at the University of Michigan.**

BILL PUGLIANO *Liaison*

ANN ARBOR, MICH.—The conversation at Lynn Conway's kitchen table moves seamlessly from computer architecture to Indian transgender cults, from the practical anthropology of technical revolutions to the risks of motorbike racing. (A hand injury two years ago sidelined Conway, but her partner, Charlie, still competes in the over-40 category.) A 14-pound brindled tomcat climbs across the counter, the table, Conway and me as we talk.

More than 30 years ago, when she was in her late 20s, Conway worked on a secret supercomputer project at IBM. She invented a way for a single central processing unit, or CPU, to perform multiple operations simultaneously without interfering with itself—unique for computers of its time. In her late 30s and early 40s, at the Xerox Palo Alto Research Center, she helped to develop the techniques for integrated-circuit design that touched off the VLSI (very large scale integration) explosion of the 1980s, a design and manufacturing approach that boosted the number of transistors on a chip from thousands to millions. The chips that brought Sun Microsystems, Silicon Graphics and other companies to prominence saw first silicon under her tutelage. By the end of that decade, computer architects used VLSI to design computers with multiple-issue and out-of-order execution capabilities like those Conway had conceived.

After her VLSI work, Conway went on to spur a similar revolution in artificial intelligence and put in a stint at the U.S. Department of Defense overseeing plans for high-performance computing. She later served as an associate dean at the University of Michigan, where she is now professor emerita of electrical engineering and computer science. Until two years ago, she also kept a secret that had contributed to the long-standing obscurity of her early work at IBM.

Born male, Conway lived most of her early life as a man. She married and fathered two children. When she finally underwent surgery to become a woman, IBM fired her, and local child-welfare authorities barred her from contact with her family. She was able to rebuild some early personal relationships only decades later.

In retrospect, she traces both her career choice and a significant part of her success to her experience as a transsexual woman, trying to figure out what worked in a world that wasn't really equipped to deal with her. "Think of my life as an Amateur Scientist experiment," she says. "I'm still collecting data."

Conway recalls having known from early childhood that she wasn't a boy, but her experimentation only started in earnest at the Massachusetts Institute of Technology, where she enrolled in 1955 as a physics major. She read up on endocrinology and learned to treat herself with black-market estrogen. She even cultivated a second, feminine identity, until a well-meaning physician convinced her that she could only become an unacceptable freak that way. She dropped out of school soon after.

Researchers estimate that a mismatch between gender identity and physical sex affects anywhere from one in 30,000 to one in 1,000 people (typically, genetic males suffer at a rate about three times that of genetic females). Although "gender dysphoria" is listed as a psychological condition—and candidates for surgery must undergo extensive evaluation and counseling—there is evidence that the condition is a result of missed hormonal signals during embryonic development. In the U.S. today about 2,500 males a year undergo surgery to bring their bodies in line with their gender identity. The precise number of transsexual women and men is not known; the vast majority do not advertise their medical status.

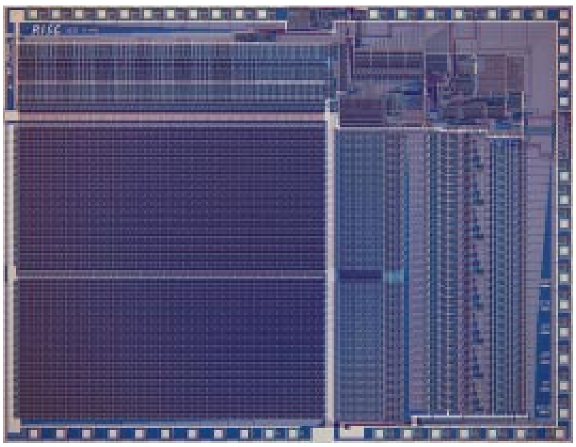
In the early 1960s, when Conway resumed her studies after several years of working as an electronics technician, a mere handful of people had undergone sex-reassignment surgery, and the stigma associated with transgender behavior was enormous. So she continued to live as a man. Enrolled at Columbia University, she was perfectly placed to learn computer science. She also studied anthropology, trying to understand as much as she could about her personal predicament. She read ethnographic accounts of cultures throughout the world where some males lived as women.

Conway hoped to quickly parlay a master's degree in electrical engineering into a high-paying job that would enable her to save enough money for surgery. But an involvement with a female co-worker led to pregnancy and marriage and postponed any thoughts of transition indefinitely. The need for a job being even more crucial, Conway landed an offer from Herb Schorr, an IBM researcher who also taught at Columbia, to work on "Project Y," later to be known as the Advanced Computer System.

The ACS was a go-for-broke project to wrest back the performance laurels the company had lost to upstart Control Data Corp. (IBM chief Thomas J. Watson wrote a blistering memo at the time, demanding to know how a company of 34 people, "including the janitor," could outdo his thousands of engineers.) The outstanding problem in computer design (then as now) was to maximize the amount of work a CPU could perform in a single clock cycle. Pipelining (the division of a complex operation, such as multiplication, into a series of steps) allowed one completed result to appear per tick even when operations took several clock cycles to complete, but it introduced complex dependencies. The input needed for one operation might be the result of another that had not yet finished, or the output of an operation might overwrite data that were still being used by another part of the pipeline. Control Data had introduced "scoreboarding" circuitry to stall conflicting operations while allowing others to proceed, but the goal of one result per cycle still seemed unattainable.

That was the state of the art in 1965, when IBM researcher John Cocke rhetorically asked the rest of the ACS staff, "Why can't we execute more than one instruction per cycle?" During the next few months, inspiration struck the young Conway in the form of an idea for a circuit that would combine information about CPU resources currently in use and those needed by upcoming instructions, tagging those instructions that could be executed without causing conflicts. "It required a lot of transistors, but it was very fast because all the checking could be done in parallel," she recounts.

So Schorr and the other senior team members decided to redesign the ACS around this so-called multiple-instruction issue. Conway programmed a software simulator that became the de facto blueprint for the ACS-1, bridging conceptual barriers among logic designers, hardware engineers and programmers. If it had come to fruition, the machine would have been able to execute a peak of 500 million operations per second, comfortably faster than the Cray-1, which stunned the computing world when it was announced in 1976.



RISC-1 MICROPROCESSOR, designed in 1982 by David Patterson's group at the University of California at Berkeley, contains 44,420 transistors. Made possible by Conway and Carver Mead's VLSI revolution, it was the progenitor of Sun Microsystems's SPARC series.

DAVID PATTERSON *University of California, Berkeley*

Instead, by 1968, internal politics and serious doubts about the feasibility of building such advanced hardware had scuttled the ACS project. Using existing integrated circuits, the CPU would have required more than 6,000 chips connected by hair-thin wires. After the project died, only a few hints of its ideas came to the outside world; years later credit for inventing multiple-instruction-issue CPUs would go to designers with no formal connection to IBM.

Meanwhile Conway's personal life had been tumultuous as well. Suicidal feelings led her to conclude that living as a man was impossible, and so she began the physical transition and had the surgery. Although her immediate supervisors tried to keep her on, IBM upper management decided that she had to go. Executives were in such a hurry that they did not even ask her to return her collection of ACS technical papers. (When contacted for this story to clarify the narratives of Conway and her former colleagues, a representative of IBM's board of directors declined to comment.)

The unexpected firing destroyed what confidence Conway's family and friends had had in her. Sudden poverty put her former wife and two children in the hands of child-welfare officials, who threatened Conway with arrest if she had any further contact with the family other than paying child support. She had to rebuild her career without reference to her work at IBM. Job offers evaporated, Conway recalls, every time she told potential employers about her medical history. Finally, she got a job as a contract programmer; it was the beginning of what she now describes as "deep stealth mode."

In 1973 came a crucial break: an opening at Xerox's fledgling Palo Alto Research Center (PARC). The freewheeling environment entranced her (even though she consistently wore skirts and suits in contrast to the standard dress of T-shirts and sandals). Without strong academic credentials or an aggressive personality, she sometimes found it hard to gain respect for her ideas in the rapid-fire give-and-take during meetings at PARC. Jeanie Treichel, now at Sun, says that Conway would seldom answer her phone directly, preferring to call back once she had marshaled all the needed information.

A new manager, Bert Sutherland, introduced Conway to Carver Mead, a semiconductor researcher at the California Institute of Technology. Sutherland had hired Mead as a consultant to "stir up the pot and make trouble," he says. Mead's work on fundamental limits to transistor size made it clear that engineers would eventually be able to put millions of transistors on a single chip—say, for example, an entire ACS-1.

Conway and Mead distilled hundreds of pages of semiconductor arcana—the "design rules" that governed how to draw patterns for metal wires, impurity-doped silicon and insulating silicon oxide—down to a few dozen lowest-common-denominator rules. They also winnowed the enormous range of circuit-design styles to a single basic methodology. Instead of half a dozen ways to draw an adder circuit or a shift register, their disciples would start by learning just one.

But even more than developing a new design method, Conway created ways to disseminate her ideas. To make VLSI design appear legitimate, she and her colleagues wrote a textbook of the kind the more established disciplines used—and composed, printed and bound it using the networked computers and laser printers that other PARC researchers had only recently developed. She test-drove the book in front of 30 students and 10 professors when she taught a course at M.I.T. in the fall of 1978. Guy Steele, now a computer language researcher at Sun, remembers her as "one of the five or six best professors I've ever had."

The course had a special attraction: PARC, Caltech and Hewlett-Packard arranged to fabricate all the class-project circuits on a chip so that they could be tested and displayed. In a couple of years, more than 100 universities were running courses and getting back working chips, as the Defense Advanced Research Projects Agency (DARPA) established MOSIS (Metal-Oxide Semiconductor Implementation Service) to meet the demand Conway and Mead had created. Researchers shared software to design and test their brainchildren using the primitive workstations of the day. Yard-wide color plots of chip designs—and eventually the chips themselves—were proudly displayed in hallways and on doors.

The notion of creating such artifacts was very deliberate. Conway's anthropological studies had convinced her that such "clan badges" would foster instant recognition among clan members and spur interest among potential adherents, where a good idea alone would not. She often cited Eugen Weber's classic *Peasants into Frenchmen* when describing how the VLSI community had come together. For the role that railroads had played carrying cultural goods in the 19th century, Conway had the Arpanet, predecessor to today's Internet. Stanford president John Hennessy (whose MIPS chip was an early beneficiary of MOSIS) estimates that the explosion of designers and design tools, along with ready access to chip foundries, accelerated the development of VLSI—and the entire computer and Internet revolution that grew from it—by as much as five years.

Suicidal feelings led Conway to conclude that living as a man was impossible.

Conway won strong loyalty among the people who worked with her. Former MOSIS program director Paul Losleben was in near awe of her ability to draw from people ideas they didn't know they had. As a manager, says Mark Stefik, an artificial-intelligence researcher who worked closely with her at PARC, she had a knack for "getting people to ask the right questions." In the early 1980s Conway and Stefik applied the VLSI clan-building methods to artificial intelligence: with buttons, contests and oversize prints, they popularized tools for representing knowledge in computerized form as the AI boom took hold.

Although her outsider status played well in universities that previously had no access to semiconductor research, it also drew heavy opposition. Many established integrated-circuit engineers derided Mead and Conway's work, saying that it was too simplistic and inefficient. At one Defense Department meeting, researchers affiliated with the competing Very High Speed Integrated Circuits program "were laughing openly" at Mead's presentation, Losleben recalls, and "not even behind his back." And although

Conway's collaborative management style inspired those around her, her success drew fire from those competing for similar turf. Her former assistant, Mary Hausladen, recollected how a rival lab manager, who had always claimed nothing would come of the VLSI work, now spread rumors that Conway was "really a man."

"But no one cared," emphasizes Hausladen, now at ImageX.com, an Internet printing company. (Stefik recounts Conway telling him that she had dared the manager in question to go public with his accusation—such as it was—and that he had backed down.) Her immediate supervisors knew her history, and many others interviewed for this story claim that they had had their suspicions, but all added that they considered it irrelevant to her accomplishments.

Shortly thereafter Conway was recruited to work for DARPA, managing the so-called Strategic Computing Initiative that was to be the Pentagon's response to Japan's ambitious "Fifth-Generation Computer" project. But her plainspoken style and penchant for end runs around bureaucratic hurdles did not mesh well with a hierarchical, military organization. "It was terrible to behold," Losleben remarks. "Like watching a friend run full-tilt into a brick wall."

Conway moved to the University of Michigan, where she could foment further unrest—pursuing studies on tools for research collaboration and helping to revamp the school of engineering—and spend some time having a life. She took up canoeing, kayaking and motorbiking and found her partner, Charlie. She worked to build the university's Media Union, a working laboratory for digital libraries, classrooms and work spaces.

In 1998, as Conway retired, she found herself back at the beginning of her career. Mark Smotherman, a computer scientist at Clemson University, began unearthing the history of the ACS-1 and its influence on later machines. Bill Wulf, now president of the National Academy of Engineering, called the machine "a stunning revelation." Conway's own archives, which had traveled with her from house to house for 30 years, became a potential treasure trove.

She attended a reunion of ACS engineers, organized by Smotherman, that included Cocke, Schorr and others and weighed her options. At last she decided that setting the record straight about her early invention outweighed maintaining her "deep stealth" status and began publicizing her ACS work.

Today she has taken on the challenge of being known as a transsexual woman with her characteristic verve. Ironically, she says, the more seamlessly transgendered people fit into their new lives, the less visible they are as role models for young people confronting the same conflicts. So her Web site, lynnconway.com, is now a significant resource on medical, legal and social issues for transsexual women, who regularly face discrimination, threats and violence. She also serves on a university committee examining transgender policies.

If not for IBM's corporate transphobia, she probably would have remained a computer architect all her career and never initiated the VLSI revolution, Conway reflects. When I comment on how much the world has gained from her trials, she retorts: "But that doesn't do anything for me," reminding me of her lost family and friends, the life she might have had. In the past 30 years gender transitions have become much smoother. And for the current generation, Conway hopes—and plans—that what caused her so much pain could be seen as one more correctable medical problem, to be mostly forgotten as soon as the surgical scars heal. Few people who know Conway would bet against her ability to help pull off this revolution as well. *—Paul Wallich*

ROBOTICS_TELESURGERY

In the Waiting Room

Robodocs may be here, but remote surgery remains remote

MOUNTAIN VIEW, CALIF.—"What this is allowing me to do is take my hands and literally put them inside a patient's body," says cardiac surgeon Mark Suzuki. He is peering into a video display and manipulating controllers on what appears to be a very expensive video game.

The device is no next-generation Nintendo, though. Inside a mock operating room at **Intuitive Surgical** is the user interface for a robotic surgery system named da Vinci. Though available for the past several years in Europe, it only recently won U.S. approval. Yet even as breakthroughs in medical robotics have greatly advanced minimally invasive surgery, the goal that has largely driven the research appears technologically out of reach: telesurgery—operations from a distance—has been put on the back burner.

The technology behind the robot-assisted surgery that Intuitive Surgical relies on was born circa 1989 at **SRI International**. After years of development work on microsurgery and laparoscopy, a eureka moment occurred, recalls retired Col. Richard Satava, professor of surgery at **Yale University** and former head of the Advanced Biomedical Technology Program at the Pentagon's **Defense Advanced Research Projects Agency** (DARPA). "A visiting medical student pointed out that if we could do surgery from a console across the room, why not set up the console at his house so he could practice at home?" Satava recounts.

With physician Philip Green, inventor of the robot-assisted surgery system that eventually was licensed to Intuitive Surgical for commercialization in 1995, Satava coined the term "telesurgery." The goal that grabbed the Pentagon's attention and a DARPA grant became known as a doc-in-a-box. Imagine: An army ranger is riddled with shrapnel deep behind enemy lines. Diagnostics from wearable sensors signal a physician at a nearby mobile army surgical hospital that his services are needed stat. The ranger is loaded into an armored vehicle outfitted with a robotic surgery system. Within minutes, he is undergoing surgery performed by the physician, who is seated at a control console 100 kilometers out of harm's way.

Such a system would also prove immensely desirable in nonmilitary areas. Surgeons could operate on, say, astronauts, Antarctica researchers or residents of a remote village.

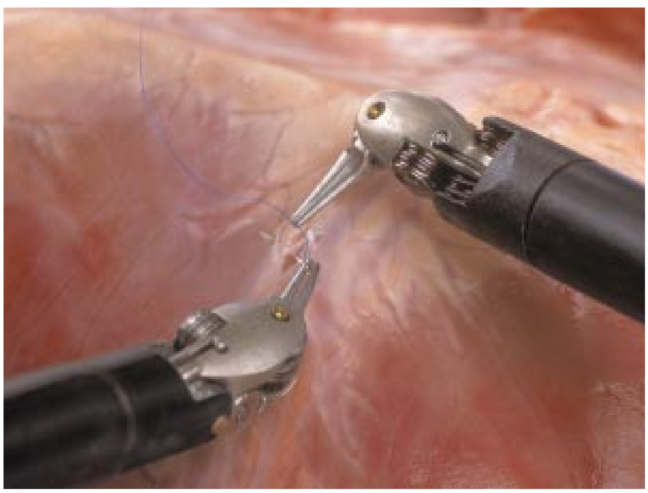
Satava succeeded in bringing that vision to light—for a moment, anyway. He impressed the Pentagon with numerous demonstrations, including one in which the secretary of defense remotely "operated" on pig intestines from a few hundred meters away via a wired connection. Then, in 1995, Satava's group introduced MEDFAST (Medical Forward-Area Surgical Telepresence), a prototype doc-in-a-box inside a tricked-out armored car. From five kilometers away, a researcher teleoperated on animal tissue over a line-of-sight wireless connection.

Though impressed, the army was noncommittal. "They did not think they could support from a logistical standpoint a large armored vehicle like our prototype," Satava remarks. "Instead they're focusing on [the] remote evacuation" of casualties, although the wearable vital-sign sensors have been used in military tests (as well as on a Mount Everest expedition).

The marketplace shares the military's misgivings regarding telesurgery. Mostly it boils down to bucks, Satava thinks. Even for robot-assisted surgery done in the same place, the cost is high: the systems not only contain pricey hardware, they require a trained support staff. Most medical facilities can't justify that kind of money for more minimally invasive procedures, even if they eventually include cardiac surgery [see "Operating on a Beating Heart," by Cornelius Borst; Scientific American, October]. The infrastructure for telesurgery would only jack up the already exorbitant price.

Beyond the business barriers, a pressing technological problem prevents the doc-in-a-box from practicing: lag time in data transmission. According to Satava, the period from when a surgeon moves his hand to the moment the scalpel mimics that motion cannot be longer than 200 milliseconds; otherwise the surgeon risks slicing at the wrong spot. "You need to transmit data very efficiently to keep telesurgery real-time," notes Fred Moll, Intuitive Surgical's co-founder. "And the farther the surgeon is from the patient, the harder it gets."

Nowhere might that be truer than in space. Though proposed as a possibility, telesurgery is not on the foreseeable



ROBOTIC SUTURING is done with video-gamelike controls.

INTUITIVE SURGICAL, INC.

time line of the **National Aeronautics and Space Administration**. The International Space Station will not be equipped for surgical procedures beyond the suturing of minor lacerations, says Sam Pool, NASA's assistant director for space medicine. "The rationale is that if there's a major need for a surgical intervention, we would come home," he explains. "The missions for which we would want, or really be forced, to do surgical interventions are still very far off in the future. And then the communication lags may almost be an insurmountable obstacle."

So far the greatest distance for which the lag time would not exceed the 200-millisecond threshold is 300 kilometers over a wire or 35 kilometers over a wireless, microwave connection, according to experiments. Improved technology could expand the range somewhat. (Telesurgery via geosynchronous satellite is physically impossible today: the round-trip signal time would be at least 480 milliseconds.)

The latency problem is "created by the video, not the control signals for the robot," according to Yulun Wang, founder and chief technology officer of Goleta, Calif.–based **Computer Motion**, Intuitive Surgical's main competitor (it has a similar robodoc called Zeus). Full-motion, high-quality video, he notes, requires about 90 megabits per second of bandwidth. Still, Wang believes that the world will soon be wired with enough bandwidth to handle the flood of information necessary for true remote surgery: "It's not a matter of yes or no, it's just a matter of when. If you had an open pipe, you could do remote surgery from anywhere on the planet." (Computer Motion is suing Intuitive Surgical for multiple patent infringements, claiming it beat Intuitive Surgical to the marketplace and that its competitor's technology resembles Computer Motion's.)

Where telesurgery might make inroads in the meantime is in the training of other physicians. Intuitive Surgical's Moll points out that surgeons are increasingly employing advanced videoconferencing and telepresence technology to "telementor" other physicians during various laparoscopic procedures (abdominal surgery accomplished by inserting a thin tube, outfitted with a camera and surgical instruments, through tiny incisions). Watching a video feed, marking the screen the way announcers do on TV sports broadcasts and even sharing control of the laparoscopic camera, the remote expert acts as a consultant for the on-site surgeon. In telementoring, "it doesn't really matter if it takes a second for the tip of the camera to move," Satava says.

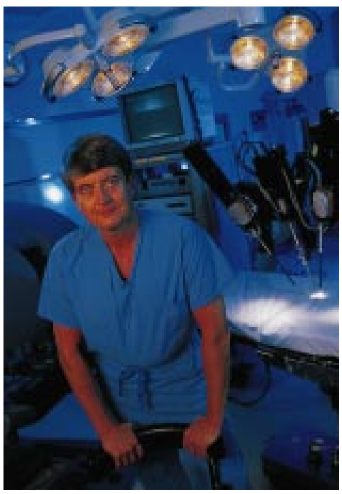
Satava's colleague James Rosser, director of endolaparoscopic surgery at Yale, demonstrated the possibilities recently by guiding a surgeon at a Santo Domingo hospital through an operation to cure a patient's acid reflux. At his Connecticut home, Rosser watched the surgery from Computer Motion's voice-controlled robotic endoscope system and made verbal and on-screen comments. For unfamiliar procedures, surgeons can't "just dial up 1-900-OPERATE," Rosser quips. "We're developing the rigid rules of engagement for a participant conducting joint maneuvers who is not there. And remote interaction is an important building block that has to be refined before we can move on to true telesurgery." *—David Pescovitz*

DAVID PESCOVITZ (david@pesco.net), based in Oakland, Calif., is a contributing editor at Wired *magazine.*

Q&A_William E. Kelley

Paging Dr. Robot

Intuitive Surgical's da Vinci Surgical System consists of a cart outfitted with mechanical limbs that end in pencil-size, teleoperated surgical tools and a high-resolution camera. Inserted into the patient through tiny incisions, the instruments are controlled by a surgeon wielding joysticklike levers. The robot digitally mirrors the surgeon's hands while scaling down his or her motions and removing any tremor: to the surgeon at the helm, an artery is like a garden hose. The first person to put the $1-million da Vinci to work after its July clearance by the U.S. Food and Drug Administration was William E. Kelley of the Richmond Surgical Group in Virginia. He has since performed several dozen gallbladder removals, hernia repairs and other operations with robotic assistance. *—D.P.*


MARTIN SIMON SABA

Q: What is the biggest benefit of robot-assisted surgery?

A: The biggest advantage is that it allows us to do complex and intricate surgical maneuvers much more precisely than we could do with either laparoscopy or open surgery. For instance, sewing is one skill in laparoscopic surgery that many surgeons have difficulty with. This enables me to make sutures in very difficult positions at awkward angles. You really can't reproduce the techniques with traditional instruments.

Q: Do you notice a resistance among your colleagues to sharing the operating theater with a robot?

A: My colleagues rejected it when I started taking out gallbladders with a laparoscope in 1989. There's always going to be that resistance. You have the people who will start very early, the majority who will wait until the kinks have been worked out and the people who don't want to ever do it. But ultimately, for example, if surgeons weren't doing laparoscopic surgery, they would have had to stop doing abdominal surgery in general.

Q: Are patients uncomfortable with the idea of a robot?

A: I've had a couple people say, "I don't want any robot doing the operation, Dr. Kelly. I want you doing it with your own hands." That's ironic because we don't use our hands directly. We use instruments. And this new technology is just an extension of the instruments. The most important thing is that we explain the options to the patient because their comfort level is every bit as important as what kind of instruments we use.

Q: What is the future of robot-assisted surgery?

A: We're really at the infancy of this technology. Everything is still evolving, and the operations will certainly become even easier. Of course, minimally invasive cardiac operations are the grand-slam home run of robot-assisted surgery. But this technology makes any surgeon better than before.

Bits of Radio

Receiving digital broadcasts becomes cheaper and easier—except in the U.S.

LONDON—The pictures, it has been said, are better on the radio. One day soon this may be literally true, though not necessarily in the U.S. At the end of September, the British company Psion, with help from the specialist company Radioscape, staked a claim to the unnoticed world of digital audio broadcasting (DAB) by releasing a £299 (about $400) device called Wavefinder. Styled like a retro, 1950s-era flying saucer crossed with a lava lamp in iMac-like translucent blue plastic, the device hooks up to your computer's USB port. It is the first of a new breed of cheap digital receivers that recently went on sale in the U.K.; previous machines cost several hundred dollars.

We may think of crackle, static, hiss and pop as being part and parcel of radio (especially given that many of us listen in moving cars), but these noises are artifacts of the analog world. Digital radio uses two techniques to create crystal-clear, near CD-quality broadcasts. One, called Musicam, reduces the amount of digital information required for a broadcast by discarding sounds that can't be perceived by the human ear—such as very quiet sounds that are masked by other, louder ones—and packages the rest more efficiently. The other, called coded orthogonal frequency division multiplexing (COFDM), uses fancy mathematics to split the signal across 1,536 different carrier frequencies and times so that even if some of the frequencies are disrupted by interference, the receiver can perfectly reassemble the original sound. To pick stations, you click on the station icon or pick a call sign from a list on a screen and travel across the country without retuning.

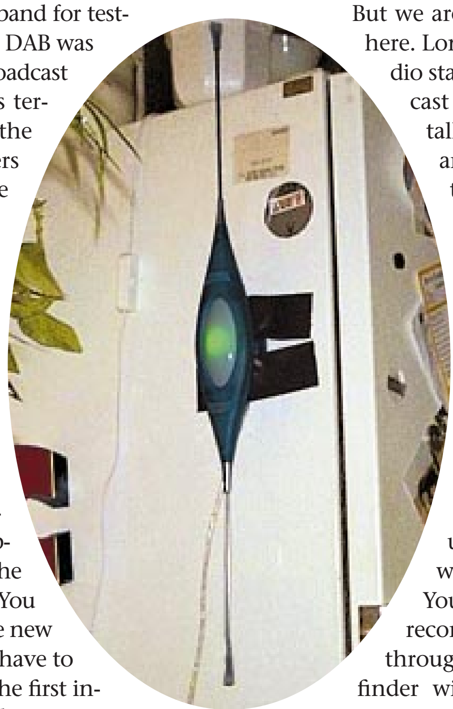
Europeans are having a good time being sarcastic about the U.S.'s place in all this: just as with mobile telephones and digital television, the U.S. is choosing to go its own way. DAB has been around for more than a decade, and in 1992 the World Administrative Radio Conference, a body of the United Nations that globally negotiates frequency allocation and satellite communications, accepted a Canadian Broadcasting Company (CBC) proposal to designate a part of the spectrum known as L-band as the worldwide standard for digital radio. The U.S. disagreed, preferring a solution known as in-band, meaning that the digital signal would be sent over the same spectrum as FM and AM.

The reasons, according to Paul Mills, who spent three years representing the English side of the CBC in this arena, were several. For one, the U.S. military was using a small part of L-band for testing. More important, DAB was capable of being broadcast by satellite as well as terrestrially, opening the way for new players to become worldwide broadcasters and alter the entire economic structure of the broadcast industry. Unlike Europe and Canada, where national radio is the province of a single public-service broadcaster, the U.S. is built on local radio. "In-band upsets the applecart the least," Mills says. "You don't have to allocate new spectrum, you don't have to give new licenses." The first in-band broadcasts and receivers may become available in a year; across Europe, DAB is a niche market, but at least the receivers already exist.

For radio buffs, the only deterrent has been either the cost of the receivers or the lack of coverage (DAB reaches 70 percent of the U.K., about average for Europe). Based on a brief trial with the Wavefinder—setting it up, duct-taping it to the refrigerator, waiting for the station map to load, having to use Internet Explorer to view datacasts—it is easy to conclude that although DAB may be the future of radio, the Wavefinder probably isn't.

In 1992 the idea of worldwide broadcasts must have seemed astonishing. Now, with the Internet and my new DSL connection, London's hidden stations are trivial compared to the fact that I can, for the first time in a decade, cook dinner while listening to *All Things Considered*. To someone who can't justify the monthly cost of DSL, DAB is of course the better deal, free once you've paid for the receiver.

These days the point of digital radio isn't the sound quality but the increase in data: a digital broadcast can whack a million people at 1.5 million bits per second without a server crash. Broadcast sound and data can share the same channel—and the licenses were sold unnoticed for a pittance next to the billions the mobile operators just paid for next-generation technology that will top out at 128,000 bits per second.



WAVEFINDER DIGITAL RADIO, unceremoniously taped to a refrigerator for testing.

But we are talking early days here. London's 35 digital radio stations mostly broadcast familiar FM fare—talk, classical, pop—and there are only two data stations. One of them broadcasts some kind of travel information, and the other broadcasts the program schedule of the BBC. They are not much, but in theory you can at least click on an item in the schedule, and the gadget will record it for you. You can even click to record a song halfway through, and the Wavefinder will save the whole song as an MP3 file.

The idea is that in a few years coverage will increase, digital radio chips will become cheaper, and you'll have DAB chips in mobile phones and many other devices. Eventually, shipping around large amounts of data that have a mass audience—say, the next Starr report—will be easy and cheap. No servers falling over, no Internet grinding to a halt—just plain old broadcast. Everywhere except the U.S., anyway. —*Wendy M. Grossman*

WENDY M. GROSSMAN, based in London, is a frequent contributor to this column. She wrote about open programming standards in the October issue.

WENDY M. GROSSMAN

Fish-shaped reptiles called ichthyosaurs reigned over the oceans for as long as dinosaurs roamed the land, but only recently have paleontologists discovered why these creatures were so successful

Picture a late autumn evening some 160 million years ago, during the Jurassic time period, when dinosaurs inhabited the continents. The setting sun hardly penetrates the shimmering surface of a vast blue-green ocean, where a shadow glides silently among the dark crags of a submerged volcanic ridge. When the animal comes up for a gulp of evening air, it calls to mind a small whale—but it cannot be. The first whale will not evolve for another 100 million years. The shadow turns suddenly and now stretches more than twice the height of a human being. That realization becomes particularly chilling when its long, tooth-filled snout tears through a school of squidlike creatures.

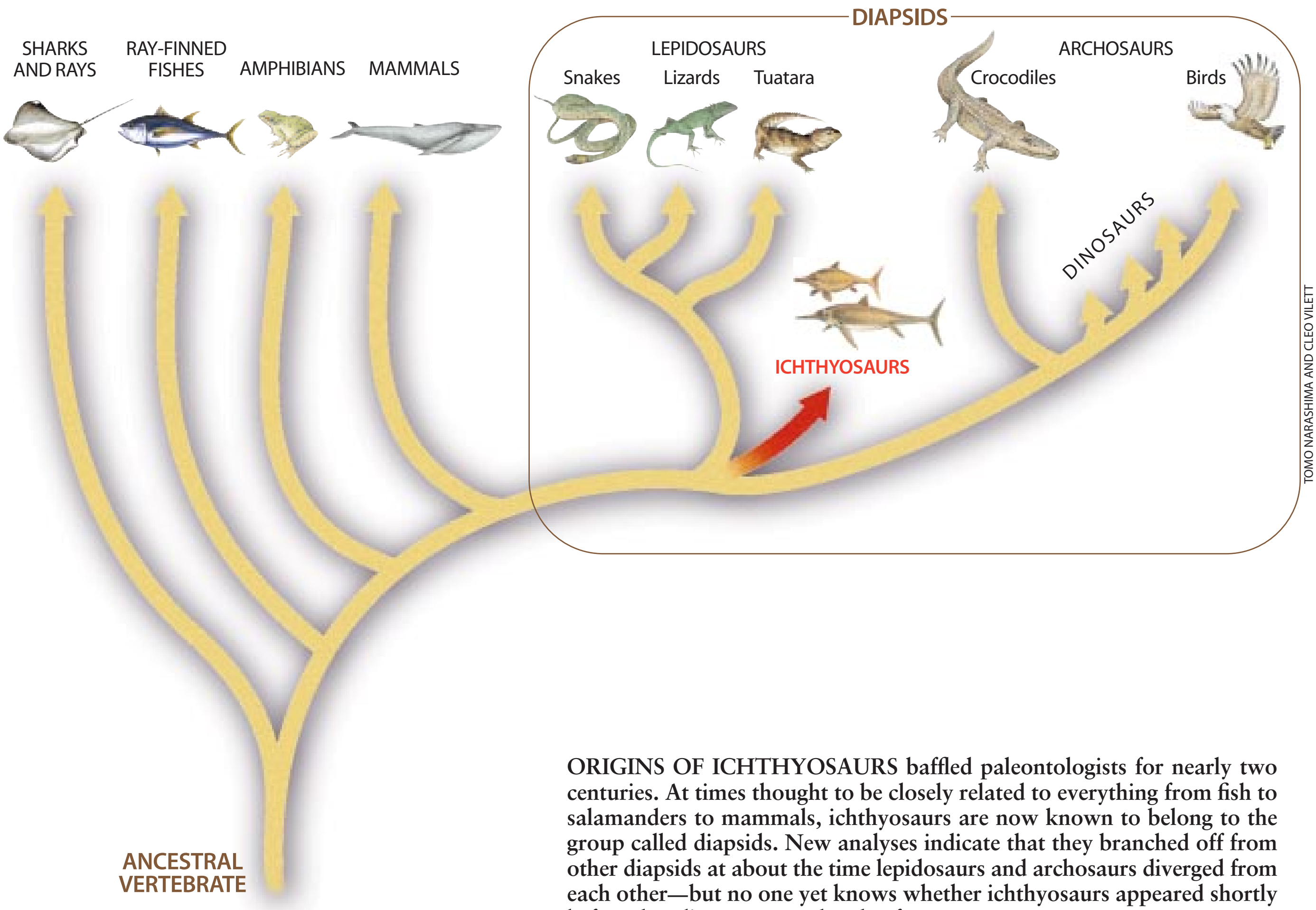
The remarkable animal is *Ophthalmosaurus*, one of more than 80 species now known to have constituted a group of sea monsters called the ichthyosaurs, or

Rulers *of the* Jurassic Seas

by Ryosuke Motani

ICHTHYOSAURS patrolled the world's oceans for 155 million years.

KAREN CARR



ORIGINS OF ICHTHYOSAURS baffled paleontologists for nearly two centuries. At times thought to be closely related to everything from fish to salamanders to mammals, ichthyosaurs are now known to belong to the group called diapsids. New analyses indicate that they branched off from other diapsids at about the time lepidosaurs and archosaurs diverged from each other—but no one yet knows whether ichthyosaurs appeared shortly before that divergence or shortly after.

fish-lizards. The smallest of these animals was no longer than a human arm; the largest exceeded 15 meters. *Ophthalmosaurus* fell into the medium-size group and was by no means the most aggressive of the lot. Its company would have been considerably more pleasant than that of a ferocious *Temnodontosaurus,* or "cutting-tooth lizard," which sometimes dined on large vertebrates.

When paleontologists uncovered the first ichthyosaur fossils in the early 1800s, visions of these long-vanished beasts left them awestruck. Dinosaurs had not yet been discovered, so every unusual feature of ichthyosaurs seemed intriguing and mysterious. Examinations of the fossils revealed that ichthyosaurs evolved not from fish but from land-dwelling animals, which themselves had descended from an ancient fish. How, then, did ichthyosaurs make the transition back to life in the water? To which other animals were they most related? And why did they evolve bizarre characteristics, such as backbones that look like a stack of hockey pucks and eyes as big around as bowling balls?

Despite these compelling questions, the opportunity to unravel the enigmatic transformation from landlubbing reptiles to denizens of the open sea would have to wait almost two centuries. When dinosaurs such as *Iguanodan* grabbed the attention of paleontologists in the 1830s, the novelty of the fish-lizards faded away. Intense interest in the rulers of the Jurassic seas resurfaced only a few years ago, thanks to newly available fossils from Japan and China. Since then, fresh insights have come quickly.

Murky Origins

Although most people forgot about ichthyosaurs in the early 1800s, a few paleontologists did continue to think about them throughout the 19th century and beyond. What has been evident since their discovery is that the ichthyosaurs' adaptations for life in water made them quite successful. The widespread ages of the fossils revealed that these beasts ruled the ocean from about 245 million until about 90 million years ago—roughly the entire era that dinosaurs dominated the continents. Ichthyosaur fossils were found all over the world, a sign that they migrated extensively, just as whales do today. And despite their fishy appearance, ichthyosaurs were obviously air-breathing reptiles. They did not have gills, and the configurations of their skull and jawbones were undeniably reptilian. What is more, they had two pairs of limbs (fish have none), which implied that their ancestors once lived on land.

Paleontologists drew these conclusions based solely on the exquisite skeletons of relatively late, fish-shaped ichthyosaurs. Bone fragments of the first ichthyosaurs were not found until 1927. Somewhere along the line, those early

FACT: The smallest ichthyosaur was shorter than a human arm;

animals went on to acquire a decidedly fishy body: stocky legs morphed into flippers, and a boneless tail fluke and dorsal fin appeared. Not only were the advanced, fish-shaped ichthyosaurs made for aquatic life, they were made for life in the open ocean, far from shore. These extreme adaptations to living in water meant that most of them had lost key features—such as particular wrist and ankle bones—that would have made it possible to recognize their distant cousins on land. Without complete skeletons of the very first ichthyosaurs, paleontologists could merely speculate that they must have looked like lizards with flippers.

The early lack of evidence so confused scientists that they proposed almost every major vertebrate group—not only reptiles such as lizards and crocodiles but also amphibians and mammals—as close relatives of ichthyosaurs. As the 20th century progressed, scientists learned better how to decipher the relationships among various animal species. On applying the new skills, paleontologists started to agree that ichthyosaurs were indeed reptiles of the group Diapsida, which includes snakes, lizards, crocodiles and dinosaurs. But exactly when ichthyosaurs branched off the family tree remained uncertain—until paleontologists in Asia recently unearthed new fossils of the world's oldest ichthyosaurs.

The first big discovery occurred on the northeastern coast of Honshu, the main island of Japan. The beach is dominated by outcrops of slate, the layered black rock that is often used for the expensive ink plates of Japanese calligraphy and that also harbors bones of the oldest ichthyosaur, *Utatsusaurus*. Most *Utatsusaurus* specimens turn up fragmented and incomplete, but a group of geologists from Hokkaido University excavated two nearly complete skeletons in 1982. These specimens eventually became available for scientific study, thanks to the devotion of Nachio Minoura and his colleagues, who spent much of the next 15 years painstakingly cleaning the slate-encrusted bones. Because the bones are so fragile, they had to chip away the rock carefully with fine carbide needles as they peered through a microscope.

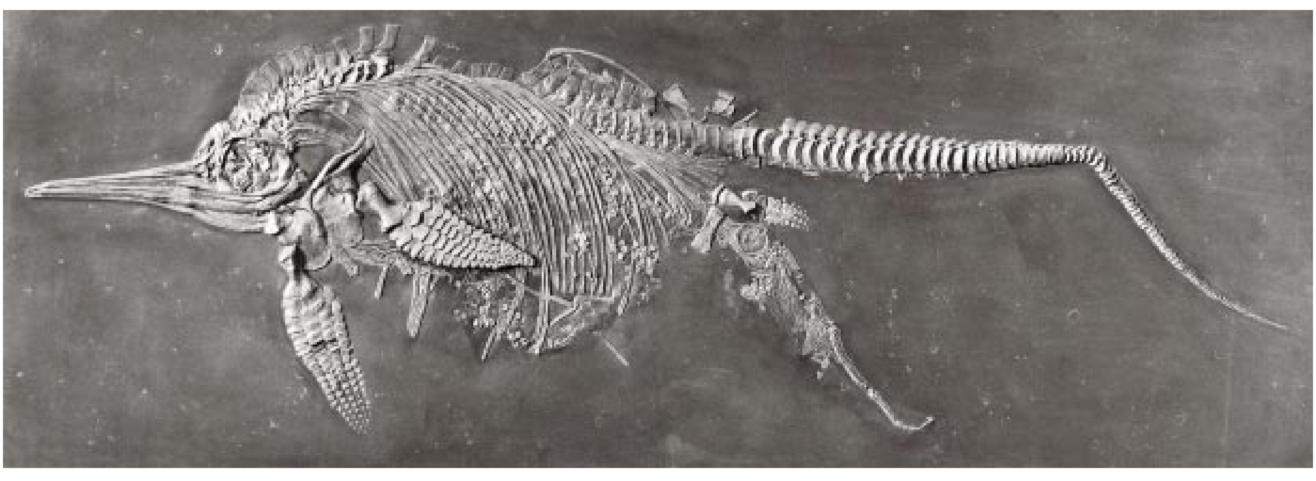
As the preparation neared its end in 1995, Minoura, who knew of my interest in ancient reptiles, invited me to join the research team. When I saw the skeleton for the first time, I knew that *Utatsusaurus* was exactly what paleontologists had been expecting to find for years: an ichthyosaur that looked like a lizard with flippers. Later that same year my colleague You Hailu, then at the Institute for Vertebrate Paleontology and Paleoanthropology in Beijing, showed me a second, newly discovered fossil—the world's most complete skeleton of *Chaohusaurus,* another early ichthyosaur. *Chaohusaurus* occurs in rocks the same age as those harboring remains of *Utatsusaurus,* and it, too, had been found before only in bits and pieces. The new specimen clearly revealed the outline of a slender, lizardlike body.

Utatsusaurus and *Chaohusaurus* illuminated at long last where ichthyosaurs belonged on the vertebrate family tree, because they still retained some key features of their land-dwelling ancestors. Given the configurations of the skull and limbs, my colleagues and I think that ichthyosaurs branched off from the rest of the diapsids near the separation of two major groups of living reptiles, lepidosaurs (such as snakes and lizards) and archosaurs (such as crocodiles and birds). Advancing the family-tree debate was a great achievement, but the mystery of the ichthyosaurs' evolution remained unsolved.

From Feet to Flippers

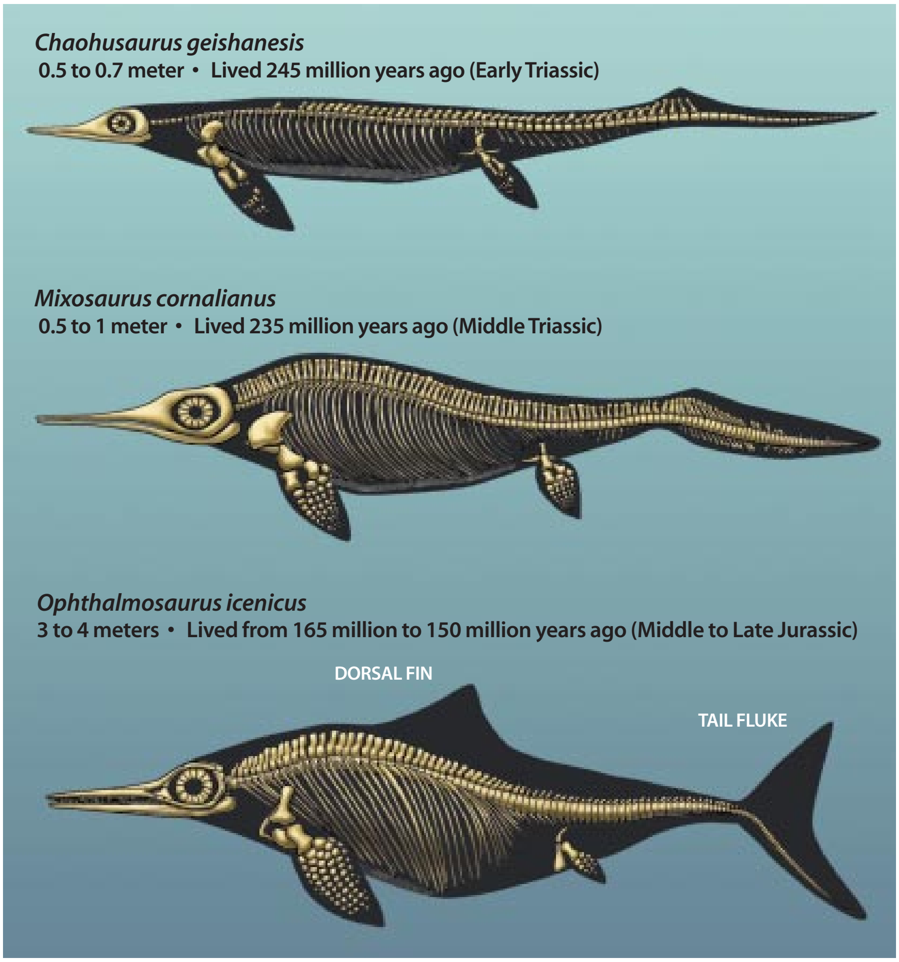
Perhaps the most exciting outcome of the discovery of these two Asian ichthyosaurs is that scientists can now paint a vivid picture of the elaborate

NEW FOSSILS of the first ichthyosaurs, including *Chaohusaurus* (*right*), have illuminated how these lizard-shaped creatures evolved into masters of the open ocean, such as *Stenopterygius,* shown below with a baby exiting the birth canal.



RYOSUKE MOTANI (*top*); STAATLICHES MUSEUM FÜR NATURKUNDE STUTTGART (*bottom*)

the largest was longer than a typical city bus



ED HECK

ANCIENT SKELETONS have helped scientists trace how the slender, lizardlike bodies of the first ichthyosaurs (*top*) thickened into a fish shape with a dorsal fin and a tail fluke.

adaptations that allowed their descendants to thrive in the open ocean. The most obvious transformation for aquatic life is the one from feet to flippers. In contrast to the slender bones in the front feet of most reptiles, all bones in the front "feet" of the fish-shaped ichthyosaurs are wider than they are long. What is more, they are all a similar shape. In most other four-limbed creatures it is easy to distinguish bones in the wrist (irregularly rounded) from those in the palm (long and cylindrical). Most important, the bones of fish-shaped ichthyosaurs are closely packed—without skin in between—to form a solid panel. Having all the toes enclosed in a single envelope of soft tissues would have enhanced the rigidity of the flippers, as it does in living whales, dolphins, seals and sea turtles. Such soft tissues also improve the hydrodynamic efficiency of the flippers because they are streamlined in cross section—a shape impossible to maintain if the digits are separated.

But examination of fossils ranging from lizard- to fish-shaped—especially those of intermediate forms—revealed that the evolution from fins to feet was not a simple modification of the foot's five digits. Indeed, analyses of ichthyosaur limbs reveal a complex evolutionary process in which digits were lost, added and divided. Plotting the shape of fin skeletons along the family tree of ichthyosaurs, for example, indicates that fish-shaped ichthyosaurs lost the thumb bones present in the earliest ichthyosaurs. Additional evidence comes from studying the order in which digits became bony, or ossified, during the growth of the fish-shaped ichthyosaur *Stenopterygius,* for which we have specimens representing various growth stages. Later, additional fingers appeared on both sides of the preexisting ones, and some of them occupied the position of the lost thumb. Needless to say, evolution does not always follow a continuous, directional path from one trait to another.

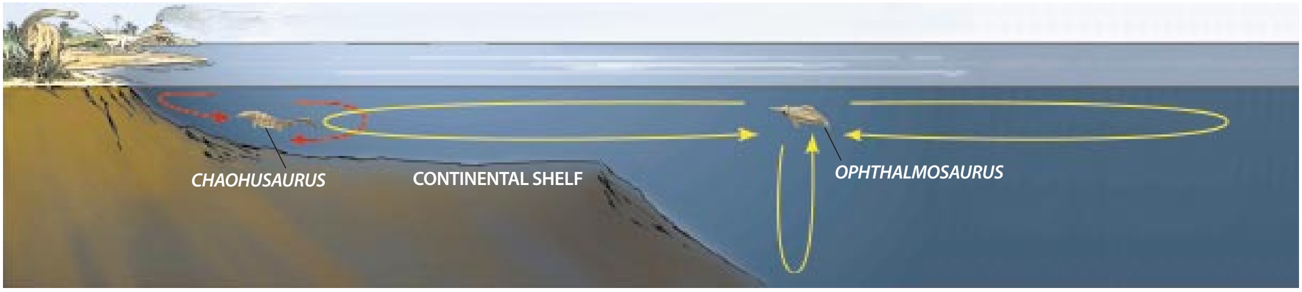
Backbones Built for Swimming

The new lizard-shaped fossils have also helped resolve the origin of the skeletal structure of their fish-shaped descendants. The descendants have backbones built from concave vertebrae the shape of hockey pucks. This shape, though rare among diapsids, was always assumed to be typical of all ichthyosaurs. But the new creatures from Asia surprised paleontologists by having a much narrower backbone, composed of vertebrae shaped more like canisters of 35-millimeter film than hockey pucks. It appeared that the vertebrae grew dramatically in diameter and shortened slightly as ichthyosaurs evolved from lizard- to fish-shaped. But why?

My colleagues and I found the answer in the swimming styles of living sharks. Sharks, like ichthyosaurs, come in various shapes and sizes. Cat sharks are slender and lack a tall tail fluke, also known as a caudal fin, on their lower backs, as did early ichthyosaurs. In contrast, mackerel sharks such as the great white have thick bodies and a crescent-shaped caudal fin similar to the later fish-shaped ichthyosaurs. Mackerel sharks swim by swinging only their tails, whereas cat sharks undulate their entire bodies. Undulatory swimming requires a flexible body, which cat sharks achieve by having a large number of backbone segments. They have about 40 vertebrae in the front part of their bodies—the same number scientists find in the first ichthyosaurs, represented by *Utatsusaurus* and *Chaohusaurus*. (Modern reptiles and mammals have only about 20.)

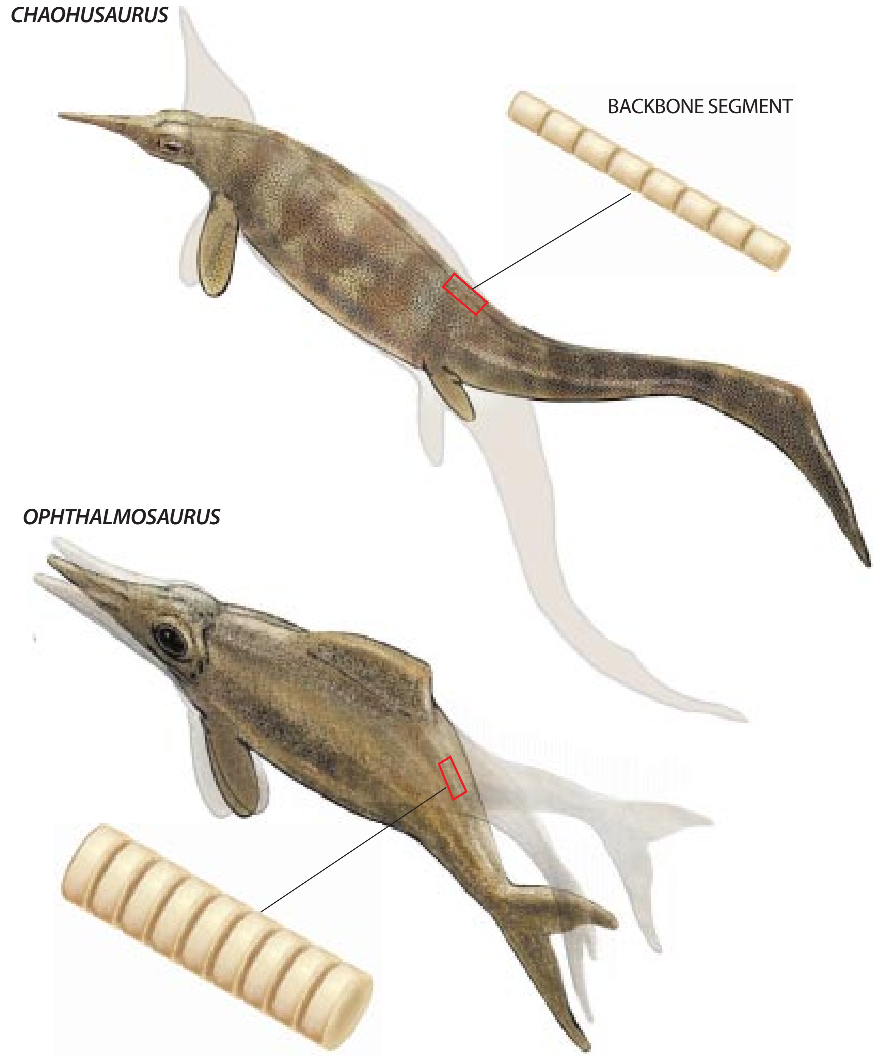
Undulatory swimmers, such as cat sharks, can maneuver and accelerate sufficiently to catch prey in the relatively shallow water above the continental shelf. Living lizards also undulate to swim, though not as efficiently as crea-

FACT: No other reptile group ever evolved a fish-shaped body



KAREN CARR

SWIMMING STYLES—and thus the habitats (*above*)—of ichthyosaurs changed as the shape of their vertebrae evolved. The narrow backbone of the first ichthyosaurs suggests that they undulated their bodies like eels (*right*). This motion allowed for the quickness and maneuverability needed for shallow-water hunting. As the backbone thickened in later ichthyosaurs, the body stiffened and so could remain still as the tail swung back and forth (*bottom*). This stillness facilitated the energy-efficient cruising needed to hunt in the open ocean.



KAREN CARR; ADRIENNE SMUCKER (*vertebrae*)

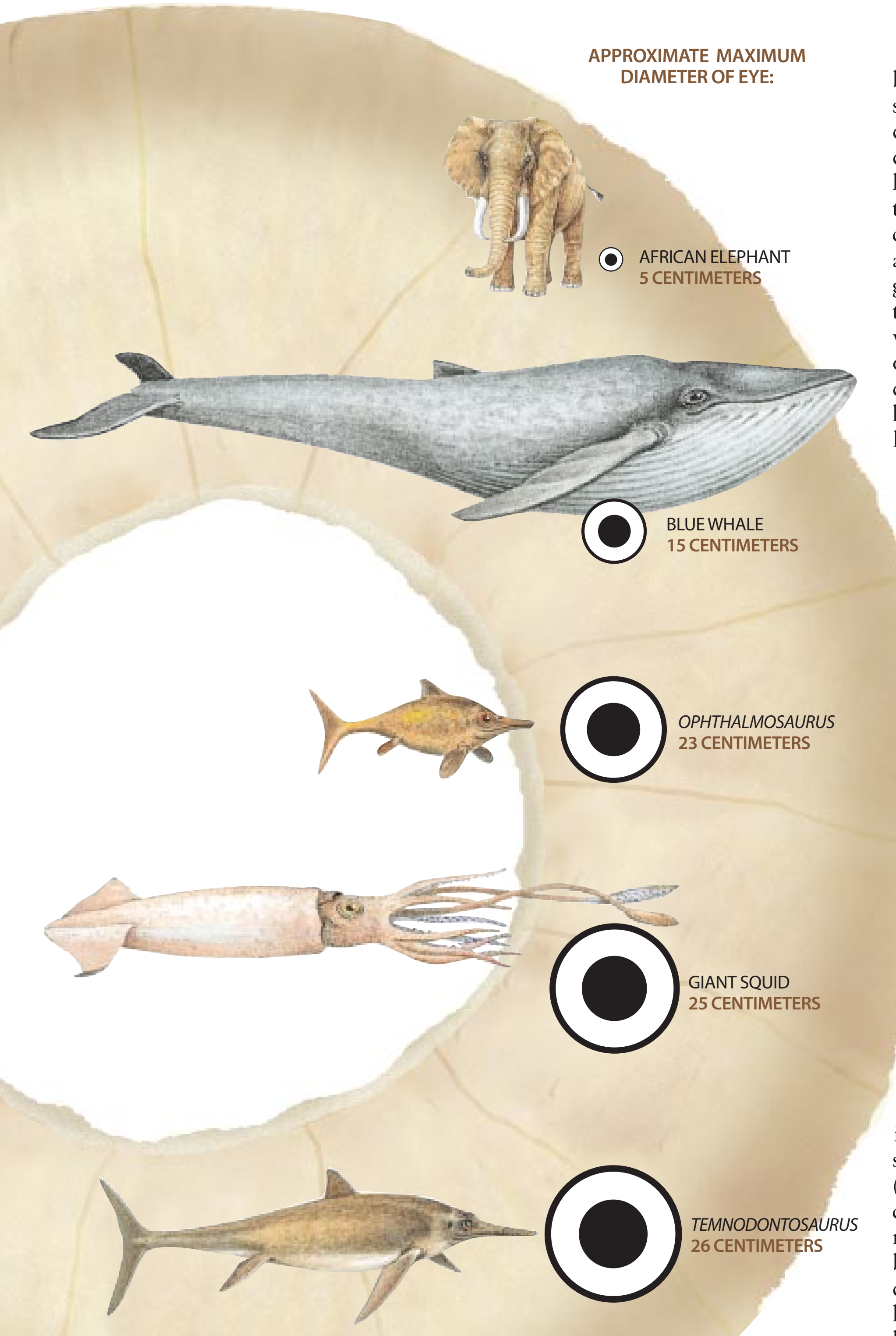
tures that spend all their time at sea. It is logical to conclude, then, that the first ichthyosaurs—which looked like cat sharks and descended from a lizardlike ancestor—swam in the same fashion and lived in the environment above the continental shelf.

Undulatory swimming enables predators to thrive near shore, where food is abundant, but it is not the best choice for an animal that has to travel long distances to find a meal. Offshore predators, which hunt in the open ocean where food is less concentrated, need a more energy-efficient swimming style. Mackerel sharks solve this problem by having stiff bodies that do not undulate as their tails swing back and forth. A crescent-shaped caudal fin, which acts as an oscillating hydrofoil, also improves their cruising efficiency. Fish-shaped ichthyosaurs had such a caudal fin, and their thick body profile implies that they probably swam like mackerel sharks.

Inspecting a variety of shark species reveals that the thicker the body from top to bottom, the larger the diameter of the vertebrae in the animal's trunk. It seems that sharks and ichthyosaurs solved the flexibility problem resulting from having high numbers of body segments in similar ways. As the bodies of ichthyosaurs thickened over time, the number of vertebrae stayed about the same. To add support to the more voluminous body, the backbone became at least one and a half times thicker than those of the first ichthyosaurs. As a consequence of this thickening, the body became less flexible, and the individual vertebrae acquired their hockey-puck appearance.

Drawn to the Deep

The ichthyosaurs' invasion of open water meant not only a wider coverage of surface waters but also a deeper exploration of the marine environment. We know from the fossilized stomach contents of fish-shaped ichthyosaurs that they mostly ate squidlike creatures known as dibranchiate cephalopods. Squid-eating whales hunt anywhere from about 100 to 1,000 meters deep and sometimes down to 3,000 meters. The great range in depth is hardly surprising considering that food resources are widely scattered below about 200 meters. But to hunt down deep, whales and other air-breathing divers have to go there and get back to the surface in one breath—no easy task. Reducing energy use during swimming is one of the best ways to conserve precious oxygen stored in their bodies. Consequently, deep divers today have streamlined shapes that reduce drag—and so did fish-shaped ichthyosaurs.



ICHTHYOSAUR EYES were surprisingly large. Analyses of doughnut-shaped eye bones called sclerotic rings reveal that *Ophthalmosaurus* had the largest eyes relative to body size of any adult vertebrate, living or extinct, and that *Temnodontosaurus* had the biggest eyes, period. The beige shape in the background is the size of an *Ophthalmosaurus* sclerotic ring. The photograph depicts a well-preserved ring from *Stenopterygius*.

TOMO NARASHIMA (*animals*); EDWARD BELL (*sclerotic ring*); RYOSUKE MOTANI (*photograph*)

Characteristics apart from diet and body shape also indicate that at least some fish-shaped ichthyosaurs were deep divers. The ability of an air-breathing diver to stay submerged depends roughly on its body size: the heavier the diver, the more oxygen it can store in its muscles, blood and certain other organs—and the slower the consumption of oxygen per unit of body mass. The evolution of a thick, stiff body increased the volume and mass of fish-shaped ichthyosaurs relative to their predecessors. Indeed, a fish-shaped ichthyosaur would have been up to six times heavier than a lizard-shaped ichthyosaur of the same body length. Fish-shaped ichthyosaurs also grew longer, further augmenting their bulk. Calculations based on the aerobic capacities of today's air-breathing divers (mostly mammals and birds) indicate that an animal the weight of fish-shaped *Ophthalmosaurus,* which was about 950 kilograms, could hold its breath for at least 20 minutes. A conservative estimate suggests, then, that *Ophthalmosaurus* could easily have dived to 600 meters—possibly even 1,500 meters—and returned to the surface in that time span.

Bone studies also indicate that fish-shaped ichthyosaurs were deep divers. Limb bones and ribs of four-limbed terrestrial animals include a dense outer shell that enhances the strength needed to support a body on land. But that dense layer is heavy. Because aquatic vertebrates are fairly buoyant in water, they do not need the extra strength it provides. In fact, heavy bones (which are little help for oxygen storage) can impede the ability of deep divers to return to the surface. A group of French biologists has established that modern deep-diving mammals solve that problem by making the outer shell of their bones spongy and less dense. The same type of spongy layer also encases the bones of fish-shaped ichthyosaurs, which implies that they, too, benefited from lighter skeletons.

Perhaps the best evidence for the deep-diving habits of later ichthyosaurs is their remarkably large eyes, up to 23

FACT: Their eyes were the largest of any animal, living or dead

SMALL ISLAND in northeast Japan turned out to harbor two almost complete skeletons of *Utatsusaurus,* the oldest ichthyosaur.


RYOSUKE MOTANI

centimeters across in the case of *Ophthalmosaurus*. Relative to body size, that fish-shaped ichthyosaur had the biggest eyes of any animal ever known.

The size of their eyes also suggests that visual capacity improved as ichthyosaurs moved up the family tree. These estimates are based on measurements of the sclerotic ring, a doughnut-shaped bone that was embedded in their eyes. (Humans do not have such a ring—it was lost in mammalian ancestors—but most other vertebrates have bones in their eyes.) In the case of ichthyosaurs, the ring presumably helped to maintain the shape of the eye against the forces of water passing by as the animals swam, regardless of depth.

The diameter of the sclerotic ring makes it possible to calculate the eye's minimum f-number—an index, used to rate camera lenses, for the relative brightness of an optical system. The lower the number, the brighter the image and therefore the shorter the exposure time required. Low-quality lenses have a value of f/3.5 and higher; high-quality lenses have values as low as f/1.0. The f-number for the human eye is about 2.1, whereas the number for the eye of a nocturnal cat is about 0.9. Calculations suggest that a cat would be capable of seeing at depths of 500 meters or greater in most oceans. *Ophthalmosaurus* also had a minimum f-number of about 0.9, but with its much larger eyes, it probably could outperform a cat.

Gone for Good

Many characteristics of ichthyosaurs—including the shape of their bodies and backbones, the size of their eyes, their aerobic capacity, and their habitat and diet—seem to have changed in a connected way during their evolution, although it is not possible to judge what is the cause and what is the effect. Such adaptations enabled ichthyosaurs to reign for 155 million years. New fossils of the earliest of these sea dwellers are now making it clear just how they evolved so successfully for aquatic life, but still no one knows why ichthyosaurs went extinct.

Loss of habitat may have clinched the final demise of lizard-shaped ichthyosaurs, whose inefficient, undulatory swimming style limited them to near-shore environments. A large-scale drop in sea level could have snuffed out these creatures along with many others by eliminating their shallow-water niche. Fish-shaped ichthyosaurs, on the other hand, could make a living in the open ocean, where they would have had a better chance of survival. Because their habitat never disappeared, something else must have eliminated them. The period of their disappearance roughly corresponds to the appearance of advanced sharks, but no one has found direct evidence of competition between the two groups.

Scientists may never fully explain the extinction of ichthyosaurs. But as paleontologists and other investigators continue to explore their evolutionary history, we are sure to learn a great deal more about how these fascinating creatures lived. SA

The Author

RYOSUKE MOTANI, who was born in Tokuyama, Japan, is a researcher in the department of paleobiology at the Royal Ontario Museum in Toronto. As a child he found ichthyosaurs uninteresting. ("They looked too ordinary in my picture books," he recalls.) But his view changed during his undergraduate years at the University of Tokyo, after a paleontology professor allowed him to study the only domestic reptilian fossil they had: an ichthyosaur. "I quickly fell in love with these noble beasts," he says. Motani went on to explore ichthyosaur evolution for his doctoral degree from the University of Toronto in 1997. A fellowship from the Miller Institute then took him to the University of California, Berkeley, for postdoctoral research. He moved back to Canada in September 1999.

Further Information

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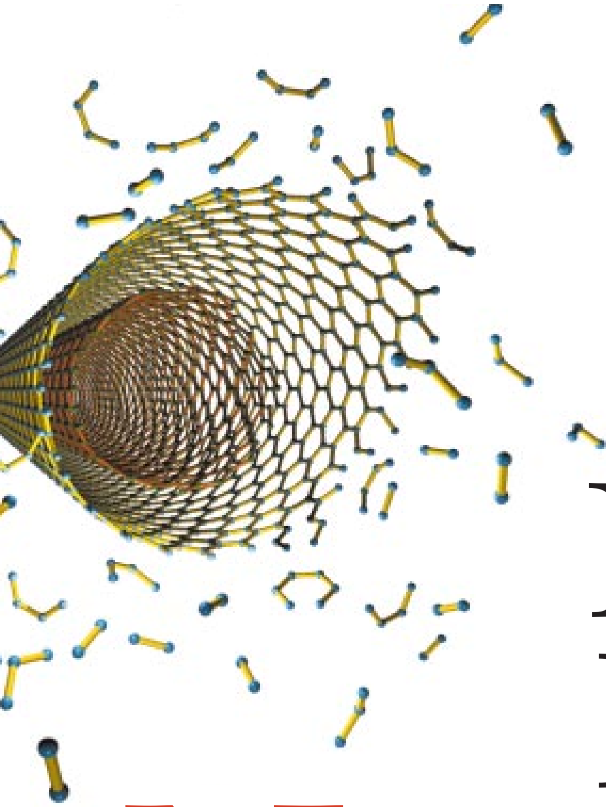
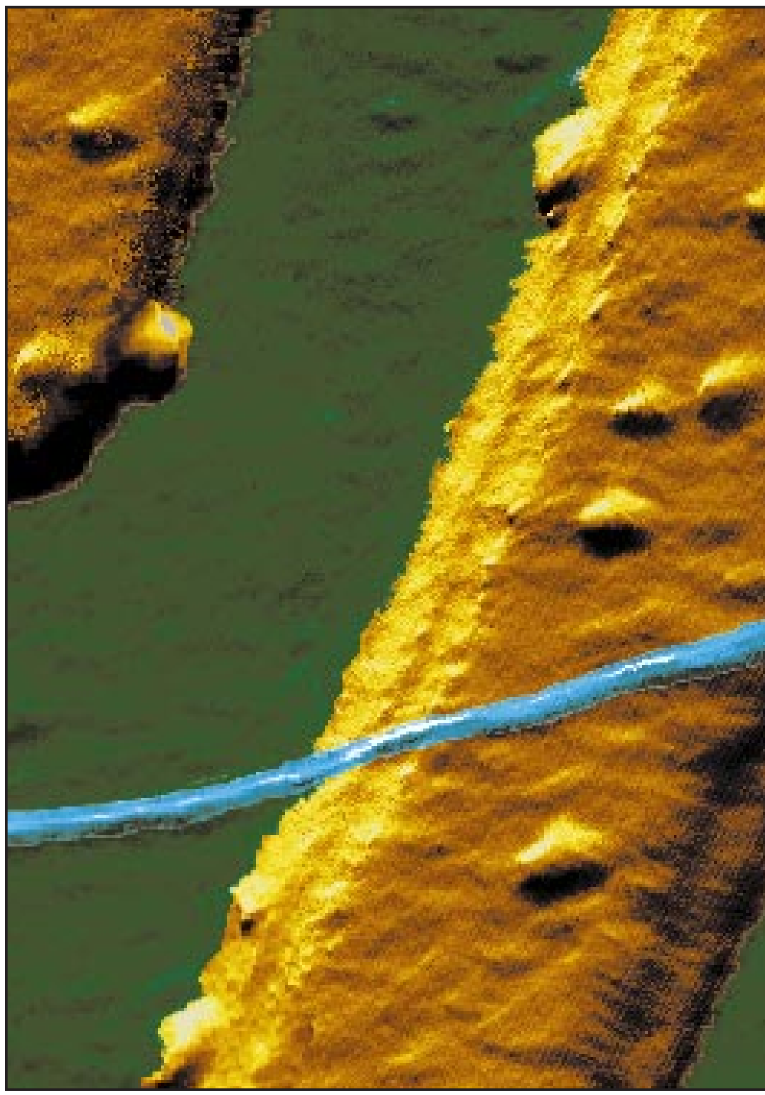


They are stronger than steel, but the most important uses for these threadlike macromolecules may be in faster, more efficient and more durable electronic devices

by Philip G. Collins and Phaedon Avouris

Nanotubes FOR Electronics



Nearly 10 years ago Sumio Iijima, sitting at an electron microscope at the NEC Fundamental Research Laboratory in Tsukuba, Japan, first noticed odd nanoscopic threads lying in a smear of soot. Made of pure carbon, as regular and symmetric as crystals, these exquisitely thin, impressively long macromolecules soon became known as nanotubes, and they have been the object of intense scientific study ever since.

Just recently, they have become a subject for engineering as well. Many of the extraordinary properties attributed to nanotubes—among them, superlative resilience, tensile strength and thermal stability—have fed fantastic predictions of microscopic robots, dent-resistant car bodies and earthquake-resistant buildings. The first products to use nanotubes, however, exploit none of these. Instead the earliest applications are electrical. Some General Motors cars already include plastic parts to which nanotubes were added; such plastic can be electrified during painting so that the paint will stick more readily. And two nanotube-based lighting and display products are well on their way to market.

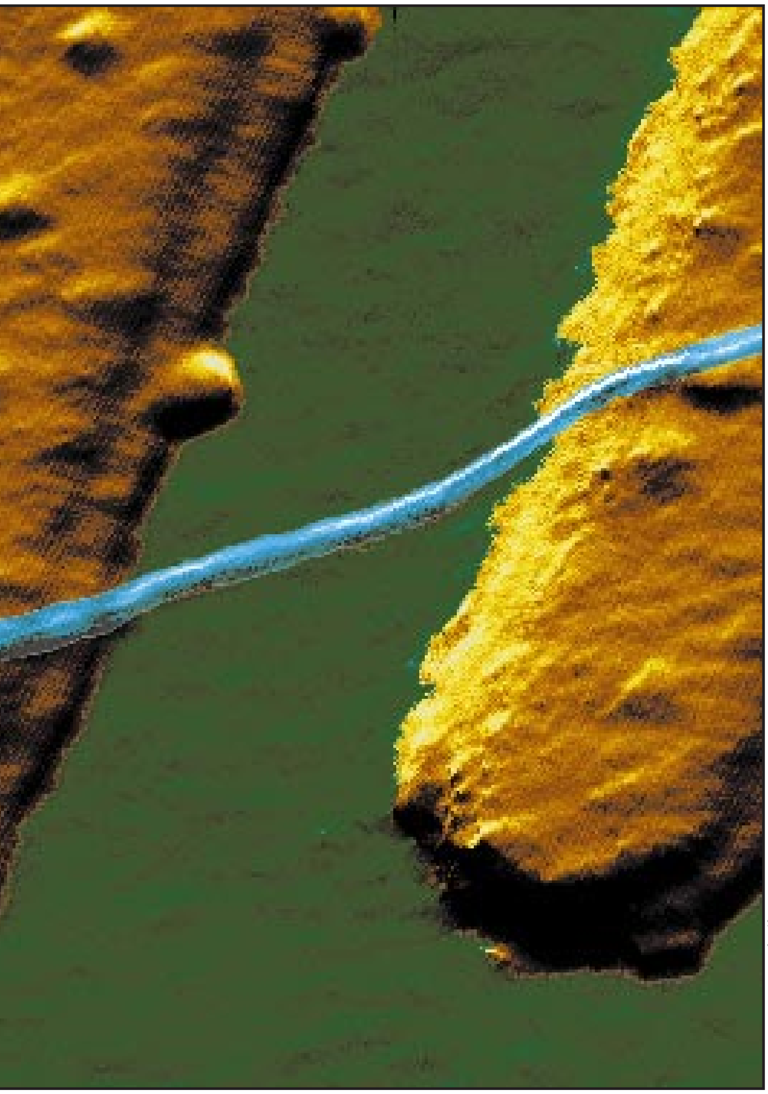
In the long term, perhaps the most valuable applications will take further advantage of nanotubes' unique electronic properties. Carbon nanotubes can in principle play the same role as silicon does in electronic circuits, but at a molecular scale where silicon and other standard semiconductors cease to work. Although the electronics industry is already pushing the critical dimensions of transistors in commercial chips below 200 nanometers (billionths of a meter)—about 400 atoms wide—engineers face large obstacles in continuing this miniaturization. Within this decade, the materials and processes on which the computer revolution has been built will begin to hit fundamental physical limits. Still, there are huge economic incentives to shrink devices further, because the speed, density and efficiency of microelectronic devices all rise rapidly as the minimum feature size decreases. Experiments over the past several years have given researchers hope

SLIM FILMS

that wires and functional devices tens of nanometers or smaller in size could be made from nanotubes and incorporated into electronic circuits that work far faster and on much less power than those existing today.

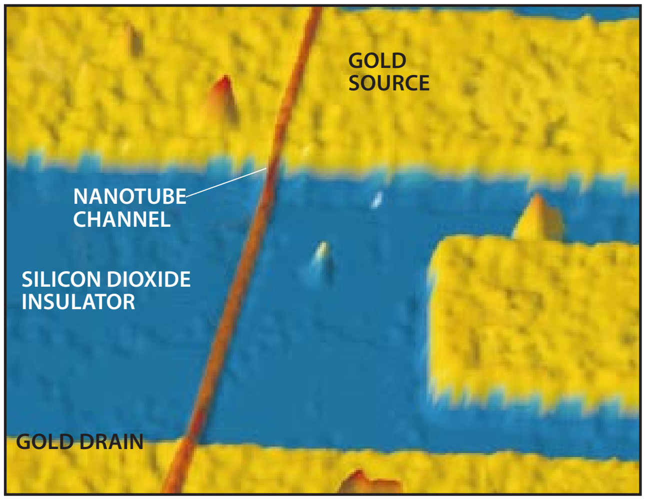
The first carbon nanotubes that Iijima observed back in 1991 were so-called multiwalled tubes: each contained a number of hollow cylinders of carbon atoms nested inside one another like Russian dolls. Two years later Iijima and Donald Bethune of IBM independently created single-walled nanotubes that were made of just one layer of carbon atoms. Both kinds of tubes are made in similar ways, and they have many similar properties—the most obvious being that they are exceedingly narrow and long. The single-walled variety, for example, is about one nanometer in diameter but can run thousands of nanometers in length.

What makes these tubes so stable is the strength with which carbon atoms bond to one another, which is also what makes diamond so hard. In diamond the carbon atoms link into four-sided tetrahedra, but in nanotubes the atoms arrange themselves in hexagonal rings like chicken wire. One sees the same pattern in graphite, and in fact a nanotube looks like a sheet (or several stacked sheets) of graphite rolled into a seamless cylinder. It is not known for certain how the atoms actually condense into tubes [see "Zap, Bake or Blast," on page 67], but it appears that they may grow by adding atoms to their ends, much as a knitter adds stitches to a sweater sleeve.


CEES DEKKER *University of Delft*

Tubes with a Twist

However they form, the composition and geometry of carbon nanotubes engender a unique electronic complexity. That is in part simply the result of size, because quantum physics governs at the nanometer scale. But graphite itself is a very unusual material. Whereas most electrical conductors can be classified as either metals or semiconductors, graphite is one of the rare materials known as a semimetal, delicately balanced in the transitional zone between the two. By combining graphite's semimetallic properties with the quantum rules of energy levels and electron waves, carbon nanotubes emerge as truly exotic conductors.



PHILIP G. COLLINS AND PHAEDON AVOURIS

MICROCHIPS OF THE FUTURE will require smaller wires and transistors than photolithography can produce today. Electrically conductive macromolecules of carbon that self-assemble into tubes (*top left*) are being tested as ultrafine wires (*left*) and as channels in experimental field-effect transistors (*above*).

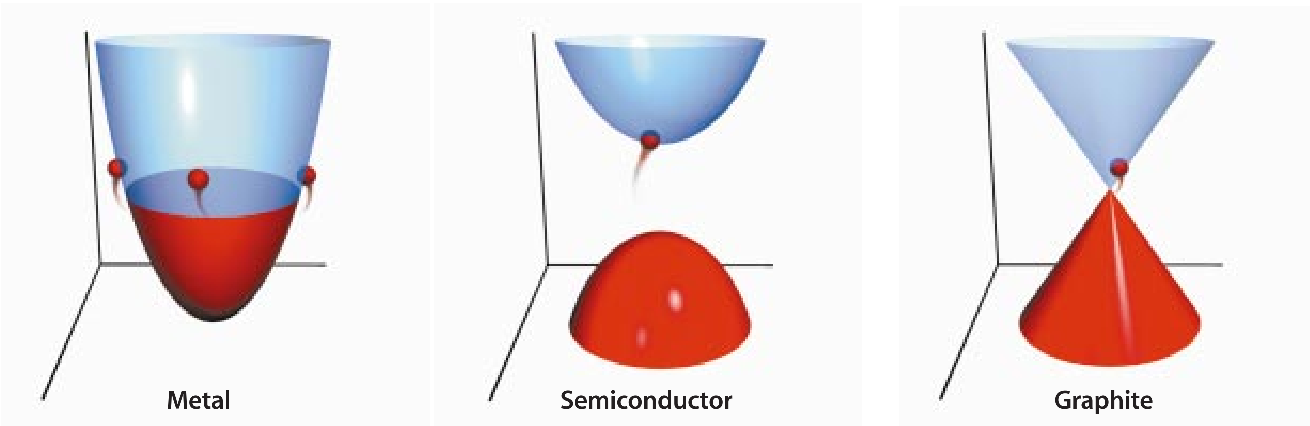
For example, one rule of the quantum world is that electrons behave like waves as well as particles, and electron waves can reinforce or cancel one another. As a consequence, an electron spreading around a nanotube's circumference can completely cancel itself out; thus, only electrons with just the right wavelength remain. Out of all the possible electron wavelengths, or quantum states, available in a flat graphite sheet, only a tiny subset is allowed when we roll that sheet into a nanotube. That subset depends on the circumference of the nanotube, as well as whether the nanotube twists like a barbershop pole.

Slicing a few electron states from a simple metal or semiconductor won't produce many surprises, but semimetals are much more sensitive materials, and that is where carbon nanotubes become interesting. In a graphite sheet, one particular electron state (which physicists call the Fermi point) gives graphite almost all of its conductivity; none of the electrons in other states are free to move about. Only one third of all carbon nanotubes combine the right diameter and degree of twist to include this special Fermi point in their subset of allowed states. These nanotubes are truly metallic nanowires.

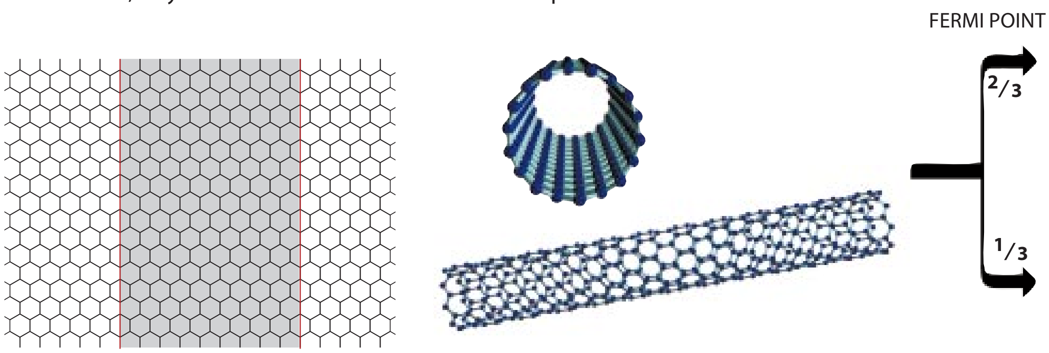
The remaining two thirds of nanotubes are semiconduc-

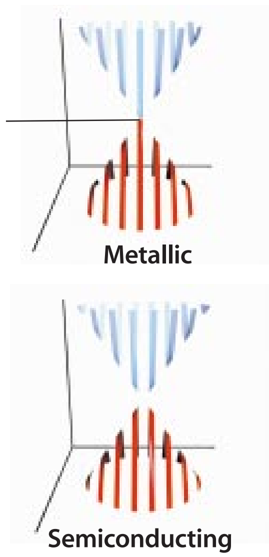
The Electrical Behavior of Nanotubes

A Split Personality

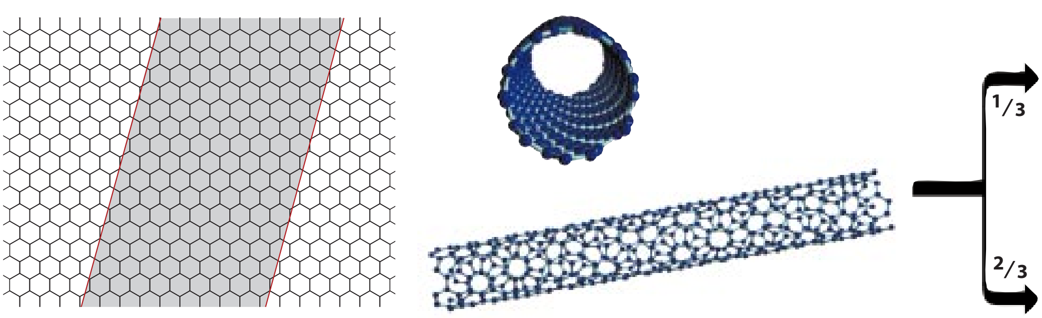


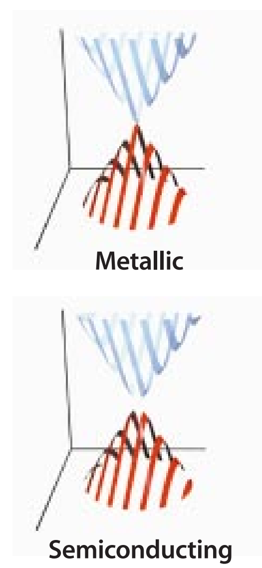
ELECTRICAL PROPERTIES of a material depend on the separation between the collection of energy states that are filled by electrons (*red*) and the additional "conduction" states that are empty and available for electrons to hop into (*light blue*). Metals conduct electricity easily because there are so many electrons with easy access to adjacent conduction states. In semiconductors, electrons need an energy boost from light or an electrical field to jump the gap to the first available conduction state. The form of carbon known as graphite is a semimetal that just barely conducts, because without these external boosts, only a few electrons can access the narrow path to a conduction state.





STRAIGHT NANOTUBES look like a straight swath cut from a sheet of graphite (*left*) and rolled into a tube (*center*). The geometry of nanotubes limits electrons to a select few slices of graphite's energy states (*right*). Depending on the diameter of the tube, one of these slices can include the narrow path that joins electrons with conduction states. This special point, called the Fermi point, makes two thirds of the nanotubes metallic. Otherwise, if the slices miss the Fermi point, the nanotubes semiconduct.





TWISTED NANOTUBES, cut at an angle from graphite (*left*), look a bit like barbershop poles (*center*). The slices of allowed energy states for electrons (*right*) are similarly cut at an angle, with the result that about two thirds of twisted tubes miss the Fermi point and are semiconductors.

W. WAYT GIBBS (*top and side rows*); CLEO VILETT (*sheets*); J. CUMINGS AND A. ZETTL *University of California, Berkeley* (*tubes*) tors. That means that, like silicon, they do not pass current easily without an additional boost of energy. A burst of light or a voltage can knock electrons from valence states into conducting states where they can move about freely. The amount of energy needed depends on the separation between the two levels and is the so-called band gap of a semiconductor. It is semiconductors' band gaps that make them so useful in circuits, and by having a library of materials with different band gaps, engineers have been able to produce the vast array of electronic devices available today.

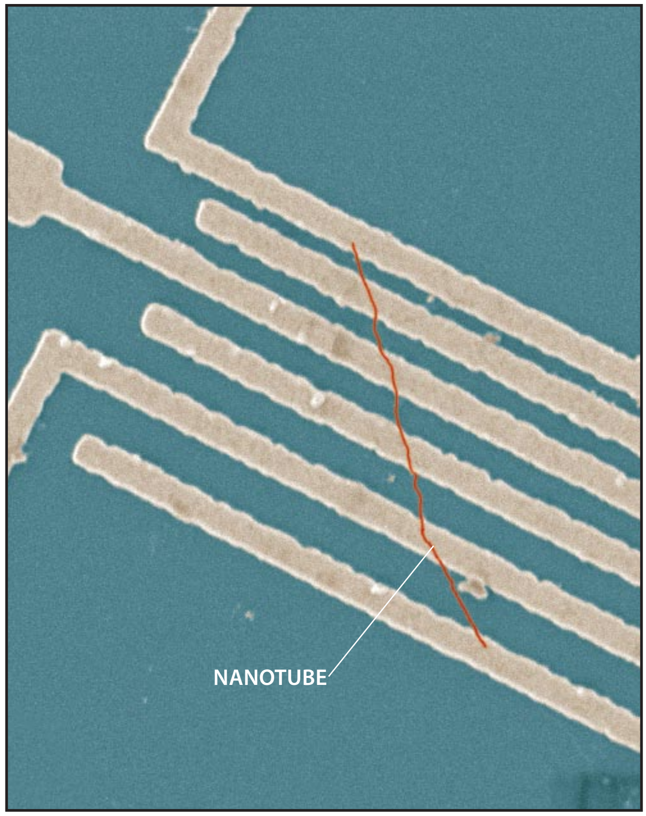
Carbon nanotubes don't all have the same band gap, because for every circumferences there is a unique set of allowed valences and conduction states. The smallest-diameter nanotubes have very few states that are spaced far apart in energy. As nanotube diameters increase, more and more states are allowed and the spacing between them shrinks. In this way, different-size nanotubes can have band gaps as low as zero (like a metal), as high as the band gap of silicon, and almost anywhere in between. No other known material can be so easily tuned. Unfortunately, the growth of nanotubes currently gives a jumble of different geometries, and researchers are seeking improvements so that specific types of nanotubes can be guaranteed.

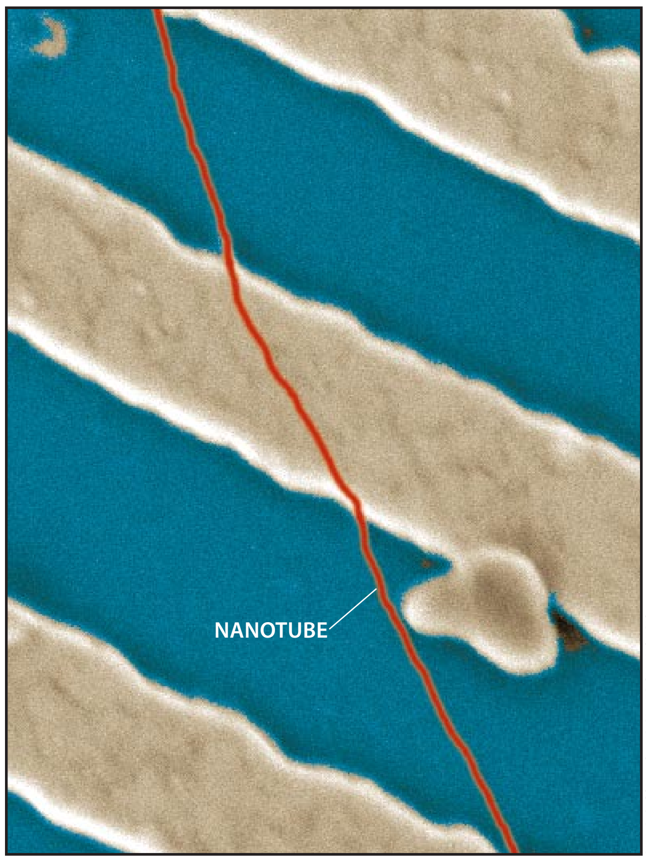
Fat multiwalled nanotubes may have even more complex behavior, because each layer in the tube has a slightly different geometry. If we could tailor their composition individually, we might one day make multiwalled tubes that are self-insulating or that carry multiple signals at once, like nanoscopic coaxial cables. Our understanding and control of nanotube growth still falls far short of these goals, but by incorporating nanotubes into working circuits, we have at least begun to unravel their basic properties.

Nanocircuits

Several research groups, including our own, have successfully built working electronic devices out of carbon nanotubes. Our field-effect transistors (FETs) use single semiconducting nanotubes between two metal electrodes as a channel through which electrons flow [*see right illustration on page 63*]. The current flowing in this channel can be switched on or off by applying voltages to a nearby third electrode. The nanotube-based devices operate at room temperature with electrical characteristics remarkably similar to off-the-shelf silicon devices. We and others have found, for example, that the gate electrode can change the conductivity of the nanotube channel in an FET by a factor of one million or more, comparable to silicon FETs. Because of its tiny size, however, the nanotube FET should switch reliably using much less power than a silicon-based device. Theorists predict that a truly nanoscale switch could run at clock speeds of one terahertz or more—1,000 times as fast as processors available today.

The fact that nanotubes come with a variety of band gaps and conductivities raises many intriguing possibilities for additional nanodevices. For example, our team and others have recently measured joined metallic and semiconducting nanotubes and shown that such junctions behave as diodes, permitting electricity to flow in only one direction. Theoretically, combinations of nanotubes with different band gaps could behave like light-emitting diodes and perhaps even nanoscopic lasers. It is now feasible to build a nanocircuit that has wires, switches and memory elements made entirely from





PHILIP G. COLLINS AND PHAEDON AVOURIS

AS ULTRATHIN WIRES, carbon nanotubes could free up space in microchips for more devices, as well as solving heat and stability problems. At a little over a nanometer in diameter, this single-walled nanotube makes lines drawn by state-of-the-art photolithography look huge in comparison.

nanotubes and other molecules. This kind of engineering on a molecular scale may eventually yield not only tiny versions of conventional devices but also new ones that exploit quantum effects.

We should emphasize, however, that so far our circuits have all been made one at a time and with great effort. The exact recipe for attaching a nanotube to metal electrodes varies among different research groups, but it requires combining traditional lithography for the electrodes and higher-resolution tools such as atomic force microscopes to locate and even position the nanotubes. This is obviously a long way from the massively parallel, complex and automated production of microchips from silicon on which the computer industry is built.


FIRST ELECTRONIC DEVICES to incorporate nanotubes include vacuum-tube lighting elements (*left*) and a full-color flat-panel display (*right*). Both products make use of nanotubes' ability to emit electrons at relatively low voltages without burning out, which translates into more efficient use of power and possibly greater durability.

ISE ELECTRONICS (*left*); SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY AND SAMSUNG SDI (*right*)

Before we can think about making more complex, nanotube-based circuitry, we must find ways to grow the nanotubes in specific locations, orientations, shapes and sizes. Scientists at Stanford University and elsewhere have demonstrated that by placing spots of nickel, iron or some other catalyst on a substrate, they can get nanotubes to grow where they want. A group at Harvard University has found a way to merge nanotubes with silicon nanowires, thus making connections to circuits fabricated by conventional means.

These are small steps, but already they raise the possibility of using carbon nanotubes as both the transistors and the interconnecting wires in microchip circuits. Such wires are currently about 250 nanometers in width and are made of metal. Engineers would like to make them much smaller, because then they could pack more devices into the same area. Two major problems have so far thwarted attempts to shrink metal wires further. First, there is as yet no good way to remove the heat produced by the devices, so packing them in more tightly will only lead to rapid overheating. Second, as metal wires get smaller, the gust of electrons moving through them becomes strong enough to bump the metal atoms around, and before long the wires fail like blown fuses.

In theory, nanotubes could solve both these problems. Scientists have predicted that carbon nanotubes would conduct heat nearly as well as diamond or sapphire, and preliminary experiments seem to confirm their prediction. So nanotubes could efficiently cool very dense arrays of devices. And because the bonds among carbon atoms are so much stronger than those in any metal, nanotubes can transport terrific amounts of electric current—the latest measurements show that a bundle of nanotubes one square centimeter in cross section could conduct about one billion amps. Such high currents would vaporize copper or gold.

Where Nanotubes Shine

Carbon nanotubes have a second interesting electronic behavior that engineers are now putting to use. In 1995 a research group at Rice University showed that when stood on end and electrified, carbon nanotubes will act just as lightning rods do, concentrating the electrical field at their tips. But whereas a lightning rod conducts an arc to the ground, a nanotube emits electrons from its tip at a prodigious rate. Because they are so sharp, the nanotubes emit electrons at lower voltages than electrodes made from most other materials, and their strong carbon bonds allow nanotubes to operate for longer periods without damage.

Field emission, as this behavior is called, has long been seen as a potential multibillion-dollar technology for replacing bulky, inefficient televisions and computer monitors with equally bright but thinner and more power-efficient flat-panel displays. But the idea has always stumbled over the delicacy of existing field emitters. The hope is that nanotubes may at last remove this impediment and clear the way for an alternative to cathode-ray tubes and liquid-crystal panels.

It is surprisingly easy to make a high-current field emitter from nanotubes: just mix them into a composite paste with plastics, smear them onto an electrode, and apply voltage. Invariably some of the nanotubes in the layer will point toward the opposite electrode and will emit electrons. Groups at the Georgia Institute of Technology, Stanford and elsewhere have already found ways to grow clusters of upright nanotubes in neat little grids. At optimum density, such clusters can emit more than one amp per square centimeter, which is more than sufficient to light up the phosphors on a screen and is even powerful enough to drive microwave relays and high-frequency switches in cellular base stations.

Indeed, two companies have announced that they are developing products that use carbon nanotubes as field emitters. Ise Electronics in Ise, Japan, has used nanotube composites to make prototype vacuum-tube lamps in six colors that are twice as bright as conventional lightbulbs, longer-lived and at least 10 times more energy-efficient. The first prototype has run for well over 10,000 hours and has yet to fail. Engineers at Samsung in Seoul spread nanotubes in a thin film over control electronics and then put phosphor-coated glass on top to make a prototype flat-panel display. When they demonstrated the display last year, they were optimistic that the company could have the device—which will be as bright as a cathode-ray tube but will consume one tenth as much power—ready for production by 2001.

The third realm in which carbon nanotubes show special electronic properties is that of the very small, where size-dependent effects become important. At small enough scales, our simple concepts of wires with resistance dramatically fail and must be replaced with quantum-mechanical models. This is a realm that silicon technology is unlikely to reach, one

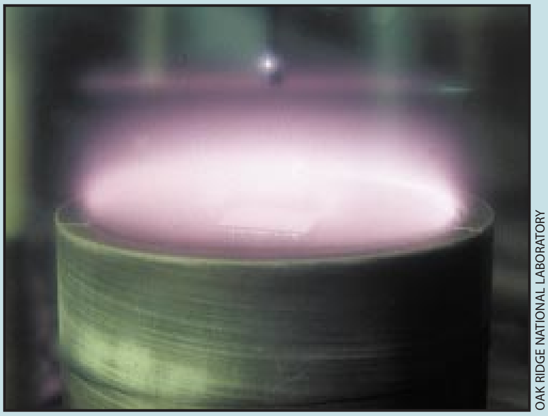
Three Ways to Make Nanotubes

Zap, Bake or Blast

Sumio Iijima may have been the first to see a nanotube, but he was undoubtedly not the first to make one. In fact, Neandertals may have made minuscule quantities of nanotubes, unwittingly, in the fires that warmed their caves. Split by heat, carbon atoms recombine however they can in soot, some in amorphous blobs but others in soccerball-shaped spheres called buckyballs or in long cylindrical capsules called buckytubes or nanotubes. Scientists have discovered three ways to make soot that contains a reasonably high yield of nanotubes. So far, however, the three methods suffer some serious limitations: all produce mixtures of nanotubes with a wide range of lengths, many defects and a variety of twists to them.

A BIG SPARK

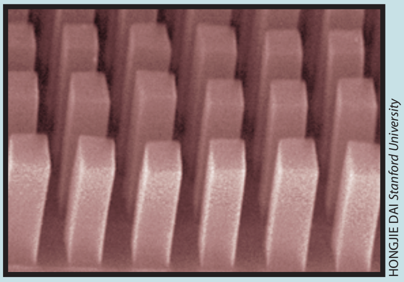
In 1992 Thomas Ebbesen and Pulickel M. Ajayan of the NEC Fundamental Research Laboratory in Tsukuba, Japan, published the first method for making macroscopic quantities of nanotubes. It is almost Frankensteinian in its design: wire two graphite rods to a power supply, place them millimeters apart and throw the switch. As 100 amps of juice spark between the rods, carbon vaporizes into a hot plasma (*right*). Some of it recondenses in the form of nanotubes.


OAK RIDGE NATIONAL LABORATORY

Typical yield: Up to 30 percent by weight
Advantages: High temperatures and metal catalysts added to the rods can produce both single-walled and multiwalled nanotubes with few or no structural defects.
Limitations: Tubes tend to be short (50 microns or less) and deposited in random sizes and directions.

A HOT GAS

Morinubo Endo of Shinshu University in Nagano, Japan, was the first to make nanotubes with this method, which is called chemical vapor deposition (CVD). This recipe is also fairly simple. Place a substrate in an oven, heat to 600 degrees Celsius and slowly add a carbon-bearing gas such as methane. As the gas decomposes, it frees up carbon atoms, which can recombine in the form of nanotubes.

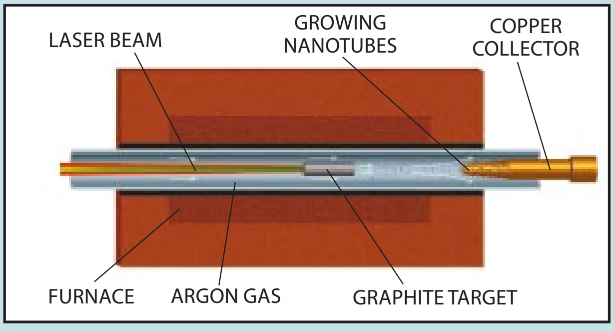

HONGJIE DAI *Stanford University*

Jie Liu and his colleagues at Duke University recently invented a porous catalyst that they claim can convert almost all the carbon in a feed gas to nanotubes. By printing patterns of catalyst particles on the substrate, Hongjie Dai and his colleagues at Stanford University have been able to control where the tubes form (*left*) and have been working to combine this controlled growth with standard silicon technology.

Typical yield: 20 to nearly 100 percent
Advantages: CVD is the easiest of the three methods to scale up to industrial production. It may be able to make nanotubes of great length, which is necessary for fibers to be used in composites.
Limitations: Nanotubes made this way are usually multiwalled and are often riddled with defects. As a result, the tubes have only one tenth the tensile strength of those made by arc discharge.

A LASER BLAST

Richard Smalley and his co-workers at Rice University were blasting metal with intense laser pulses to produce fancier metal molecules when the news broke about the discovery of nanotubes. They swapped the metal in their setup for graphite rods and soon produced carbon nanotubes by using laser pulses instead of electricity to generate the hot carbon gas from which nanotubes form (*left*). Trying various catalysts, the group hit on conditions that produce prodigious amounts of single-walled nanotubes.

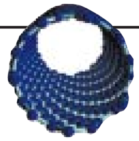


CLEO VILETT

Typical yield: Up to 70 percent
Advantages: Produces primarily single-walled nanotubes, with a diameter range that can be controlled by varying the reaction temperature.
Limitations: This method is by far the most costly, because it requires very expensive lasers. *—P.G.C. and P.A.*

that may yield surprising new discoveries but will also require significantly more scientific research than will either nanocircuits or nanotube field-emission devices.

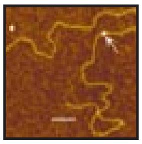
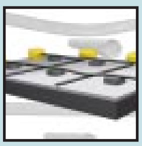
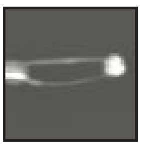
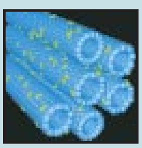
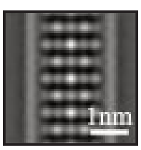
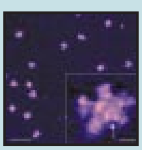
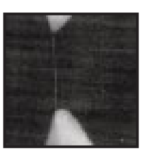
For example, researchers are currently debating exactly how electrons move along a nanotube. It appears that in defect-free nanotubes, electrons travel "ballistically"—that is, without any of the scattering that gives metal wires their resistance. When electrons can travel long distances without scattering, they maintain their quantum states, which is the key to observing effects such as the interference between electron waves. A lack of scattering may also help explain why nanotubes appear to preserve the "spin" state of electrons as they surf along. (Electron spin is a quantum property, not a rotation.) Some researchers are now trying to make use of



Other Uses for Nanotubes

Beyond Electronics

Feasibility Ratings
0 = Science Fiction
2 = Demonstrated
4 = Ready for Market

		THE IDEA	OBSTACLES	FEASIBILITY
	**Chemical and Genetic Probes** Tagged strand of DNA	A nanotube-tipped atomic force microscope can trace a strand of DNA and identify chemical markers that reveal which of several possible variants of a gene is present in the strand.	This is the only method yet invented for imaging the chemistry of a surface, but it is not yet used widely. So far it has been used only on relatively short pieces of DNA.	3
	**Mechanical Memory** Nonvolatile RAM	A screen of nanotubes laid on support blocks has been tested as a binary memory device, with voltages forcing some tubes to contact (the "on" state) and others to separate (the "off" state).	The switching speed of the device was not measured, but the speed limit for a mechanical memory is probably around one megahertz, which is much slower than conventional memory chips.	2
	**Nanotweezers** Pincers five microns long	Two nanotubes, attached to electrodes on a glass rod, can be opened and closed by changing voltage. Such tweezers have been used to pick up and move objects that are 500 nanometers in size.	Although the tweezers can pick up objects that are large compared with their width, nanotubes are so sticky that most objects can't be released. And there are simpler ways to move such tiny objects.	2
	**Supersensitive Sensors** Oxygen sticks to tubes	Semiconducting nanotubes change their electrical resistance dramatically when exposed to alkalis, halogens and other gases at room temperature, raising hopes for better chemical sensors.	Nanotubes are exquisitely sensitive to so many things (including oxygen and water) that they may not be able to distinguish one chemical or gas from another.	3
	**Hydrogen and Ion Storage** Atoms in hollow core	Nanotubes might store hydrogen in their hollow centers and release it gradually in efficient and inexpensive fuel cells. They can also hold lithium ions, which could lead to longer-lived batteries.	So far the best reports indicate 6.5 percent hydrogen uptake, which is not quite dense enough to make fuel cells economical. The work with lithium ions is still preliminary.	1
	**Sharper Scanning Microscope** Individual IgM antibodies	Attached to the tip of a scanning probe microscope, nanotubes can boost the instruments' lateral resolution by a factor of 10 or more, allowing clearer views of proteins and other large molecules.	Although commercially available, each tip is still made individually. The nanotube tips don't improve vertical resolution, but they do allow imaging deep pits in nanostructures that were previously hidden.	4
	**Superstrong Materials** Nanotube stress test	Embedded into a composite, nanotubes have enormous resilience and tensile strength and could be used to make cars that bounce in a wreck or buildings that sway rather than crack in an earthquake.	Nanotubes still cost 10 to 1,000 times more than the carbon fibers currently used in composites. And nanotubes are so smooth that they slip out of the matrix, allowing it to fracture easily.	0

Compiled by W. Wayt Gibbs, staff writer this unusual behavior to construct "spintronic" devices that switch on or off in response to electrons' spin, rather than merely to their charge, as electronic devices do.

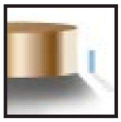
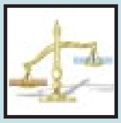
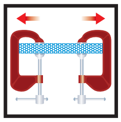
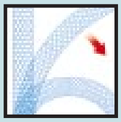
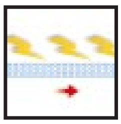
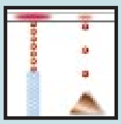
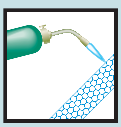
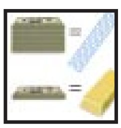
Similarly, at the small size of a nanotube, the flow of electrons can be controlled with almost perfect precision. Scientists have recently demonstrated in nanotubes a phenomenon called Coulomb blockade, in which electrons strongly repulse attempts to insert more than one electron at a time onto a nanotube. This phenomenon may make it easier to build single-electron transistors, the ultimate in sensitive electronics. The same measurements, however, also highlight unanswered questions in physics today. When confined to such skinny, one-dimensional wires, electrons behave so strangely that they hardly seem like electrons anymore.

Thus, in time, nanotubes may yield not only smaller and better versions of existing devices but also completely novel ones that wholly depend on quantum effects. Of course, we will have to learn much more about these properties of nanotubes before we can rely on them. Some problems are already evident. We know that all molecular devices, nanotubes included, are highly susceptible to the noise caused by electrical, thermal and chemical fluctuations. Our experiments have also shown that contaminants (oxygen, for example) attaching to a nanotube can affect its electrical properties. That may be useful for creating exquisitely sensitive chemical detectors, but it is an obstacle to making single-molecule circuits. It is a major challenge to control contamination when single molecules can make a difference.

Nevertheless, with so many avenues of development under way, it seems clear that it is no longer a question of whether nanotubes will become useful components of the electronic machines of the future but merely a question of how and when. SA

Properties of Carbon Nanotubes

Going to Extremes

	PROPERTY	SINGLE-WALLED NANOTUBES	BY COMPARISON
	Size	0.6 to 1.8 nanometer in diameter	Electron beam lithography can create lines 50 nm wide, a few nm thick
	Density	1.33 to 1.40 grams per cubic centimeter	Aluminum has a density of 2.7 g/cm^3
	Tensile Strength	45 billion pascals	High-strength steel alloys break at about 2 billion Pa
	Resilience	Can be bent at large angles and restraightened without damage	Metals and carbon fibers fracture at grain boundaries
	Current Carrying Capacity	Estimated at 1 billion amps per square centimeter	Copper wires burn out at about 1 million A/cm^2
	Field Emission	Can activate phosphors at 1 to 3 volts if electrodes are spaced 1 micron apart	Molybdenum tips require fields of 50 to 100 V/µm and have very limited lifetimes
	Heat Transmission	Predicted to be as high as 6,000 watts per meter per kelvin at room temperature	Nearly pure diamond transmits 3,320 W/m·K
	Temperature Stability	Stable up to 2,800 degrees Celsius in vacuum, 750 degrees C in air	Metal wires in microchips melt at 600 to 1,000 degrees C
	Cost	$1,500 per gram from BuckyUSA in Houston	Gold was selling for about $10/g in October

LAURIE GRACE

The Authors

PHILIP G. COLLINS and PHAEDON AVOURIS are scientists at the IBM Thomas J. Watson Research Center, where they are investigating the electrical properties of various types of nanotubes. Collins holds degrees in physics and electrical engineering from the Massachusetts Institute of Technology and the University of California, Berkeley. Besides working as a physicist, he has spent two years as a high school teacher and is a professional whitewater-rafting guide. Avouris, who manages the nanoscience and nanotechnology group for IBM Research, was awarded the Feynman Prize for Molecular Nanotechnology. He is also an avid tropical ornithologist.

Further Information

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Carbon Nanotubes. Special section in *Physics World,* Vol. 13, No. 6, pages 29–53; June 2000.

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The Secrets

by J. Mayo Greenberg

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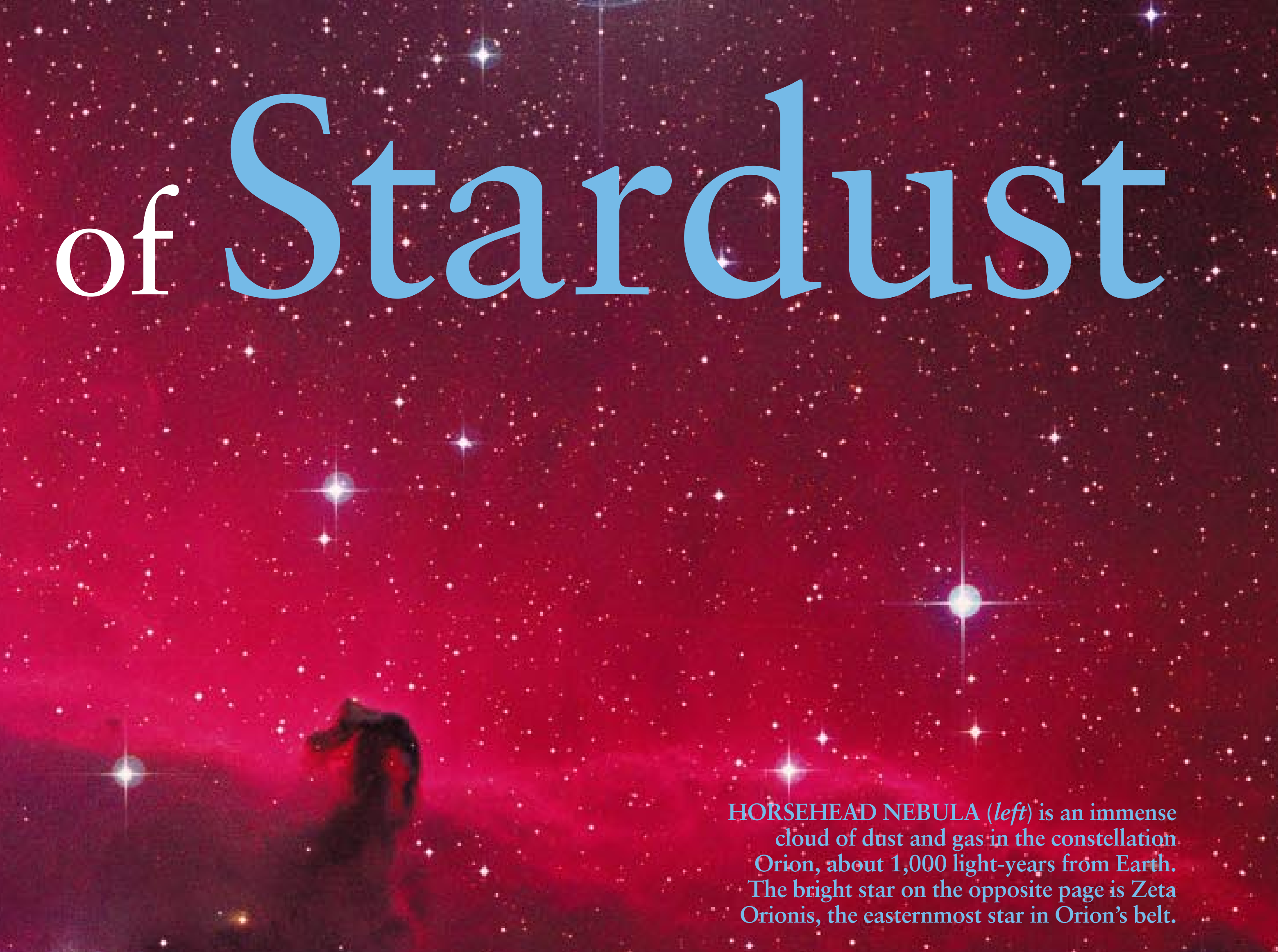
Tiny grains of dust floating in interstellar space have radically altered the history of our galaxy

# of Stardust



HORSEHEAD NEBULA (*left*) is an immense cloud of dust and gas in the constellation Orion, about 1,000 light-years from Earth. The bright star on the opposite page is Zeta Orionis, the easternmost star in Orion's belt.

Look up at the sky on any clear night, and you will see dark patches in the Milky Way, the fuzzy band of light generated by the billions of stars in our galaxy. Sir William Herschel, the 18th-century English astronomer, thought the patches were literally "holes in the sky," empty spaces in the heavens. In the early 20th century, astronomers discovered that the dark patches are actually tremendous clouds of dust that obscure the light of the stars behind them. The individual particles of cosmic dust are minute: less than one hundredth the size of the particles that you sweep up with a dust mop. And yet these tiny dust grains have greatly influenced the evolution of our galaxy and the formation of stars throughout the universe.

Until the 1950s, many astronomers considered the dust a nuisance because it kept them from seeing distant stars. In recent years, however, researchers have focused on the interstellar dust grains, measuring their distribution and chemical composition using ground- and space-based telescopes. The wealth of new data has made it possible to develop a plausible hypothesis of how this stardust has evolved. Aigen Li, my former student and now a postdoc at Princeton University, and I have devised a theory that we call the unified dust model. Although other researchers have advocated alternative theories, we believe our model provides the best explanation of the new observations.

In the Milky Way, dust clouds are concentrated in the galactic plane, particularly along the inner edges of the galaxy's spiral arms. These areas appear extremely patchy, with dense clusters of stars interspersed among the dust clouds. The clouds reduce the intensity of starlight more strongly in the blue and ultraviolet parts of the spectrum than in the red and infrared parts. Therefore, when astronomers see stars through the dust, they always appear redder than they really are. Similarly, our sun looks redder near the horizon because dust and gas in the Earth's atmosphere scatter its light.

It turns out that the largest interstellar dust motes are about the same size as the particles in cigarette smoke. The extinction curve for interstellar dust, which portrays the reduction of light intensity at each wavelength, shows that there must be three kinds of dust grains [*see illustration on opposite page*]. The particles that block light in the visible spectrum are elongated grains nearly 0.2 micron (two ten-millionths of a meter) wide and about twice as long. They account for about 80 percent of the total mass of interstellar dust. Each grain contains a rocky core surrounded by a mantle of organic materials and ice. A "hump" in the ultraviolet part of the extinction curve indicates the presence of smaller particles (with a diameter of about 0.005 micron), which make up about 10 percent of the total dust mass. These grains are most likely amorphous carbonaceous solids that probably contain some hydrogen but little or no nitrogen or oxygen. And an even smaller kind of particle, only about 0.002 micron across, is responsible for blocking light in the far ultraviolet region. These specks, which constitute the remaining 10 percent of the dust mass, are believed to be large molecules similar to the polycyclic aromatic hydrocarbons (PAHs) emitted in automobile exhaust.

Because the dust grains are usually far from stars, they are extremely cold, reaching temperatures as low as –268 degrees Celsius, or just five degrees above absolute zero. In the 1940s the brilliant Dutch astronomer Henk van de Hulst (my dear friend and mentor) theorized that some of the atoms known to exist in interstellar space—hydrogen, oxygen, carbon and nitrogen—would adhere to the cold surfaces of the dust grains and form mantles of frozen water, methane and ammonia. I later dubbed this theory the "dirty ice" model.

It was not until the early 1970s, however, that astronomers found strong evidence for the theory. While studying the infrared spectra of starlight passing through interstellar dust clouds, researchers detected the distinctive absorption lines of silicates—compounds of silicon, magnesium and iron. Silicates make up the rocky cores of the dust grains. At about the same time, scientists also observed the absorption line of frozen water in the infrared spectra. Later observations indicated the presence of carbon monoxide, carbon dioxide, formaldehyde and many other compounds as well. These substances are classified as volatiles—they freeze on contact with the cold dust grains but evaporate if the dust is warmed up. In contrast, the substances in the cores of the dust grains are called refractories—they remain solid at higher temperatures.

Interstellar dust constitutes about one thousandth of the Milky Way's mass—an amount probably hundreds of times more than the total mass of all the galaxy's planets. The particles are sparsely distributed: on average, you will find only one dust grain in every million cubic meters of space. But as starlight travels through thousands of light-years of dust, even this wispy distribution can effectively dim the radiation. So the question arises: How did our galaxy get so dusty?

From Dust to Dust

In the first era of the universe, some 15 billion years ago, there was no dust. Like all the other early galaxies, the Milky Way consisted solely of hydrogen, helium and a smattering of other light elements created in the big bang. During this period, only extremely massive clouds of hydrogen and helium could contract into stars, because a truly enormous amount of gravitational attraction was needed to overcome the pressure caused by the gases' thermodynamic motion. Thus, our galaxy was dominated by gigantic O- and B-type stars, which exploded in supernovae only a few million years after their birth. The first dust was produced by these supernovae; astronomers see evidence of it in the early galaxies observed by far-infrared telescopes that view submillimeter wavelengths. But this dust did not last long in the interstellar medium—the shock waves from subsequent supernovae destroyed the particles soon after they were created.

After about five billion years, though, the storm of supernovae subsided and the stars that were not quite so massive entered the red-giant phase of their lifetimes. As these stars cooled and expanded, rocky silicate particles formed in the stars' atmospheres and were blown into interstellar space. Some of these silicate particles entered the clouds of molecular gas that were constantly moving among the stars. In the low temperatures inside the clouds, every atom or molecule that encountered a silicate grain immediately froze on its surface, just as drops of water vapor freeze on a cold windowpane. In this way, an icy mantle grew on each of the silicate cores.

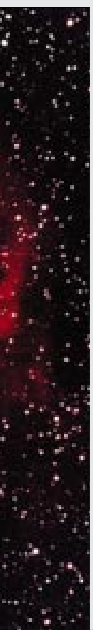
As dust concentrated in the molecular clouds, the density of the grains rose tens of thousands of times higher than the density outside the clouds. The dust became thick enough to block nearly all radiation from entering the clouds, lowering the temperature of the gas still further. Because the clouds were cooler than before, not as much mass was needed to overcome the gas pressure. Smaller gas clouds, then, could contract, and smaller stars such as our own sun could be born. By easing the constraints on star formation, the presence of dust radically changed the makeup of the Milky Way.

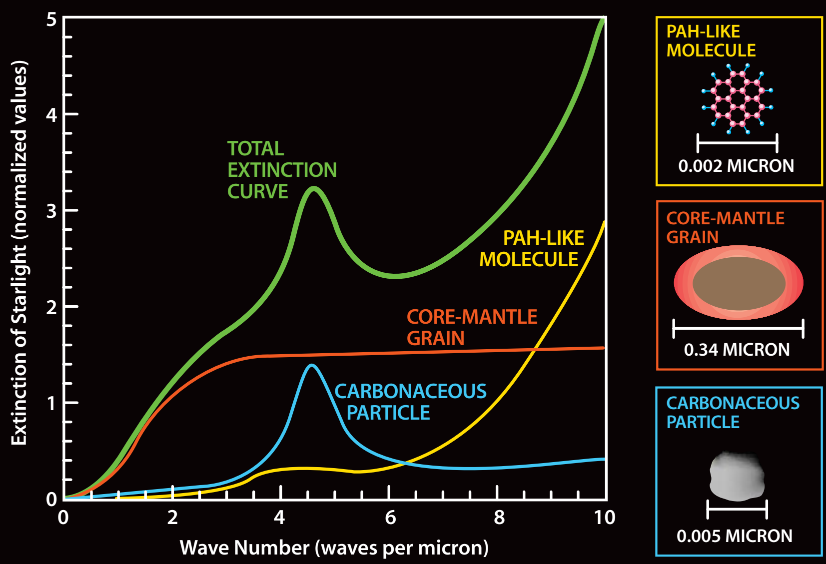
What is more, our galaxy's dust is continually recycled. When a dense cloud of gas and dust contracts to form a star, the dust grains closest to the star-forming region evaporate. (The silicon and other elements from these dust grains either become part of the star or later condense to form rocky planets

OUR DUSTY GALAXY

Dust clouds such as those in the Rosette Nebula (*below*) are stellar nurseries. The dust grains block radiation within the gaseous clouds, making it easier for them to collapse and form stars. In the process,

most of the dust is blown away to emptier regions of space. Measurements of the extinction of starlight passing through these sparse regions (*below*) indicate the presence of three types of dust particles: core-mantle grains, amorphous carbonaceous solids, and large molecules similar to polycyclic aromatic hydrocarbons (PAHs). The core-mantle grains can also account for the starlight polarization at all wavelengths.





© ANGLO-AUSTRALIAN OBSERVATORY/ROYAL OBSERVATORY, EDINBURGH (*photograph*); CLEO VILETT (*graph*)

and asteroids.) But the great majority of the dust is blown away into diffuse clouds—regions of space where the gas is much less dense. In this harsher environment, the ice mantles on the dust grains not only cease to grow but are destroyed or eroded away by ultraviolet radiation, particle collisions and supernova shock fronts. The grains are not reduced to their silicate cores, however. Underneath the outer mantle of ice is an inner mantle consisting of complex organic materials.

Three decades ago I proposed the existence of this organic mantle because I determined that silicates alone could not account for the amount of light extinction caused by the dust in diffuse clouds. I hypothesized that the layer of carbon-rich material on the dust grain is produced by chemical reactions in the ice mantle that begin when the grain is still in the dense cloud of molecular gas. According to my theory, when energetic ultraviolet photons strike the ice mantle, they break the water, methane and ammonia molecules into free radicals, which then recombine to form organic molecules such as formaldehyde. Continued ultraviolet irradiation eventually gives rise to more complex compounds called first-generation organics. They remain as a residue on the silicate core even after the dust grain leaves the molecular cloud and the ice mantle is destroyed. In fact, the organic mantle helps to shield the silicate core from supernova shocks, preserving the dust grain until it returns to the shelter of another dense gas cloud.

Yellow and Brown Stuff

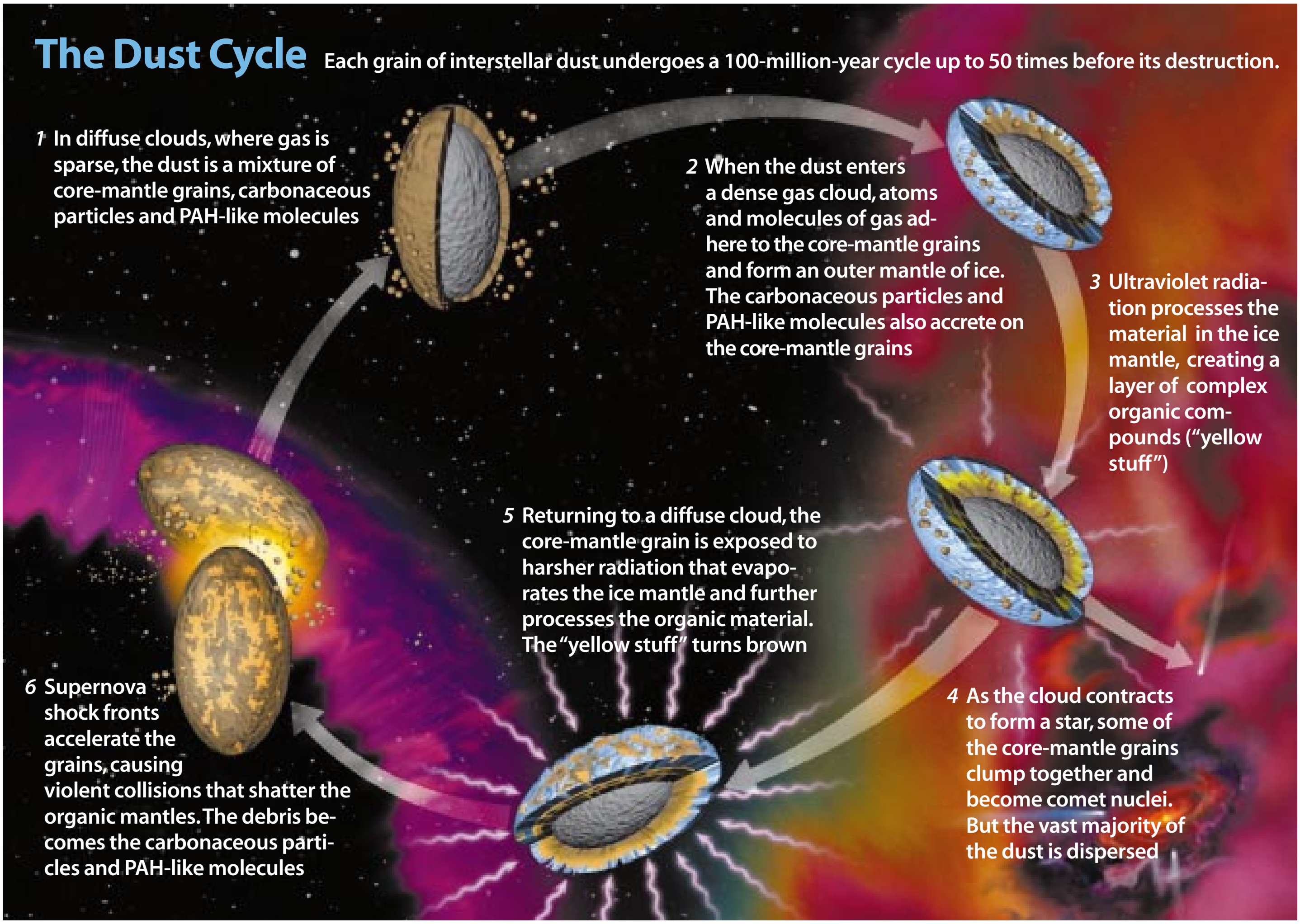
To test this theory, I began laboratory experiments that simulated the conditions affecting the ice mantles. The work started at the State University of New York at Albany in 1970 and continued at the University of Leiden in the Netherlands in 1975. Our research group subjected various ice mixtures to ultraviolet radiation at a temperature of –263 degrees C, then warmed the mixtures. The result was a yellow-colored residue that we called, appropriately enough, "yellow stuff." The residue contained glycerol, glyceramide, several amino acids (including glycine, serine and alanine), and a host of other complex molecules.

At about the same time, astronomers had detected evidence of complex organic compounds in the dust of diffuse clouds by measuring the absorption of starlight passing through them. Our lab results did not precisely duplicate the absorption lines in the infrared spectra, but we should not have been surprised by this discrepancy. In the exposed environment of diffuse clouds the dust grains are subjected to ultraviolet radiation 10,000 times more intense than that in molecular clouds. This radiation transforms the material in the inner mantles to second-generation organics. The extra amount of ultraviolet processing was difficult to reproduce in the laboratory.

Fortunately, opportunity knocked at the lab door. In the late 1980s Gerda Horneck of DLR, Germany's space agency, invited us to use a satellite platform called the Exobiology Radiation Assembly, which was originally designed for exposing biological specimens to long-term ultraviolet radiation. It was also ideally suited for the ultraviolet processing of our "yellow stuff." Our research group, which included Menno de Groot, Celia Mendoza-Gómez, Willem Schutte and Peter Weber, prepared the organic residues and sent them into orbit in the European Retrievable Carrier (EURECA) satellite, which was launched by the space shuttle in 1992.

After a year (but only four months of actual exposure to solar ultraviolet radiation), the shuttle retrieved the satellite, and the samples were returned to us. What went up yellow came back brown. The color change indicated that the material had become richer in carbon. When we studied the "brown stuff" with an infrared spectrometer, we found the exact same pattern of absorption lines that had been detected in the infrared observations of interstellar dust. Even though the radiation exposure for the sample was only about one tenth the maximum exposure for a dust grain in a diffuse cloud, our sample closely approximated the organic refractory materials in cosmic dust.

These experiments laid the groundwork for the unified dust model that Aigen Li and I constructed. The theory postulates that the two smaller types of interstellar dust grains—the amorphous carbonaceous particles and the molecules similar to PAHs—arise from the ultraviolet processing of the organic materials in the larger core-mantle dust grains. We brought our sample of "brown stuff" to Seb Gillette of Stanford University for



analysis using the sophisticated mass spectrometry techniques developed by Stanford chemist Richard Zare. Gillette found that the sample was extremely rich in PAHs. The unified dust model suggests that the chemical processing in the core-mantle grains can account for nearly all the small carbonaceous particles and PAH-like molecules in interstellar dust. In the diffuse gas clouds the small particles break off from the organic mantles when supernova shocks shatter the larger dust grains [*see illustration above*]. Each core-mantle particle generates a swarm of hundreds of thousands of the minuscule grains.

Eventually the entire ensemble of dust is captured by a dense molecular cloud. Inside the cloud, collisions between the dust particles and the atoms and molecules of gas become more frequent. After a million years or so, the larger dust grains accrete an ice mantle dominated by frozen water and carbon monoxide. Observations of the dust in very dense clouds around stars have indicated the presence of these compounds, along with smaller amounts of carbon dioxide, formaldehyde and ammonia. Although no one has directly observed what happens to the carbonaceous particles and PAH-like molecules in a molecular cloud, it is inevitable that they will also accrete on the larger dust grains and be taken up in the ice mantles. The organic molecules are then reprocessed by ultraviolet radiation, and the cycle begins anew.

Other scientists have proposed alternative models that can explain the extinction effects of interstellar dust without the need for organic mantles on the larger dust grains. For example, John S. Mathis of the University of Wisconsin–Madison has hypothesized that the larger grains are porous aggregates of small graphite and silicate particles. But these models cannot adequately explain another effect of interstellar dust: how it polarizes the light passing through it, orienting the electromagnetic waves in a particular direction. To account for this phenomenon, we know that each of the larger dust grains must be shaped roughly like a cylinder or a spheroid and spin around its shorter axis like a twirling baton. Furthermore, we know that the spin axes of all the dust grains must be pointing in the same direction to polarize the light. (Magnetic fields in the dust cloud are believed to align the spin axes.) The unique achievement of the unified dust model is that the hypothesized core-mantle particles can account for the observed polarization at all wavelengths.

From Dust to Comets

Comets are believed to be the most pristine relics of the protosolar nebula—the cloud of gas and dust that gave birth to our own solar system. As astronomers make new discoveries about the chemical composition of both comets and interstellar dust, they are becoming convinced that comets originally formed as clumps of dust grains. It therefore stands to reason that comet observations will tell us more about the dust.

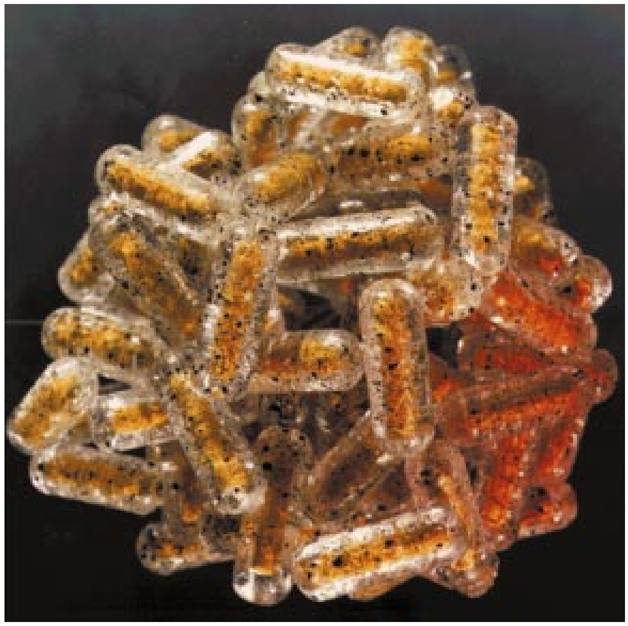
When the planets and comets were born along with the sun about 4.6 billion years ago, the core-mantle dust grains in the protosolar cloud had most likely absorbed all the smaller carbonaceous particles and PAH-like molecules, as well as all the carbon monoxide and other volatiles in the gas. Only the hydrogen and helium remained free. The dust grains collided with one another frequently enough to form large, loosely clumped aggregates. The prevailing theory is that these "fluffy" clusters of interstellar dust particles evolved into the nuclei of the comets. Each nucleus would be very porous—that is, it would contain a lot of empty space. My own model of a piece of a comet nucleus contains 100 average-size protosolar dust grains jumbled together in a three-micron-wide aggregate, in which 80 percent of the volume is empty space [*see illustration at right*].

Since their birth, the comets have been orbiting the sun in the regions of the Oort Cloud and the Kuiper Belt at distances far beyond the orbits of the planets. Occasionally, though, gravitational disturbances kick comets into orbits that take them closer to the sun. A revolution in our understanding of comets occurred in 1986, when the space probes Giotto and Vega 1 and 2 flew by Comet Halley, which approaches the sun every 76 years. All three spacecraft carried spectrometers for measuring the mass and chemical composition of the particles from Halley's coma, the cloud of gas and dust surrounding the nucleus. The dust particles hit the detectors at 80 kilometers per second and broke up into their atomic components. The instruments detected a wide range of particle masses, including the 10^{-14} gram expected for individual core-mantle dust grains and the 10^{-18} gram typical of smaller carbonaceous particles.

Jochen Kissel of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, Franz R. Krueger of the Krueger Inigenieurburo in Darmstadt and Elmar K. Jessburger of the University of Münster later confirmed that the dust from Halley consists of aggregates of particles with silicate cores and organic refractory mantles—just as my origin theory for comets predicts. Their conclusion was based on the fact that the oxygen, carbon and nitrogen atoms from the organic mantles hit the spacecraft's detectors just before the silicon, magnesium and iron atoms from the cores did.

How old is the dust contained in Halley and the other comets? We know that when the dust clumped together to form the comets it was already about five billion years old, because a typical dust grain remains in interstellar space for about that long before it is consumed in star formation. And because the comets are themselves 4.6 billion years old, the dust probably dates back to nearly 10 billion years ago. Analyzing comet material therefore allows us to probe the infancy of the Milky Way.

Comet dust may also have played a role in seeding life on Earth. Each loose cluster of comet dust not only contains organic materials but also has a structure that is ideal for chemical evolution once it is immersed in water. Kissel and Krueger have shown that small molecules could easily penetrate the clump from the outside, but large molecules would remain stuck inside. Such a structure could stimulate the production of ever larger and more complex molecules, possibly serving as a tiny incubator for the first primitive life-forms. A single comet could have deposited up to 10^{25} of these "seeds" on the young Earth.


LOEK ZUIDERDUIN

MODEL OF COMET DUST constructed by the author shows 100 core-mantle grains in a loose, three-micron-wide cluster. Rich in organic compounds, these clumps could have seeded life on Earth.

The National Aeronautics and Space Administration and the European Space Agency (ESA) are undertaking missions that will reveal more about the nature of comets and interstellar dust. NASA's Stardust craft, launched last year, is scheduled to rendezvous with Comet Wild-2 in 2004 and bring back a sample of the dust from that comet's coma. While in transit, the probe is also collecting samples of the interstellar dust streaming through our solar system. The ESA's Rosetta mission is even more ambitious. Scheduled for launch in 2003, the craft will go into orbit around the nucleus of Comet Wirtanen and send a probe to land on the surface of the porous body. An array of scientific instruments on the lander will thoroughly analyze the comet's physical structure and chemical composition. My research group will participate in the effort by preparing laboratory samples of organic materials for comparison with those observed in Wirtanen's nucleus and dust.

These space missions will no doubt open new paths for research. Astronomers no longer consider interstellar dust a nuisance. Rather it is a major source of information about the birth of stars, planets and comets, and it may even hold clues to the origin of life itself. SA

The Author

J. MAYO GREENBERG received his Ph.D. in theoretical physics from Johns Hopkins University in 1948. In 1975 he came to the University of Leiden in the Netherlands to establish and direct its Laboratory for Astrophysics, where he has studied the chemical evolution of interstellar dust, the composition of comets and the origin of life.

Further Information

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Piecing Together Alzheimer's

The stunningly complex biochemical puzzle that underlies this crippling disease remains incomplete, but parts that seemed unrelated just a decade ago are now fitting into place

by Peter H. St George-Hyslop

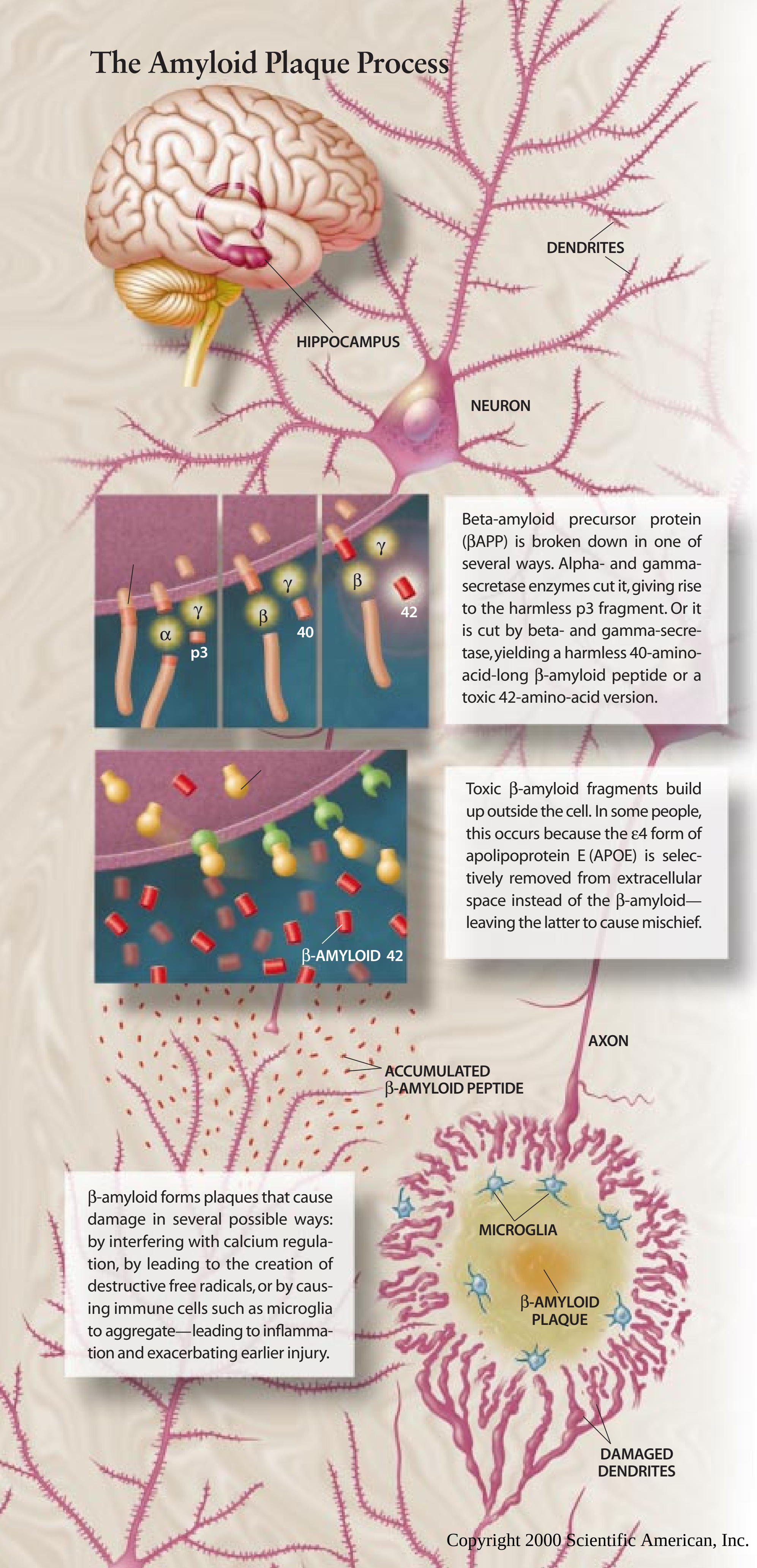
Many families suffer the anguish of caring for an intellectually incapacitated parent or grandparent who, just a few years earlier, was an active, vibrant member of the family—one involved with grandchildren, hobbies and life in general. The problem typically starts with seemingly innocent absent-mindedness, with questions repeated two or three times. The person then begins to have trouble following complex discussions or loses the ability to pursue challenging pastimes. Initially the family attributes these minor problems to age or fatigue. But the grandparent becomes increasingly forgetful—less able to find the way home from the corner store or even to recognize the faces of loved ones. Ultimately this once independent individual needs help with every aspect of daily living, from bathing and dressing to eating and walking outside.

This general description portrays several illnesses, called dementias, in which parts of the brain stop working, causing disruptions in memory, judgment, reasoning and emotional stability. Dementias are nothing new: eloquent accounts of them can be found in ancient Greek and medieval literature. Most dementias occur more frequently as people age. As a result, in societies where life expectancy has been considerably extended, these diseases are becoming a major public health concern. Approximately 15 percent of people who live to the age of 65 will develop some form of dementia; by age 85, that proportion increases to at least 35 percent.

Of all the dementias, Alzheimer's disease is the most common. Four million Americans currently suffer from the condition, and experts estimate that 22 million people around the world will be so afflicted by 2025. Until recently, researchers had almost no understanding of the disorder's causes, and it still lacks preventive or cura-

DEVASTATION wrought by Alzheimer's disease affects millions of people and their families. It is one of several neurodegenerative dementias that, tragically, are increasing in incidence as the world's population ages.

ED KASHI



tive therapies. But findings from epidemiology, genetics, molecular and cell biology, and other disciplines are now fitting together, permitting researchers to identify some of the mechanisms that underlie it.

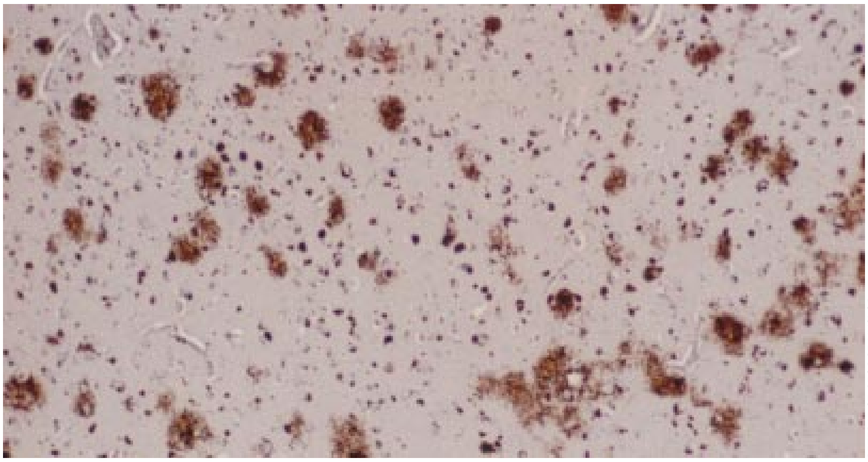
It appears that Alzheimer's arises because the normal processing of certain proteins goes terribly wrong, littering brain cells and the space between them with pieces of toxic protein. Intriguingly, it is becoming apparent that many other neurodegenerative disorders—among them frontotemporal dementia, Parkinson's disease and Creutzfeldt-Jakob disease—are also characterized by protein processing gone haywire. These insights are suggesting tantalizing new ways of treating Alzheimer's and other dementias, possibly including vaccines that could direct the body to rid itself of some of these toxic protein fragments.

Reading the Brain

The foundation of today's understanding of Alzheimer's was built by researchers who directly examined patients' brains. Microscopic views have revealed a loss of nerve cells in certain regions of the brain, such as the hippocampus, a center for memory, and the cerebral cortex, which is involved in reasoning, memory, language and other important thought processes. Since the 1970s researchers have known that some of these dying neurons are cholinergic—that is, they communicate using the neurotransmitter acetylcholine, which is ultimately broken down by an enzyme called acetylcholinesterase. Drugs that became available in the past decade, such as tacrine and donepezil, prevent acetylcholinesterase from doing its job. By conserving acetylcholine, these compounds slow the development of impairments in people experiencing the early stages of Alzheimer's. Sadly, once cholinergic neurons degenerate fully and can no longer produce the neurotransmitter, the drugs become useless.

The other directly observable hallmarks of Alzheimer's disease are clusters of proteins in the brain. These accumulations occur in two forms: those found inside nerve cells and those found between cells. The clusters in the interior are called neurofibrillary tangles, and they resemble pairs of threads wound around each other in a helix. Analyses performed in the 1980s at several laboratories made it clear that these tangles

JOHN W. KARAPELOU



PETER H. ST GEORGE-HYSLOP

BETA-AMYLOID PLAQUES are one of the first hallmarks of Alzheimer's disease to appear, although they are not correlated to the severity of dementia that a patient experiences. This light microscope picture—from the cortex of a person who suffered from the disease—shows the plaques as dense dark patches. The creation of the toxic fragments of β-amyloid peptide that make up these plaques begins with the misprocessing of the β-amyloid precursor protein and culminates in damage to the nerve cell that occurs in several possible ways (*opposite page*).

consist of a protein called tau. Tau is significant because it binds to a protein named tubulin, which in turn forms structures known as microtubules. Microtubules are crucially important. Like the girders and pillars of buildings, they run through cells, imparting support and shape. Microtubules also provide routes along which nutrients, other molecules and cellular components such as vesicles and mitochondria move through cells.

Tangles of tau, however, are not unique to Alzheimer's disease. For that reason, even though the high density of neurofibrillary tangles in Alzheimer's patients is distinctive and strongly correlates with the severity of dementia, many investigators have not considered disruptions of tau to be as important as the second kind of protein deposits observed in Alzheimer's: amyloid plaques. (Tau has recently gained prominence, but I will come to that story later.)

Unlike neurofibrillary tangles, deposits of amyloid protein gather in the spaces between nerve cells. The nearby neurons often look swollen and deformed, and the clusters of protein—sometimes called senile or amyloid plaques—are usually accompanied by reactive inflammatory cells called microglia, which are part of the brain's immune system and might be trying to degrade and remove damaged neurons or perhaps the plaques themselves. It is unclear whether the neurons in or near these plaques function normally, because the density of plaques is only weakly correlated with the severity of dementia. Further, such plaques are present in most elderly people. Nevertheless, their extensive presence in the hippocampus and the cerebral cortex is specific to Alzheimer's patients, and they appear long before neurofibrillary tangles do.

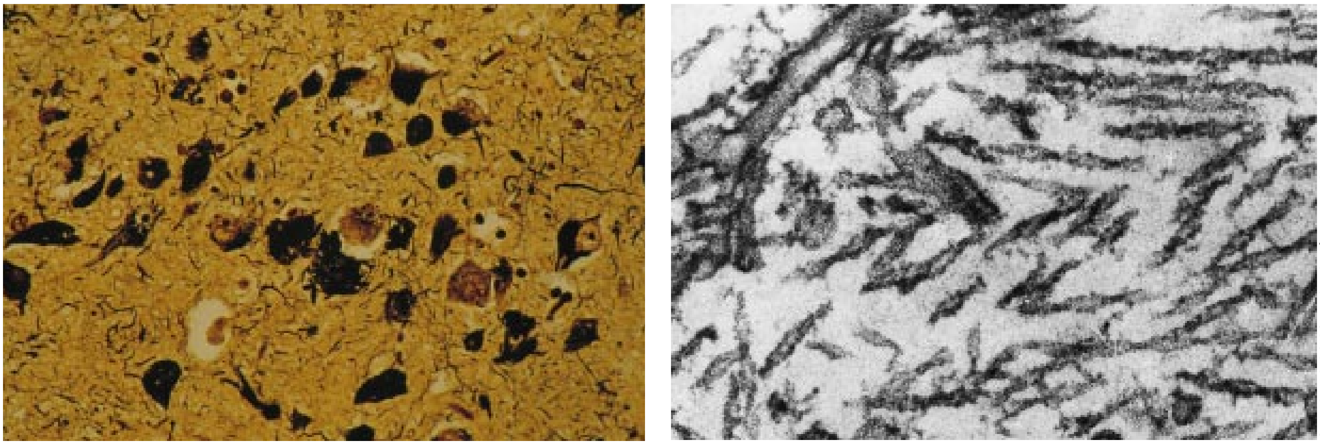
Because of the high density of plaques and their early presence in the disease, researchers have long thought that understanding their biochemistry could yield clues about the cause of Alzheimer's. Intensive efforts to isolate the ingredients of these plaques culminated in 1984 with the discovery by George G. Glenner of the University of California at San Diego that a principal component was a peptide—that is, a very short protein fragment—made up of either 40 or 42 amino acids (the building blocks of proteins). This identification of what is now termed the beta-amyloid peptide was quickly followed by the sequencing of the gene for the longer protein from which this peptide originates: the β-amyloid precursor protein, or βAPP. These biochemical discoveries dovetailed nicely with information simultaneously coming out of another area of research: genetics.

Ever since German neurologist Alois Alzheimer identified Alzheimer's disease in 1907, epidemiologists have sought to understand its patterns. They have tried to determine, for instance, whether it runs in families, and is therefore influenced strongly by the genes, or is set in motion by something in the environment. In the 1980s research began to show that certain families are at increased risk for developing this dementia. Investigators found families in which the disease is transmitted from one generation to the next—to half the children (both male and female) of the affected patients. This pattern indicated that in some families vulnerability arises from the inheritance of a defective gene on an autosomal—or nonsex—chromosome, and it suggested that the mutant gene inherited from the affected parent is dominant over the normal gene inherited from the unaffected parent.

Epidemiologists also tracked the occurrence of Alzheimer's in people who were not from such families, establishing that genetics is not the sole cause of the affliction in the general population. The disease clearly has diverse and complex triggers—inheritance most likely plays some role in a significant proportion of cases (estimates vary from 1 to 40 percent). Yet attempts to identify environmental catalysts, which might act alone or in conjunction with heredity, have not been conclusive. The few risk factors identified so far are intriguing but not entirely illuminating. It appears that poor early-childhood education, serious head injury and—albeit much less definitively—exposure to aluminum in drinking water correlate with higher risk. Correlation, however, does not mean causality, and it may turn out that these factors are actually indicators of other agents or events. For instance, head injury might simply reduce the number of neurons, thereby causing the symptoms of Alzheimer's to appear earlier than they otherwise would have.

The few risk factors identified so far are intriguing but not entirely illuminating.

Nevertheless, the recognition of genetic components opened an exciting avenue of research, because any findings in that realm would have relevance for all cases of Alzheimer's. The clinical, neuropathological and biochemical abnormalities are identical in every kind of Alzheimer's—whether genetically determined or sporadic, as the other forms



CATHERINE BERGERON *University of Toronto* AND ROBERT D. TERRY *University of California at San Diego*

TAU TANGLES appear late in the disease and seem to correlate very strongly with the severity of dementia. These neurofibrillary tangles appear as black triangles in the light microscope image at the left and as paired helical filaments in the electron microscope picture at the right. The tau tangles disrupt the microtubule structures in the nerve cell, pushing them to one side and thereby impairing the transport of nutrients as well as the transmission of neuronal messages (*opposite page*).

are called. Sure enough, when combined with the discovery of the composition of the plaques and the tangles, the genetic insights led to some seminal experiments. The isolation of the β-amyloid peptide and the isolation of the gene for βAPP were quickly followed by the discovery that the βAPP gene was located on chromosome 21. At about the same time, studies indicated that chromosome 21 might carry a defect in some families with Alzheimer's. It was known from other work that people with Down syndrome (who have three rather than two copies of chromosome 21) almost invariably display at least some features of Alzheimer's by the age of 40.

These observations suggested that the β-amyloid precursor protein gene might be the site of mutations causing some cases of Alzheimer's. This prediction was rapidly borne out in the early 1990s, when researchers—including Blas Frangione and Efrat Levy of New York Medical Center, Alison M. Goate of Washington University School of Medicine, Michael Mullan of the University of Southern Florida, Lydia Hendriks and Christine Van Broeckhoven at the University of Antwerp, and Harry Karlinsky and my colleagues of the University of Toronto—identified such mutations in individuals with familial Alzheimer's. (Because genes contain the instructions for the synthesis of proteins, a mutation in a gene can mean that the protein it specifies will turn out different than it should. This difference can lead to problems—just as substituting the wrong cog in an engine can.) It suddenly became clear that abnormal processing or activity of βAPP caused the disease. This novel idea spurred efforts to determine how the long protein was transformed into the β-amyloid peptide in the first place.

Although the precise biological role of normal βAPP molecules remains obscure, scientists now know that many kinds of cells and tissues produce βAPP and that it can be between 695 and 770 amino acids long. The protein runs through the outer cell membrane, with a short piece jutting into the cell and a longer piece sticking into the extracellular space. The β-amyloid peptide, for its part, is snipped out of the section of βAPP that spans the cell membrane. Work in a number of laboratories revealed that in the course of its life βAPP is cut in one of two ways. In one process, the protein is first cleaved by an enzyme called alpha-secretase. (Alzheimer's researchers commonly refer to this enzyme as a "putative" one, because we assume it exists—and have good evidence that it does—but we have not yet isolated it.) It is then cut by another putative enzyme, gamma-secretase. Together these cuts produce a harmless peptide fragment called p3.

The Unkindest Cut

The second way in which βAPP is cleaved is another two-step process, one that is not always so harmless. First, an enzyme called beta-secretase—which has been isolated by Martin Citron and his colleagues at Amgen—clips the protein. One of the resulting pieces, called C99-βAPP fragment (because it is 99 amino acids long), is then snipped by gamma-secretase, and the β-amyloid peptide is born.

Under normal conditions, most of these β-amyloid strings contain 40 amino acids. But a small number of them, fewer than 10 percent, have two extra amino acids. Peter T. Lansbury and Bruce Yankner of Harvard, as well as Paul E. Fraser and Joanne McLaurin of the University of Toronto, among others, have shown that this slightly longer form is the one that gives rise to plaques and that it has a direct toxic effect on neurons.

Studies are under way to identify exactly how the 42-amino-acid version damages nerve cells, but preliminary work suggests it acts in several ways. First, the peptide seems to disrupt calcium regulation, which can lead to cell death. Second, it may damage mitochondria, causing the release of free oxygen radicals, which then damage proteins, lipids and DNA. Finally—as noted earlier—there is evidence that the 42-amino-acid peptide and the injury it causes may bring about the release of cellular compounds. Those, in turn, may attract immune cells, engendering an inflammatory response, which could exacerbate any other injuries initiated by the peptide, creating a vicious cycle of escalating damage. Although these possible mechanisms are intriguing, their relative importance in the development of dementia remains, for now at least, a matter of disagreement.

As molecular biologists were unraveling the activities of βAPP and the β-amyloid peptide fragment, geneticists continued to home in on the mutations in the βAPP gene. They identified several that caused substitutions of amino acids at the very places along the βAPP strand where the alpha-, beta- and gamma-secretase enzymes do their cutting. Not unexpectedly, these mutations either augment the amount of both forms of β-amyloid produced or increase the production of the toxic, lengthier version.

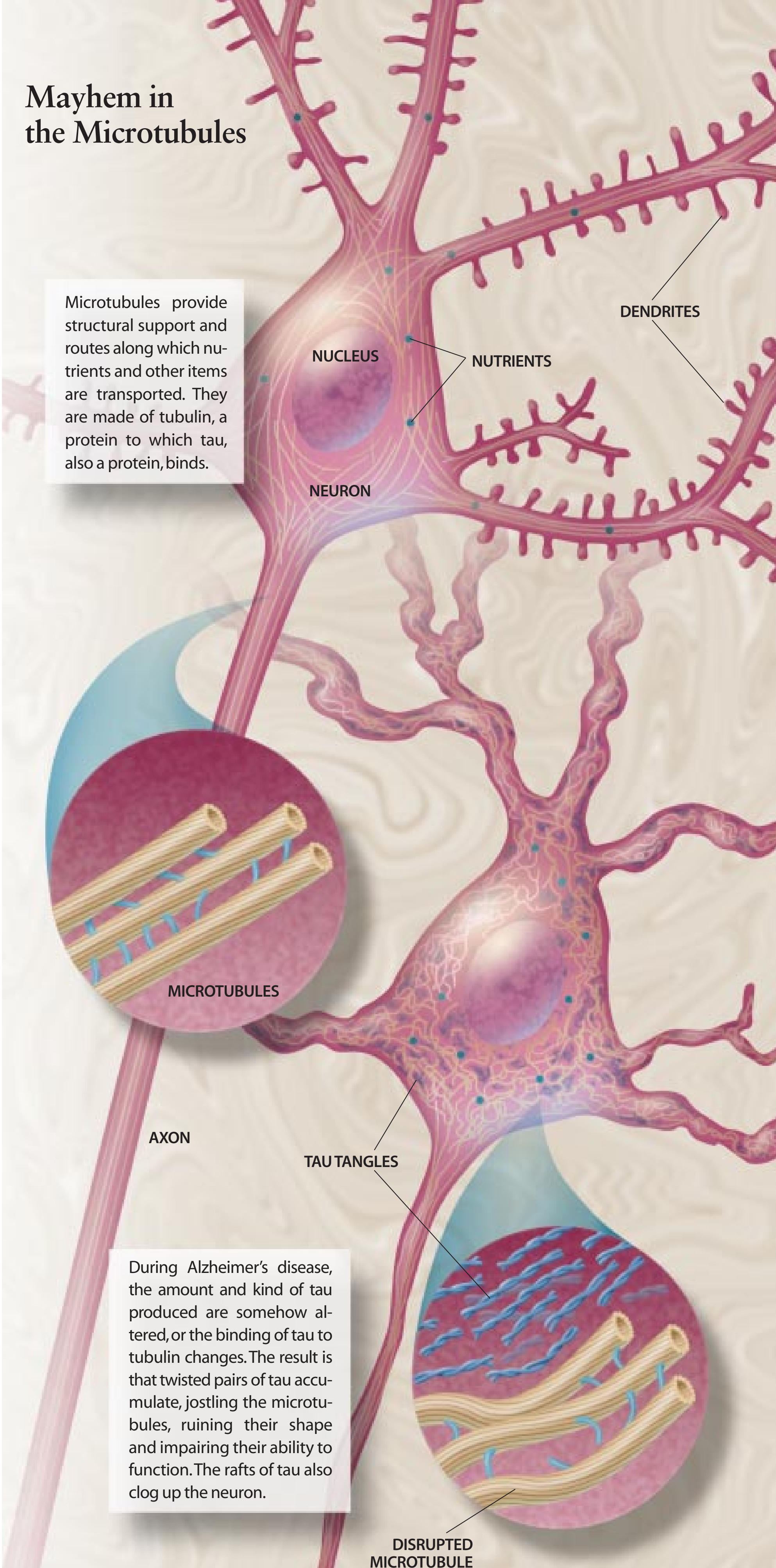
The concept of changes in βAPP processing being central to Alzheimer's disease gained further support when investigators discovered mutations in a set of genes that interfere with the cutting of βAPP. In 1995 my colleagues and I cloned two genes, *presenilin 1* and *presenilin 2;* disruptions in these genes—which are located, respectively, on chromosome 14 and chromosome 1—cause a very aggressive form of early-onset Alzheimer's. (Early-onset forms are generally seen in about 10 to 60 percent of patients with familial Alzheimer's.) Both genes encode proteins that weave across the cell membrane several times, like a series of stitches in a piece of fabric. These proteins undergo a complicated maturation process during which they are cut into two pieces, both of which are incorporated into a complex of proteins that in turn has the job of cutting other membrane-bound proteins like βAPP and notch, which is involved in embryonic development.

In the Wrong Place

Several studies—by Bart De Strooper of the Flanders Interuniversity Institute for Biotechnology in Leuven, Belgium, by Christian Haass of Maximillians University in Munich, by Gopal Thinakaran of the University of Chicago, and by my group at Toronto—indicate that certain induced mutations in the individual presenilin proteins disrupt the activity of these complexes and, accordingly, alter the processing of the proteins they act on. We know that βAPP is one target of the complexes, because man-made mutations in mice cause them not to produce *presenilin 1*. As a consequence, gamma-secretase does not make its final cut of βAPP, and the mice produce no β-amyloid. In these mice, several other membrane proteins are not cut properly either—including the notch protein.

Presenilin 1 and *2* mutations found in people with familial Alzheimer's, however, do the reverse: they bring about an *increase* in cutting by gamma-secretase and, consequently, an overproduction of β-amyloid peptide, especially of the destructive longer version. It is too early to know for sure, but it is possible that

Mayhem in the Microtubules



Microtubules provide structural support and routes along which nutrients and other items are transported. They are made of tubulin, a protein to which tau, also a protein, binds.

During Alzheimer's disease, the amount and kind of tau produced are somehow altered, or the binding of tau to tubulin changes. The result is that twisted pairs of tau accumulate, jostling the microtubules, ruining their shape and impairing their ability to function. The rafts of tau also clog up the neuron.

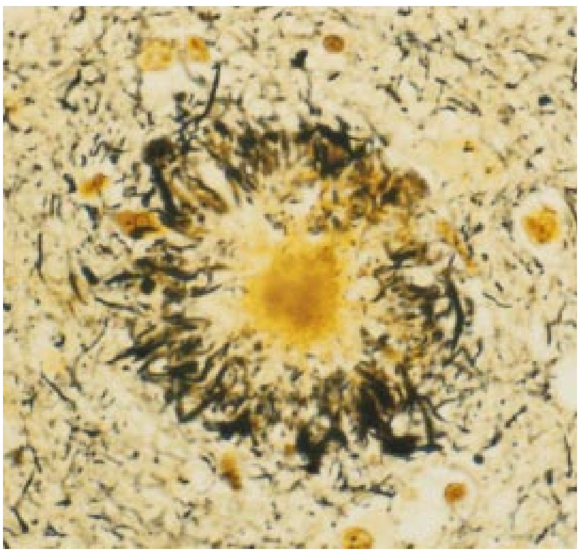
JOHN W. KARAPELOU

the presenilins are gamma-secretase itself. Or perhaps the presenilins are involved with gamma-secretase in some indirect way—maybe they activate it or mediate its activity by bringing the enzyme into contact with βAPP.

Although mutations in βAPP and presenilin genes have a dramatic effect, they are responsible for only 50 percent of the cases of early-onset familial Alzheimer's patients—that is, they account for, at most, 5 percent of all instances of the disease in the general population. It turns out that another gene is involved in a greater proportion of cases.

In 1993 studies by Allen D. Roses, now at Glaxo Wellcome, and his colleagues Margaret Pericak-Vance of Duke University and Jonathan Haines of Vanderbilt University implied the existence of a gene on chromosome 19 that is associated with the more typical form of Alzheimer's that appears late in life. Roses, then at Duke, and Warren J. Stritmatter, also at Duke, isolated apolipoprotein E, or APOE, which transports cholesterol in the bloodstream and is involved in cellular repair and regeneration. The gene for APOE comes in three forms, or alleles, the frequencies of which vary slightly in different populations: the ε3 variant is considered normal and occurs in 40 to 90 percent of the population; ε2 and ε4 are less common, occurring in 2 percent and 6 to 37 percent of the population, respectively. In Alzheimer's patients, however, Roses and his colleagues found that the incidence of ε4 was quite high: roughly 40 percent.

Having the ε4 allele may increase risk for Alzheimer's in various ways. One explanation holds that the ε4 form of the protein competes with the β-amyloid peptide for removal from the space between cells. It has been found that one molecule responsible for hauling materials away from the intercellular spaces carts off the ε4 protein more efficiently than it transports β-amyloid. Consequently, β-amyloid accumulates and becomes available for biochemical troublemaking. Support for this scenario comes from the fact that patients with the ε4 variant of APOE have more β-amyloid buildup than do Alzheimer's patients with the ε2 or ε3 versions. In addition, patients who have both a βAPP mutation and the ε4 allele develop Alzheimer's disease much earlier than do people who have the same βAPP mutation but the ε2 or ε3 form of the APOE gene.



PETER H. ST GEORGE-HYSLOP

PLAQUES AND TANGLES are shown together here as they occur in the later stages of Alzheimer's disease. The ß-amyloid core of the plaque appears orange and is surrounded by a halo of nerve endings containing black tau filaments. The brain's inflammatory cells—microglia and astrocytes—can be seen as small brown angular structures in between the nerve endings.

Whatever the future of treatment holds, it is gratifying that there are now so many angles to pursue at the same time.

The accumulated evidence of the past decades definitely indicates that one of the initiating events for Alzheimer's is an abnormality in the processing of βAPP and β-amyloid peptide. Nevertheless, several important pieces of information are missing. The problems with βAPP cleavage and β-amyloid accumulation begin early in the disease. But what happens later? And why does the density of β-amyloid plaques not reflect the severity of dementia? The issue, at heart, is whether clumps of β-amyloid peptide actually give rise to dementia, and this fundamental and lingering question has for years driven both debate and research. My own view is that abnormalities of βAPP and β-amyloid peptide initiate Alzheimer's by activating a series of events that ultimately damage and kill neurons, giving rise to dementia itself. One of those later deleterious events may be the appearance of neurofibrillary tangles.

Returning to Tau

Until recently, the abnormally entwined pairs of tau protein filaments were thought to be innocuous secondary events. But analysis of a disease called frontotemporal dementia has raised questions about this conclusion. Frontotemporal dementia is a rare form of dementia in which, in some patients, tau deposits are present. As with Alzheimer's disease, some cases of frontotemporal dementia are familial. Genetic studies done by Kirk C. Wilhelmsen of the University of California at San Francisco and others indicate that genes contribute to the familial form of the disease.

One of these genes lies on chromosome 17, home of the tau gene. By looking at patients who had the form of frontotemporal dementia characterized by the buildup of tau, Gerard D. Schellenberg of the University of Washington identified a mutation in the tau gene. Schellenberg's 1998 discovery was important because it suggested that dementia can arise directly from the abnormal processing and accumulation of tau.

Neurofibrillary tangles are therefore probably integral parts of Alzheimer's disease as well—a possibility that provides a better explanation for the fact, pointed out a decade ago by Robert D. Terry and Robert Katzman of U.C.S.D., that the density of neurofibrillary tangles in Alzheimer's disease is related to the severity of the dementia. We do not know yet exactly how mutation in the tau gene causes frontotemporal dementia, but experiments point to the idea hinted at above: mayhem in the microtubules. Errors in the tau gene may interfere with the way tau binds to tubulin—the backbone of microtubules—or they may cause an imbalance in the types of tau protein that are produced.

BRAIN ATROPHY reveals the damage caused by Alzheimer's disease. Certain regions of the brain—including the hippocampus and cortex—lose neurons, and the normally convoluted surface of the brain ultimately wastes away. This destruction is apparent when the brain of a patient with Alzheimer's (*left*) is compared with that of a normal individual of the same age (*right*).

The net effect of both events would cause a buildup of excess free tau, which accumulates in paired helical filaments. The microtubule structures would then not work properly, and the accumulated bundles of tau would throttle the cellular transport mechanism. As a result, neurons could neither transmit electrical signals nor transport nutrients and other important items to the far reaches of the cell. It seems quite likely that abnormalities in βAPP and β-amyloid peptide set in motion a series of events, a subset of which alter tau, which in turn further damages the neurons, leading to dementia.

New Treatments

The biochemical, molecular, genetic, epidemiological and clinical discoveries of the past 10 years or so have significantly advanced our understanding of the mechanisms underlying Alzheimer's disease and make it increasingly likely that, in the years to come, useful treatments will be generated. Some of these will probably come from the recent insights into the misprocessing of tau. Indeed, the insights into βAPP and β-amyloid peptide are already fueling treatment research.

For instance, some investigators are designing compounds that will block the ability of either the beta- or the gamma-secretase enzyme to cut βAPP—thus preventing the creation of the damaging β-amyloid peptide. Others are seeking to alleviate the peptide's effects once it has been created. Clinical trials are under way to see whether antioxidants such as vitamin E or nonsteroidal anti-inflammatory drugs such as ibuprofen could alleviate some of the toxic effects of β-amyloid.

A number of investigators are also working to reduce the accumulation of β-amyloid peptide by using compounds that mimic dyes such as Congo red, which can insert themselves into amyloid plaques, or molecules called glycoaminoglycans, which appear to be involved in the clustering of β-amyloid peptide. Such compounds could break down the aggregations of β-amyloid peptide from within.

Following this line of reasoning, Dale Schenk and his colleagues at Elan Pharmaceuticals in South San Francisco recently reported designing a vaccine based on β-amyloid. They found that in mice with a version of Alzheimer's (characterized by amyloid plaques but not tau tangles) a vaccine made of β-amyloid peptide reduced the number of plaques. In other words, they could train the body to attack and dispose of β-amyloid clusters. Whether this vaccine therapy will be effective in people with Alzheimer's disease will be the subject of interesting clinical research.

Whatever the future of treatment holds, it is gratifying that there are now so many angles to pursue at the same time. The exciting information gleaned about the different stages of the disease and the many biochemical actors that play roles has finally given researchers a better vantage point from which to examine Alzheimer's—one that seems to offer an almost panoramic view. SA

The Author

PETER H. ST GEORGE-HYSLOP is a neurologist and molecular geneticist. After receiving his M.D. degree from the University of Ottawa, he did postgraduate work in internal medicine and neurology at the University of Toronto and postdoctoral training in molecular genetics at Harvard Medical School. He is currently director of the Center for Research in Neurodegenerative Diseases at the University of Toronto and director of the Memory Disorders Clinic at Toronto Western Hospital. He is interested both in basic research into the molecular causes of Alzheimer's disease and in translating recent fundamental scientific insights into clinically useful methods for dealing with the disease.

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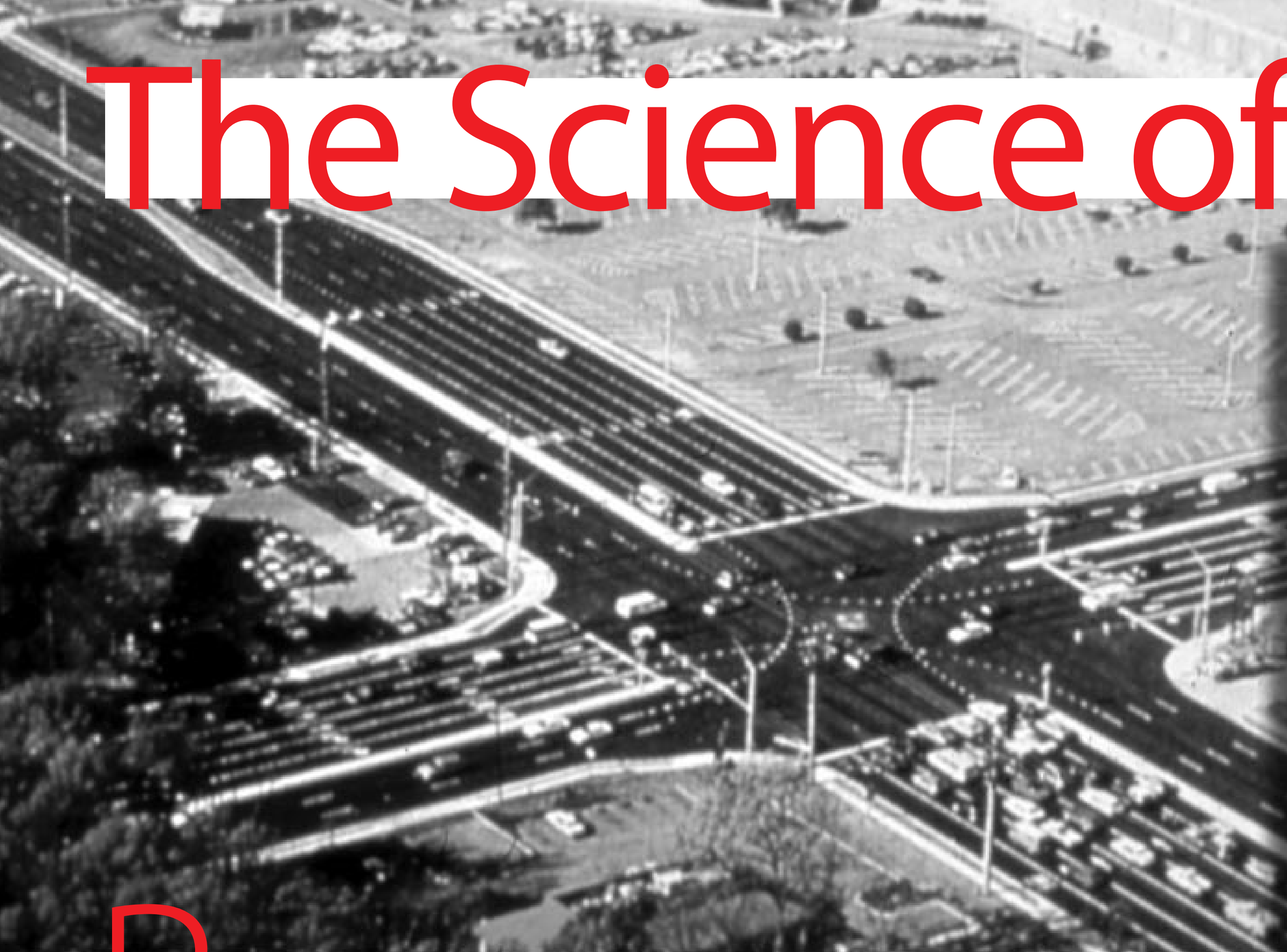
The Science of



COURTESY OF DUANY PLATER-ZYBERK & CO. (*traffic intersection*); URBAN DESIGN ASSOCIATES (*Park DuValle*)

Rome wasn't built in a day, but Atlanta comes pretty close. In the 1990s metro Atlanta redefined the boomtown, leading the nation in population growth, job openings, home building and highway construction. The city once known for being burned to the ground during Sherman's march was called the fastest-growing human settlement in history.

But now Atlanta again appears to be a city under siege. This time the enemy is said to be urban sprawl. Scattered over an area larger than the state of Delaware, the region's workers face the nation's longest average commute and some of its most congested freeways. Atlanta's smoggy skies produced 69 "ozone-alert" days in 1999 and 45 such days during the first eight months of this year. Nearly two years ago a federal judge ordered a stop to highway building until local agencies come up with a better plan to improve regional air quality. Large corporations such as Hewlett-Packard have started to look elsewhere to locate new facilities because of quality-of-life concerns. Against such odds, can Atlanta stage another spectacular comeback?

On a less superlative scale, hundreds of other regions also have been wrestling with growing pains. Over the past several years, citizens nationwide have passed hundreds of ballot initiatives supporting land preservation, park improvements, community reinvestment, public transit and other measures to curb sprawl. A recent Pew Center opinion poll found that of all local issues, such as crime, jobs and education, Americans are most worried about sprawl and traffic. For media pundits, these concerns have provided much fodder for political analysis as they slice and dice the resonance of Vice President Al Gore's "livable communities" initiatives and the effectiveness of state and local campaigns to promote smarter growth.

By focusing on the political theater, however, many miss the real story: that widespread concerns about sprawl have unleashed a wave of innovation. It includes creative economic incentives, new construction technologies, rewritten building and zoning codes, sophisticated marketing and demographic forecasting techniques, and a push to inform the public about scientific estimates of the costs of sprawl. New research centers to study land development have been established at the University of Maryland, George Washington University and Harvard University, joining those at other leading institutions such as the University of Miami, Rutgers University and the University of California at Berkeley. Although sprawl has been studied since the 1950s, researchers now have an unprecedented opportunity to evaluate anti-sprawl measures that have never before been tested on American soil.

Not Your Father's Sprawl

Why is sprawl suddenly such a hot topic? After all, it is hardly a new issue. Though often derided as bland and boring, sprawl has become the mainstay of American middle-class housing since World War II and, for many, the physi-

Smart Growth

Are there any alternatives to urban sprawl? Pundits and pols may endlessly debate that question, but the only way to get an answer is to go out and see what works in the real world

by Donald D. T. Chen

CARS OR PEOPLE? The automobile-oriented style of land development (*opposite page*), popularized in the 1950s, is falling out of favor with home buyers who increasingly demand walkable neighborhoods, often built on redeveloped urban sites such as Park DuValle in Louisville, Ky. (*above*).

cal embodiment of the American dream. So what has changed?

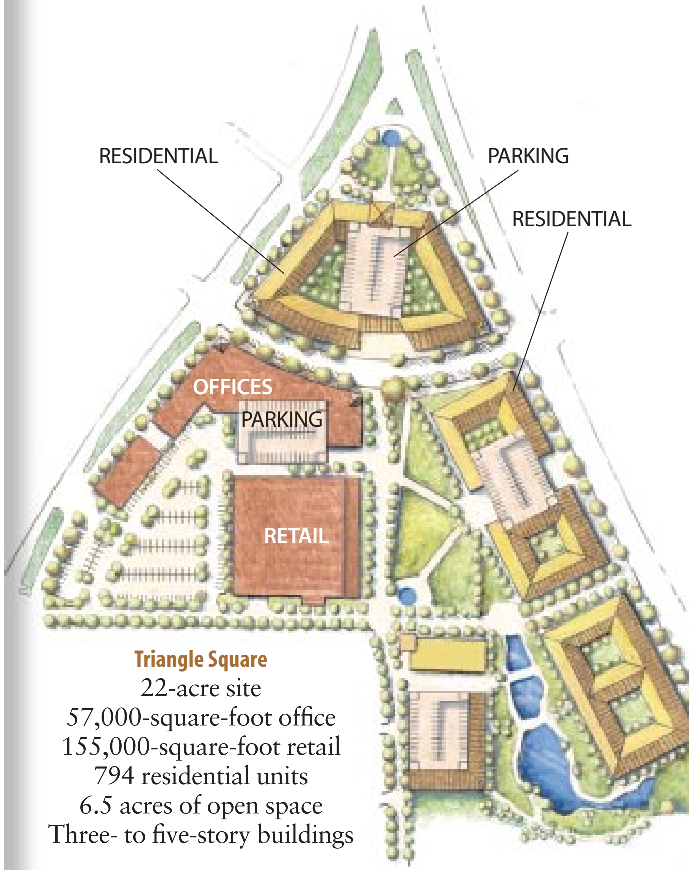
The answer may lie in the evolving definition of "sprawl." For the social critics of the 1950s and 1960s, it was commonly equated with "the suburbs," which they condemned as culturally and architecturally homogeneous. Predictably, these complaints tended not to resonate beyond the urban cocktail-hour crowd, as millions of Americans made their homes in the suburbs.

The substance and rhetoric of today's arguments against sprawl are starkly different. They depict sprawl not as a place where people live but as a process that has spiraled out of their control. In other words, sprawl is no longer equated just with a type of dispersed development characterized by large, separate zones for residences, shops and businesses. It is viewed as the seemingly unstoppable spread of such development, leading to worse congestion, escalating tax rates, disinvestment in older communities and the devouring of open space. This perception is partly fueled by the sheer pace of land development, which, according to the U.S. Department of Agriculture, is roughly double what it was a decade

Two Designs Compared

Smart Growth Matrix Project Criteria	Points Available	Triangle Square	Missing Oaks Mall
Location of Project (choose one)			
Downtown	45		
Urban core	28	28	28
Desired development zone	12		
Mixed Use			
Includes residential above first floor	20	20	0
Street-level pedestrian uses	15	15	15
Includes two uses	15	15	0
Includes three uses	25	25	0
Streetscape Treatment			
Street trees	9	9	0
Weather protection (awnings, arcades, etc.)	3	3	0
Minimum of 10-foot-wide sidewalk along street frontage	9	9	0
Crossing treatment at street intersections	12	12	0
Accessible Open Space			
Area greater than 500 square feet	4	4	0
Seating	2	2	0
Landscaping, including trees	2	2	0
Outdoor public art	4	0	0
Building Location			
Oriented to pedestrian network	3	3	0
Buildings built up to right-of-way	12	12	0
Parking located at rear of building	6	6	0
Total points for all Smart Growth Criteria, including those not shown here		402	169

SOURCE: City of Austin PECSD



Triangle Square
22-acre site
57,000-square-foot office
155,000-square-foot retail
794 residential units
6.5 acres of open space
Three- to five-story buildings

ILLUSTRATIONS BY CLEO VILETT; SOURCE: CITY OF AUSTIN PECSD

ago. As communities become dissatisfied with haphazard growth, they are rebelling against the conventional wisdom that continued sprawl is desirable, immutable and inevitable. Urban, suburban and rural residents have joined forces in coalitions that would once have seemed improbable.

In local debates, the most commonly cited concern is the environment. Although only about 5 percent of the nation's total land area has been built on, areas that are primed for development include a disproportionately large number of wildlife habitats, wetlands and watersheds. The two biologically richest parts of the U.S., Florida and southern California, are also among the fastest-growing. According to the Nature Conservancy, Florida has lost half its original stock of wetlands. The U.S. Fish and Wildlife Service has estimated that more than 90 percent of the Californian coastal sage ecosystem has succumbed to development.

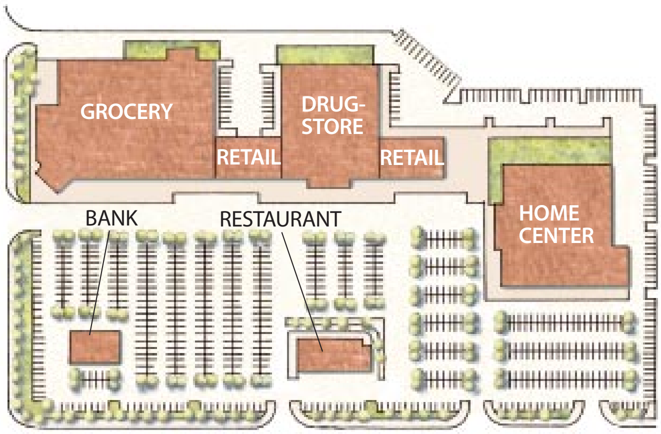
Even though individual species sometimes become celebrities in development battles, environmentalists are now becoming more concerned about broad ecosystem degradation. An entire branch of ecology has arisen over the past several years to study the burden that urbanized areas place on their less developed hinterlands, and many "green" groups have started to link land development with the gamut of environmental issues. The Chesapeake Bay Foundation, for example, recently ran a radio ad featuring a talking fish that criticizes new highway construction, saying that vehicle pollutants would eventually wash into the bay.

On land, preservation groups such as Scenic America have launched campaigns to protect picturesque vistas. Some of the most active opponents of sprawl are historical societies devoted to protecting Civil War battlefields. In five states preservation groups and amateur astronomers have even secured state legislation safeguarding the starry night sky, which is being washed out by "light pollution" from an increasing array of settlements.

A second area of concern is economic. In Virginia, Loudoun County supervisor Scott K. York decided to push for new growth strategies after citizens started demanding action on overcrowded schools and increased taxes. "It wasn't because I'm a great environmentalist or because I get stuck in traffic every day," he said. "It was the budget in Loudoun County."

Numerous fiscal-impact studies have found that low-density, noncontiguous growth is more likely to generate higher costs for municipal services and infrastructure than more compact forms of development. Robert W. Burchell and David Listokin of Rutgers have determined that modest increases in density could reduce total capital costs by 25 to 60 percent for roads and 15 to 40 percent for water and sewer lines. School construction also becomes a huge issue as communities scramble to accommodate shifts in population. Between 1970 and 1995, public school enrollment in Maine fell by 27,000, yet over a similar period the state government alone spent $338 million to build new schools and classrooms. In most areas, property-tax revenues fail to make up for these extra costs, creating pressure to raise tax rates.

The other topic that has come to dominate the politics of



Missing Oaks Mall
23-acre site
180,000-square-foot retail
8,500-square-foot bank
7,500-square-foot restaurant
No open space
One-story buildings

EVEN SHOPPING MALLS are getting a makeover. Like many other cities, Austin, Tex., has provided infrastructure improvements to encourage development. But now it devotes a portion of those funds to projects that include "New Urbanist" characteristics such as pedestrian access, mixture of uses and other amenities (*table on opposite page*). The Triangle Square development got $7.6 million in incentives. Typical mall site plans like "Missing Oaks," a dummy project used to calibrate the grading system, would receive no public investment.

sprawl is traffic. According to the Texas Transportation Institute, traffic delays per capita in the nation's largest urban areas increased by 20 percent from 1993 to 1997. The additional wasted time and fuel adds up to $74 billion a year. For a typical family, these costs are manifested in an unwavering reliance on driving: chauffeuring kids to and from school, baseball games and play dates; pushing through herds of sport-utility vehicles just to buy a gallon of milk; leaving earlier and earlier in the morning to beat the traffic.

The lack of alternatives to driving also has direct health consequences. In the *Journal of the American Medical Association* last year, Jeffrey P. Koplan and William H. Dietz of the Centers for Disease Control and Prevention argued that the absence of safe walking and bicycling opportunities in sprawling areas is contributing to sedentary lifestyles and an "epidemic" of obesity among both adults and children. "Automobile trips that can be safely replaced by walking or bicycling offer the first target for increased physical activity in communities," they wrote.

What Choice?

Public outcry against sprawl has led to a search for alternatives, often referred to as smart growth. This term is sometimes equated with urban growth boundaries, such as the one around Portland, Ore. But in fact it encompasses a range of measures intended to encourage development that offers transportation options, preserves open space and revitalizes older communities. Although many of these efforts—such as urban reinvestment and "New Urbanist" projects [*see box on page 90*]—have proved popular, they have had to overcome the entrenched practices that facilitate sprawl.

The theories explaining why sprawl occurs are as numerous as they are politically controversial, but most fall into one of six categories [*see table on next page*]. None of these explanations suffices on its own. But their combination has made sprawl the path of least resistance for property developers. Over the past half-century, the design, construction, financing, regulation and marketing of development have become standardized. Planning agencies nationwide impose myriad requirements on new subdivisions: streets wide enough to accommodate vehicles traveling at 65 miles per hour, setbacks that place buildings far from streets, parking lots of a particular size, and so on. One may observe the result everywhere in America: buildings on wide streets surrounded by a sea of asphalt accessible only by car.

Some of the nation's most appealing older communities, such as Annapolis, Md., Pioneer Square in Seattle and North Beach in San Francisco, could never have been built under these rules. Developers who try to break out of the paradigm must navigate a costly obstacle course of permits, variances and other procedural hurdles. Bankers balk at the shortage of "comparables"—a track record of successful projects—so developers often have to put up their personal assets as collateral in what is known in the industry as recourse financing.

The result has been a very limited range of choices in the style and location of new housing—typically, single-family homes in automobile-oriented neighborhoods built on what was once forest or farmland. The prevalence of this pattern is often mistaken as a reflection of consumer preferences, as many commentators wonder why sprawl is so bad if home buyers seem to fuel its expansion. Had these skeptics been around for the sale of Model Ts, they may have also believed that Henry Ford's customers actively preferred that their cars be painted black. The fact is that people have simply not been given much of a choice.

The Vision Thing

The emerging alternatives to sprawl get around these obstacles in different ways. On a broad scale, state and local governments have begun implementing smart-growth plans that preserve open space and redevelop urban areas. Over the past two years, New Jersey has set aside 81,000 acres of farmland and open space; the ultimate goal is one million acres. The effort exemplifies a national trend of purchasing development rights—often referred to as conservation easements—to pay farmers not to convert their land. Property owners remain free to continue working their lands or even to sell their parcels, so long as the land is never developed.

Meanwhile New Jersey has encouraged the renovation of older buildings through a new urban code adopted in 1997. Within a year rehabilitation investment had jumped 83 percent in Jersey City, 60 percent in Newark and 40 percent in Trenton. Maryland passed a similar measure in April of this year. Other regions are also scuttling old urban and architectural codes to spur the construction of new pedestrian-friendly and mixed-use neighborhoods. Examples include the Transit-Oriented Development ordinance in

Public concern about sprawl is fueled by the sheer pace of land development, which, according to the U.S. Department of Agriculture, is roughly double what it was a decade ago.

Why Do Cities Sprawl?

Affluence
Periods of rapid land development coincide with prosperity. Sprawl is an inevitable sign of good times.
Objection: Developers and home buyers do not shoulder the entire cost of sprawl; other taxpayers foot the bill for infrastructure and services.

Government Subsidy
Sprawl is encouraged by government spending, such as federally discounted mortgages, highway construction and subsidies for water, sewer, electricity and other utilities.
Objection: Over the years, public subsidies have been scaled back. Yet sprawl has not diminished.

White Flight
By the 1940s, cities had growing numbers of African-Americans and immigrants. Masses of white Americans left cities to live in the suburbs. The resulting physical segregation by race and class has been reinforced through mortgage-lending discrimination and exclusionary zoning.
Objection: Postwar white flight is well documented, but nowadays race is less of a factor than quality-of-life issues such as traffic and schools.

Population Growth
Birth and immigration rates drive sprawl.
Objection: Sprawl has occurred in every metropolitan area whose population has stagnated or shrunk. Also, a Federal Highway Administration report calculated that population growth accounted for only 13 percent of the increase in driving in recent years.

Technological Change
Sprawl is a consequence of the popularization of the car, the construction of better-quality roads and innovations in assembly-line-style construction.
Objection: Other countries, even with abundant land, underwent the same changes without producing as much sprawl.

Government Shortsightedness
Sprawl is the result of governments' inability to plan for future growth or stick to existing plans.
Objection: Poor execution is less a cause than an effect. Had there been a will, governments would have found a way.

Sacramento County, California; the Rural Village ordinance in Loudoun County, Virginia; and the Traditional Neighborhood Development ordinance in Huntersville, N.C. [see "Between Burb and Burg," by George Musser; Scientific American, March].

For many municipalities, dismantling the maze of zoning, planning and financing conventions is too gargantuan a task. Their approach is to redirect subsidies for sprawl into more desirable forms of growth. Austin, Tex., for instance, wanted to counteract the decentralization and traffic problems that had started to plague the region but found that the city government's planning and zoning powers were relatively weak. So instead the city established a system of incentives, the "Smart Growth Criteria Matrix." It assesses new projects using a checklist that gives points for proximity to transit, access for pedestrians, availability of existing infrastructure, mix of uses, redevelopment of abandoned industrial sites (so-called brownfields) and other attributes.

Projects that accumulate enough points receive benefits, including expedited granting of permits, the waiving of development fees, provision of new infrastructure by the city, and purchase of parkland and streets within projects. To ensure that the subsidies are worth it, the city has set a ceiling for the incentives based on expected property-tax revenues over a five- to 10-year period. Although these incentives may amount to as little as 1 percent of the total cost of a project, they have been large enough to get developers to upgrade their plans significantly [*see illustration on pages 86 and 87*].

This leveraging of existing subsidies is also beginning to catch on at the state level. In 1997 Maryland approved its Smart Growth and Neighborhood Conservation initiative, which, among other things, establishes "priority funding areas"—older neighborhoods, economically depressed districts, and small towns—that are entitled to receive state assistance for infrastructure and other community improvements. "We told communities that they're still free to build sprawl," Governor Parris N. Glendening said. "We're just not going to subsidize them anymore." In Utah a grassroots effort called Envision Utah has developed a "quality growth" plan, which promotes major investment in public transit.

Many such projects have adopted ideas from Europe. The German Marshall Fund of the United States runs an exchange program to bring American officials to places in Europe that have a longer track record of experimentation in smart growth. Delegations have seen the modern tram system in Strasbourg, France; projects in Munich based on the city's "compact, urban, green" policy; and Copenhagen's Finger Plan for development along transit corridors.

The Quest for New Markets

How can a developer be sure that unconventional projects will make money? Typically, future sales are appraised using crude methods that focus on the aggregate supply and demand for housing—treating homes as generic commodities such as pork bellies, which are all essentially the same, rather than as consumer products such as cars or clothing, which vary according to people's preferences. The standard approach determines how many houses people want, but not what kind of houses. It tends to be ineffective in evaluating the market for new homes in older urban areas, townhouses in walkable neighborhoods, and single-family houses with porches and adjacent alleys.

But some firms are now blending ordinary forecasting measures with demographic analysis and marketing techniques from the retail industry. One pioneer is Zimmerman/Volk Associates (ZVA), a residential market analysis firm whose projects include urban infill and New Urbanist developments. Using data from the Census Bureau, the Internal Revenue Service and household surveys—all geographically indexed down to the neighborhood level—ZVA deduces the housing preferences of different demographic clusters.

The company applied its methodology to an ambitious affordable-housing project in Louisville, Ky., known as Park DuValle [*see photograph on page 85*]. For decades, Park DuValle represented the worst kind of subsidized housing: barracks-style buildings in a neglected and isolated part of town.

Within a year of the adoption of a new urban code in Jersey City, investment in building renovation had jumped 83 percent.

PAUL A. SOUDERS *Corbis*

Assisted by federal funding, the city set out to redevelop the area. But rather than laying out conventional ranch-style houses, the architects, Urban Design Associates, designed the new site to look like old Louisville, with its rich vernacular of Victorian architecture and Fredrick Law Olmsted parks. An analysis by ZVA projected at least 39 sales—a figure regarded as highly optimistic by the housing authority and local realtors. Park DuValle reached this target within three months.

Park DuValle is part of a broader federal effort, the HOPE VI program, to end the practice of warehousing families in massive housing projects in favor of blending affordable units with market-rate homes in attractive neighborhoods. The Ellen Wilson Homes in southeast Washington, D.C., is another example. Facing the multiple pressures of cost constraints, modern codes, federal guidelines and historic-preservation requirements, the architect, Amy Weinstein, came up with several innovations to streamline construction and mass-produce Victorian details: bricks that could be rotated to show a variety of textured patterns, simple paint-by-numbers diagrams that builders could easily follow, a panelized construction method in which wood was precut, and the use of only five floor plans. The numerous permutations of these features produced a kaleidoscope of building facades at low cost.

The challenges that Park DuValle and the Ellen Wilson Homes initially encountered are not unique to the inner city. In the heart of Silicon Valley, the city of Mountain View faced the problem of what to do with a dead shopping mall. Standard practice would have been to entice a new developer to come in and renovate it. Instead the city took a chance and decided to raze the mall and replace it with a neighborhood. Peter Calthorpe, one of the nation's leading New Urbanist architects, redesigned the site, which is now called "The Crossings." The mix of shops, offices and homes has a fairly high density—12 to 15 single-family homes per acre, compared with three to seven units per acre for a typical development in the area. To make the compact design more appealing, Calthorpe's team applied a number of technologies to maximize natural light and a feeling of spaciousness within each home. One of these is the generous use of light tubes—flexible Mylar-lined tubes that connect skylights with lower-level rooms. Despite their inability to secure conventional financing from banks, the developers managed to sell all the units two to three years ahead of schedule.

Urban Homearama

These projects are examples of successful "infill"—the redevelopment of decaying properties or construction on vacant lots in mature neighborhoods. As cities rebound, such projects are increasingly common, drawing the real-estate industry into areas they once avoided. Detroit, for instance, went three decades without issuing a single new housing permit. In 1987 a dozen local developers took the unusual step of building two houses each in one of the city's distressed neighborhoods, as part of a Homearama, a common technique for selling homes in new suburban subdivisions. Unit sales in the development (renamed "Victoria Park") were brisk, outpacing their suburban counterparts—the first of several indicators of robust demand for urban housing. Since then, some of the city's most crime-ridden neighborhoods have become some of the region's most desirable properties.

There are ways, however, in which cities are becoming victims of their own success. The decades-old call to reinvest in

Walkable intersection

Car-oriented intersection

WIDE STREETS AND CURVED CORNERS encourage suburban drivers to step on the gas. In traditional and New Urbanist neighborhoods, narrower streets and sharper corners slow the pace—making it easier and safer to walk around.

GARAGES dominate the front of a house in conventional suburbia. In traditional and New Urbanist neighborhoods, garages are off to the side or rear—making the house and sidewalk more inviting.

Snout-house garage

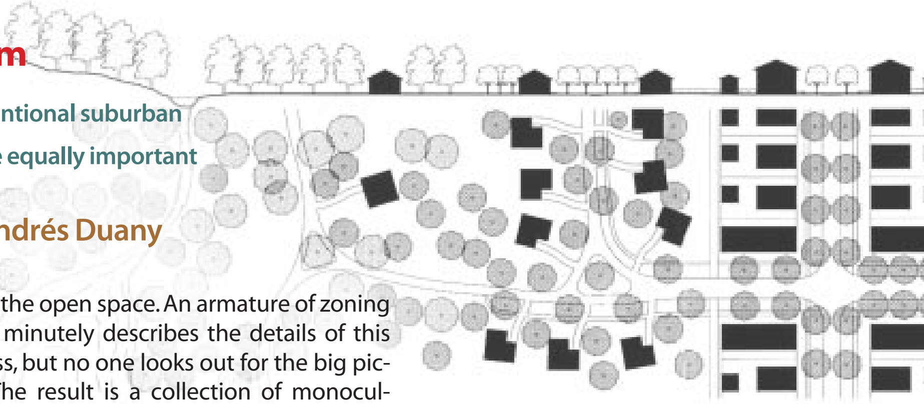
Hidden garage

COURTESY OF DUANY PLATER-ZYBERK & CO. *(top three)*; RICHARD McLAUGHLIN *(bottom)*

A New Theory of Urbanism

New Urbanists are best known for redesigning conventional suburban developments as small towns. But their principles are equally important for urban, rural and regional planning

by Andrés Duany



The word "growth" once had positive connotations for Americans: better jobs, better shops, better education, a better quality of life. But mention the word these days, and you are likely to hear fulminations about congested traffic, higher taxes, crowded schools and the paving-over of the landscape. How did it come to pass that a nation proud of three centuries of growth, one whose people built the constellations of beautiful villages, towns and cities across a continent, should have so radically changed its outlook?

The reason is that the urban pattern has shifted. Before World War II, when a green field was lost, a hamlet, village or town was gained. It was an even trade. But today when an open space is built on, a housing subdivision, a shopping center or a business park replaces it. For most Americans, it seems like a losing transaction. Whereas prewar developers were generalists—they set out to build entire villages or urban neighborhoods—today's developers are specialists. One builds only shopping centers, another office parks, another houses. Traffic engineers design only the roads; environmental analysts worry only about the open space. An armature of zoning codes minutely describes the details of this process, but no one looks out for the big picture. The result is a collection of monocultures: a disaggregation of the elements of community into specialized areas.

Individually, the decisions that these specialists make are quite plausible, but collectively they lead to a pattern that is dysfunctional. Wide residential streets, for example, seem like a reasonable way to speed emergency vehicles on their way. Yet wide streets are more dangerous for pedestrians, particularly children, and often allow for fewer road interconnections, which may actually make it more difficult for fire trucks to get where they need to go. Whether it is street width, housing density, building placement or landscape layout, no design decision should come in isolation. This is the fundamental insight of the New Urbanists: paying careful attention to how the urban design coheres, drawing on the lessons of prewar developers.

Some have criticized New Urbanism as too suburban; they do not want to live in a modern version of the traditional American small town. They may also prefer the bustle of city or the quiet of the countryside. But New Urbanism is now general enough to take in a diverse range of human habitats. It has a comprehensive design strategy that works for the full continuum of development, from remote wilderness to dense downtown. The system, known as the transect, now guides many new towns and is in the process of being adopted as code by several counties in the U.S.

The transect is a concept drawn from ecology. It is a geographical cross section through a sequence of environments—for example, from wetland to upland, or tundra to foothill.

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urban areas assumed that such investment would benefit lower-income households. But now that urban living is back in fashion, poor families are being pushed out by gentrification. According to the Department of Housing and Urban Development, over the past three years, urban house prices have increased twice as fast as inflation and rents 50 percent faster. Despite the appeal of Park DuValle and the Ellen Wilson Homes, such projects offer fewer subsidized units than the housing blocks they replaced.

To counterbalance this trend, various programs have sought to bring home ownership to a greater number of lower- and moderate-income families. One of the most promising is the Location-Efficient Mortgage (LEM), which rewards home buyers for choosing compact neighborhoods served by public transit. Families living in these areas can often do without a second car, or any car at all. Because the average car costs $6,200 a year in maintenance, depreciation, insurance and fuel, the savings can be substantial. The LEM lets prospective home buyers apply those savings to finance mortgages that are $15,000 to $50,000 more than they would normally qualify for. Already, banks in Seattle, Chicago and California are offering this service, and Fannie Mae (a government-chartered organization that repackages mortgages as investment securities) has committed to purchasing $100 million in such mortgages during a test period.

Some of the nation's most appealing older communities, such as downtown Annapolis, Md., could never have been built under existing planning and zoning rules.

A Trend, or Trendy?

At this point, it is too early to tell whether smart growth is a trend—or simply trendy. But the label is so popular that a confusing array of projects and policies is adopting it. Some, such as more highway construction and large-lot zoning, which is one form of exclusionary zoning, would in fact accelerate sprawl or perpetuate social inequities. And even well-designed projects may worsen sprawl. A recent report by the Sierra Club criticized a new walkable, mixed-use, energy-efficient subdivision, Hidden Springs in Boise, Idaho, for its "good intentions in the middle of nowhere." Despite the project's desirable elements, its remote location requires new infrastructure and promotes strip development along the connecting roads.

Despite the learning curve, a remarkable transformation in urban planning has taken place. Even in Atlanta, the nation's poster child for sprawl, developers, businesses and politicians that once opposed smart growth have come to see it as a matter of survival. The old Atlantic Steel works site in midtown Atlanta is being redeveloped into a transit-

DUANY PLATER-ZYBERK & CO. (*top*); MICHAEL MORRISSEY (*bottom row*)

TRANSECT is an idealized geographical slice from the countryside to the city, shown in cross section (*top row*) and plan view (*bottom row*). A set of design principles applies to each increment in density.

Less Density	More Density
Primarily Residential	Primarily Commercial
Smaller Buildings	Larger Buildings
Most Buildings Detached	Most Buildings Attached
Deep Setbacks	Shallow Setbacks
Road & Lane Sections	Street & Alley Sections
Paths & Trails	Sidewalks & Passages
Open Swales	Raised Curbs
Mixed Tree Clusters	Single Tree Species

The transect extends the natural environments to the human habitat by increasing density and immersive urban character. The gradient spans from the villa in the woods to the large suburban lots in a common lawn served by a spare network of roads and on to urbanized sectors of ever greater complexity and continuity. Villages and towns are composed, in varying measures, of these environments. Cities extend the range to an urban core made of buildings, with little if any nature. All sections fulfill the set of human needs and desires. Based on our observations of vibrant communities, we find a commonality among the design principles for each section of the transect. At the boundaries between sections, including that from the natural to the man-made, an overlap of the envisioned characteristics allows them to fit together smoothly.

The transect does not eliminate the standards embodied in present zoning codes. It merely assigns them to the sections of the transect where they belong. Thus, the existing requirements for street width are not deemed to be right or wrong but rather correctly or incorrectly allocated. Wide streets may be appropriate where speed of movement is justified, even at the expense of the pedestrian environment. Similarly, current standards for closed drainage systems are not wrong; it is just that they are appropriate only for urban areas with curbs and sidewalks. In rural areas, rainwater can infiltrate through deep, green setbacks and swales. In fact, the transect widens the range of design options. Under conventional codes, for example, front setbacks must either be a 25-foot grass yard or a paved parking lot. The transect offers at least six more options.

Not all possible environments fit into the transect. Civic buildings such as religious, educational, governmental and cultural institutions often demand special treatment. Airports, truck depots, mines and factories are also better off in their own zones. But the transect does away with other, unjustified forms of single-use zoning whereby any attempt to unite the places of daily life—the dwellings, shops and workplaces—is considered an aberration that requires variances. In this regard, a transect-based code reverses the current coding system, forcing the specialists to integrate their work. It is a new system that, as Modernist architect Le Corbusier said in a different context, makes the good easy and the bad difficult. And in so doing, it may reconcile the American public to the growth that has become inevitable.

ANDRÉS DUANY is one of the most influential town planners in the U.S. With his wife, Elizabeth Plater-Zyberk, he is a founder of the Congress for the New Urbanism. He says he was introduced to the concept of the transect in 1983 by his brother, Douglas, who showed him a natural transect on the beach at Grayton, Fla.

oriented mixed-use community. One of the region's biggest employers, Bell South, has announced that it would close 75 suburban offices and consolidate them in three new offices located at rail stations. And Georgia governor Roy E. Barnes has created the nation's most powerful regional governing agency, the Georgia Regional Transportation Authority, to manage infrastructure and land use.

In an act of half-full optimism, some local leaders are starting to regard the federal court's moratorium on highway construction as a blessing in disguise, because it has enabled the region to spend federal transportation funds on badly needed improvements in transit, walking, bicycling and traffic-management projects. When the moratorium is finally lifted—a new growth plan is still being developed—the region will have had a long period of reflection and planning to think about its future. When that time comes, Atlanta will once again be in the spotlight. Surely, if smart growth can make it there, it can make it anywhere. SA

The Author

DONALD D. T. CHEN is director of Smart Growth America, a Washington, D.C.–based coalition of 50 groups—including the Congress for the New Urbanism, the Natural Resources Defense Council, the American Farmland Trust and the Enterprise Foundation—that advocates affordable housing, urban reinvestment, preservation of open space and more reliable transportation. Chen has done research on transportation policy, pedestrian safety and income inequality. In the late 1980s he was a volunteer organizer on hunger and homelessness issues in New Haven, Conn., for which he earned the President's Community Service Award at Yale University.

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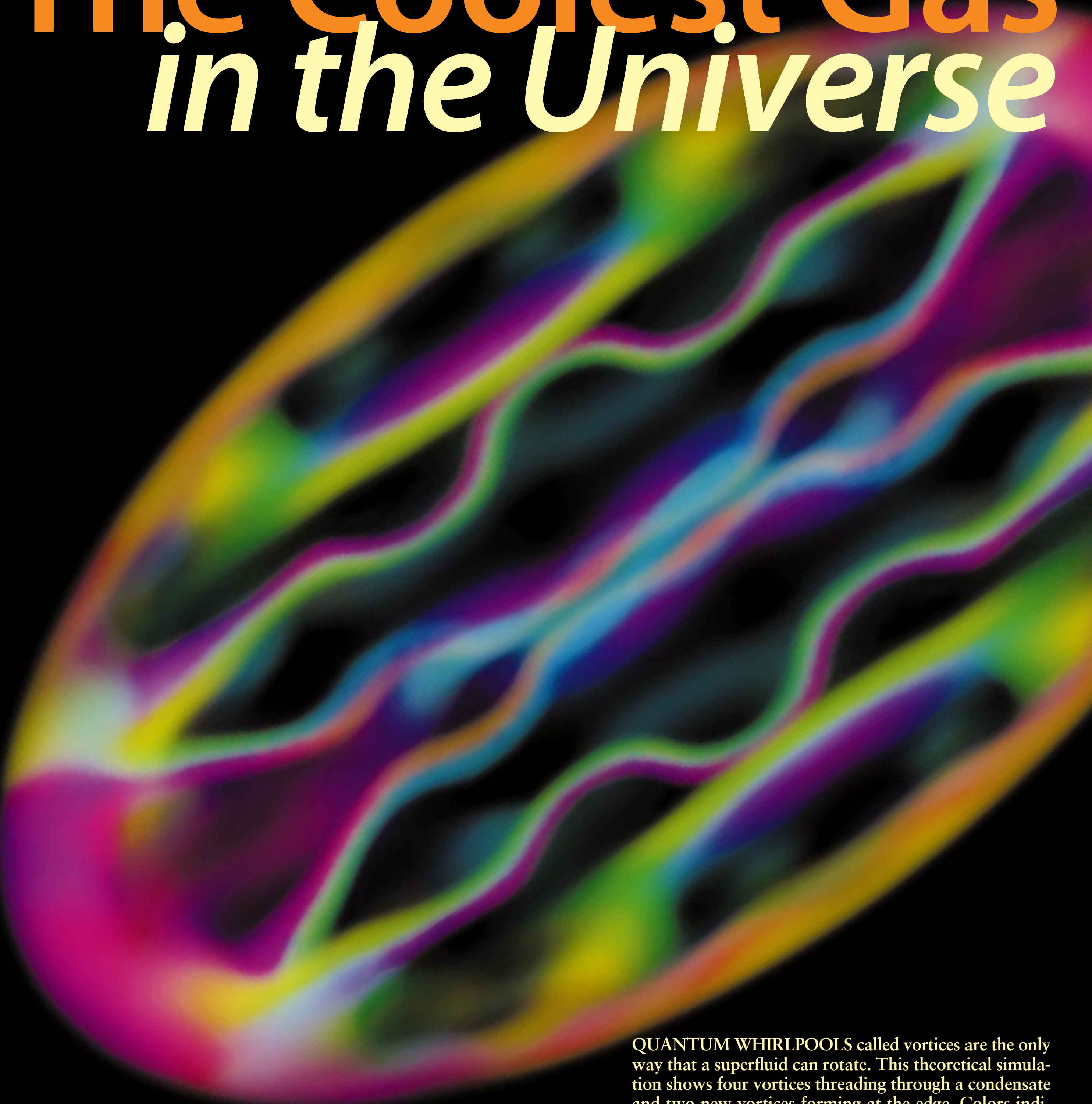
Trends in Physics

The Coolest Gas *in the Universe*



DAVID FEDER AND PETER KETCHAM *National Institute of Standards and Technology (NIST)*

QUANTUM WHIRLPOOLS called vortices are the only way that a superfluid can rotate. This theoretical simulation shows four vortices threading through a condensate and two new vortices forming at the edge. Colors indicate the quantum "phase" around each vortex.

Bose-Einstein condensates are one of the hottest areas in experimental physics

by Graham P. Collins, *staff writer*

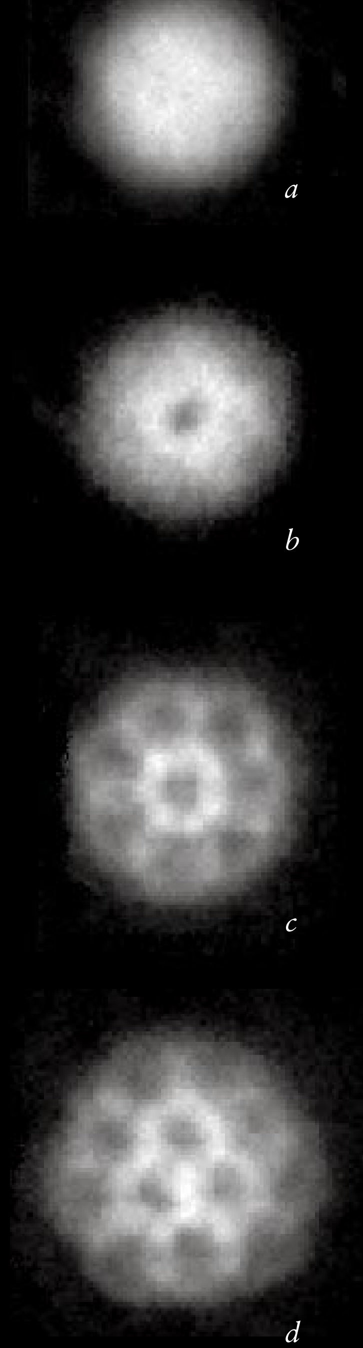
Imagine that you could magically shrink yourself down to the size of a large molecule and watch the motion of atoms in a gas. The atoms might appear to be unbreakable glass marbles, darting around an almost empty space before you, ricocheting off one another incessantly. You might nod to yourself, recognizing the scene from descriptions of an "ideal gas" from high school or college.

Now you notice that the marbles are flying around less frenetically than they were when you stepped out of the miniaturizer. Aha! Some process is cooling the gas down. At first the marbles merely lose speed and become somewhat less widely spaced; the density of the gas is rising as it cools. But then, contrary to expectation, you see that the marbles themselves are changing. The slowest-moving ones are growing thousands of times in size, and their formerly mirror-sharp surfaces have become indistinct. These increasingly wraithlike atoms pass through one another, sometimes without deflection, sometimes rebounding as if something hard inside collided.

Near the center of the region, two of the slowest, cloudiest atoms overlap and seem to merge, forming a single large globule. This ellipsoid absorbs other atoms in ones and twos and by the dozen, and with a startling suddenness only it remains, a huge motionless blimp. What has happened to all the individual atoms? What is this mysterious object?

It is a quantum-mechanical entity called a Bose-Einstein condensate (BEC), the coldest form of gas in the universe. And although the atoms still exist within it, composing it, they have lost their individuality.

Quantum mechanics rules the world. Most of the time the bizarre features of quantum mechanics are hidden behind a facade of classical physics. We mistake the facade for the substance of reality, and from it comes our com-



VORTEX LATTICES have been imaged in a stirred condensate of rubidium atoms. The condensate does not rotate (*a*) until the stirring is strong enough to generate a whole vortex (*b*), in which each atom has one quantum of angular momentum. Faster stirring increases the rotation by adding more vortices. The examples here have eight (*c*) and 12 (*d*). In the dark vortex cores, the rotation is fastest and the gas density is lowest.

KIRK MADISON *École Normale Supérieure, Paris*

Cousins of BEC

Other Condensates

The condensates made in 1995 were not the first examples of Bose-Einstein condensation, but several properties distinguish them as uniquely pure examples of the phenomenon. To be precise, the new condensates are dilute, gaseous and made of atoms. Prior condensates and related systems include:

Superfluid helium. When liquid helium 4 is cooled below 2.2 kelvins, it takes on the astonishing property of superfluidity. The liquid flows totally without viscosity, enabling feats such as the helium fountain (*right*). The superfluid state occurs because a fraction (up to about 10 percent) of the helium atoms undergo Bose condensation. The strong interactions among the atoms in the liquid make it very hard to study the intrinsic quantum properties of the condensate fraction in detail, either in theory or experiment.

HELIUM FOUNTAIN, triggered by the heating coil, is a spectacular example of superfluidity. Up to one tenth of the helium atoms are in the form of a liquid Bose-Einstein condensate.

Lasers. Light from a laser shares many features of a Bose-Einstein condensate. Light is made up of wavelike particles called photons. In ordinary light, as from a lightbulb, the photons' waves are unsynchronized. In a laser, all the waves are "in phase," meaning that the crests and troughs are aligned; the photons march in lockstep, like soldiers on parade. That is, the photons are all in the same quantum state. The amplification process that produces a laser beam makes use of bosons' propensity to collect in the same quantum state.

Superconductors. Bose condensation of pairs of electrons generates superconductivity, the flow of electric current without resistance. Unpaired electrons cannot Bose-condense, because they are fermions, not bosons. Loosely bound pairs of electrons form only under certain conditions, such as in aluminum cooled to 1.2 kelvins. Such pairs *are* bosons, and they immediately Bose-condense. The pairing process and the electric charge of the pairs conspire to make superconductors a very different system from a neutral, dilute condensate. A similar pairing and condensation occurs in superfluid helium 3, whose atoms are fermions.

Excitons. In semiconductors, the absence of an electron can behave like a positively charged particle, called a hole. A hole and an electron, generated by a laser pulse, can pair up briefly as an entity called an exciton. In 1993 physicists observed evidence of such excitons forming a short-lived gaseous condensate in a copper oxide semiconductor. —*G.P.C.*

monsense understanding of how things work: objects have definite locations, motions and identities, and their behavior is rigidly prescribed by deterministic laws.

The very heart of quantum mechanics, in contrast, defies our everyday intuition. The locations and motions of particles are fundamentally equivocal and ruled by probabilities. Even the idea of objects having distinct identities is radically modified for quantum particles. A Bose-Einstein condensate is a collection of matter behaving in one of the purest quantum-mechanical fashions known.

What's more, condensates are huge—100,000 times larger than the biggest ordinary atoms, larger even than human cells—so physicists can watch the quantum behavior of a condensate in ways ordinarily unthinkable. As Steven L. Rolston of the National Institute of Standards and Technology (NIST) in Gaithersburg, Md., emphasizes, "The pictures we show of BECs are true pictures of quantum-mechanical wave functions—we can actually see quantum mechanics at work."

Gaseous Bose-Einstein condensates were first created in the laboratory in 1995, a full 70 years after the phenomenon was predicted by Albert Einstein based on work by Indian physicist Satyendra Nath Bose [see "The Bose-Einstein Condensate," by Eric A. Cornell and Carl E. Wieman; SCIENTIFIC AMERICAN, March 1998]. Experimenters create these condensates in atom traps—constructions of laser beams and magnetic fields that capture, hold and cool a very dilute cloud of atoms inside a vacuum chamber [*see box on page 97*]. The distinguished atomic physicist Daniel Kleppner of the Massachusetts Institute of Technology calls the creation of these condensates "the most exciting single development in atomic physics since the development of the laser."

Research groups around the world, some headed by Nobel laureates and laureates-to-be, have been working furiously for five years to explore the exotic realm opened up by that breakthrough. They have poked and prodded the condensates with laser beams, jiggled the traps that hold them, and watched as the gas has bounced, sloshed and vibrated in the expected quantum ways.

In addition to being exemplar quantum systems, condensates embody a curious amalgam of several broad fields of physics: atomic physics (individual atoms), quantum optics (laser beams and their interactions) and many-body physics (collections of matter that make up solids, liquids and gases, including the technologically vital realm of electrons flowing in metals and semiconductors). The study of condensates not only draws on all those fields in an interdisciplinary way, it contributes directly to our understanding of the basic laws that govern them.

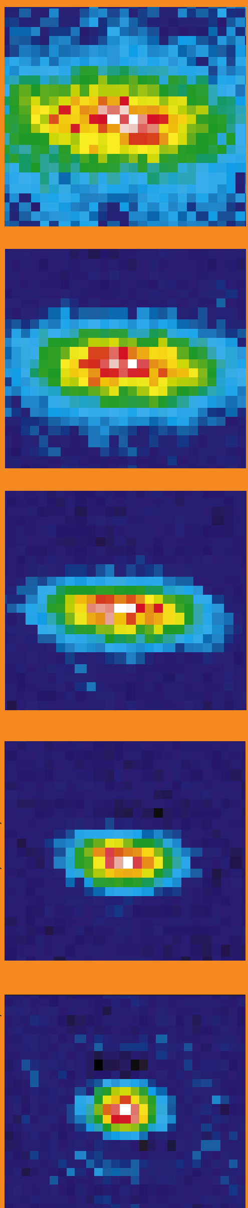
This article can sample only a few of the amazing and diverse experimental achievements that physicists are obtaining with BECs. The results highlight some of the many faces that a condensate presents to experimenters: its behavior as a superfluid akin to liquid helium, as a finely controllable atomic gas and as a kind of laser beam made of matter instead of light.

BECs, Superfluids and Vortices

When liquid helium is cooled to within 2.2 kelvins of absolute zero, a number of strange things happen. As Soviet physicist Pyotr Kapitsa and Canadian John F. Allen discovered in 1938, below that temperature helium becomes a superfluid, flowing completely without viscosity and capable of

JOHN F. ALLEN *University of St. Andrews*; COURTESY OF RUSSELL DONNELLY *University of Oregon*

Physicists can modify the interactions in a condensate at will—an experimenter's dream



ADAPTED FROM S. L. CORNISH ET AL., *PHYSICAL REVIEW LETTERS*, VOL. 85, 2000

FORCES acting among the atoms of a condensate alter its size and proportions. Here researchers adjusted the forces from strongly repulsive (*top*) to almost zero strength (*bottom*). Tuning the forces further and making them weakly attractive caused the condensates to collapse and explode like miniature supernovae.

tricks such as slithering up the walls and out of an open container. Bose-Einstein condensation in the helium produces these effects [*see box on opposite page*].

Experimenters have been eager to see if the gaseous condensates could exhibit superfluidity, but doing so has not been a trivial task. Superfluid helium can be produced in large enough quantities for one to watch its tricks with the naked eye. The new condensates, in contrast, are minuscule wisps of gas barely more substantial than a vacuum, held in place by magnetic fields for a scant few minutes at best. What would it mean for such a gossamer vapor to be a superfluid?

A dramatic effect involves producing vortices in a rotating superfluid. If you rotate a bucket of ordinary liquid helium on a turntable, the helium rotates with the bucket, much as water would. Superfluid helium, in contrast, forms an array of quantum whirlpools called vortices. The minimum rotation allowed has a single vortex, spinning rapidly in the middle of the helium and slowly at the edges. If you try to rotate the superfluid more slowly, it will remain motionless.

These effects occur because the atoms in a condensate are in the same quantum state, and therefore all must have the same angular momentum. But angular momentum can exist only in discrete units, or quanta. In the motionless state the atoms all have zero angular momentum; in a vortex they each have one unit of it.

In 1999 a research group at JILA (formerly the Joint Institute for Laboratory Astrophysics) in Boulder, Colo., led by Carl E. Wieman and Eric A. Cornell produced vortices in BECs using a technique that their colleagues James E. Williams and Murray J. Holland had proposed. They started with a double condensate, a highly versatile system pioneered by the group involving two overlapping condensates made of the same element (rubidium) but in slightly different quantum states.

The researchers shone microwaves and a laser beam on the double condensate, with the effect of imprinting one condensate with the precise circular quantum phase required for a vortex. This process, which to anyone but a quantum physicist does not seem to be *moving* any of the atoms, produces the rotating vortex state. By looking at how the two condensates interfered with each other, the group was then able to verify the quantum phase properties of the vortex, something that had never been achieved so directly in 60 years of work on superfluid helium.

Later in 1999 a group at the École Normale Supérieure in Paris, led by Jean Dalibard, succeeded where previous efforts had failed in emulating the "rotating bucket" approach to generating vortices. To produce the rotation, Dalibard's team moved a laser beam around the edge of the trap, creating the semblance of a rotating distortion in its shape. These investigators have imaged arrays of up to 14 vortices. In a paper published this past September, they reported measuring the angular momentum of their condensates: in agreement with theory, the momentum is zero until the first vortex appears, at which point it jumps to one whole unit.

Beyond its interest as fundamental physics, the quantum dy-

Key Concepts

Quantum mechanics describes how nature works at the scale of atoms and has many features that are counterintuitive to our everyday experience. One feature of quantum mechanics is that particles have wavelike properties—the "wave function" of a particle defines its quantum state. Also, every elementary particle is intrinsically either a fermion or a boson.

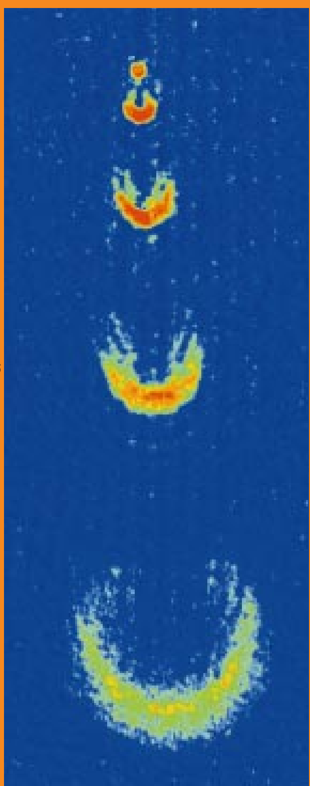
Fermions behave claustrophobically—two fermions cannot occupy identical quantum states in the same location. Electrons, protons and neutrons are fermions. [See "Quantum Claustrophobia," News and Analysis, SCIENTIFIC AMERICAN, November 1999.]

Bosons behave gregariously. Bosons of a particular species tend to gather together in identical states if given the opportunity. Photons (particles of light) are bosons. Composite particles such as atoms are also either bosons or fermions. An atom made of an even number of protons, neutrons and electrons is a boson.

Bose-Einstein condensation (BEC) occurs when a collection of bosons of one species is made sufficiently cold and dense without locking together as a solid. Wave functions enlarge at extremely low temperatures, and when the bosons' wave functions overlap, all the bosons accumulate in one quantum state.

Behavior of BECs sheds light on the fundamentals of an assortment of subfields of physics. These include quantum mechanics, superfluidity, superconductivity, the properties and interactions of atoms, laser physics and nonlinear optics. —*G.P.C.*

STEVEN L. ROLSTON *NIST*



DALLIN DURFEE AND MICHAEL ANDREWS *Massachusetts Institute of Technology*

ATOM LASERS are in essence moving condensates, material analogues of optical laser pulses or beams. The first atom laser (*left*) was "powered" by gravity. Pulsed radio waves hitting a trapped condensate (*circle at top*) released clumps of condensate (*crescents*). Repulsion between the sodium atoms produces the crescent shape and accelerates the crescents' expansion. In the first directed atom laser (*above*), atoms were propelled sideways out of the trap by laser beams.

namics of vortices is important for high-temperature superconductor technology: Magnetic fields penetrate these materials by creating an array of vortices of electric current in the material. The motion of such flux vortices dissipates power, spoiling the highly desirable "zero-resistance" property of superconductors. Studies of the BECs may help tame this problem.

Malleable Atomic Interactions

Vortices in superfluid helium have cores only a tenth of a nanometer in diameter, making them virtually impossible to examine in detail. The cores of the Colorado and Paris vortices are about 5,000 times larger, because compared with liquid helium the gaseous condensates have extremely low density and their atoms interact very weakly.

Essentially nothing can be done about liquid helium's density and interactions, but the density of gaseous BECs can be adjusted by tightening or loosening the magnetic traps that hold the gas. In addition, physicists have the remarkable ability to modify the interactions in the gaseous BECs at the turn of a dial. Such an ability is an experimenter's dream—imagine how chemistry could be studied if we could weaken or strengthen the bonds between atoms at will.

The atoms in a gaseous condensate experience a small mutual repulsion or attraction, depending on their species. For example, atoms of sodium, rubidium 87 and hydrogen repel their own kind. Lithium 7 and rubidium 85 atoms attract. These forces, though tiny, modify innumerable properties of a condensate, such as its internal energy, its size, its modes of oscillation and its rate of formation. Most important, a repulsion stabilizes a condensate, whereas an attraction is destabilizing. Consequently, experiments using repulsive rubidium 87 or sodium routinely condense millions of atoms at a time, and the condensates can be 20 times larger than they would be in the absence of the repulsion. Conversely, the attraction limits lithium 7 condensates produced by Randall G. Hulet's group at Rice University to about 1,500 atoms. Above that size, the condensate contracts and becomes too dense, triggering collisions that spill atoms out of the trap. These results are now well understood by sophisticated theoretical modeling, but as recently as the early 1990s physicists doubted that attractive atoms could form a condensate at all.

The atoms' interactions can be modified by so-called Feshbach resonances, named after nuclear theorist Herman Feshbach of M.I.T., who studied an analogous phenomenon in colliding nuclei in the 1960s. In a gas, a strong magnetic field distorts the atoms and at certain strengths causes two atoms to resonate when they collide. In a condensate the atoms continuously feel the effects of these resonances because their quantum waves overlap; the resonances modify the forces between the atoms, with the largest effects occurring near the resonant magnetic-field strength.

One difficulty is that a strong magnetic field can ruin the magnetic trapping of the atoms. Wolfgang Ketterle's group at M.I.T. solved that problem in 1998 by transferring sodium condensates from a magnetic trap to a laser-based one. But although the M.I.T. group was able to observe the effects of Feshbach resonances, extended studies were impossible: to the researchers' great surprise, when the magnetic fields were tuned close to a resonance, the sodium condensates disintegrated within microseconds.

Long-lived condensates with tunable interactions were developed earlier this year by Cornell and Wieman's group, us-

A laser knocks atoms out of the trap through the "circle of death"

ing rubidium 85 and a conventional magnetic trap. Ordinarily, rubidium 85's attractive interactions prevent its condensate from growing beyond a measly 80 atoms. But by using Feshbach resonances to switch these forces to be repulsive, the Colorado group achieved stable condensates of up to 10,000 atoms with lifetimes as long as 10 seconds.

The most spectacular effects occurred when the group gradually decreased the artificial repulsion. As predicted by theory, the giant condensates shrank smoothly in size and became dense. Finally, about five milliseconds after the interactions crossed back to attractive, the condensates exploded—a phenomenon that Wieman has whimsically dubbed a "Bose nova," by loose analogy with the implosion that fuels exploding stars. The explosions blasted perhaps a third of the condensate atoms completely out of the trap, leaving behind a remnant condensate surrounded by a hot cloud of atoms (if a temperature of 100 billionths of a degree can be called "hot").

Atom Lasers

A possible application of the interaction tuning is the delicate control of beams of atoms emitted from condensates. Such beams are known as atom lasers. Atomic beams are already used in a variety of scientific and industrial applications, including atomic clocks, precision measurements of fundamental constants and production of computer chips. But all those beams lack the brightness and "coherence" of an atom laser, just as ordinary light lacks the brightness and coherence (and thus the versatility) of a laser beam. (Coherence means that all the atoms or photons in the beam move in a kind of quantum synchrony, with their associated waves closely aligned.)

It took the laser decades to go from being an esoteric experimental device in 1960 to an almost ubiquitous element of consumer electronics. Some researchers suggest that in the decades to come, atom lasers could have an equally fruitful future, in ways as inconceivable now as today's uses of lasers were in the 1960s. Major obstacles lie in the path of this prophecy, of course, not least being the need to send atom beams through a vacuum instead of through air.

The earliest atom lasers generated their pulses and beams in a fashion completely unlike optical lasers (prompting some to insist that atom "laser" was a misnomer). In essence, an atom laser is any coherent, freely moving lump or stream of BEC. The atoms of a BEC are confined in a magnetic trap by their own tiny magnetic dipole, or spin. Correctly tuned radio waves will flip the spins of atoms and make them immune to the trapping fields. Ketterle's group took advantage of this effect in 1997 to create the first atom laser. They pelted a sodium condensate with pulses of radio waves. Atoms whose spins had been flipped dropped out of the trap—crescent-

Machines for Cooling and Trapping Atoms

Quantum Coolers

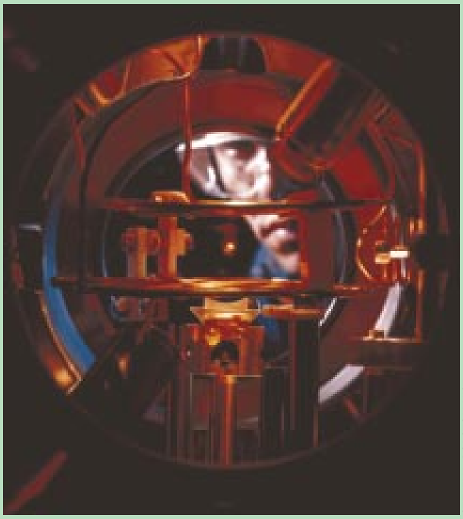
Laser cooling. To create a gaseous Bose-Einstein condensate, experimenters must cool a dilute gas of atoms in a vacuum chamber to an extremely low temperature. The first step in almost all the experiments is laser cooling, in which laser beams slow down the motion of atoms, cooling them from perhaps room temperature (300 kelvins) or much higher to about 50 microkelvins—one twenty-thousandth of a degree above absolute zero.

Magneto-optical trap (MOT). The most common precooling device used in BEC experiments is the magneto-optical trap, which combines laser cooling with trapping of the atoms by magnetic fields. The magnetic fields help to compress the gas to a higher density. Many groups use a sequence of two MOTs, optimized respectively for collecting atoms and then for cooling them.

Evaporative cooling. The final cooling stage in BEC experiments is analogous to the cooling of a cup of coffee. While a magnetic trap holds the atoms, the hottest fraction of atoms is continuously removed, so that increasingly lower-temperature gas remains. Unlike laser cooling, evaporative cooling works best at higher densities.

TOP trap. Used by the group of Eric A. Cornell and Carl E. Wieman at JILA to create the first gaseous atomic condensate in 1995, the time-averaged orbiting potential magnetic trap has been adopted by several groups. Its coils produce a magnetic field that has a zero point from which atoms can leak. By moving the field rapidly around in a circle, the trap confines the atoms in an ellipsoidal region inside the orbit of the leak (the "circle of death").

Ioffe-Pritchard (IP) traps. Named after Russian physicist M. S. Ioffe (whose Ioffe trap was for trapping plasmas of charged ions) and David Pritchard of M.I.T., Ioffe-Pritchard traps produce a trapping field without a leaky zero point. They are the main alternative to TOP traps and come in a diverse array of designs, with condensates ranging from nearly spherical to long cigar shapes. Their magnetic fields are produced by running current through four parallel bars or through coils shaped like letter D's, the seams of a baseball or four-leaf clovers.



STEVEN L. ROLSTON *NIST*

GLOWING SODIUM ATOMS are held in a magneto-optical trap and watched by Kristian Helmerson of the National Institute of Standards and Technology. Coils produce a magnetic field, and laser beams enter from six directions, holding and cooling the atoms.

Permanent magnet trap. This style of IP trap employs permanent magnets to produce the fields. Randall G. Hulet's group at Rice University uses it to produce condensates in lithium. The permanent magnets cannot be turned off, so the condensate can only be imaged in situ. *—G.P.C.*

shaped pulses of moving condensate propelled by gravity!

In late 1998 Theodore Hänsch's group at the University of Munich demonstrated a similar system that emitted a continuous beam of rubidium atoms. The Munich group estimated that its atomic beam was more than a million times brighter than similar (but nonlaser) beams of atoms produced by other techniques. Around the same time, William D. Phillips, Steven Rolston and their co-workers at NIST finally produced an atom laser that could be pointed in a direction other than down. Optical-laser pulses knocked atoms out of the condensate and through a circulating hole on the outskirts of their trap (a location known as the circle of death). A sequence of laser pulses carefully synchronized with the circle of death produced a finely collimated, essentially continuous beam—described in one report as "an atomic ray gun with laserlike precision," which sounds like hyperbole but is technically factual.

The "a" in "LASER" stands for "amplification," but in the atom lasers described so far, the only amplification to speak of occurs in the initial creation of the BEC, when the population of atoms in the single quantum state is "amplified" by Bose condensation. Amplification of atom-laser beams, also known as matter-wave amplification, was only achieved in late 1999, by an M.I.T. group led by Ketterle and Pritchard and, independently, by Takahiro Kuga and his co-workers at the University of Tokyo.

Matter-wave amplification does not mean that matter is created out of energy by the amplifier. Rather a small atom-laser pulse is created in a BEC, and that pulse is amplified

Hydrogen Man

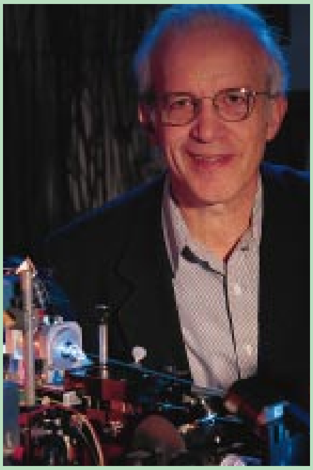
The Godfather of BEC

In the year or two after the creation of BEC, Daniel Kleppner of M.I.T. would be introduced at conferences as "the godfather of BEC." He couldn't be "the father of BEC," after all, because his own group, distressingly, still hadn't produced a condensate. And yet he loomed paternally over the field as both pioneer and continuing participant and as a mentor to the young upstarts who had seized the grail as their own.

The three groups that first demonstrated BECs in 1995 and 1996 were led by Kleppner's students and "grandstudents." Wieman worked in his laboratory as an undergraduate in the early 1970s. Cornell was a graduate student of Pritchard's, who in turn was a graduate student of Kleppner's. Ketterle first worked on cold atoms as a postdoc of Pritchard's. Hulet was a grad student in Kleppner's group, as was Nobel laureate Phillips, whose group made a BEC in 1998. Like any teacher, Kleppner takes great pride in his students' accomplishments. "But they can overdo it," he quips.

When his former students were making their spectacular condensates of rubidium, sodium and lithium (alkali atoms), Kleppner was battling with his career-long atom of choice: hydrogen. He has been studying hydrogen since he was a graduate student and postdoc at Harvard University in the late 1950s. Working there with Norman Ramsey, Kleppner helped to invent the hydrogen maser, a kind of laser operating at microwave frequencies that has seen applications in extremely precise measurements, including tests of Einstein's general relativity. (The maser was among the work cited when Ramsey won the Nobel Prize in 1989.) In 1966 Kleppner moved across town from Harvard to M.I.T., where he is now acting director of the Research Laboratory of Electronics.

Kleppner got into the Bose-Einstein game around 1976, working with a form of hydrogen called spin-polarized. "I thought the idea was nutty," Kleppner recalls, but a young professor named Thomas Greytak persuaded him of its merits. They have worked together ever since.


SAM OGDEN

DANIEL KLEPPNER began pursuing Bose-Einstein condensation in hydrogen back in 1976, racing against a Dutch group: "It took a little longer than any of us expected."

In spin-polarized hydrogen, all the atoms have their spins aligned the same way (think of the spin as a tiny magnetic compass needle that each atom carries around). Such a gas is as inert as helium because two hydrogen atoms must have oppositely aligned spins to form a molecule. Alone among all the elements, this form of hydrogen should remain a gas all the way down to absolute zero.

Inspired by these predicted properties, in the late 1970s Kleppner and Greytak at M.I.T. and competitors at the University of Amsterdam began work to create a BEC in spin-polarized hydrogen, never dreaming how long the quest would take or that condensates in *metallic* atoms, of all things, would beat them to the punch.

Although it wasn't first to the prize, Kleppner's group made several key advances on the road to BEC, such as demonstrating evaporative cooling in spin-polarized hydrogen in 1987, a feat that the alkali-atom groups only duplicated seven years later. By 1991 the Kleppner-Greytak group had pushed to within a factor of three of the temperature and density needed for a condensate (alkali atoms were about a factor of a million behind). Alas, some perverse properties of hydrogen threw up roadblocks at this point, including difficulties in observing key properties of the gas to confirm creation of a condensate. In the alkali-atom gases, visible light and standard laser techniques can be used. The corresponding light for hydrogen is ultraviolet and requires a more sophisticated approach.

Finally, in June 1998, Kleppner received a late-night phone call from two of his current students to come into the lab. A Bose-Einstein condensate in hydrogen had been observed at last! A month later, at a conference in Varenna, Italy, Kleppner announced his group's success. The assembled experts—colleagues, competitors and former students—gave the proud new parent a long standing ovation. —*G.P.C.*

when additional BEC atoms follow their Bose nature and join it. Concurrent scattering of light from a pump laser beam ensures that momentum and energy are properly conserved.

The M.I.T. group realized that matter-wave amplification by this process was possible when, earlier in 1999, they hit one of their cigar-shaped condensates with a polarized laser beam and were startled to see clumps of atoms emerging at 45 degrees and light beaming out of each end of the "cigar." The process was a form of scattering called superradiance that involved rudimentary amplification.

These processes amount to condensates acting in their most lightlike manner, in sharp contrast to their liquid behavior as superfluids. A tremendously active field in optics over the past decade has been nonlinear optics, involving the interactions of light with itself. Nonlinear effects are increasingly important, for example, in optical fibers operating at the highest data rates.

Normally, light barely interacts with itself, so high intensities or special media are needed to achieve these nonlinear effects. The weak interactions of atoms in condensates automatically produce nonlinear effects, which makes them ideal for studying such processes. The simple classical notion of atoms as particles colliding like tiny marbles utterly fails to account for the observed results of these experiments.

CHRIS H. GREENE *University of Colorado at Boulder*

"TRILOBITE MOLECULE" of two rubidium atoms, 1,000 times larger than a typical diatomic molecule, could be formed within a condensate by appropriate laser excitation. Gold curves indicate the density of the calculated electron cloud forming the bond. The green ball is one atom; the other is obscured under the "twin towers." Groups have produced more ordinary ultracold molecules in condensates by similar laser techniques but have not yet demonstrated a condensate of molecules.

Ersatz Black Holes?

One feat of nonlinear optics is to slow light down to a stunning degree. In a vacuum, electromagnetic waves—including radio, x-ray and light waves—travel at the ultimate speed limit: 300,000 kilometers (186,000 miles) per second. Light zips along less swiftly in a medium, moving at about three fourths of its top speed in water and two thirds in a typical glass. In 1999, by shining a beam through an ultracold and optically modified gas, Lene Vestergard Hau of the Rowland Institute for Science in Cambridge, Mass., slowed light down to 17 meters per second, the pace of a speedy bicycle. In a November paper, Ketterle's group reported observing light traveling at one meter per second through a condensate, a walking pace. One does not need a condensate to produce such effects, but the intense cold of condensate gases has features that are ideal for inducing the most extreme examples.

Sound waves near vortices might mimic black hole phenomena

Intriguingly, Ulf Leonhardt and Paul Piwnicki of the Royal Institute of Technology in Stockholm suggested in 1999 that slow light propagating near a vortex in a condensate might serve as a tabletop analogue for processes near rotating black holes. For example, the light could be dragged into the core of a vortex, particularly if the beam was moving "upstream" against the rotational flow.

In unpublished papers Peter Zoller, Ignacio Cirac and their co-workers at the University of Innsbruck in Austria show that with current state-of-the-art technology, it should be possible to build *sonic* models of black holes—that is, ersatz black holes in which sound waves take the place of light. Their calculations indicate that such black holes would explode in a burst of phonons, the quanta of sound waves. Such explosions might be analogous to the evaporation of microscopic gravitational black holes via Hawking radiation, a thermal mix of particles predicted to emerge as a result of quantum effects.

In an August paper, Wayne Hu and his co-workers at Princeton University speculate that the unseen "dark matter" that makes up perhaps 90 percent of the universe could exist in the form of a Bose-Einstein condensate of exceedingly low mass particles permeating space. Such a condensate form of dark matter might, they suggest, solve some problems that dog the otherwise quite successful "cold dark matter" cosmology theories. If that remarkable hypothesis is true, the coolest gases in the universe may also turn out to be the most abundant. SA

Further Information

The Yin and Yang of Hydrogen. Daniel Kleppner in *Physics Today*, Vol. 52, No. 4, pages 11–13; April 1999.

Atom Lasers. Kristian Helmerson, William D. Phillips, Keith Burnett and David Hutchinson in *Physics World*, Vol. 12, No. 8, pages 31–36; August 1999.

Bose Condensates Make Quantum Leaps and Bounds. Yvan Castin, Ralph Dum and Alice Sinatra in *Physics World*, Vol. 12, No. 8, pages 37–42; August 1999.

Experimental Studies of Bose-Einstein Condensation. Wolfgang Ketterle in *Physics Today*, Vol. 52, No. 12, pages 30–35; December 1999.

Bose-Einstein Condensation Homepage at Georgia Southern University is at http://amo.phy.gasou.edu/bec.html

DIAPERS_DISPOSABLE

Superabsorbers

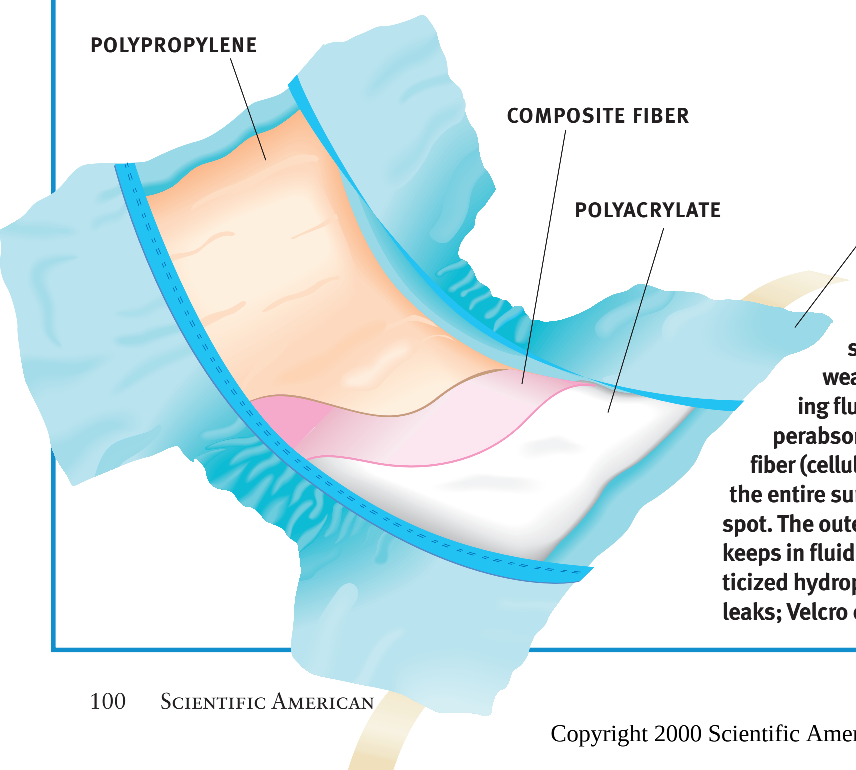
If you've taken a diaper off a baby sometime in the past decade, you were probably surprised—not at how messy it is, but at how heavy it is. Today's disposable diapers can hold pounds of pee and still feel quite dry, which may be why fewer than 5 percent of American babies use cloth diapers.

This astonishing absorbency comes from a family of hydrophilic ("water-loving") polymers called polyacrylates. Perhaps the simplest of these is sodium polyacrylate, which can hold 800 times its weight in distilled water. Of course, there's more to urine than water. Dissolved salts and ions reduce the absorbency by more than a factor of 10. The leading brands of diapers use combinations of polyacrylates that presumably do better—but it might be easier to find the recipe for an atom bomb than for a diaper filling. It's a competitive industry.

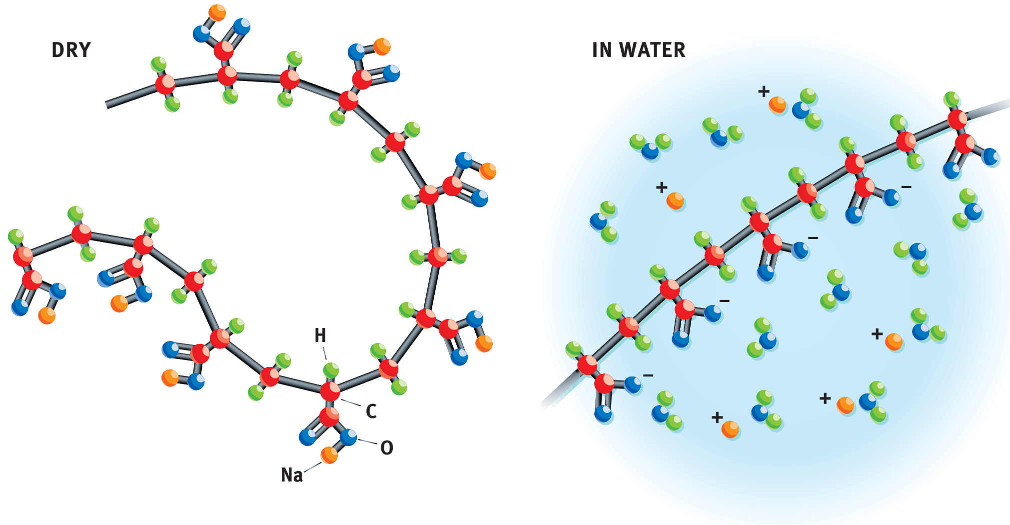
Because they keep the skin drier than cloth, disposable diapers are probably better for baby, although the margin is unclear in practice—babies in cloth diapers are changed more often and don't have seem to have diaper rash more frequently. Advocates of cloth diapers point to the enormous environmental cost of disposables. The overall environmental equation of washable versus disposable diapers is hard to quantify, but the latter form a significant chunk of the urban waste stream. Disposable diapers add about 2.7 million metric tons of pee, poop, plastic and paper to U.S. landfills every year.

In tropical countries, babies often go diaper-free; it's cheaper just to mop up the floor. In fact, as this mother was informed (sometimes by virtual strangers) during a visit to India, it's considered cruel and unusual treatment to subject a baby to the breezeless confinement of a diaper. Result: no rash and no trash.

—Madhusree Mukerjee, staff writer



MOST MATERIALS used in a disposable diaper are synthetic. Polypropylene, used in winter athletic underwear, makes up the inner layer; it is soft and stays dry, drawing fluid away from the skin. At the core is the polyacrylate superabsorbent powder, combined with fluffy cellulose. A layer of fiber (cellulose or synthetic) fights gravity by distributing fluid over the entire surface of the powder instead of letting it pool in one spot. The outermost layer is mostly microporous polyethylene; it keeps in fluid but lets out vapor. Adhesives hold it all together: elasticized hydrophobic polypropylene cuffs around the thighs contain leaks; Velcro or sticky tabs hold the diaper on the baby.



SODIUM POLYACRYLATE has sodium carboxylate groups hanging off the main chain. In contact with water the sodium detaches, leaving only carboxyl ions. Being negatively charged, these ions repel one another so that the polymer unwinds and absorbs water, which is attracted to the sodium atoms. The polymer also has weak cross-links, which effectively leads to a three-dimensional structure. In addition, it has molecular weights of more than a million; thus, it cannot dissolve but instead solidifies into a gel.

LARGE DISPOSABLE DIAPER can hold half a gallon of water. Superabsorbents are the secret.

DID YOU KNOW . . .

- Superabsorbents are useful not only for personal hygiene (diapers, adult incontinence pads, and so on) but also for mopping up medical wastes in hospitals, for protecting industrial power and optical cables from water leaks, for filtering water out of aviation fuel and for conditioning garden soil to hold water—not to mention as toys that expand when placed in water.

- A study published in 1999 found that mice who were exposed to disposable diapers suffered eye, nose and throat irritations, some resembling an asthma attack. Gases emanating from solvents and other chemicals in the diapers were suspected to be responsible. Superabsorbents were withdrawn from use in tampons after an outbreak of toxic shock syndrome in 1980.

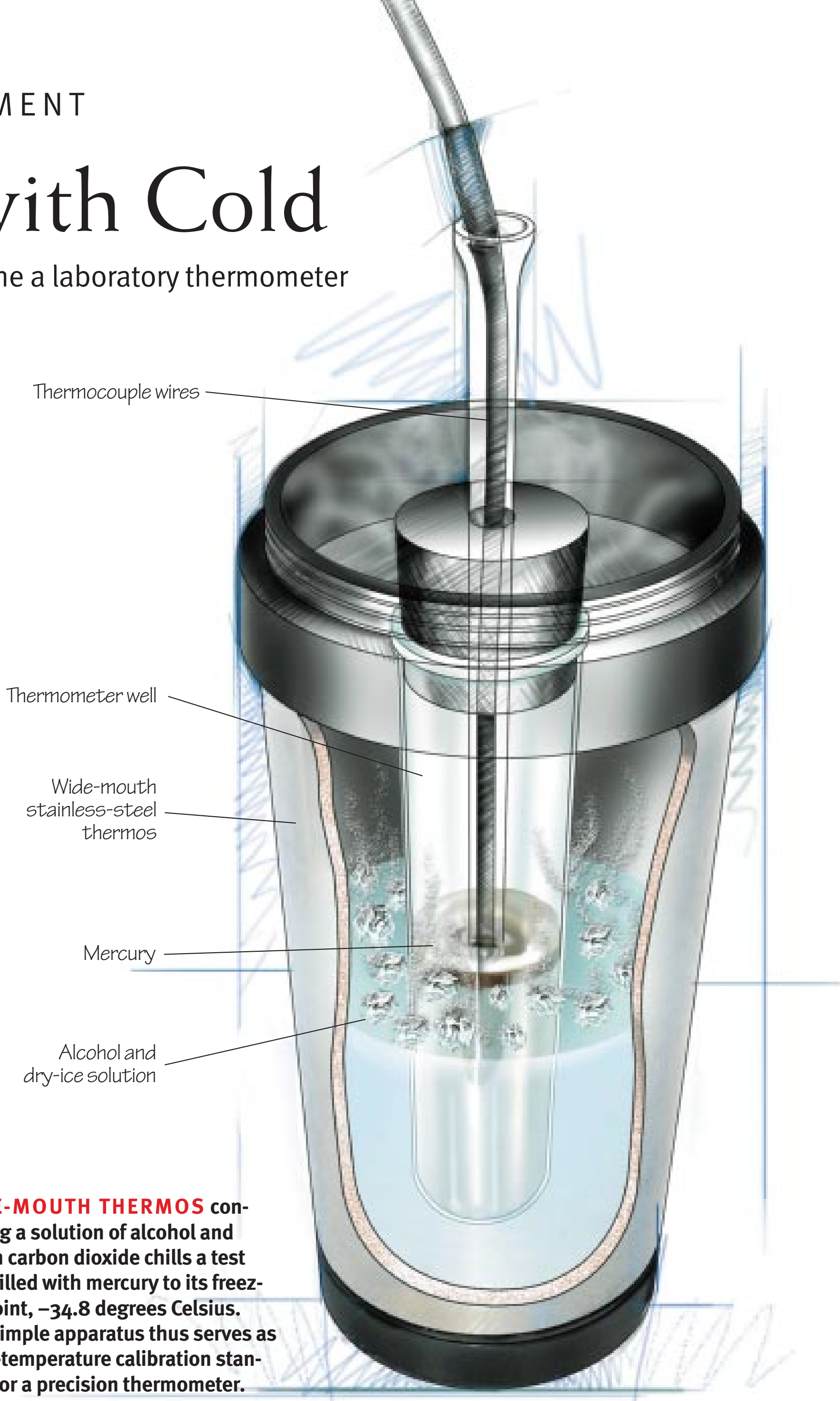
- Babies in cloth diapers are toilet-trained almost a year earlier than babies in disposables. Although that could be a matter of cultural mores, it is probably also because the disposables are so absorbent that often neither baby nor caregiver can tell when the baby eliminates, and so the child can't easily associate the act with using the toilet.

ILLUSTRATIONS BY BRYAN CHRISTIE AND GEORGE RETSECK; VINCENT OLIVER *Stone* (photograph)

TEMPERATURE_MEASUREMENT

Calibrating with Cold

Shawn Carlson shows how to fine-tune a laboratory thermometer



WIDE-MOUTH THERMOS containing a solution of alcohol and frozen carbon dioxide chills a test tube filled with mercury to its freezing point, –34.8 degrees Celsius. This simple apparatus thus serves as a low-temperature calibration standard for a precision thermometer.

After having lived in balmy California all my life, I just moved to Rhode Island. I love it, but the frigid weather here requires some getting used to. Wintering in the Northeast has also forced me to check the operation of some of my laboratory instruments, especially my outdoor electronic thermometers.

In general, one calibrates a thermometer by finding out what it reads at two known temperatures and interpolating between them. Until now, I've always calibrated my thermometers down to 0 degrees Celsius. That strategy worked well because the weather around my former home in San Diego rarely dipped below freezing. The same can't be said for New England. So when accuracy counts, amateur meteorologists living in colder climates must be able to perform a truly chilly temperature calibration.

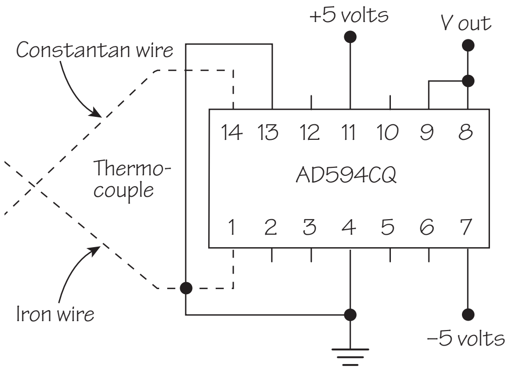
My own temperature station relies on a J-type thermocouple [*see illustration on page 104*]. The thermocouple wire costs $10 for a spool (Omega; see www.omega.com or call 800-872-9436). Just strip the insulation off and twist the ends together to form the sensor. The integrated circuit to which it attaches runs about $24 (Analog Devices AD594CQ, available from Pioneer-Standard Electronics; check www.ied.pios.com/onestop/ or call 440-720-8500), which may seem a bit pricey, but it is worth every penny, because the device automatically compensates for several subtle effects that otherwise complicate thermocouple measurements. This simple setup is accurate to about one degree if you interpolate temperature values from the table on page 104.

But you can do about 10 times better by calibrating your thermometer. My usual procedure was to record the output voltage of the circuit when the thermocouple was immersed in a slurry of distilled water and ice chips, which gave me 0 degrees Celsius, and also in distilled boiling water, which gave me 100 degrees Celsius. The latter remains a useful high-temperature end point for the calibration. Be aware, however, that the boiling temperature of water depends on atmospheric pressure (which changes with altitude and with the weather). So you will need to know the barometric pressure to determine the exact boiling temperature of water; for this task you could use one of the handy calculators available on the Internet (for example, www.biggreenegg.com/boilingPoint.htm).

To learn how to make a truly low-temperature standard, I turned to my good friend George Schmermund. After perfecting his triple-point-of-water cell (described in The Amateur Scientist of February 1999), George began developing other temperature standards, including one based on the freezing point of mercury, which falls at –34.8 degrees C. Mercury is somewhat expensive (the 500 or so grams you will need costs more than $100), but it is widely available (try Thomas Scientific; www.thomassci.com or 800-345-2100). And although it is a potent poison, it can be handled with complete safety by strictly following a few commonsense precautions.

Begin by filling a wide-mouth stainless-steel thermos (the kind used to keep

ALL ILLUSTRATIONS BY DANIELS & DANIELS



INTEGRATED CIRCUIT, the Analog Devices AD594CQ, makes a J-type thermocouple into a highly accurate thermometer for a home weather station.

soup warm) about halfway with a solution of 91 percent isopropyl alcohol. (This is the least dilute variety George can buy at his drugstore.) Next obtain a small block of frozen carbon dioxide from a nearby liquor store. (Check the Yellow Pages under "dry ice" to find a local supplier.) Wrap the frosty mass inside a towel and hammer it into small fragments. Transfer some of the chips to the thermos using tongs and stir the concoction with a wooden spoon until it stops bubbling.

The effervescence gives off a highly flammable cloud of alcohol vapor, so work only where a fan blows plenty of fresh air over your work area. And, obviously, keep cigarettes and all open flames well away. Position the thermos inside a plastic food-storage container to catch any liquid that might escape. Note that you should never pour room-temperature alcohol into the cold solution. The chilled liquid contains a lot of carbon dioxide, and if suddenly warmed by the addition of more alcohol, CO_2 vapor will burst out of solution, causing a frothy foam to erupt from the thermos.

Before you go to the trouble of making up the cold liquid, though, you'll need to fashion a "thermometer well"—something to protect your thermocouple when it is immersed in the mercury. You can buy just the right piece of glassware as part of a kit from the Society for Amateur Scientists, or you can make your own from a slender Pyrex tube by following the procedure for fabricating test tubes that was given in the May 1964 installment of this department.

With the appropriate thermometer well and cold bath, a temperature calibration at the freezing point of mercury is easy to perform. Secure a large test tube and a matching rubber stopper from a purveyor of scientific supplies (one is Fisher Scientific; www.fisherscientific.com or 800-766-7000). Make sure the stopper comes with a hole that is the right size to accept the thermometer well, stuck just far enough in that it hangs about two centimeters from the bottom of the test tube. Fill the test tube two thirds full with mercury. Pour some alcohol in the well and insert your thermocouple so that it is about one centimeter from the bottom and, if possible, not touching the glass. Then immerse the well in the mercury and push the stopper snug. Finally, place the entire assembly gently into the thermos containing the chilled alcohol solution.

Be careful! The vapor pressure of mercury at room temperature is sufficiently high that prolonged exposure can cause brain damage. Don't allow pregnant women or children anywhere near, work only in a well ventilated area, and wear protective clothing and safety glasses. Also, keep your containers of mercury tightly sealed. And because spills are notoriously difficult to clean up, think through all the ways that an accident might happen before you begin. Make sure, for example, that you can fully contain any spills if one does take place by keeping the mercury-filled test tube low to the table and over a large food-storage container. Once contaminated, plastic can never be completely cleaned, so clearly and permanently label it "DANGER! MERCURY CONTAMINATED—DO NOT USE FOR FOOD."

I should emphasize that mercury is rightly classified as hazardous waste, and by law it must be disposed of safely. Because regulations vary regionally, you'll have to contact the hazardous materials office of your local fire department for guidelines.

To carry out the calibration, carefully monitor the output of your thermometer as the temperature plummets. When the mercury begins to freeze, the voltage will remain nearly constant and won't drop again until all the mercury has solidified. After you see the voltage fall for a second time, remove the test tube and place it in a sturdy stand. Then record the output of the circuit as the mercury melts. Again, it should linger at one voltage for a while. If the voltage stabilized at the same value as before, you can be confident that the temperature plateau occurred at exactly –34.8 degrees C.

If the two voltages (at freezing and at melting) were different, your mercury is contaminated. To purify it, submerge the test tube in the chilled alcohol and wait until about half the metal has solidified. Pour the remaining liquid into a separate container for waste mercury. Repeating these steps a second time should yield mercury that is at least 99.99 percent pure. Produce enough of it for your needs and then perform the calibration as described.

Once you have determined the output voltages for the freezing point of mercury and for the freezing and boiling points of water, check these numbers against the table below. This comparison will immediately reveal the corrections you should apply to the tabulated values at –34.8, 0 and 100 degrees. You can then interpolate the appropriate changes to all temperatures within this range, which brackets even the coldest winter nights that Rhode Island is ever going to see. Now my home weather station is operational again—just as long as I don't ever decide to move to the South Pole. SA

Temperature (degrees Celsius)	Output (volts)
–34.8	–0.327
–20	–0.189
–10	–0.094
0	0.003
10	0.101
20	0.200
25	0.250
30	0.300
40	0.401
50	0.503
60	0.606
80	0.813
100	1.022

The Society for Amateur Scientists will offer a kit for this project until December 2001. The package contains a large, hand-blown test tube with a flat bottom, a rubber stopper and a glass thermometer well, a plastic spill guard, protective gloves and an insulated flask for the dry-ice solution. Mercury and alcohol are not included. The price is $150. To order, call the Society for Amateur Scientists at 877-527-0382. You can write the society at 5600 Post Road, #114-341, East Greenwich, RI 02818. To purchase Scientific American*'s new CD-ROM containing every article published in this department through the end of 1999 (more than 800 in all), consult www.tinkersguild.com or dial toll-free: 888-875-4255.*

Jumping Champions

Ian Stewart leaps over the gaps between prime numbers

Mathematics is full of surprises. Who would have imagined, for instance, that something as straightforward as the natural numbers (1, 2, 3, 4,...) could give birth to anything so baffling as the prime numbers (2, 3, 5, 7, 11, ...)? The pattern of natural numbers is obvious: no matter which one you pick, it's easy to determine what the next one is. You can't say that for the primes. And yet it's a simple step from natural numbers to primes. Just take the natural numbers that have no proper divisors.

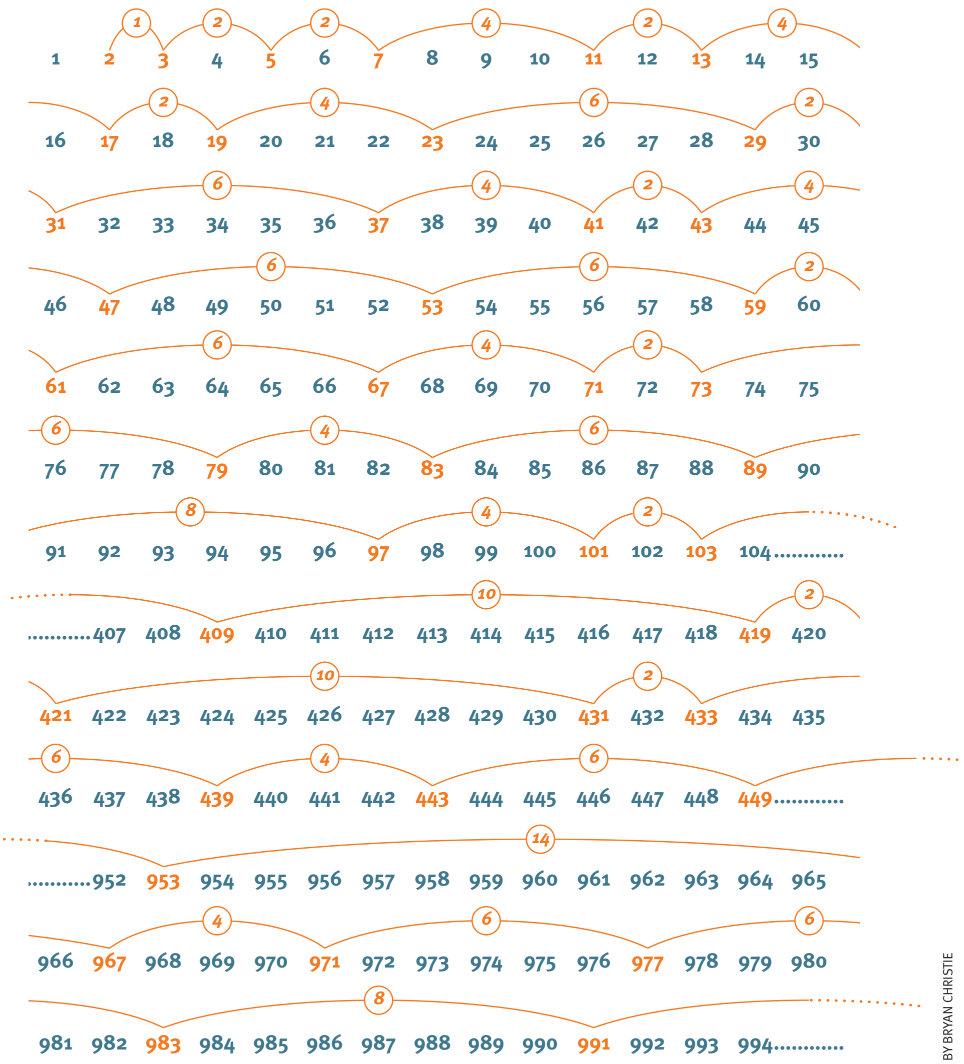
We know a lot about the primes, including some powerful formulas that provide good approximations when exact answers aren't forthcoming. The Prime Number Theorem states that the number of primes less than x is approximately $x/\log x$, where log denotes the natural logarithm. So, for instance, we know that there are roughly 4.3×10^{97} primes with less than 100 digits—but the exact number is a total mystery.

Recently Andrew Odlyzko of AT&T Labs, Michael Rubinstein of the University of Texas and Marek Wolf of the University of Wroclaw in Poland turned their attention to the gaps between successive primes. In an article in *Experimental Mathematics* (Vol. 8, No. 2, 1999), they addressed the following problem: What number is the most common gap between successive primes less than x? This question was posed in the late 1970s by Harry Nelson of Lawrence Livermore National Laboratory. Later on, John Horton Conway of Princeton University coined the phrase "jumping champions" to describe these numbers.

The primes up to 50 are 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43 and 47. The sequence of gaps—the differences between each prime and the next—is 1, 2, 2, 4, 2, 4, 2, 4, 6, 2, 6, 4, 2 and 4. The number 1 appears only once because all primes except for 2 are odd. The rest of the gaps are even numbers. In this sequence, 2 occurs six times, 4 occurs five times, and 6 occurs twice. So when $x = 50$, the most common gap is 2, and this number is therefore the jumping champion.

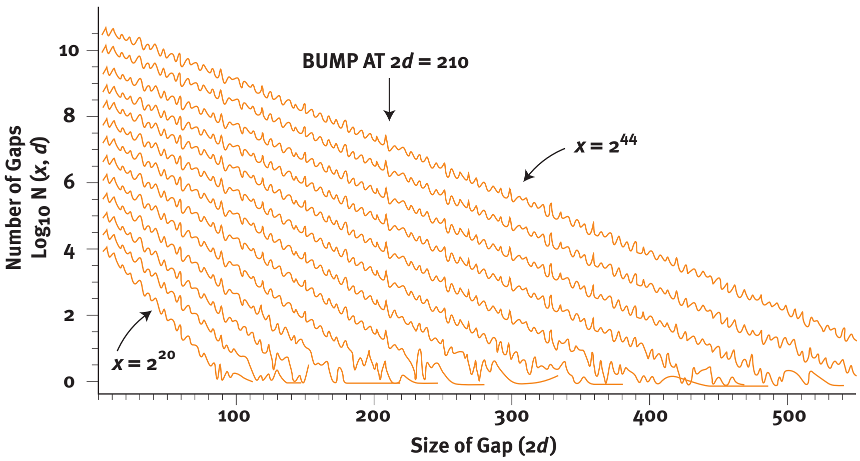
Sometimes several gaps are equally common. For instance, when $x = 5$ the gaps are 1 and 2, and each occurs once. For higher x, the sole jumping champion is 2 until we reach $x = 101$, when 2 and 4 are tied for the honor [*see illustration below*]. After that, the jumping champion is either 2 or 4, or both, until $x = 179$, when 2, 4 and 6 are involved in a three-way tie. At that point the challenge from 4 and 6 dies away, and 2 reigns supreme until $x = 379$, where 2 is tied with 6. Above $x = 389$ the jumping champion is mostly 6, occasionally tied with 2 or 4, or both. But when x ranges from 491 to 541, the jumping champion reverts to 4. From $x = 947$ onward the sole jumping champion is 6, and a computer search shows that this continues up to at least $x = 10^{12}$.

It seems reasonable to conclude that apart from some initial competition from 1, 2 and 4, the only long-term jumping champion is 6. But even a pattern that



MOST COMMON GAPS between successive prime numbers are 2, 4 and 6 for the sequences running up to 1,000. But no one knows the jumping champions for very long sequences of primes.

ALL ILLUSTRATIONS BY BRYAN CHRISTIE



LOGARITHMIC PLOT shows how the number of gaps between successive primes less than x varies with the size of the gap ($2d$). The plot suggests that 210 may be a jumping champion.

persists up to numbers in the trillions may well change as the numbers get still bigger. And that's where the surprise comes in. Odlyzko and his colleagues provide a persuasive argument that somewhere near $x = 1.7427 \times 10^{35}$ the jumping champion changes from 6 to 30. They also suggest that it changes again, to 210, near $x = 10^{425}$.

Except for 4, the conjectured jumping champions fit into an elegant pattern, which becomes obvious if we factor them into primes:

$$2 = 2$$
$$6 = 2 \times 3$$
$$30 = 2 \times 3 \times 5$$
$$210 = 2 \times 3 \times 5 \times 7$$

Each number is obtained by multiplying successive primes together. These numbers are called primorials—like factorials, but using primes—and the next few are 2,310, 30,030 and 510,510. In their article, Odlyzko and his co-authors propose the Jumping Champions Conjecture: the jumping champions are precisely the primorials, together with 4.

Here's a brief explanation of their analysis. Anyone who looks at the sequence of primes notices that every so often two consecutive odd numbers are prime: 5 and 7, 11 and 13, 17 and 19. The Twin Prime Conjecture states that there are infinitely many such pairs. It is based on the idea that primes occur "at random" among the odd numbers, with a probability based on the Prime Number Theorem. Of course, this sounds like nonsense—a number is either prime or not; there isn't any probability involved—but it is reasonable nonsense for this kind of problem. According to a calculation of probabilities, there is no chance that the list of twin primes is finite.

What about three consecutive odd numbers being prime? There is only one example: 3, 5, 7. Given any three consecutive odd numbers, one must be a multiple of 3, and that number is therefore not prime unless it happens to equal 3. Yet the patterns $p, p + 2, p + 6$ and $p, p + 4, p + 6$ cannot be ruled out by such arguments, and they seem to be quite common. For example, the first type of pattern occurs for 11, 13, 17 and again for 41, 43, 47. The second type of pattern occurs for 7, 11,13 and again for 37, 41, 43.

About 80 years ago English mathematicians Godfrey Harold Hardy and John Edensor Littlewood analyzed patterns of this kind involving larger numbers of primes. Using the same kind of probabilistic calculation that I described for the twin primes, they deduced a precise formula for the number of sequences of primes with a given pattern of gaps. The formula is complicated, so I won't show it here; see the article in *Experimental Mathematics* and the references therein.

From the Hardy-Littlewood work, Odlyzko and his colleagues extracted a formula for N (x, d), which is the number of gaps between consecutive primes when the gap is of size $2d$ and the primes are less than x. (We use $2d$ rather than d because the size of the gap has to be even.) The formula is expected to be valid only when $2d$ is large and x is much larger. The illustration at the left shows how log N (x, d) varies with $2d$ for 13 values of x ranging from 2^{20} to 2^{44} (in this graph, log denotes a base 10 logarithm). Each plot line is approximately straight but has lots of bumps. A particularly prominent bump occurs at $2d = 210$, the conjectured jumping champion for very large x. (It would look even more prominent if the logarithmic graphing didn't flatten it out.) This kind of information suggests that the N (x, d) formula is not too wide off the mark.

Now, if $2d$ is going to be a jumping champion, the value of N (x, d) has to be pretty big. The best way to achieve this is if $2d$ has many distinct prime factors. Also, $2d$ should be as small as possible subject to this condition, so the most plausible choices for $2d$ are the primorials. The known jumping champion 4 is presumably an exception. It occurs at a size where the N (x, d) formula isn't a good approximation anyway. The formula also lets us work out roughly when a given primorial takes over from the previous one as the new jumping champion.

What's left for recreational mathematicians to do? Prove the Jumping Champions Conjecture, of course—or disprove it. If you can't do either, try searching for other interesting properties of the gaps between primes. For example, what is the least common gap (that actually occurs) between consecutive primes less than x? And which gap occurs closest to the average number of times? As far as I know, these questions are wide open, even for relatively small values of x. SA

READER_FEEDBACK

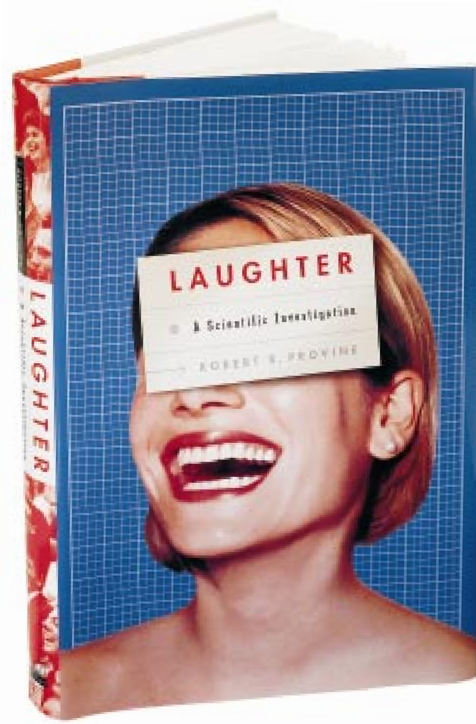
In a recent column on logical paradoxes ["Paradox Lost," June], I argued that the Surprise Test paradox rests on an inconsistent interpretation of the word "surprise" and isn't really a paradox at all.

Several readers drew my attention to an article entitled "Surprise Maximization" in *American Mathematical Monthly* (Vol. 107, No. 6, June–July 2000). The authors define a measure of surprise and ask what strategy the teacher should follow to maximize the students' surprise. They conclude that in choosing the day of the week for the test, the teacher should use a probability distribution that remains roughly constant through the early part of the week but increases rapidly in the last few days. Under this strategy, Friday would be chosen most often. —*I.S.*

REVIEWER_FRANS B. M. DE WAAL

Laugh and the World Laughs with You

Robert R. Provine cracks the laugh code



BETH PHILLIPS

Laughter: A Scientific Investigation
by Robert R. Provine
Viking, New York, 2000 ($24.95)

One morning the principal's voice sounded over the intercom of my high school with the shocking announcement that a popular French teacher had just died in front of his class. Everyone fell silent. While the principal went on to explain that it had been a heart attack, I couldn't keep myself from a laughing fit. To this day, I feel embarrassed.

What is it about laughter that makes it unstoppable even if triggered by circumstances that aren't amusing? Extreme bouts of laughter are positively worrisome, marked by loss of motor control, shedding of tears, gasping for air, even the wetting of pants while rolling on the floor! What a weird trick has been played on our linguistic species to express itself with such stupid "ha ha ha" sounds. Why don't we leave it at a cool "that was funny"?

These questions are old, going back to philosophers who have puzzled over why one of humanity's finest achievements—its sense of humor—is expressed in such an animal-like fashion. There can be no doubt that laughter is an inborn characteristic. It is a universal human expression that we share with our closest animal relatives, the apes. This was already known to Charles Darwin and confirmed by a Dutch ethologist, Jan van Hooff, who set out to elucidate under which circumstances apes utter their hoarse, puffing laughing sounds. He concluded that laughter is associated with a playful attitude in both humans and apes, even though play is considerably more physical (such as tickling and wrestling) in apes.

Laughter: A Scientific Investigation builds on this work in that it assumes animal origins of laughter and follows van Hooff's distinction between the laugh and the smile. The two expressions are often mentioned in the same breath because they tend to grade into each other, yet they derive from quite different primate displays, with the smile expressing affection and appeasement rather than playfulness. Robert R. Provine has set himself the task of cracking the laugh code, as he calls it, rather than tackling the much more complex issue of humor. The two may appear inseparable, but one of the revelations of this book is that the stand-up comedy model of laughter as a response to jokes is mistaken. The large majority of laughs measured by Provine and his students in the shopping malls and on the sidewalks of the human natural habitat occurred after statements that were far from humorous. In spontaneous social contacts, people burst into laughter at unfunny comments such as "I see your point" and "Put those cigarettes away" far more often than at funny ones, such as "He tried to blow his nose, but he missed." This shows that humor is not the issue: social relationships probably are.

Laughter is a loud display that much of the time seems to signal mutual liking and well-being. Some of its uses are unique to our species, such as the guffaws of bonding. When a group of people laugh, sometimes at the expense of outsiders, they broadcast solidarity and togetherness not unlike a howling pack of wolves. According to Vanderbilt University psychologist Jo-Anne Bachorowski [see "More Than the Best Medicine," News and Analysis, Scientific American, August], the unifying function of laughter is particularly clear among men. Provine expands on this theme with the observation that women laugh more in response to men's remarks than the reverse. The asymmetry between the sexes starts early in life, between boys and girls, and seems to be cross-cultural. The man as laugh-getter also turned up in an analysis of personal ads, in which Provine found that women generally sought partners with a sense of humor, which male advertisers claimed to have in great measure.

Provine's well-written, often amusing and always fascinating exposé presents laughter in all its complexity and with all its contradictions. He does not try to sell us a one-issue explanation the way so many have tried before, such as that humor is a celebration of the detection of incongruity (Schopenhauer), an expression of derision (Hobbes), a safety valve for pent-up energy (Freud), and so on. Provine notes the armchair background of these high-flung notions and makes no secret that even after all his research he still finds laughter a baffling behavior that can be both hostile (as in ethnic jokes) and congenial and both a response to subtle humor and triggered by something as banal as a laughing box or a Tickle Me Elmo doll.

The stand-up comedy model of laughter as a response to jokes is mistaken.

The amazing contagiousness of laughter even works across species. Below my office window at the Yerkes primate center, I often hear chimpanzees laugh when they tickle one another (they have the same tickling spots as we do: under their armpits and on their bellies), and I cannot suppress a chuckle in response. Tickle matches must be the original context of laughter, and the fact that tickling oneself is notoriously ineffective attests to its social significance. Tickling and laughter are essentially play patterns, with the latter having achieved a considerably expanded meaning in our species.

The book reads like a first exploration of a behavior so common that it has been overlooked by science. As Provine notes, it may not be good for one's reputation to study jokes and laughter. In his eagerness to claim this new field for himself, however, the author neglects to mention people who went before him or who are currently tackling the same domain. For example, the pioneering work of van Hooff is buried in a footnote, even though it addressed some of the same points 25 years earlier.

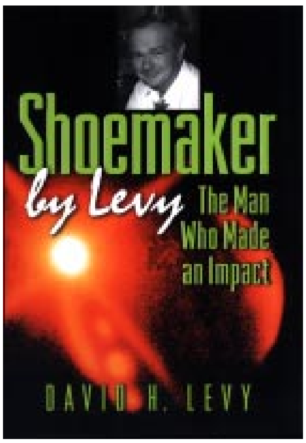
Toward the book's end, the author discusses neural disorders associated with laughter and laughing epidemics as well as the opposite: the healing power of laughter exploited by some churches and therapists. It is obvious that his research not only opens new avenues into human social life but also carries mental health implications. My own reaction to the death of a teacher was only a mild case of laughter under odd circumstances compared with the clinical, sometimes fatal cases reviewed here. The fact that we can lose control over this expression, that it may become mirthless, tragic, eerie, sly or sardonic, shows how close comedy can get to tragedy. We like to see ourselves as fully rational beings, but much of this dissolves when someone yanks our laughing muscle. SA

FRANS B. M. DE WAAL, author of Chimpanzee Politics *and* Good Natured, *is director of the Living Links Center at the Yerkes Regional Primate Research Center in Atlanta and professor of psychology at Emory University.*

THE EDITORS_RECOMMEND

DAVID H. LEVY'S *Shoemaker by Levy: The Man Who Made an Impact.* Princeton University Press, Princeton, N.J., 2000 ($24.95).

Their names are memorably linked to Comet Shoemaker–Levy 9, which they discovered in 1993 and which captured worldwide attention when 21 fragments of it crashed into Jupiter in July of 1994. Eugene M. Shoemaker, who died in an automobile accident in 1997, was a geologist who spent much of his career studying impact craters on the moon and Earth. (He "practically invented the field of astrogeology," according to Paul W. Chodas of the Jet Propulsion Laboratory.) Levy is a writer on astronomy and the discoverer of 21 comets. He skillfully describes Shoemaker's work and sharply delineates his strong personality. Shoemaker got his lifelong wish to see an impact when that comet struck Jupiter. And his wish to go to the moon, thwarted by his health, was fulfilled when the spacecraft Lunar Prospector, carrying one ounce of his ashes, crashed onto the lunar surface five years to the week after the last traces of Comet Shoemaker–Levy 9 disappeared.



PAUL W. EWALD'S *Plague Time: How Stealth Infections Cause Cancer, Heart Disease, and Other Deadly Ailments.* Free Press, New York, 2000 ($25).

Ewald's thesis is that the medical profession has been and remains slow to recognize that many chronic diseases have an infectious causation. "Thousands suffered and died because antibiotic treatment of peptic ulcers was generally recognized in 1995 instead of 1955. Thousands more probably suffered and died over a similar period because cervical cancer was treated as bad luck rather than a preventable sexually transmitted disease."

Ewald, professor of biology at Amherst College, says the situation results from medicine's poor understanding of microbial evolution. "Throughout the twentieth century, leading authorities in the health sciences believed that coevolution of pathogens with their hosts would inevitably lead to benign coexistence." But "a more careful application of evolutionary principles leads to the conclusion that some pathogens will evolve toward benignity and some will not." Ewald presents his view of that process and lists several chronic diseases (among them atherosclerosis, Alzheimer's, impotence and some cancers) that probably will be proved to have an infectious causation.

When SETI Succeeds: The Impact of High-Information Contact. Edited by Allen Tough. Foundation for the Future, Washington, D.C., 2000 ($10).

The Search for Extraterrestrial Intelligence has yet to discover any alien radio signals or other signs of life elsewhere, but some astronomers give it a 50–50 chance of success within the decade. What might a positive result mean for human society? The question has long engaged some of science's leading thinkers. This anthology contains papers from a conference last year on the subject. Through their discussions, the conferees said they hoped to get humanity ready for the revolutionary consequences—not all of which will be good—for our knowledge, religion, politics, art and self-conception. A few suggested that scientists should take UFO reports and other anomalous phenomena more seriously (see members.aol.com/AllenTough/mel.html). The author list reads like a who's who of SETI research. This, alas, is also the book's flaw: conspicuously absent are social scientists, such as Duquesne University political philosopher Charles Rubin, who believe the impact of a SETI detection would not be as great as generally thought (see www.coseti.org/mov/2704-11.ram).

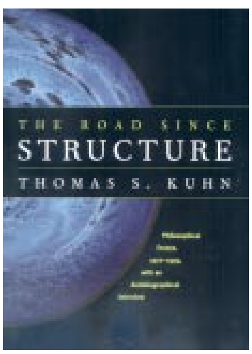
JEFFREY K. MCKEE'S *The Riddled Chain: Chance, Coincidence, and Chaos in Human Evolution.* Rutgers University Press, New Brunswick, N.J., 2000 ($27).

McKee wonders, as everyone must, how we got here. "How could an aimless evolutionary process, patching together random biological novelties and oddities through trial and error, lead to *Homo sapiens*?" Probably humans would not appear, he says, if evolution could have restarted. "This is because the evolution of life is subject to fates wantonly dictated by three ubiquitous and mischievous forces: chance, coincidence, and chaos."

Elaborating on the effects of those forces, McKee proposes a bottom-up model of evolution rather than the top-down model favored by many evolutionists. "In the standard top-down model, outside environmental influences are more important, and the species is a pivotal unit. In the bottom-up model, genetic variants must be tested through successive levels within members of a species before any adaptation to outside influences can take place." And he suggests that because of the huge number of genetic variations made possible by the large human population, "our species may be set to evolve at an unprecedented rate." McKee, associate professor in the departments of anthropology and evolution, ecology, and organismal biology at Ohio State University, has a way with examples and analogies that greatly enhances his argument.

THOMAS S. KUHN'S *The Road since* Structure: *Philosophical Essays, 1970–1993, with an Autobiographical Interview*. Edited by James Conant and John Haugeland. University of Chicago Press, Chicago, 2000 ($25).

The title refers to Kuhn's seminal *The Structure of Scientific Revolutions,* published in 1962, in which he argued that the history of science is not gradual and cumulative but instead is punctuated by a series of more or less radical "paradigm shifts." The new book reprints 11 essays in which Kuhn defends, develops and, in some cases, modifies the views he put forward in *Structure*. Trained as a physicist, Kuhn as a young man turned his interest to the history and philosophy of science. He discussed that change in an absorbing three-day interview that he had with three Greek scholars in 1995, the year before he died. "I think I would have been a damn good physicist," he remarked, but increasingly the field seemed to him to be "fairly dull, the work was not interesting." Of *Structure*, he said: "I wanted it to be an important book; clearly it was being an im-



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portant book—I didn't like most of the ways in which it was being an important book." And, surprisingly for such an influential writer, he said that he had always found it "very hard to write."

CLIFFORD GEERTZ'S *Available Light: Anthropological Reflections on Philosophical Topics*. Princeton University Press, Princeton, N.J., 2000 ($24.95).

Anthropology and philosophy regard each other warily, Geertz says. "The anxiety that comes with a combination of a diffuse and miscellaneous academic identity and an ambition to connect just about everything with everything else and get, thereby, to the bottom of things leaves both of them unsure as to which of them should be doing what." Geertz, who was trained in philosophy and then took up anthropology, ruminates in this collection of essays on some of the things that anthropology and philosophy have or might have in common. He also looks back on his career, which for almost 30 years as a faculty member at the Institute for Advanced Study has involved "struggling to keep an unconventional School of Social Science going in the face of—how shall I put it?—a certain institutional timorousness and self-conceit."

Geertz thinks that "a number of serious adjustments in thought must occur if we, philosophers, anthropologists, historians, or whoever, are to have something useful to say about the disassembled, or anyway disassembling, [modern] world of restless identities and uncertain connections."

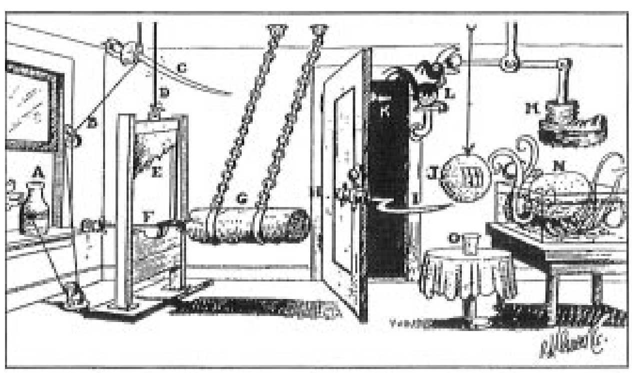
THOMAS HOMER-DIXON'S *The Ingenuity Gap: How Can We Solve the Problems of the Future?* Alfred A. Knopf, New York, 2000 ($30).

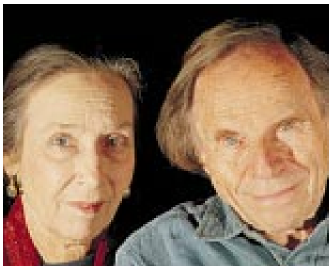
"In this book I'll argue that the complexity, unpredictability, and pace of events in our world, and the severity of global environmental stress, are soaring. If our societies are to manage their affairs and improve their well-being they will need more ingenuity—that is, more ideas for solving their technical and social problems." Homer-Dixon, associate professor of political science at the University of Toronto and director of the Peace and Conflict Studies Program there, cites markets and science as sources of the needed ideas. Markets provide an incentive to produce knowledge, he says, but the incentive is often skewed or too weak and produces wrong or inadequate solutions. In science, "there is often a critical time lag between the recognition of a problem and the delivery of sufficient ingenuity" to solve it. Acknowledging the astonishing adaptability and ingenuity that many societies and individuals have shown, Homer-Dixon nonetheless warns that the hour is late for coping with the world's problems. "When we look back from the year 2100, I fear we will see a period when our creations—technological, social, and ecological—outstripped our understanding, and we lost control of our destiny."

MAYNARD FRANK WOLFE'S *Rube Goldberg: Inventions*. Simon & Schuster, New York, 2000 ($25).

Rube Goldberg is so renowned for his zany and splendidly overcomplicated "inventions" that his name has made it into dictionaries as an adjective. "Used for describing any very complicated invention, machine, scheme, etc., laboriously contrived to perform a seemingly simple operation" is the entry in *Webster's New World Dictionary*. According to *Merriam-Webster's Collegiate Dictionary*, the adjective means "accomplishing by complex means what seemingly could be done simply." The inventions appeared in newspapers every day from 1914 to 1964 as a single panel of drawings with an elaborate caption. Wolfe, a photojournalist who also holds patents for product design, presents a collection of Goldberg's inventions, comic strips, editorial cartoons, and sketches and provides a biography of Goldberg. The reader is easily lost in contemplation of such Goldbergian wonders as "Simple Way to Open an Egg without Dropping It in Your Lap," "Simple Orange-Squeezing Machine" (*below*) and "Easy Way for Tired Tourist to Enjoy Italian Art."

FROM *RUBE GOLDBERG: INVENTIONS*





Gleaning Nuggets

Philip and Phylis Morrison offer their perspective on the enduring nobility of native metals

M.I.T. has a fine view of Boston proper across the Charles River from our riverside campus, and we never ignore the dome of Mr. Bulfinch's Federalist Statehouse atop Beacon Hill. Once the highest point of the skyline, it is rather a minor hemisphere among a dozen vitreous skyscrapers that lie behind it. Small on today's scale, it remains by its golden glitter a true attractor to the eye. The frugal legislators in prosperous times had it gilded—coated by hand-size leaves of nearly pure gold, a metal that does not react with rain, ice or city air and that long retains its shine. Its endurance is impressive once you realize that metallic gold is almost fully reflecting in these leaves, only a couple of dozen atoms thick (a bright light seen through gold leaf shows dimly blue-green). Public gold is not common these days; personal jewelry is more popular, but on the scale of a city lot the sheen of gold still makes an impressive show.

Gold, silver and copper are names not merely of three elements but also of their lustrous colors—yellow, silvery white and reddish. They used to be the chief coinage metals, and it is disappointing that no U.S. coins now in wide circulation are gold or silver—even our shiny red-gold pennies are only copper-plated zinc. The three metals have been prized worldwide, surely for their visual properties and their degree of "nobility," with gold undisputedly noblest of the three. All good electrical conductors, all ductile and malleable, all reactive with strong mineral acids—gold gave in only to a partnership of two strong acids—they form crystals of one simple class, their atomic units constituting a cube.

But what of the golden luster? A look through gold leaf discloses the source: the electron-filled levels of the bound gold atoms reflect all the visible colors, except the blue-green that gold leaf transmits stingily. What is not absorbed from white light on reflection is the color we see in pure and near-pure gold. (The metallic gleam is the sign of a population of electrons that reradiate almost all the photons that come to it.) Copper absorbs greener photons than does gold, so its specific reflection is reddened. Silver reflects a wider band of energies: its hue is a balanced silvery white. The spectral details of the free atoms can, through the quantum theory of solids, predict what electron levels are left unfilled and available in the solid metal. So far we have an explanation for why they attract the visually alert.

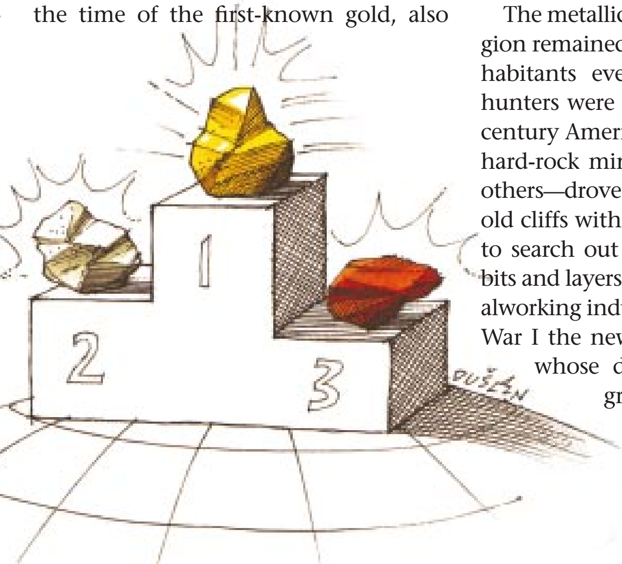
But whence the ancient supply? The primary ores of these metals are not colorful, and they yield up the metals only after more or less elaborate processing with fire and chemical change. Happily, there are nuggets to catch the eye. Copper, silver and gold are locally found in elemental metallic form, rarely as grand finds, more commonly as less showy, small flakes, grains and wires. The Native American craftsmen of upper Michigan, living in a predominantly hunter-gatherer society long before maize arrived from the tropics, first cold-worked metallic copper for use and for ornament about 6,000 years ago. That was around the time of the first-known gold, also mainly worked cold, without fire, in predynastic Egypt, by the artisans of a larger society long agricultural.

Shining copper was to be found for the looking on the shores, riverbanks and bottomlands south of Lake Superior, in particular in the Keweenah peninsula of upper Michigan. It erodes there out of the dark cliffs, layered by many ancient basalt flows. For more than 5,000 years, another lasting flow is well mapped in this land, the spread of unmistakable objects of native copper—facial and ear ornaments, cutout figures, spearheads and arrow points, all hammered and cut deftly out of the pure metal. These treasures were traded far and wide to many Native American sites, to Tampa Bay, the Gulf of St. Lawrence, even west to the desert and the Rockies. Eventually, smelted copper sheet came from Europe to mix with the old lakeside nuggets. First from this stream were whole copper kettles traded by Basque cod fishermen with the coastal people of New York and New England during the decades after Columbus.

Public gold is not common these days; personal jewelry is more popular.

The metallic copper of the Michigan region remained a major resource for its inhabitants even after Native American hunters were far outnumbered. In 19th-century America, for decades, immigrant hard-rock miners—Finnish, English and others—drove tunnels and shafts into the old cliffs with picks and blasting powder to search out and dispatch pure copper bits and layers by the shipload to the metalworking industries. By the end of World War I the new copper mines, giant pits whose dark rock bears only tiny grains of dark copper sulfide ores, shiny only after purification by furnace and electrolysis, were found in the Rockies, the Andes

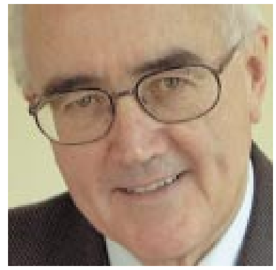
Continued on page 116



DUSAN PETRICIC

Not Nelson's Obelisk

James Burke draws monumental conclusions from wax, dinner sets, greenhouses, Argentina, prisons and the king of beasts


DAVE PAGE

I bet most of the Trafalgar Square tourists getting a crick in the neck (as I did the other day) while eyeballing the Admiral up there don't know he's standing on what was nearly Nelson's Obelisk. The idea of E. H. Baily, who got the statue job as consolation prize (1840) for losing the monument-to-the-hero competition to somebody else's design for a column.

Not that Baily needed the work, carving as he did for many other top places: Buckingham Palace, Marble Arch, the National Gallery. Baily's rise to the heights was meteoric: from provincial nobody to Royal Academy Gold Medal by his 20s. Mostly thanks to a little help from his teacher, John Flaxman (who'd had his own design for a 200-foot-high Britannia statue on Greenwich Hill turned down). At one point, Flaxman spent seven years in Italy drawing anything that crumbled, came back home famous for it and then for doing more funerary memorial reliefs (eight in Chichester Cathedral alone) than anybody, ever.

Early on, from 1775, he'd spent a few years turning out wax models for the ceramic medallions, friezes and such items designed by Josiah Wedgwood, the first mass-market potter and science freak (well, his daughter became the mother to Charles Darwin, who married his granddaughter). And while you work that one out, let me add that Wedgwood's innovative sales catalogues were the 18th-century equivalent of online shopping, complete with novel, money-back guarantees. Wedgwood was a hot ticket, consumer-wise. Furnace-wise, too, with the pyrometer he invented for checking his kiln temperatures by measuring the amount of shrinkage the heat caused in small clay cylinders.

Pyrometry techniques were improved in 1830 (late in his career) by one John Frederic Daniell, an Anglo chemist who had started in sugar refining, moved on to coal-gas manufacture and from there, logically enough, to the invention of the Daniell cell (the first continuous-current battery), thence to meteorology and a job advising the navy on lightning. The weather in England being predominantly wet, it will come as no surprise that in 1824 Daniell also produced a magisterial paper on getting humidity levels right in a greenhouse.

A must-read for young Joseph Paxton, foreman-gardener (and traveling companion) to His Dukeness of Devonshire. In 1850, after years of experience building a fancy ducal conservatory, it became transparently clear to Paxton how the proposed Great Exhibition building should look. His winning design, scribbled on a bit of blotting paper, was for the mother of all glass houses, 108 feet high and covering 17 acres. When built in 1851, it became known as the Crystal Palace, and Paxton became known as Sir Joseph. Said he'd been inspired by the structural design of the underpart of the Amazonian water lily, when he was the first European to get one of these monsters to flower, in 1849.

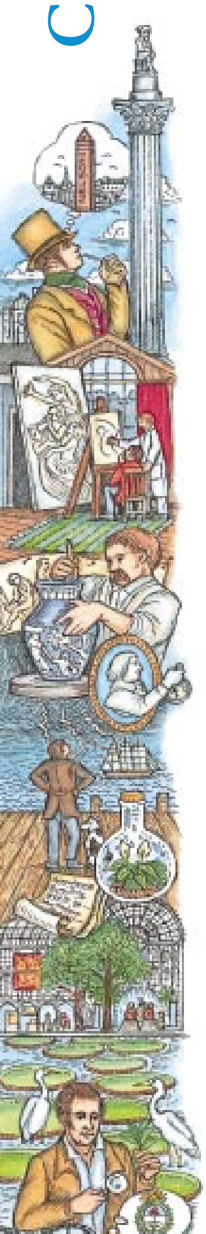
Originally named *Victoria regia* (after the queen), the plant became a Victorian cult object, replete with imperial overtones. Having been discovered by a Great British Explorer (in fact, a first-generation German immigrant), Robert Hermann Schomburgk, when he was in British Guiana (now Guyana) drawing the Schomburgk Line that showed those Venezuelan johnnies next door where the frontier was so they wouldn't dare cross it!

Of course, other people claimed to have found the lily earlier, the most colorful of whom (so I'll stick with him) being French botanist Aimé Bonpland, who wrote from Montevideo to claim priority. Bonpland had started out really well, in 1799, with five years up the jungle as expedition secretary to only the greatest adventurer in the world, Alexander von Humboldt, who went on to become Extremely Famous and Important. So what went wrong for Humboldt's poor sidekick? Well, after The Trip (60,000 specimens, 3,000 new species, 6,000 miles and a zillion measurements), in 1816 Bonpland was in London and met a guy who made him an offer he couldn't refuse: to set up a brand-new natural history museum in Buenos Aires. Money no object.

So what went wrong for Humboldt's poor sidekick?

Alas, when he got there the bureaucrats had never heard of him, and there was no money, so for a time he ran a fruit-and-vegetable stall. In 1820 he moved to Paraguay, ran afoul of the authorities, got stuck in jail for nine years and then became variously involved in botanic matters, arms dealing, military uniforms, spying and medicine. And all this thanks to that London encounter with the about-to-be first president of Argentina, Bernardino Rivadavia, who also goes down in history as the founder of the University of Buenos Aires and for being too much of a libertarian to last long as president.

Some of which (libertarianism) Rivadavia may have picked up, during his England jaunt, on meeting Jeremy Bentham, already famous radical and general thorn in the flesh of the harrumph. Bentham cleared more



PATRICIA J. WYNNE

cobwebs off the English legal system than anybody and in the best sense was the do-gooder's do-gooder. Apart from advising princes and potentates on constitutional matters, he brought a reformer's eye to ethics, taxation, political economy, poverty, jurisprudence and colonial administration and was apparently no slouch on the violin. All this and penal reform, including designs for a more humane prison, known as a panopticon, with the cells set in a circle around a central guardhouse.

He got the basic idea from his brother, Sam, who spent 15 years becoming a general in the Russian navy and at one point (while running a highly innovative shipyard) designed an office at the center of radiating workshops so managers could more easily keep an eye on things.

In 1795 Sam went back to England and did innovative things to Royal Navy shipbuilding, before becoming bogged down when he tried reforming the navy's fuddy-duddy shipyard administration. In 1801 he did, however, manage to facilitate one sneaky novelty, proposed by an ex–French royalist émigré and ex–chief engineer of New York City: Marc Brunel. Whose idea was for one of the first fully mechanized production lines (to manufacture ships' pulley blocks), which by 1806 made it possible for 10 men to turn out the same number of blocks as had previously been done, by hand, by 110 men. Saved the navy a fortune and eventually became known as the American System of Manufacture. Guess why. (A hint is contained in the next sentence.)

In 1825 Brunel started the Rotherhithe Tunnel under the Thames; he finished it 17 years of strikes later. The hard-pressed on-site manager was his son, Isambard, headed for fame as one of the preeminent engineers of all time and about whom I have previously written so much that I'll just mention: the biggest ship in the world, tunnels, bridges, docks, prefab hospitals, railroads and viaducts. And (unusually for an engineer) oodles of money. Some of which he spent on a posh house in London, where for one room he commissioned some Shakespeare-inspired art from a painter better known for every imaginable way you could paint a dog: dogs as lawyers, dogs as mourners, rescue dogs, sleeping dogs. If it wuffed, Edwin Henry Landseer immortalized it. In 1859 he went upscale with a commission to sculpt four gigantic bronze lions.

You can still see them today, sitting at the foot of what is not Nelson's Obelisk. SA

Wonders, *continued from page 113*

and the highlands of Africa. Today native copper is only a collector's item, whereas the world uses some 10 million tons of smelted copper a year.

In the Keweenah region there are about 800 abandoned mining sites, with 2,000 walk-in passages into the basalt cliffs, some as long as 1,000 feet. Nuggets may still be found by patient search, but now the cavities are valued more than the rock. The little brown bats of the region, in the hundreds of thousands, make some of these openings their hibernation sites, tempering the harsh winters. Bats are at home in our dark mine caverns as much as pigeons are in our city cliffs of open masonry. A vigorous campaign aims to safeguard these refuges and to spread the wonder of this convergence: human accomplishment over 6,000 years now extended to wildlife.

Silver is still often mined as pure metal deep in veins within granite, mostly in Mexico. Much gold is dredged in volume out of old river deposits, where natural streams have sorted the durable heavy grains slowly downstream, to fall in quiet waters. The deep South African mines extracted most of today's gold from an ancient lusterless rock in the depths. The least expected of native metals is abundant iron, whose red, green and drab compounds paint half the world's rocks and soils with its complex rusts. Earthly iron processed from ores entered use in only about 1500 B.C. Yet metallic iron, durably alloyed with nickel, is found wherever it dropped from the sky, as many languages proclaim, naming iron as a "star metal." Such meteoric iron was worked into blades by court swordsmiths in old Delhi, by Inuit hunters in Greenland, and into a ring by Phylis in Cambridge, who laboriously drilled and sawed a fragment brought from the West Australian desert by the generous finder.

Native nonmetals include the "nuggets" of crystalline carbon, diamonds, the bright yellow pure sulfur that paints volcanic districts, and the most abundant of all free elements at the surface of the globe—molecular dinitrogen and dioxygen, vital minerals of the ocean of air. SA

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by Shawn Carlson

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Anti Gravity

DAN WAGNER

Final Frontier Exam

Here's one way to find out if you have at least a little bit of the right stuff, says **Steve Mirsky**

A company with ties to NASA, Dreamtime Holdings Inc., proposed—at meetings Monday with CBS, ABC, and Fox—a show that would use NASA facilities at the Johnson Space Center in Houston to train 20 contestants hoping to be selected to spend a week aboard the new International Space Station, executives at the three networks said.—New York Times, *Sept. 21, 2000*

Thank you for your interest in being a contestant on *Space Survivor* (working title). Because of the great interest on the part of the public, we have received literally thousands of applications. In order to limit our interviews to those individuals most knowledgeable about space, we have created the following series of multiple-choice questions. Please take no more than five minutes to answer the following. Good luck, live long and prosper, use a No. 2 pencil.

Questionnaire for prospective contestants on *Space Survivor* (working title):

The shuttle is
a) the U.S. spacecraft that lands like an airplane and is eventually launched back into orbit
b) still circling somewhere between Logan and LaGuardia

MACHOs are
a) what astronomers call "massive compact halo objects"
b) one of the gangs in *West Side Story*

Retrograde motion is
a) the apparent reversal of a planet's orbit resulting from the relative position of that planet and Earth
b) when you get left back in school

The Inflationary Universe refers to
a) a model in which the universe went through a brief but huge expansion
b) the store where Marlon Brando buys pants

A Pulsar is
a) a rapidly rotating neutron star sending out pulses of electromagnetic radiation
b) a prize for outstanding journalistic achievement

A Galaxy is
a) a large group of stars and associated matter
b) probably up on blocks in the front yard

The three-degree microwave background radiation is
a) the nearly isotropic energy remnant of the big bang
b) gonna take forever to bake your potato

A countdown is
a) the elapsed time leading to a lift-off
b) when they finally drive the stake into Dracula

The Apollo missions were
a) the efforts to send teams of three astronauts to the moon
b) the plots of *Rocky* and *Rocky II*

The Red Planet refers to
a) Mars
b) Clark Kent's socialist newspaper

A supernova is
a) the explosion of a star
b) a really good episode of that PBS show

"Houston, we've had a problem" are the famous words uttered by
a) Jim Lovell, commander of the crippled *Apollo 13* spacecraft
b) Bobby Brown

White dwarfs are
a) hot core remnants of burned-out stars of roughly the same mass as our sun
b) the last Knicks off the bench

Charon is
a) the moon of Pluto
b) when you give half your peanut butter sandwich to a friend

The *Vomit Comet* is
a) the airplane that briefly approximates weightless conditions, used in astronaut training
b) the worst nickname ever for an Olympic sprinter

John Glenn is
a) the first American to orbit Earth, the oldest man ever in space, a former U.S. senator from Ohio, a former Marine pilot
b) pretty ticked off if he's read this far

Cosmology is
a) the science of the origin and structure of the universe
b) the science of Helen Gurley Brown

The Keck is
a) the Hawaiian observatory featuring twin telescopes that enable astronomers to probe the deepest regions of the universe
b) wide right by Norwood: Giants 20, Bills 19, Super Bowl XXV

Buzz Aldrin was
a) the second man on the moon
b) what the other test pilots used to do to Aldrin

An asteroid is
a) a planetary body usually between the orbits of Mars and Jupiter, with a diameter of less than 500 miles
b) no excuse for missing work

Extra-credit question:

Daniel S. Goldin is
a) the administrator of NASA
b) going to take one small step off a high building before he takes the one giant leap of sending a game-show contestant into space SA