END-OF-THE-MILLENNIUM SPECIAL ISSUE

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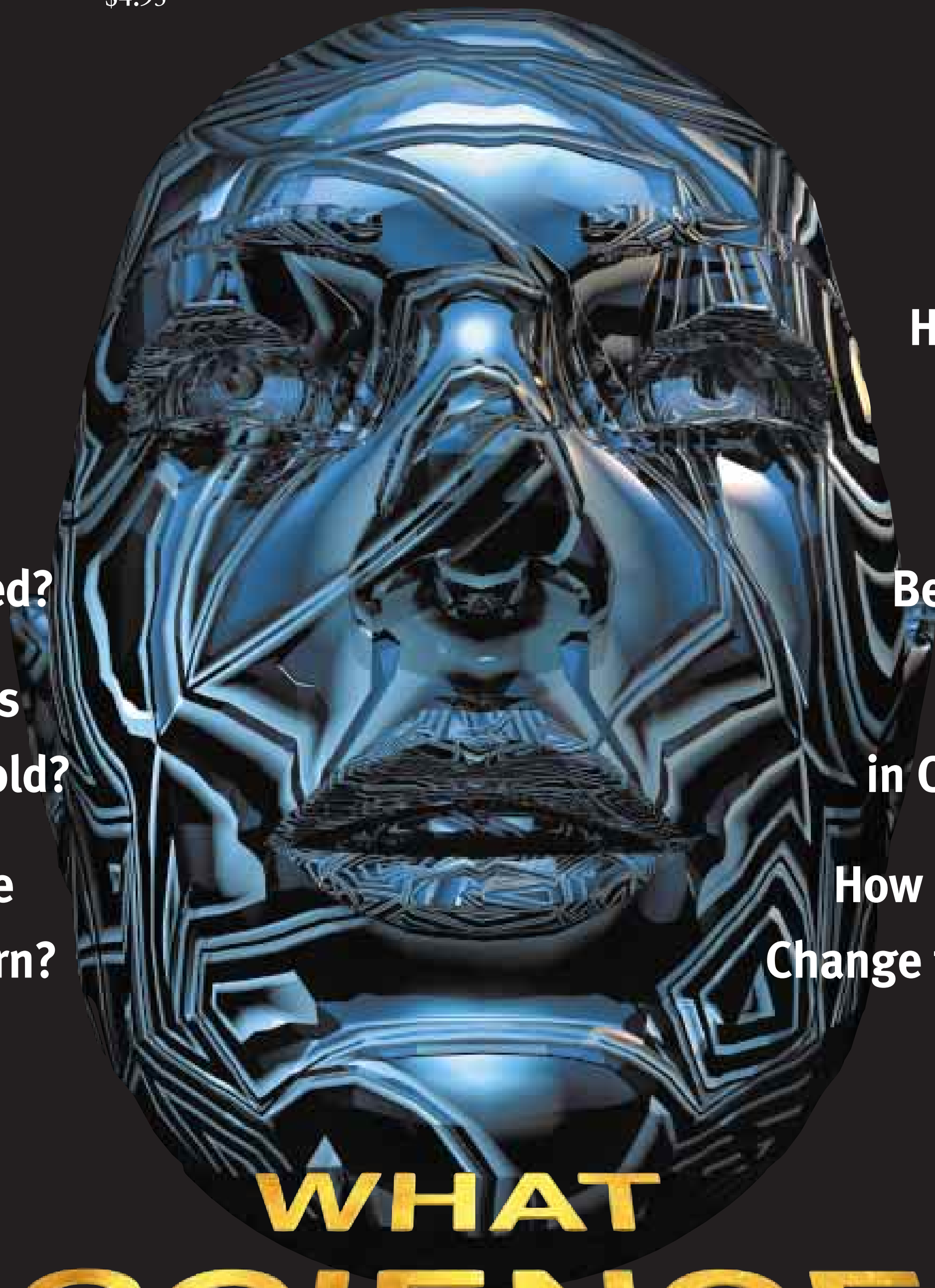


Can Physics Be Unified?

Can Aging Be Postponed?

What Secrets Do Genes Hold?

How Was the Universe Born?

How Does the Mind Work?

Can Robots Be Intelligent?

Is There Life in Outer Space?

How Much Do We Change the Climate?

WHAT SCIENCE WILL KNOW IN 2050

SCIENTIFIC AMERICAN

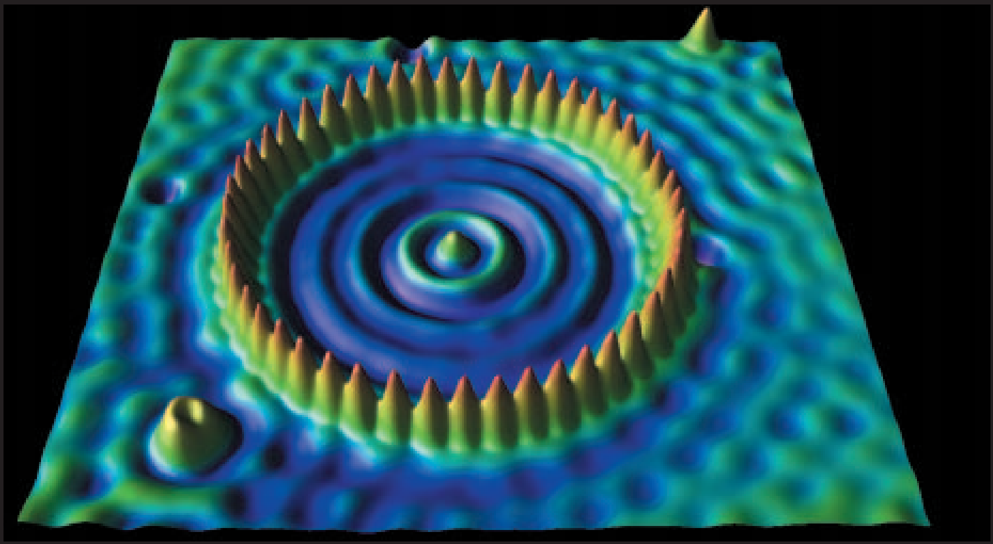
NEWS AND ANALYSIS

Lost Observer (page 32)

End-of-the-Millennium Special Issue

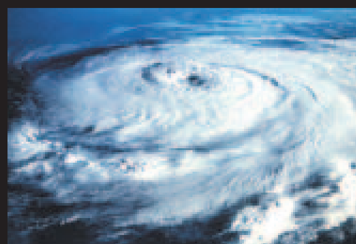
WHAT SCIENCE WILL

Today's top scientific authorities speculate on the great questions that further research will answer within the next five decades.



December 1999 Volume 281 Number 6

KNOW IN 2050



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FROM THE EDITORS

Overtaking Tomorrow

What will be our shorthand for the future now? For all our lives, prognosticators have used "the 21st century" and "beyond 2000" as airy dates for scheduling future wonders. Now that century is on the doorstep, and the stores are full of year 2000 Word-A-Day calendars. Miraculously, the words themselves still have a Buck-Rodgers luster, but that will undoubtedly tarnish before the snow tires are off our cars. What will we say to mean the future then? Even 2001 is only a year away.

"The 22nd century" doesn't inspire as "the 21st" does; it sounds like a plodding successor, not the dawn of a new era. The year 2100 is like a rounded entry in an accounting ledger. Going further ahead to the 25th century or the year 3000 gets the blood pumping once again, but those times are hopelessly far off. Given how quickly events unfold, no one can guess meaningfully what the state of the human race will be 500 or 1,000 years hence.

ERICA LANSNER

"In the 21st century" sounds much more impressive than "sometime next month."

And there's the real problem. The rates of change in technology, scientific knowledge and public affairs are so great that imagination falls short. Less than 10 years ago the Internet was not much more than a secret among sophisticated computer users. Today e-commerce is the most invigorating force in the U.S. economy. Cloning and the regeneration of brain cells were thought to be impossible five years ago.

Science keeps its own schedule. Researchers in basic science do not know precisely when new discoveries will be made, but they keep at least in their hearts some expectations about when pieces of their puzzles will fall into place. For this special issue of *Scientific American,* we invited leading investigators to speculate about the future of their fields. Because a century seemed too far ahead, we asked them to think about major questions that might be answered by 2050: Can physics develop and test a theory of everything? What is the nature of self-awareness, and how does it arise? How much will knowledge of the genome allow us to learn about the limits of life?

The scientists were under no obligation to predict what the answers to those questions might be—although, as you will soon read, some of them have strong opinions. Rather their assignment was to explain why advances will accumulate rapidly enough for answers of some kind to be available. (That 2050 date holds the added advantage that many of us can hope to live to see whether these educated guesses are right.)

Our authors' exhilarating responses suggest that many of the questions that most intrigue us about the origins of the universe and humanity's place in it will be substantially answered within 50 years. In fact, many of those answers will be in long before then. So we do still have a useful shorthand term for the amazing future: tomorrow. And tomorrow has never sounded so rich in promise.

JOHN RENNIE, *Editor in Chief*
editors@sciam.com

LETTERS TO THE EDITORS

Our August issue prompted an array of responses, ranging from comments on fingernail hardness to accusations of politicking. And reactions to individual topics were equally diverse. The special report on M.I.T.'s Oxygen project, for example, left some readers enthusiastic about the future of technology and others wondering whether such advances really will make our lives easier.

Most of the letters commented on single articles, but Frank Papen of Ashland, Ore., noted an unintended connection among "The Lurking Perils of *Pfiesteria,*" by JoAnn M. Burkholder, "Trailing a Virus," by W. Wayt Gibbs, and Philip and Phylis Morrison's commentary on synthetic nitrogen production. "The bloom of *Pfiesteria* on the eastern shore has been attributed in part to runoff from pig and poultry operations. These facilities and the pig farms in Malaysia (where the Nipah virus appears to have jumped from swine to humans) probably both depend on grain produced using synthetic nitrogen," Papen writes. "We may have exceeded the carrying capacity of the biosphere and are entering into a dangerous period when very large and perhaps uncontrollable epidemics can occur." Additional reader responses to articles in the August issue follow.

MOLDING MORALITY

Regarding "The Moral Development of Children," by William Damon, few murderers, rapists, thieves, embezzlers or computer crackers were raised in an environment that was conducive to such pursuits. Few of these perpetrators' parents encouraged or condoned wanton repudiation of values. Even siblings raised in the same environment may eventually make very different choices. Human beings are not predetermined automatons; they cannot be intellectually dissected, analyzed, categorized and manipulated. It is impossible to predict accurately what a given person will do in a specific situation. This, however, will probably not discourage psychologists, sociologists and philosophers from trying.

ROBERT HAUPTMAN
Department of Information Media
St. Cloud State University

JIM NOELKER *The Image Works*

***EMPATHY* requires consistent nurturing.**

William Damon correctly notes that infants are born with the capacity for empathy. But early work by psychologists such as Harry Harlow indicated that without regular, comforting, physical contact and sensory stimulation from birth, the biological capacity for sociality—the precondition for empathy and conscience—cannot develop. This has recently been confirmed by the cases of thousands of eastern European orphans, sensorially deprived from birth for months or years. Many of these children, adopted in the early 1990s into loving American homes, have been both sociopathic and cognitively impaired. Thus, Damon's case of the young man who brutalized the elderly woman and showed no remorse, along with many other cases of children who seem to lack a conscience, might be the result of improperly developed sociality in infancy, early childhood or adolescence. Without regular social stimulation, the acquisition of social rules and values may be difficult or even impossible.

PHILLIPS STEVENS, JR.
Department of Anthropology
State University of New York at Buffalo

Damon replies:

I would not presume, as Hauptman writes, to "predict accurately what a given person will do in a specific situation" any more than I could predict what the weather will be in St. Cloud on July 31, 2000. But I can make some informed inferences in both cases. For example, I am quite sure that it will not be snowing on that date in St. Cloud. The better our science gets, the better our inferences will be. In the case of moral behavior, we can even go one better than with the weather: we can actually do something about it. Now that we can identify social conditions that promote young people's moral growth, we can work to establish these conditions in our families, schools and communities.

I agree with Stevens that empathy requires the nurturing provided by early social relationships. The point I tried to make in the article is that empathy comes naturally to our species. Consequently, socialization is a matter of further developing a response system that is already a part of the child's emotional repertoire. In other words, positive morality does not need to be forced on children; rather a moral code of conduct can be built on tendencies that exist at birth.

DEBATING DEFENSE

I cannot agree more with the conclusions drawn by George N. Lewis, Theodore A. Postol and John A. Pike in "Why National Missile Defense Won't Work." A missile defense system against nuclear or other mass-destruction warheads has to be 100 percent reliable to be successful, whereas the offense can be "successful" even if only one warhead reaches its target. I don't know of any other machine or system in the civilian or military world that has to perform to this extreme degree. The billions of dollars that would be spent on a system that won't work would be much better spent on taking missiles out of dangerous hands.

JAMES WATTENGEL
São Paulo, Brazil

"Why National Missile Defense Won't Work" is really more of a political argument than a technical argument. This has no place in *Scientific American*. For the past 25 years or so the magazine has been running articles on arms control that have taken a political viewpoint and presented it as a scientific one, and I have always felt very uncomfortable with that. How can Pike, whose organization is dedicated to defeating any type of national ballistic-missile defense system, provide an honest, objective and scientific assessment?

ROBERT L. VIRKUS
via e-mail

Editors' note:
Articles on national defense and nuclear arms have always appeared in *Scientific American* because political decisions rest in part on whether these goals are technically feasible. Scientists and defense experts of diverse political views criticize the current antimissile defense proposals on the grounds listed in the article; Pike and his co-authors did a particularly good job of presenting them.

TOUGH AS NAILS

With regard to James Burke's "Sound Ideas" [Connections], it is not at all strange that fingernails are included in the Mohs hardness scale for minerals. Rather this is the basis for a low-tech, portable mineral identification technique (pennies and steel knife blades are likewise part of the Mohs scale). If a geologist finds an unknown mineral that can be scratched with a fingernail, which has a hardness of two, any minerals with hardness values that are higher than two can be excluded from consideration.

Another geologic fingernail connection is the observation that the earth's tectonic plates move at the rate of centimeters a year—about as fast as one's fingernails grow. So geologists who abrade their fingernails by scratching minerals may have to wait for mountains to move before they can get back to business.

MARCIA BJØRNERUD
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Lawrence University

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.

50, 100 AND 150 YEARS AGO

DECEMBER 1949

SUPERNOVAE—"It is clear that supernovae explosions are not of a chemical nature, for at the tremendous temperatures of stellar material all chemical compounds are completely dissociated. We know that stars obtain their energy supply from some system of thermonuclear reactions, the most plausible being the so-called carbon cycle that transforms hydrogen into helium. Suppose that at a certain stage of a star's evolution some energy-absorbing reaction caused the central pressure to drop suddenly. The body of the star would collapse, much like the roof of a burning building. —George Gamow"

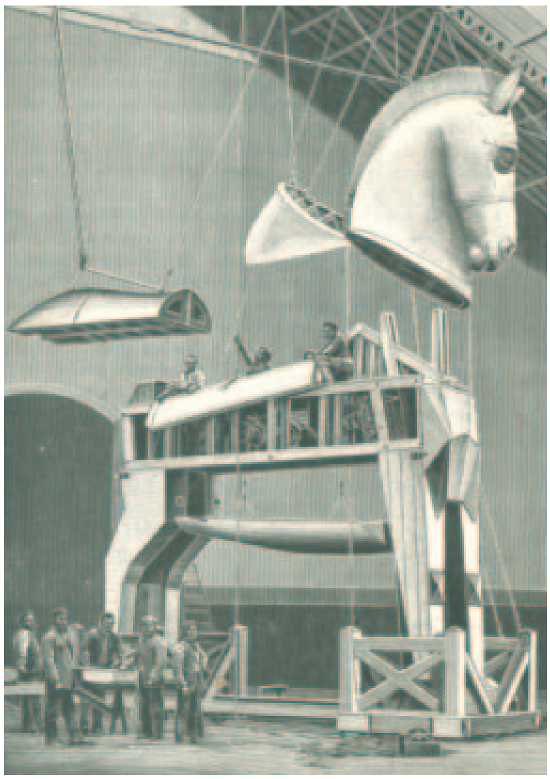
NEW HORMONE TREATMENTS—"In terms rare for a physician, Walter Bauer of the Harvard Medical School, speaking at a conference on hormone drugs, hailed the discovery of the therapeutic effects of ACTH [adrenocorticotropic hormone] as 'the opening of a new era in medicine.' ACTH and cortisone have been dramatically successful in treating arthritis and a muscular condition called myasthenia gravis. Others reported good results with ACTH in asthma, gout and eczema. But investigators at Columbia University's College of Physicians and Surgeons have said that it can cause severe headaches and raise blood pressure. Also, it has peculiar psychological effects, such as mental confusion or violence."

UNIVERSAL TRANSLATOR?—"If machines can be built to count, calculate, play chess, even 'think,' why not a machine to translate one language into another? British workers are planning a translator based on the storage or 'memory' apparatus in a mathematical machine. After 'reading' the material to be translated by means of a photoelectric scanning device, the machine would look up the words in its built-in dictionary in the instrument's memory unit, and pass the translations on to electric typewriters."

DECEMBER 1899

THE BIG PHYSICS QUESTIONS—"What is matter? What is gravitation? Newton and the great array of astronomers who have succeeded him have proved that, within planetary distances, matter attracts with a force varying inversely as the square of the distance. But where is the evidence that the law holds for smaller distances? Then as to the relation of gravitation and time, what can we say? Can we for a moment suppose that two bodies moving through space with great velocities have their gravitation unaltered? I think not. Neither can we accept Laplace's proof that forces of gravitation act instantaneously through space, for we can readily imagine compensating features unthought of by Laplace."

LAST OF THE BUFFALO—"One of the most extraordinary events that has characterized the last half of the present century is the extermination, the wiping out, of the American bison. It is the 'crime of the century.' In the southern herd, from 1872 to 1874 there were 3,158,780 killed by white people and the skins shipped east over the Atchison, Topeka and Santa Fé road. During the same time the Indians killed 390,000, and settlers and mountain Indians killed 150,000. But the blame really lies with the government that in all these years permitted a few ignorant Congressmen to block the legislature in favor of the protection of the bison."



Art and artifice—the Trojan horse at the Paris Opera

TROJAN HORSE—"The Opera House of Paris has put upon the stage a work of Berlioz named 'The Taking of Troy.' If we refer to the *Iliad* and *Aeneid,* it may well be conceded that the present horse resembles the machine of war that the Greeks constructed, but as the Opera House does not give the same play every day, it was necessary that it should be capable of being easily dismantled [*see illustration at left*]. The horse is not inhabitable, since the piece does not require the exit of Greek warriors before the audience."

DECEMBER 1849

CALIFORNIA DREAMING—"By the latest news from California we learn that a Constitution has been adopted, and they are knocking for admission into the Union. Quite a number of Chinese are in California acting the part of carpenters, and they are very industrious and peaceable *citizens.* Gold is still plenty, and the prospects still good, with hard work and, unfortunately, a chance for sickness. Provisions were very high, and there was no little political excitement. One divorce has been granted."

LETTER ON LEAD—"Gentlemen: I noticed in one of your late numbers that the United States had granted a patent for the use of Acetate of Lead in the refining of sugar. Can it be possible that the use of this virulent poison in a most important article of food is legalized by our Government?"

NEWS AND ANALYSIS

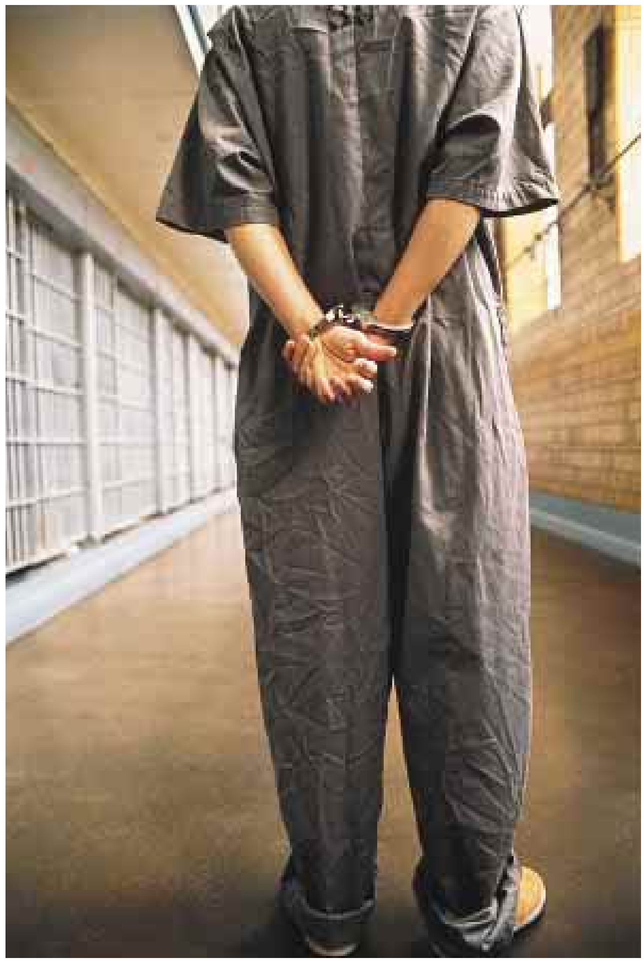
IN FOCUS

THE ABORTED CRIME WAVE?

A controversial article links the recent drop in crime to the legalization of abortion two decades ago

Since the early 1990s crime has fallen annually in the U.S., last year by about 7 percent. Many explanations have been put forward for this drop: more police walk the beat, more people are in prison, the economy has improved, crack use has fallen, alarms and guards are now widespread. The emphasis given to any one of these rationales varies, of course, according to philosophical bent or political expediency. In New York City, for instance, plummeting crime has been attributed to improved policing. Yet the decline exists even in cities that have not altered their approach, such as Los Angeles.

The above explanations are unsatisfactory to many researchers, among them two economists who have studied crime. Steven D. Levitt of the University of Chicago and John J. Donohue III, currently at Yale University, have proffered an alternative reason: the legalization of abortion in 1973 reduced the number of unwanted children—that is, children more likely to become criminals. In 1992, the first year crime began to fall, the first set of children born after 1973 turned 18. Because most crimes are committed by young adult males between the ages of 18 and 24, Levitt and Donohue argue that the absence of millions of unwanted children led to fewer crimes being done by that age group. In total, the researchers maintain, the advent of legal abortion may be responsible for up to 50 percent of the drop in crime.



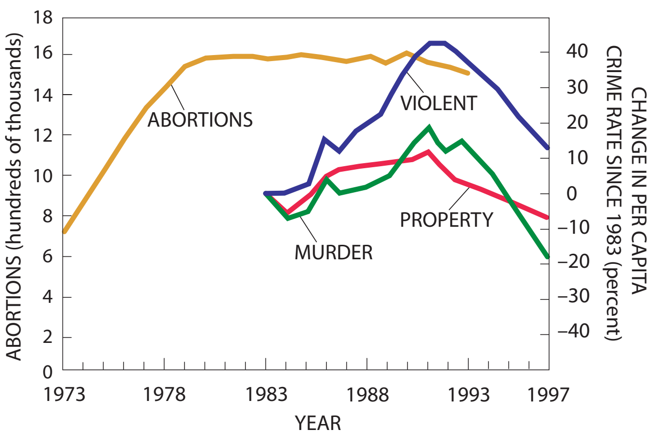
KEVIN HORAN *Tony Stone Images*

***YOUNG ADULT MALES** are responsible for most crime, which has been dropping in the U.S. in the 1990s.*

Their hypothesis, presented in the as yet unpublished paper "Legalized Abortion and Crime," has triggered everything from admiration for its innovative thinking to outrage for its implications. Groups on both sides of the abortion divide remain wary: some right-to-life representatives describe the findings as strange, while pro-choice groups worry that the conclusions will make people view abortion as a vehicle for social cleansing. The response has shocked both academics. The work "is not proscriptive, but descriptive," Levitt maintains. "Neither of us has an agenda with regard to abortion."

Some economists, for their part, want questions answered about certain aspects of the methodology—and they want more evidence. "Most interesting is that they put forth an alternative explanation that is conceivably possible," says Phillip B. Levine, an economist at Wellesley College. "In terms of the evidence, I think it is somewhat suggestive. I wouldn't go so far as to say it is conclusive." Levine also points out that although the paper surprised the public, it actually follows logically from previous work in this area.

Indeed, Levitt and Donohue are not the first to connect crime and abortion. As they note in their paper, a former Minneapolis police chief made the same suggestion several years ago. But they are the first to examine data to determine whether there could be a correlation. They looked at how crime rates differed for states that legalized abortion before the U.S. Supreme Court decision on *Roe v. Wade:* New York, Washington, Alaska and Hawaii. In those states, crime began to drop a few years before it did in the rest of the country, and states with higher abortion rates have had steeper drops in crime. Fewer unwanted children, the two conclude, ultimately means fewer crimes.



***CRIME RATES** dropped after 1991, just when children born after* **Roe v. Wade** *would be reaching 18.*

The idea that unwantedness could adversely affect children is also not new. Levine and several colleagues explored the economic and social ramifications for children of the legalization of abortion in a paper published earlier this year in the *Quarterly Journal of Economics*. They estimated that children who were aborted would have been from "40 to 60 percent more likely to live in a single-parent family, to live in poverty, to receive welfare, and to die as an infant."

Real-world evidence also links unwantedness to some poor outcomes for children. A 1995 Institute of Medicine report, *The Best Intentions: Unintended Pregnancy and the Well-Being of Children and Families,* reviewed studies on this topic, concluding that women who did not mean to get pregnant were more likely to expose their fetus to harmful substances and that these children were at higher risk for low birth weight and abuse.

And a few long-term studies have found an association between unwantedness and criminality. Levitt and Donohue cite a handful of European studies that have followed for several decades children born to women who were denied abortions they had requested—repeatedly, in some cases. These studies did find that unwanted children had somewhat higher rates of criminality and psychiatric troubles. "It is correct that there is more evidence of difficult behavior and criminal behavior," says Henry P. David, co-author of an ongoing 38-year study of unwanted kids in Prague and an editor of the 1988 review *Born Unwanted: Developmental Effects of Denied Abortion*. "But the numbers are small; it would be difficult to say that they became criminals because of unwantedness. Certainly that was a factor, but we don't know how much."

The "how much" seems the crux of the matter for some economists. Theodore J. Joyce of Baruch College argues that when Levitt and Donohue factor in regional variability, the strength of their correlation vanishes. In other words, one of their own charts seems to suggest that some underlying—and unspecified—differences ("omitted variables," as they write) between the regions explain the drop in crime, not the abortion rate, he says.

In addition, Joyce and other scholars note that relying on abortion occurrence data is problematic. Levitt and Donohue use figures for the number of abortions performed in a state—which do not specify whether the woman came from out of state. When Joyce recently reviewed estimates for abortions by state of origin that were made in the early 1970s by the Alan Guttmacher Institute in New York City, he says he found that 30 percent of New York's abortions were performed on women from elsewhere. Such dramatic interstate movement was not accounted for in Levitt and Donohue's paper, Joyce states, and it suggests that their correlations could be off-kilter. "To say that legalization has some kind of effect is certainly plausible," he concludes. "But I think it should be questioned because the magnitude of the finding is so large: 50 percent seems way too large."

Despite these concerns, scholars generally agree that Levitt and Donohue are asking a reasonable question. And if the two are right, the association should show up in other realms as well: teenage pregnancy should be dropping, as should adolescent and young adult suicide, unemployment, and high school dropout rates, and education levels should be rising.

Levitt says that the 2000 census will allow researchers to investigate some of those other correlates but that for now he and Donohue are focusing on teen pregnancy. At first glance, at least, their expectation seems to be holding up. A 1998 article in *Pediatrics* notes that teen pregnancy has been declining steadily this decade—a total of 13 percent between 1991 and 1995—and the extent of the decline varies enormously by state and ethnicity.

In addition, teenage and young adult behavior is changing on many fronts. In 1994 and 1995, notes Laura D. Lindberg of the Urban Institute in Washington, D.C., drug use, sexual activity and suicidal ideation began to decline in adolescents after what had seemed a never-ending increase. "But how you connect very recent declines with [Levitt and Donohue's] idea of a shock to the system is very unclear," Lindberg cautions. "Many things are changing over time."

So the jury remains out. Researchers are waiting to see whether the paper withstands ongoing scrutiny and whether other evidence emerges. "It is a fascinating theory," David declares. "I suspect there is some kernel of truth, but how much is hard to say." *—Marguerite Holloway*

SARAH L. DONELSON

ECOLOGY

A PLAN FOR PANAMA

As the U.S. turns over the canal, Panama prepares for visitors

While many of us are worrying about what we might not have when Y2K arrives (say, electricity or cash), people in Panama are focusing on what they *will* have: control of the Panama Canal and all the U.S. military bases in the area. According to a 1977 treaty between the U.S. and Panama, the waterway itself, as well as the 10-mile-wide, 50-mile-long tract of land on the banks of the canal (known as the Canal Zone, property of the U.S. since 1904), will revert to local control by the end of this year.

Over the past two decades, one third of the Canal Zone has been gradually transferred to Panama. This year the pace has quickened: three major U.S. installations are closing, leaving Panama with a hefty inheritance of old barracks, training grounds and the like.

Of course, the military did not pave the entire Canal Zone with concrete. A good portion is still virgin forest, thanks to almost 100 years of extremely restricted access. Anxious to buffer the economy against the effects of base closings and, at the same time, put the new land holdings to good use, Panamanian authorities have come up with a plan to protect both the country's natural and financial resources—tourism.

Why the fuss about where people go on vacation? According to a report released earlier this year by Washington, D.C.–based Conservation International, tourism is becoming increasingly centered on the tropics—places such as Southeast Asia, Africa, the Caribbean and South America, home to most of the world's biodiversity. Money brought in by visitors can provide much-needed resources for developing countries and high profits for investors: by 2010, international tourism is expected to generate an estimated $1.55 trillion.

The project in Panama, known as the Tourism-Conservation-Research (TCR) Action Plan, is the brainchild of Hana Ayala, president of EcoResorts International. Ayala, a landscape ecologist and former professor at the University of California at Irvine, has an impressive list of partners, including the Smithsonian Tropical Research Institute (STRI) and the American Association for the Advancement of Science. For the last year, EcoResorts, based in Irvine, has been working with STRI to lay the foundations in Panama for what Ayala calls "heritage tourism." The idea is to develop a network of officially recognized travel itineraries across Panama that will steer tourists away from fragile ecosystems while still satisfying their desires to experience the country's cultural and natural heritage.

Ayala cites a recent survey indicating that 90 percent of today's travelers list "having the opportunity to learn something" as their reason for choosing a particular vacation spot. "They want to know about the medicinal properties of plants or about the characteristics of the ecosystem," she says—information that scientists are best suited to provide.

As the TCR project continues, more converted military land will appear in the Panama guidebooks. One former U.S. radar tower is already an unusual treetop hotel (and bird-watching site) in Soberanía National Park. The former Fort Sherman encompasses nearly 25,000 acres of jungle, which the government is developing for use by both tourists and wildlife.

Yet as the U.S. hands over such installations, it also passes along their history. Soldiers en route to Vietnam, for example, routinely passed through Fort Sherman for jungle-warfare training. As a result, parts of the Canal Zone remain contaminated with unexploded ordnance: grenades, mortar rounds and shells. Rumors have also surfaced about nuclear waste and leftover chemical and biological warfare agents.

Air Force Colonel David Hunt told Reuters News Service in September that the military has complied with the requirements set forth in the original treaty, adding that "we knew in 1977 that we could not remove 100 percent of unexploded ordnance in the impact area of the ranges without doing irreparable damage to the environment." Nevertheless, the Panamanian government plans to launch its own environmental survey of the Canal Zone.

Surprisingly, yesterday's tools of destruction might actually protect some ecosystems. Over the past few years, the U.S. Fish and Wildlife Service (USFWS) has converted several U.S. military bases to wildlife refuges. Patuxent Research Refuge in Maryland, for instance, includes land formerly part of nearby Fort Meade. Eric Eckl, spokesperson for the USFWS, puts it this way: "If there are unexploded ordnance on the ground, this is not an issue for a bird nesting nearby. If a bear comes along, it could be killed, but the [overall] risk to wildlife is minimal." After all, bombs don't kill forests, people kill forests. —*Sasha Nemecek*

JULIE PLASENCIA *AP Photo*

***ATTRACTING TOURISTS** to the Panama Canal could help preserve its ecosystem.*

STRESS TEST

The tragedy in Turkey may aid earthquake forecasting

The magnitude 7.4 Izmit earthquake, which struck north-central Turkey on August 17, killed at least 15,000 people. Yet the catastrophe also helped to validate a relatively new technique in earthquake science, known as stress-transfer analysis, which may save lives in the future. The practitioners of this technique attempt to gauge the likelihood of earthquakes by studying how faults interact with one another over time and space.

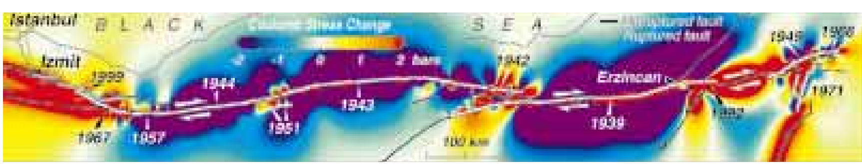
When a segment of a fault ruptures, explains geophysicist Ross S. Stein of the U.S. Geological Survey in Menlo Park, Calif., the stress on that segment drops, but part of the released stress goes to nearby regions. This transfer—a consequence of the elasticity of the earth's crust—affects adjacent segments as well as other faults in the vicinity. Depending on each fault's location, orientation and direction of slip, its likelihood of rupture may increase or decrease.

Typically Stein and his colleagues find that the transferred stresses are quite small—only a few percent of the total stress that accumulates on a fault from one rupture to the next. Even so, when the group examined the seismic history of several regions of California, they found a marked tendency for earthquakes to occur selectively on those faults that had experienced a stress increase as a result of a prior earthquake nearby.

About three years ago Stein, USGS colleague James H. Dieterich and geologist Aykut A. Barka of Istanbul Technical University turned their attention to Turkey's North Anatolian fault. This 1,400-kilometer-long (870-mile-long) fault is the line along which the Anatolian microplate is rotating westward with respect to the Eurasian plate. Since 1939 a sequence of disastrous earthquakes has progressed westward along the fault, reaching the area east of Izmit in 1967. Earthquakes have also progressed eastward from the 1939 rupture, though in a less orderly fashion.

According to the group's analysis, most of the ruptures started at points on the fault that had experienced stress increases as a result of previous ruptures. They also found that the yet unbroken segments near Izmit had been subjected to higher stress as a result of the ruptures to the east of the city. They estimated a 12 percent probability that a magnitude 6.7 or larger earthquake would strike the Izmit area within 30 years. With the benefit of hindsight, this prediction might seem excessively cautious. In the notoriously controversial business of earthquake forecasting, however, it represents a modest success.

YANNIS KONTOS *Corbis/Sygma*



ROSS S. STEIN/USGS

***IZMIT EARTHQUAKE** in Turkey is part of a larger pattern of ruptures on the North Anatolian fault, beginning with a 1939 earthquake and leading to raised* (red) *or lowered* (purple) *levels of stresses along the fault, as measured by an index called the Coulomb failure stress (a large earthquake releases about 100 bars of stress). The August 1999 Izmit rupture* (light blue line) *occurred in a zone of increased stress.*

Unlike the North Anatolian fault, California's San Andreas fault is embedded in a dense network of other active faults. Geophysicist Steven N. Ward of the University of California at Santa Cruz uses the stress-transfer approach to model the behavior of this network. Within the safe confines of his computer, Ward allows the faults to rupture repeatedly over thousands of years, and he looks for spatiotemporal patterns in the resulting "earthquake movie." He finds that stress transfers between faults largely prevent the San Andreas fault from breaking in orderly, progressive sequences. The same phenomenon may explain why earthquakes along the eastern part of the North Anatolian fault form a less orderly sequence than they do to the west.

Still, significant patterns emerge from Ward's movie. A major rupture on the northern San Andreas fault, for instance, tends to decrease the likelihood of earthquakes on other San Francisco Bay Area faults for several decades. In fact, the Bay Area has enjoyed just such a period of seismic quiescence since the great San Francisco earthquake of 1906. But a recent increase in the number of small earthquakes, as well as the 1989 Loma Prieta earthquake, have signaled that the truce is coming to an end.

Ruth A. Harris and Robert W. Simpson of the USGS have applied stress-transfer analysis to the 1992 magnitude 7.5 Landers earthquake, which originated near Palm Springs, Calif. They find that the Landers rupture partially "unclamped" the San Andreas fault near San Bernardino, east of Los Angeles. This unclamping brought the date of the next earthquake—expected to be up to a devastating magnitude 8—about 14 years closer than would otherwise have been the case. Because a precise seismic history for the San Bernardino segment is lacking, Harris and Simpson have not translated this estimate into a probability forecast. Even without their analysis, however, the area has been rated as among the most hazardous in the U.S. It has a 60 percent chance of experiencing a damaging earthquake before the year 2024, according to the Working Group on California Earthquake Probabilities.

The Landers earthquake also increased the stress in a zone extending northeastward to the Mojave Desert—an area struck by the October 16 magnitude 7.1 earthquake. This so-called Hector Mine earthquake, which caused little damage thanks to its remote location, further demonstrates the influence of transferred stresses on future ruptures, Stein says.

The stress-transfer approach is valuable but incomplete, according to geophysicist Steven M. Day of San Diego State University. A fully adequate description of earthquake behavior, he says, needs to incorporate dynamic processes that are ignored in the static stress-transfer models. The actual shaking of the earth ahead of an advancing rupture, for example, may permit the rupture to extend for a greater distance than the static models would predict, thus unleashing a more powerful earthquake. Day believes that it may be premature to use the results of stress-transfer analysis for the routine estimation of seismic hazards.

Still, Stein and his group are busy thinking about what may happen next on the North Anatolian fault. According to their preliminary calculations, the Izmit earthquake has increased stresses on the Yalova segment of the fault, which runs westward across the floor of the Sea of Marmara, southeast of Istanbul. Consistent with this finding, the rate of small earthquakes under the Sea of Marmara has increased markedly since the Izmit temblor. An earthquake on the Yalova segment could devastate Istanbul. "If you look at the records for the 1,000-year-old Hagia Sophia mosque," Stein says, "you'll see that it's a seismometer—they've had to rebuild it over and over again. It's not rocket science to say that Istanbul is at risk." *—Simon LeVay*

SIMON LEVAY is a neuroscientist turned science writer based in Los Angeles. He co-authored The Earth in Turmoil *(W. H. Freeman, 1998).*

PHYSICS

APOCALYPSE DEFERRED

A new accelerator at Brookhaven won't destroy the world after all

It all began in the "Letters to the Editors" section of the July issue of this magazine. In response to a March article about the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, several readers expressed alarm about the experiments planned for the Upton, N.Y., facility. The newly built accelerator is designed to smash gold ions together at unprecedented energies; researchers hope the high-energy collisions will momentarily reproduce the hot, dense quark-gluon plasma that filled the universe in the first moments after the big bang. Some readers worried, however, that the experiments might also produce a miniature black hole that would sink to the earth's core and devour the whole planet in minutes.

Fears of a man-made apocalypse spread quickly on the Internet and soon appeared as screaming headlines in British newspapers ("Big Bang Machine Could Destroy Earth," the *Sunday Times* of London warned). Physicists argued that RHIC would not even come close to creating black holes—for that to happen, the ions would have to be compressed to a density 10^{60} times greater than that produced by the RHIC collisions. But another doomsday scenario was harder to dismiss. Some researchers believe the ion smashups could generate a new form of matter called strangelets. These subatomic bundles would combine three species of quarks: the commonplace "up" and "down" quarks that are the building blocks of protons and neutrons, and the rarer "strange" quarks that are found in short-lived particles such as kaons.

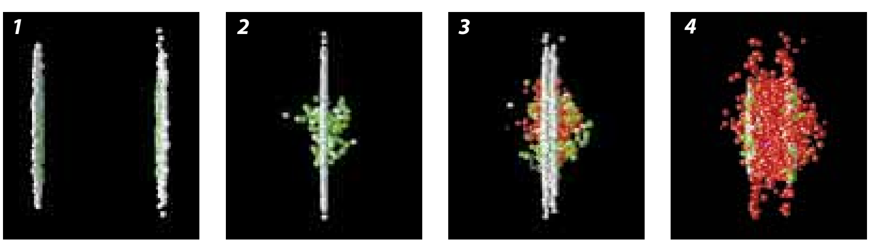
Scientists have never observed a strangelet, so they can only guess at its properties. The most dangerous possibility would be the creation of a long-lived strangelet with a negative charge. This type of strangelet would not act like an ordinary negatively charged particle; it would grow rapidly by gobbling up all the positively charged atomic nuclei that it encountered. Such a voracious beast could consume our planet just as effectively as a black hole could.

Brookhaven's director, John Marburger, responded to the ominous headlines by stating that "there is no chance that any phenomenon produced by RHIC will lead to disaster." To be certain, though, Marburger asked a group of physicists to review the issue. Their report, completed in September, is reassuring. According to Robert L. Jaffe, the Massachusetts Institute of Technology theorist who chaired the group, strangelets can be produced only under conditions of extremely high pressure and low temperature. "It's effectively impossible to make them in an ion collider," Jaffe says. "The only place where it could happen is in the core of a neutron star."

Even if, by some fluke, RHIC created a strangelet, it would decay long before it could approach a nucleus. And the physicists determined that even a long-lived strangelet would be harmless because its up and down quarks would outnumber its strange quarks, thus giving the particle a positive charge. The strangelet would simply attract a pair of electrons and act like an unusually heavy isotope of helium.

If that argument isn't enough to assuage you, consider this: ion collisions exactly like those planned for RHIC occur all the time in interstellar space. Despite the scarcity of gold, there are about 1,000 high-energy impacts of gold ions every year in each cubic light-year of our galaxy. If these impacts could generate long-lived, negatively charged strangelets, some of the dangerous particles would eventually be pulled into nearby stars, causing them to explode. This process would trigger about a million supernovae in our galaxy every year—but in reality, astronomers have observed only a handful in the past millennium. One must conclude that the ion collisions are not producing anything so volatile.

Bolstered by the physicists' report, Brookhaven officials are pushing ahead with their plans for RHIC, scheduling the first collisions by the end of this year. Jaffe believes the furor over the accelerator stemmed from a common misconception. "People think we can play with the fabric of the universe," Jaffe says. "But the things we do with accelerators are not unique." *—Mark Alpert*



BROOKHAVEN NATIONAL LABORATORY

SIMULATION OF ION COLLISION** shows two gold nuclei, flattened by relativistic effects, speeding toward each other* (1), *crashing* (2) *and passing through each other* (3). ***The impact may produce a plasma of quarks and gluons (4).

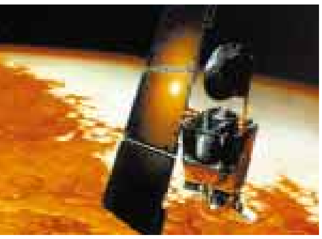
IN BRIEF

Blocking HIV

Peter S. Kim of the Whitehead Institute for Biomedical Research and his colleagues have discovered a new class of compounds to attack HIV. The team looked at a coat protein of HIV called gp41, which contains a pocket that, when blocked, prevents HIV from entering immune cells. Several peptides can serve as blockers; moreover, such substances can be taken orally. (Another blocker, called T-20, is in clinical trials but must be injected.) Unlike current treatments, a drug developed from this study would attack HIV before the virus could infect. The work appears in the October 1 *Cell*. —*Philip Yam*

Out of Spin Control

On September 23, ground controllers accidentally steered the Mars Climate Orbiter deep into the atmosphere of the Red Planet, presumably to its demise. A preliminary review found that Lockheed Martin Astronautics, builder of the $125-million orbiter, had failed to convert thrust data from pounds (used by U.S. aerospace companies) to its metric cousin, newtons (used by the Jet Propulsion Laboratory). The data thus overstated the force provided by thrusters. Project scientist Richard Zurek said hints of a problem showed up in tracking data, but ground controllers judged a last-minute course correction too risky. Other errors might also have contributed to the fiasco. —*George Musser*



Lost cause

NASA/JPL/CALTECH

On Target

Pentagon officials report that on October 2 a missile launched 6,880 kilometers (4,300 miles) away intercepted a dummy warhead over the Pacific Ocean. Using heat-seeking technology, the interceptor vehicle, ignoring a decoy, slammed into the warhead at more than 25,000 kilometers per hour, obliterating it. The test is the first missile-defense success in 16 tries that does not appear to have been rigged to succeed (a criticism leveled by Congress). After more testing next year, the Pentagon may recommend by the summer that the U.S. proceed with missile-defense development. —*P.Y.*

More "In Brief" on page 34

ANTI GRAVITY

Notes from the Underground

Neither rain, nor sleet, nor gloom of night will stop readers from sending mail. "Anti Gravity" gets its fair share. The column has run for four years now, and regular readers recognize it as a somewhat offbeat take on science, a break from the rest of the magazine's exposition of the weighty work, the gravitas, of teasing out nature's secrets.

Some of the mail decries the very existence of this column, with the reader feeling cheated out of two thirds of a page of meat and potatoes. To them, I offer only regrets that they care not for the occasional ice cream cone and advice that they turn the page with a greater sense of urgency. Some mail carries the reader's umbrage with me. To them, I offer thanks for sharing their thoughts and advice that they get their own magazine column. (And this note: Letters containing the phrase "I have a sense of humor, but…" inevitably announce the lack of same.) Amazingly, some mail indicates that the reader actually likes the column, proving that there's no accounting for taste.

Finally, some mail educates. In September, this space discussed the matter of dead rattlesnakes still capable of delivering nasty bites. This entry prompted a response from Thomas Reisner of the literature department at Laval University in Quebec: "[The] review of a warning recently published in the *New England Journal of Medicine,* concerning the hazards of manipulating dead rattlesnakes prematurely, rang a bell with me. On further reflection, I recalled having come across the idea of snakes inflicting bites on their handlers postmortem in, of all places, the poetical works of Percy B. Shelley.

"In 1820, when Shelley showed his recently completed *Witch of Atlas* to his wife Mary (of Frankenstein fame), she was apparently unimpressed. Her response goaded him into writing a good-natured apology for the poem, beginning with the lines:

> How, my dear Mary,—are you critic-bitten
> (For vipers kill, though dead) by some review,
> That you condemn these verses I have written,
> Because they tell no story, false or true?
> What, though no mice are caught by a young kitten,
> May it not leap and play as grown cats do,
> Till its claws come? Prithee, for this one time,
> Content thee with a visionary rhyme.

"Since at the time the Shelleys were living near Pisa, in northern Italy (a region infested with vipers, though not with rattlesnakes), his allusion may have been based on personal experience. In any event, there is, I believe, something deeply satisfying in seeing the findings of modern science scooped by a mere Romantic, almost two centuries earlier!"

There is also something deeply satisfying in, even for a moment, bridging the gap between C. P. Snow's two cultures. Especially in light of another recent letter to the *New England Journal of Medicine,* from Howard Fischer of Children's Hospital of Michigan. He recounts the sad story of a hospitalized 51-year-old high school teacher. This fellow, imprisoned by the various tubes and lines attached to him, remarked that he felt as though he were in "Peter Coffin's inn." This reference to the claustrophobic lodging house in *Moby Dick* was lost on a nurse, who heard the word "coffin," put two and two together to make 22 and assumed the teacher might be suicidal. The patient then had to prove himself to the psychiatrists who were brought in to make sure he wasn't planning the mortal coil shuffle. (The nurse might think this odd maneuver refers to a dance step.) Fischer notes that "physicians and nurses need a broader education in the humanities."

MICHAEL CRAWFORD

Indeed, even in the sciences we should all strive to be men and women of letters. Or at least postcards. —*Steve Mirsky*

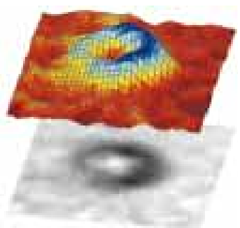
In Brief, continued from page 32

Resisting Cancer

In the October *Nature Medicine,* researchers from the National Cancer Institute report good news about a cancer vaccine. Tumor cells from patients with lymphoma were fused with mouse cells that churned out tumor proteins. Injected into the patients, the proteins provoked an immune response; 18 of 20 patients remain in remission four years after being vaccinated. Unlike previous vaccine trials, this study succeeded apparently because the patients were newly diagnosed and therefore retained a potent immune response. In another study, appearing in the October 14 *Nature,* investigators created mice immune to some cancers. These mice had three of four so-called *Id* genes, which govern blood vessel growth, knocked out. The mice apparently resisted injected malignant cells because the cells could not establish blood supplies. —*P.Y.*

Bose-Einstein Vortex

Two reports in the September 27 *Physical Review Letters* indicate long-sought superfluid behavior in gaseous Bose-Einstein condensates.



Quantum whirlpool

BRIAN P. ANDERSON/JILA

Physicists at the National Institute of Standards and Technology and the University of Colorado at Boulder used lasers to coax a condensate of rubidium atoms to form a spinning state called a vortex—a quantum whirlpool characteristic of superfluids, liquids that flow with no viscosity. A group at the Massachusetts Institute of Technology found superfluid activity using a laser beam as a stirring rod. When the "rod" was moved slowly, the condensate flowed around the rod without being disturbed but was heated when the rod was stirred faster—behavior characteristic of superfluids. —*Graham P. Collins*

You Deserve a Break Right Now

After four million keystrokes and 6,200 hours of computer use by 21 test subjects, Alan Hedge of Cornell University found that workers made 13 percent fewer errors if on-screen alerts periodically appeared to tell them to sit up straight, take breaks or stretch. The improvement reflects a 1 percent jump in overall productivity (see ergo.human.cornell.edu/CUHFdownloads.html). —*P.Y.*

SA

FIELD NOTES

CAVE INN

A visit to a Neanderthal home

From Croatia's capital city, Zagreb, Vindija cave is about a 90-minute drive through the rolling, rugged terrain of a northwestern region known as the Hrvatsko Zagorje. Today quaint cottages dot the countryside, the dwellings of farmers who coax corn and cabbages from the rocky soil. Thousands of years ago, however, Neanderthals inhabited these hills, and I have come to visit this cave that some of them called home.

The roads narrow as paleontologist Jakov Radovčić of the Croatian Natural History Museum and I approach Vindija, and the last 100 or so meters (about 330 feet) to the site have to be traversed on foot. "They chose a place near a spring," he observes, acknowledging the sound of trickling water that greets us as we step out of the car. A rock-strewn trail takes us into the woods and up a steep hill. Through the trees the landscape below is visible for a considerable distance. "The Neanderthals were trying to control the region," Radovčić remarks, adding that other Neanderthal shelters in Croatia bear similar strategic profiles: all are elevated, with a proximal water source.

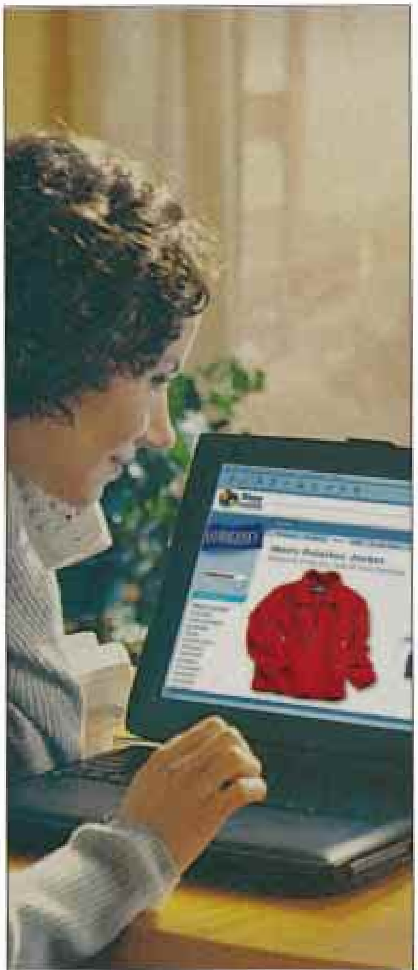
The cave mouth opens an impressive 15 meters wide and 15 meters high. But it is only once I'm inside, after my eyes adjust to the darkness, that I realize how vast the space is—the cave stretches 50 meters deep, swelling in height and width. Along one wall unexcavated sediments display the stratigraphy of the site; the banded layers tell a color-coded story of glacial and interglacial periods.

Radovčić draws my attention to a grayish green band, the so-called G3 level that contained some of the Neanderthal fossils he himself unearthed, and fishes a cast of one of the ancient bones out of his pocket. "The Vindija hominids were modernized Neanderthals," he says, showing me the partial lower jaw featuring the beginnings of a chin—one of the hallmarks of modern human morphology. And although other fossils from the site reveal typical Neanderthal traits such as the pronounced browridge, they are more delicate and modern in shape in the Vindija people than in earlier Neanderthals. Radovčić and others who have studied these remains believe this apparent shift toward the modern condition suggests interbreeding between Neanderthals and moderns—a case that is strengthened by early modern human fossil finds from central Europe that bear some Neanderthal-like features. (Many researchers, however, maintain that the two groups did not exchange genes. To them, these similarities simply reflect convergent evolution.)

Vindija has also yielded intriguing bone and stone tools, found in association with the Neanderthal fossils, that exhibit a sophisticated workmanship broadly characteristic of early modern humans. But whether these tools were discovered in their original contexts is the subject of debate: the seasonal freezing and thawing of the ground may have mixed the layers up, or denning cave bears may have disturbed the

KATE WONG

VINDIJA CAVE in Croatia sheltered Neanderthals 28,000 years ago, the most recent ones known.



remains. If in fact Neanderthals made the more advanced tools, many archaeologists might have to rethink the evolution of these cultural traditions and reconsider who originated such modern human behavior. (Exactly how the October announcement by scientists that Neanderthal bones found in a French cave exhibit evidence of cannibalism affects the cultural picture is unclear.)

Unfortunately, a recent attempt to date directly the most modern-looking tool—a split-base bone point from the younger G1 level—has failed, according to a report in the October 26 *Proceedings of the National Academy of Sciences USA*. Despite that disappointing result, the international team succeeded in dating the G1 Neanderthals. Previously, a date from an associated cave bear bone had implied that these remains were 33,000 years old, but the new dates, taken directly on the human fossils, reveal that Neanderthals persisted in Croatia as late as 28,000 years ago, making them the most recent

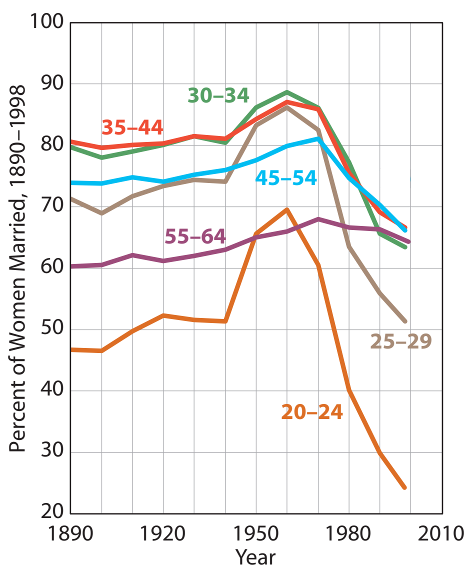
BY THE NUMBERS

The Decline of Marriage

Only 67 percent of American women aged 35 to 44 were legally married as of 1998. This contrasts with 81 percent in the period 1890–1940, before the unusually high marriage levels of the baby boom years. This trend—it is more or less paralleled by other countries on the map, with the exception of Poland and Romania—reflects several developments, including rising age of marriage, increasing popularity of cohabitation, high divorce rates and growth in the number of children born out-of-wedlock.

That people are staying single longer may stem in part from the option of living together without marrying, which has lost much of its stigma in recent years. But perhaps a more basic motivation is widespread pessimism about marriage, particularly among women, as noted by David Popenoe and Barbara Dafoe Whitehead of the National Marriage Project of Rutgers University. They suggest that this attitude may reflect certain expectations of emotional intimacy in marriage and of men's participation in child-rearing and household work. (Their observations are based on U.S. data and so may not apply to other countries.) Another factor contributing to women remaining single is the increase of higher education in many Western countries, which presumably causes some men and women to put off marriage.

Divorce rates in most Western countries are much higher now than they were before 1970, probably resulting in part from the growing economic independence of women, which makes it easier for wives to walk away from bad marriages. The divorce rate tends to be higher in those countries where women are most apt to work at paid jobs. According to a novel theory advanced by economists George A. Akerlof, Janet L. Yellen and Michael L. Katz of the University of California at Berkeley, wider availability of the birth-control pill and legal abortion led to dramatic changes in American attitudes toward marriage. Before the early 1970s, the stigma of unwed motherhood was so great that few unmarried women were willing to have sex unless it was understood that marriage would follow if pregnancy occurred. In those days, if a woman became pregnant, the man felt obliged to marry her. Such "shotgun marriages" became rarer, thanks to abortion and contraception. Because women could, theoretically,



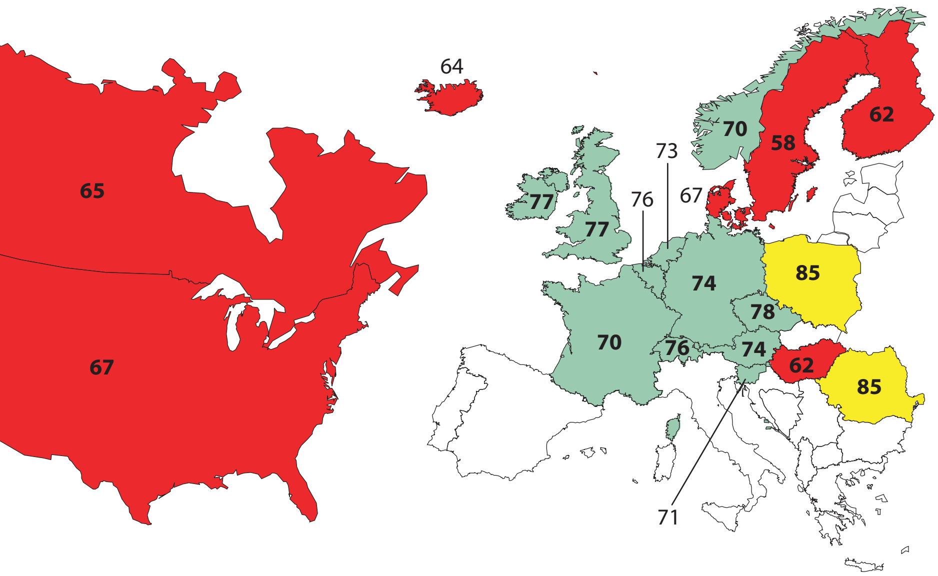
SOURCE: U.S. Bureau of the Census

ones known from anywhere in Eurasia.

"We had known that Neanderthals existed until around 30,000 years ago in southwestern France and the Iberian Peninsula," says team member Fred H. Smith, a paleoanthropologist at Northern Illinois University. That they still lived in central Europe 28,000 years ago, he remarks, "suggests to me that the interaction between Neanderthal populations and modern humans was a lot more complex than we thought—it wasn't just a matter of pushing the Neanderthals out of the way."

Whether they warred with moderns and ultimately lost, or were peacefully absorbed into the population, the debate over how human the Neanderthals really were continues. But as I stood inside Vindija cave looking out, sheltered from an afternoon shower, I couldn't help thinking that 28,000 years ago a Neanderthal might have rested here on a drizzly day in late summer and savored the quiet, verdant beauty.

—Kate Wong near Zagreb, Croatia



PERCENT OF WOMEN 35 TO 44 WHO ARE MARRIED

UNDER 70 70 TO 79 80 OR MORE NO DATA

SOURCE: Eurostat (Statistical Office of the European Communities) and statistical bureaus of individual countries. Shown are all countries for which data are available for 1996 or a later year. Data are for 1998, except for the Netherlands, which are for 1999, and Canada, Denmark, Ireland and the U.K., which are for 1996.

ROGER DOYLE

choose not to give birth, men began feeling that it was the woman's fault if an unwanted pregnancy was carried to term and therefore felt no responsibility for the child. Increasingly, women no longer believed that they could ask for a promise of marriage in the event of pregnancy.

Still, for a number of reasons, many unintentionally pregnant women did not get an abortion. The result was an increase in the proportion of births by unmarried white women from 5 percent in 1964–1969 to 26 percent in 1998, and among black women, the proportion rose from 35 to 69 percent. The Akerlof-Yellen-Katz theory seems to be better supported than alternatives, such as the notion that welfare is a major cause of the rise in out-of-wedlock births. Although other Western countries experienced growth in out-of-wedlock births, the theory, like that of Popenoe and Whitehead, may not apply to other countries, because it was developed using U.S. data.

Children may suffer from the decline in marriage rates. One comprehensive analysis of 92 studies on the effects of divorce concluded that the negative repercussion on minors was weak. Other studies, however, have suggested that the adverse effects are delayed and only become manifest when children are grown. Another consequence of the decline in marriage, suggested by Akerlof, is that men who delay marriage or remain single are less likely to be employed, tend to have lower incomes than married men and are more prone to crime and drug use.

—Rodger Doyle (rdoyle2@aol.com)

PROFILE

Driven Up a Tree

Botanist Margaret D. Lowman opened up the tops of the rain forest for science

Perched at the top of an oak tree, Margaret D. Lowman surveys the tips of tall palms and jungle plants and the fragment of Florida sea peeking through the foliage way below her. For her, the climb to the little platform wedged in the branches was effortless; despite the humidity, there's not a bead of sweat on her forehead. She inhales the early morning air and exudes contentment. The 45-year-old botanist later confesses that she prefers coming down to clambering up. "Man was not made to live in the trees like monkeys," she declares. It's a strange observation for Lowman to make. She's come about as close as anyone to giving monkeys some real competition.

Lowman has made thousands of climbs in her quest to discover more about one of the earth's last frontiers: the rain-forest canopy. The difficulty of getting up into the canopy had preserved its status as one of world's most uncharted territories—until Lowman and a handful of other high-minded scientists devised various means of scaling those heights. When she's not using ropes to haul herself into the treetops, she might rely on a hot-air balloon to suspend herself over them or a crane to lower herself into them. When she was pregnant, she squeezed into a cherry picker to continue her research. Her pioneering work on ways to get into the canopy has taken her to Cameroon, Peru, Belize, Samoa, Panama and Australia and was recognized in 1997 when she was made a fellow of the venerable Explorers Club, one of 12 botanists among its 2,800 members.

Children's drawings and a poison-dart blowgun from the Amazon share wall space in her office at the Marie Selby Botanical Gardens—a lush patch of tropical plants established on the grounds of what was once a Texaco oilman's Sarasota, Fla., home—where she is director of research. On her desk is a copy of the *New York Times Book Review,* which warmly reviewed her recently published autobiography, *Life in the Treetops.*

STEVEN J. NESIUS *Silver Image*

***TREE-CLIMBING SCIENTIST** Margaret D. Lowman helped to pioneer techniques to reach forest canopies.*

Although her work is physically demanding, the slender Lowman does not look particularly strong. But her small frame contains a dynamo of energy and enthusiasm, and she is constantly on the move, whether scrambling up a tree or making a quick dash to the supermarket for groceries to feed her family and a visiting journalist.

She seems most calm when we climb up to the viewing platform in the garden, where I observe as I reclip my safety harness that there must have been very few safety rules when she started climbing. "Oh, no, no rules," she confirms brightly, then admits that it's still a largely unregulated business. She's only had one minor fall in her 20-year career, but several friends have had to "have their insides sewn back together" after accidents, she says.

Lowman began her arboreal career in Australia in the late 1970s. Born in upstate New York, she arrived at the University of Sydney in 1978 to pursue her doctorate in rain-forest research, only to discover that it was far from fashionable there. Not only was her supervisor not studying rain forests, no one else in the botany department was either. "I think he really just took me on as a kindness because he had met me on a sabbatical in England, and I had talked to him with this great enthusiasm about studying the rain forests," Lowman recalls. She also rather naively did not realize that the Australian tropics were 600 miles from Sydney.

Initially Lowman set her heart on studying butterflies, but when her supervisor pointed out that they could be elusive, she changed her focus to leaves—a less mobile subject but with one significant drawback: it required her to climb. She struggled to think of alternatives to clambering up, even toying with the idea of training a monkey, but in the end it seemed unavoidable. Mountaineering shops and supplies were then not available in Sydney, so Lowman turned to university spelunkers for advice on climbing techniques and hardware. Following their instructions, she hand-sewed her harness out of car seatbelt straps. She made it up her first tree by using a slingshot to propel her ropes up into the branches.

"I remember the next day my legs were really sore, because I had obviously tightened all the wrong muscles thinking I could hug the tree and save my life," she explains. "But I was really thrilled. It was really great, because then I knew I could do this project." With her newly found access into the foliage, Lowman studied the growth of rain-forest leaves and the impact of herbivores on them, her research helping to question the assumption that such leaves live only for one to three years. In fact, although leaves in the sunny treetops live just that long, leaves in the shady understory can live as long as 15 years. Such insights challenged scientific understanding of leaf growth, which had largely been based on observations made in temperate forests, and revealed the complexity of the rain forest in comparison with other types of forests.

Then, in 1983, Lowman's unusual skills suddenly came into demand in rural Australia. Eucalyptus trees were dying in frightening numbers, in a phenomenon called dieback. First recorded in Australia in 1878, dieback had by the early 1980s reached epidemic proportions in the farming regions inland from Sydney, posing a severe economic and ecological threat to local communities. So Lowman moved to the outback and began climbing trees there in a bid to find the cause. After three years of work, she and her coworker Harold F. Heatwole made a significant breakthrough, naming a common beetle as the immediate cause of a complex condition and thus clearing the native koalas of any culpability. The introduction of nonnative grasses and livestock had created a boom in beetle numbers. Trees weakened by drought and soil erosion were unable to withstand the insect onslaught.

By the time Lowman had identified the problem with the eucalypti, however, she had some problems of her own. She had married a local grazier, and after the births of their two sons, she says, her husband and in-laws wanted her to devote herself entirely to traditional duties on their 5,000-acre sheep station. At the same time, environmentalists were fighting to save Australia's rain forests, and there were increasing demands on Lowman's skills. "Rain forests were getting more important in Australia, not less," she recalls. In an effort to juggle motherhood and science, she took her then four-month-old first child, Eddie, on a trip to Queensland. She would go out into the rain forest to study tropical seedling growth and rush back from the field to feed him during the day. But after eight years in the bush, trying to work without family support, Lowman could no longer neglect her science. She moved back to the U.S. with her children, nearer her parents and brother, and later divorced her Australian husband.

Since then, she has been at the cutting edge of new canopy-access technology. In 1991 she worked with a French team that used a hot-air balloon to suspend an inflatable platform over the Cameroon jungle. It's Lowman's favorite way of getting into the canopy. "It's kind of like being in a trampoline," she says. She helped to build the first elevated walkway through the tropical treetops in Australia and constructed the first one in North America as well. Networks of these walkways now exist throughout the world, allowing scientists and members of the general public to climb into the canopy more safely.

PHILIP K. WITTMAN *Canopy Quest*

DANGLING FROM A DIRIGIBLE is Lowman's favorite way of reaching the treetops.

When she could, Lowman has taken her boys on her trips, schooling them in jungle etiquette (don't touch spiders) and using a system of hand-squeeze signals so they would know when not to disturb working scientists. One gentle squeeze, for instance, meant "don't talk, just listen." "My colleagues were totally impressed because the kids were so good," she says. "Now I get phone calls from my male colleagues saying, 'I really want to take my child to Costa Rica, how can I do that?' "

In recent years Lowman has devoted her boundless energy to bringing together those working in the fledgling field of canopy research, organizing the first and second conferences on the subject. "She has been a great energizer of the community," observes Terry Erwin, a research entomologist at the Smithsonian Institution. In 1995, with Nalini M. Nadkarni of Evergreen College, Lowman co-edited the first book to consolidate studies on the canopy and thus make the information more easily available. The numbers of people involved in canopy research have blossomed ever since. Erwin praises Lowman's ability to inspire others: "She's got to be one of the most enthusiastic persons I've ever met. She's charming, and she makes you want to do stuff."

The stuff she is most keen on her colleagues doing right now is promoting their knowledge to help in rain-forest conservation. "I think a lot of it has to be translated into public education really quickly," she states. "It's not good enough just for scientists to learn about it and to share it in their scientific journals." Uncovering the medicinal riches of rain forests could also help promote their conservation, Lowman believes. "I think we probably are missing the boat with some of those natural medicines and some of those ethnic uses that only the locals know," she surmises. She hopes botanists will pursue funding partnerships with pharmaceutical companies to explore the medicinal potential of rain-forest plants.

Indigenous people, however, do have a claim to ownership of the products, she maintains. "They not only inhabit the forests, but they have also spent many generations developing the uses of these plants that we are now learning about as medicines," she says. "In future years, hopefully there will be beneficial partnerships between drug companies and local villagers, all of which will ultimately benefit rain-forest conservation."

Having spent 20 years of her life exploring the treetops, Lowman has no intention of coming down just yet. "I hope I can last five or 10 more years," she says. For Lowman, it seems that a life lived only on the ground would be a life only half-lived. *—Julie Lewis*

JULIE LEWIS is a freelance journalist based in Washington, D.C., and has written for the South China Morning Post, *the* Sydney Morning Herald, *the* Melbourne Age *and* Australian GQ.

ROCKET SCIENCE

FLY ME TO THE STARS

Lightweight propulsion devices might boost satellites and send probes beyond the sun's realm

Inspired by the challenge of providing quick and easy space launches, rocket engineers have started to think about propulsion systems that would make the X-33, an innovative test vehicle now being built at Lockheed Martin's Skunk Works in Palmdale, Calif., look conservative by comparison. The X-33 is supposed to show how to cut by 10-fold the cost of lofting a payload into orbit. But because the craft's novel engines and its large composite fuel tanks are proving more difficult than expected, its initial flight has been postponed until fall 2000.

One of the most intriguing new ideas is shortly to undergo a test firing at the Massachusetts Institute of Technology. Postgraduate student Adam London has built a prototype thrust chamber for a miniature rocket engine using the same techniques employed to build computer chips. But M.I.T.'s neighbors in Cambridge need not worry about their windows being shattered: the device is about half the size of a postage stamp and will produce only up to 15 newtons (two or three pounds) of thrust.

The thruster, which will burn oxygen and methane for its test firing, consists of six layers of silicon fused together. The whole structure is just three millimeters (just over a tenth of an inch) thick; the main challenge London faced was to prevent it from melting. Ethanol coolant will circulate in minute channels around the tiny, flat thrust chamber. London was planning a test shot in late 1999 or early 2000.

A hundred or so rocket microengines derived from London's test rocket (but probably made of harder silicon carbide) could one day launch satellites: the expected thrust level from micromachined devices is very high in relation to their mass. London thinks that a two-stage microrocket vehicle weighing some 80 kilograms (176 pounds) at launch might be sufficient to put a Coke-can-size payload, perhaps bearing eavesdropping sensors, into orbit—or send it undetected to the other side of the world in 45 minutes. Microrocket engines might also be valuable for returning samples from the surface of Mars and for maneuvering satellites in or between orbits.

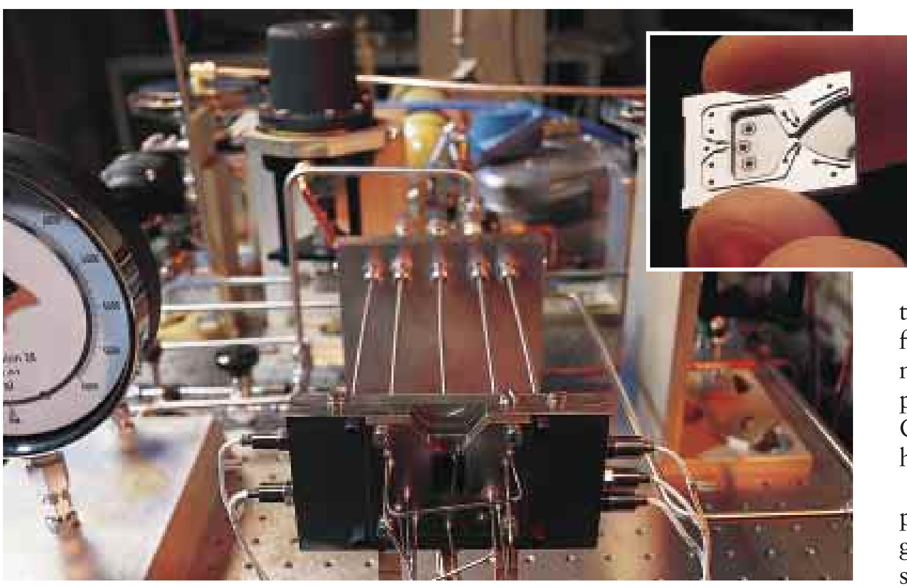
London's project is an offshoot of a larger effort at M.I.T. to build a jet engine the size of a shirt button that could power a miniature jet plane—a possible payload for the rocket vehicle. Both the jet engine and the rocket will need superhard, accurately micromachined parts for pumps and turbines that rotate at extremely high speeds. The National Aeronautics and Space Administration has funded the project for several years, and M.I.T.'s Alan Epstein, who heads the effort, plans next year to test a gas turbine that measures just a few millimeters across. He points out that because of the high efficiency that should be possible, a micro gas turbine powering a generator can in principle pack 30 times more energy into a small space than any battery. Refueling would replace recharging.

At the University of Washington, geophysicist Robert M. Winglee has an even more startling idea, which he calls mini-magnetospheric plasma propulsion. Winglee envisages a chamber the size of a pickle jar attached to a spacecraft and surrounded by a helical heating coil powered at a few kilowatts. When a small amount of a gas such as hydrogen or helium is injected into the device, it forms a dense, hot, magnetized plasma. Once in space, the plasma would spread out rapidly from the open ends of the pickle jar until it had a radius of more than 16 kilometers (10 miles).

According to Winglee, the magnetic field would spread along with the plasma and interact with the solar wind, acting like a giant sail that would transfer force to the heating coil and hence the spacecraft. Winglee estimates that a spacecraft with his propulsion system could gain enough velocity over weeks or months to exit the solar system within a few years. He says he got his idea when studying coronal mass ejections on the sun, which also inflate magnetic fields. Winglee and two colleagues are now performing tests and building a prototype: NASA's Institute for Advanced Concepts was impressed enough to give him $500,000 to work on the idea.

If the tests now under way bear out the promise on paper, Winglee's device could greatly extend the range of unmanned spacecraft. Long after the X-33 is retired to the National Air and Space Museum, lightweight could be the way to go in space, for launches and for the long haul.

—*Tim Beardsley in Washington, D.C.*



SAM OGDEN

***TEST RIG FOR A SILICON MICROROCKET** will supply gaseous methane fuel, oxygen and ethanol coolant at precise rates. The thruster will be in the foreground, pointing upward. The inset shows half a thruster, revealing the combustion chamber (with intake apertures), expansion nozzle and coolant channels.*

But Where Are the Cupholders?

Lightweight flight propulsion is not just for spacecraft. Proving that the era of magnificent men in their flying machines is not yet over, Moller International in Davis, Calif., is preparing to test a four-person, vertical-takeoff "skycar" sometime this winter. The vehicle—model M400—has a composite airframe and employs eight rotary internal-combustion engines to generate thrust. Early test models will run on diesel, but gasoline and natural gas versions are possible. The high-efficiency engines are made mainly of aluminum and weigh only 135 pounds (61 kilograms), yet each produces 150 horsepower. Deflection vanes redirect airflow downward during vertical takeoff.

Eight engines might sound like a lot for a pilot to think about, but Moller vice president Jack Allison notes that three computers actually control them, so no special skills are needed. An earlier, two-seater skycar has flown, tethered, to an altitude of 40 feet (12 meters) within Moller's property lines. The computer system on the M400 will be able to control the vehicle even if one or more engines fail (although the vehicle will be able to deploy two parachutes, just in case). Moller says the skycar will have a range of 900 miles (1,450 kilometers) and that it will fly at up to 350 miles per hour and reach an altitude of 30,000 feet.

Moller intends to sell skycars for about $1 million at first but expects prices to "approach that of a luxury automobile" as production volume increases. The company plans to have demonstrator models flying within 18 months. A version certified by the Federal Aviation Authority is at least two years away. Even so, Allison says 100 production M400s have already been ordered.

—Tim Beardsley in Washington, D.C.

MOLLER INTERNATIONAL

M400 SKYCAR being built by Moller International could combine vertical-takeoff capability and high speed—if safety tests planned for this winter are successful.

SEMICONDUCTORS

BAD CONNECTIONS

Deleading solder creates worries about electronics reliability

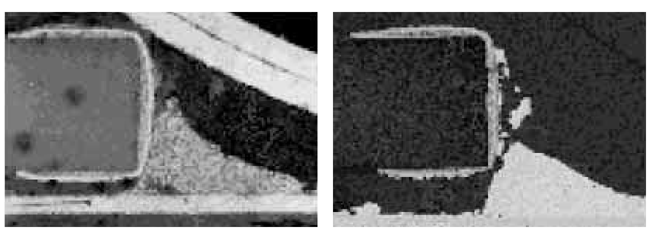
Joining a metal bowl and handle using another metal with a lower melting point is a practice that dates back more than 4,500 years. A Sumerian civilization, the Early Dynastic period of Ur, bound a silver loop to a copper bowl with a primitive tin-containing solder in about 2700 B.C.E. Two millennia later the Romans alloyed lead and tin to fuse the lead pipes that carried water in their aqueducts. The attraction that these materials held for the Romans is just as apparent to engineers at Intel and Motorola, who use a lead-tin formulation on their printed circuit boards.

In an industry that routinely ponders deep solid-state physics questions, such as how quantum-mechanical effects disrupt electrons, the act of soldering a microchip to a circuit board is one of the unsexiest processes in electronics manufacturing. And that is just how semiconductor technical mavens like it. "The whole reason we use it is because it's boring," notes Carol Handwerker, chief of metallurgy at the National Institute of Standards and Technology, based in Gaithersburg, Md.

Anything that could affect the reliability of this timeworn process makes manufacturers squirm. So an emerging worldwide movement to get toxic lead out of solder—lead lowers the melting point of the solder to an ideal processing temperature—has the industry worried. A higher melting point means that processing unleaded solder could damage electronic components and the entire manufacturing cycle might have to be revamped to ensure their integrity. Many of the replacement materials, which range from polymers to alloys for tin, such as copper and bismuth, do not form strong joints. "We could use new solders," Handwerker says. "But it may mean drastically poor reliability, more damage and lower yields." Compromising reliability could mean that consumers would have to cope with a dead cell phone or a car that will not start.

Manufacturers fret about the "popcorn effect," which occurs when residual moisture in the epoxy coating that shields an integrated circuit vaporizes at the high temperatures needed to melt the solder. The epoxy then detaches from the chip and pops open, which lets in contamination and can cause stresses in the coating.

A replacement for lead-tin solder could



CAROL HANDWERKER NIST

***STRONGER JOINTS** are formed with a lead-tin solder* (left) *than with a newer formulation that uses tin, silver and bismuth* (right)*, which can be seen breaking up.*

cost U.S. industry $140 million to $900 million a year, depending on the materials incorporated, according to a study by the National Center for Manufacturing Sciences, a research consortium in Ann Arbor, Mich. But the largest expense may result from having to deploy other materials throughout the circuit board that can withstand the higher temperatures encountered during soldering; a substitute may be needed for the thin polymer that protects copper wiring on the board, for instance. These changes will prove troubling to circuit board suppliers, which measure profits in single-digit percentages. Companies have devised replacement processes, but none are as all-encompassing as existing methods. Earlier this year Lucent Technologies introduced an all-tin electroplating method to fuse connections. But concerns linger about its reliability, and electroplating can only be used for about a third of the solder on a board.

Some industry officials see little reason to alter the status quo, as lead-based solder accounts for 2 percent or less of world industrial consumption of lead, most of which goes into products such as automobile batteries. Still, the European Union is considering banning lead from electronic equipment by 2004. Some Japanese companies have introduced consumer electronics containing lead-free solders and have plans to eliminate lead-based solder early in the new decade, actions that will pressure the U.S. industry to go lead-free. The IPC, a Northbrook, Ill., trade association for circuit board and other electronics subcontractors, was scheduled to meet in late October to map out a strategy for adopting lead-free solder.

Even if lead-tin solder remains, manufacturers may eventually run into other difficulties with the alloy. Lead can emit alpha particles, which result from radioactive decay within the element that can cause errors in chip circuitry. This problem may become more acute as electronics makers fabricate finer circuits that are more sensitive to alpha particles. Industry suppliers are considering making solder with lead salvaged from ships that are hundreds of years old or perhaps from the roofs of 1,000-year-old cathedrals, metal that is old enough that its decay into a nonradioactive end product has already occurred. Worries about the presence or absence of lead, though, means that the lowly solder bump has begun to raise goose bumps on the flesh of manufacturing managers. —*Gary Stix*

CABLE-FREE

Free-air optical networks go for a test run

For regular Web surfers, it's frustrating enough when the network goes down even briefly. A natural disaster—an earthquake-induced landslide, say—could knock out Internet access for days if the damage to the fiber-optic line is deeply buried. What can be done in the meantime to restore bandwidth? Lucent Technologies's WaveStar OpticAir system may be the ideal Band-Aid. At least that's one potential use Global Crossing of Bermuda, developers of a high-capacity fiber-optic worldwide network, sees for the free-space laser communications system the company began beta-testing this month.

Capable of handling any network traffic, from computer data to telephone calls, OpticAir employs laser light to bridge physical gaps of up to several miles in optical networks. And stopgap solutions are not the technology's biggest benefit, either. "Imagine a company rents two office spaces in a skyscraper, one on the 40th floor and one on the 80th—they could use this system to beam high-capacity signals up and down the building without having to pull cable through the ceiling," says Gerry Butters, president of Lucent's Optical Networking Group. The price of WaveStar OpticAir, he estimates, will be comparable to that of a traditional fiber-based system minus the cost of the cable.

Each mailbox-size WaveStar OpticAir unit houses a diode laser, amplifier and receiver that will operate at speeds up to 10 gigabits per second, outshining the bandwidth of current wireless radio technologies by a factor of 65. Thanks to Lucent's dense wave division multiplexing technology, numerous streams of data can be transmitted from each unit via unique and invisible wavelengths of light. The flagship product to be launched in March transmits 2.5 gigabits of data in both directions simultaneously on one channel; a four-channel system is slated for next summer.

On the other hand, OpticAir is a line-of-sight solution, causing its range to vary according to atmospheric conditions. A field test proved OpticAir to be effective over a 2.7-mile stretch in New

Jersey, from Whippany to Convent Station, yet the range of the first commercial version will be limited to one mile to ensure near-constant connectivity. "We always say we can trade off availability for distance," says Jim Auborn, Lucent's director of communications technology. "Over very short distances, we can have 99.9 percent availability."

Whereas rain or snow doesn't trip up OpticAir as it does many radio-frequency transmissions, heavy fog does block the beam. Still, Auborn maintains, "we can generally transmit one and a half times the distance you can see." Additionally, a lens spreads the beam, preventing data interruptions caused by birds breaking the beam. Meanwhile high winds are compensated for by a small tracking laser that feeds data back to alignment motors inside the unit.

Indeed, the self-adjusting capabilities proved invaluable during a U.S. Navy test of the system earlier this year. Connectivity between the port operations building in San Diego and an aircraft carrier bobbing with the tide more than 200 yards out was nearly continuous for a month and a half, Auburn says.

The OpticAir technology grew from an independent study in the early 1990s of high-powered optical amplifiers for government intersatellite communications. Yet the idea of using beams of light to transmit information through the air is nothing new. Bell Laboratories began researching the use of LEDs and helium-neon lasers for free-space laser communications in the early 1970s. Other firms, such as SilCom Manufacturing Technology and A. T. Schindler Communications (both in Ontario), also offer infrared laser connectivity between buildings. But at the moment, none can match the bandwidth offered by Lucent's system. Ironically, Lucent's stock certificate depicts Alexander Graham Bell's photophone, an 1880s predecessor to OpticAir.

And Butters expects that, like the photophone, OpticAir will be ideal for video transmissions. "We've been approached by companies who have been fooling around with multiple cameras and microphones for media-rich pay-per-view," Butters remarks. "The thing bothering them was coming up with a transmission system with enough capacity but without the expense of fiber and coaxial cable. With OpticAir, you don't have to deal with any of that." —*David Pescovitz*

DAVID PESCOVITZ, based in Oakland, Calif., is a contributing editor to Wired *and* ID *magazines and is coauthor of* Reality Check *(HardWired, 1996). He also wrote the Cyber View column this month.*

DEFENSE TECHNOLOGY

SEEN BEFORE

To guard against terrorism, the Pentagon looks to image-recognition technology

In the East London borough of Newham, a surveillance network of more than 200 cameras keeps watch on pedestrians and passersby, employing a facial-recognition system that can automatically pick out known criminals and alert local authorities to their presence. Not surprisingly, civil liberties groups oppose the system—Privacy International, a human-rights group, gave the Newham council a "Big Brother" award last year on the 50th anniversary of the publication of George Orwell's famous novel. The council, however, claims overwhelming support from citizens who are more concerned about crime than about government intrusions. It could count as one of its supporters the U.S. Department of Defense, which is keeping tabs on the Newham system as well as on other, related technologies. The department hopes that some combination of "biometrics" will vastly improve its ability to protect its facilities worldwide.

For the military, biometrics usually means technologies that can identify computer users by recognizing their fingerprints or voices or by scanning their irises or retinas. But after a terrorist truck bomb blew up the Khobar Towers U.S. military barracks in Saudi Arabia in 1996, killing 19, the Pentagon elevated to the top of its priority list the need for "force protection"—namely, keeping troops abroad safe from attack. That spurred the Defense Advanced Research Projects Agency, essentially a Pentagon hobby shop, to action. Building on some ongoing work with video surveillance and modeling techniques, as well as on commercial (but still experimental) technologies such as those used to identify automatic-teller machine customers by scanning their faces, DARPA set out to investigate the potential for a network of biometric sensors to monitor the outsides of military facilities.

The result is a program known as Image Understanding for Force Protection (IUFP), which the agency hopes to get started in 2001. Described by the Pentagon as "an aggressive research and development effort," IUFP is supposed to improve site surveillance capabilities by "creating new technologies for identifying humans at a distance."

Biometric systems in use with ATM machines and computers have two advantages over what DARPA has in mind: proximity and cooperation. For military

AP PHOTO/U.S. NAVY

TERRORIST ATTACK in 1996 on Khobar Towers, U.S. military barracks in Saudi Arabia, prompted the Pentagon to consider new remote-identification technologies.

purposes, biometric sensors and networks must be able to "see" and identify subjects from distances of between 100 and 500 feet—subjects who probably don't want to be identified. In addition, they must be capable of picking faces out of crowds in urban environments, keeping track of repeat visitors who, according to DARPA's George Lukes, "might be casing the joint," and alerting users to the presence of known or suspected terrorists. Databases could even be shared by different facilities, informing security officials, for example, that the same person is showing up repeatedly near different potential targets.

The software behind Newham's anticrime system that has drawn DARPA interest is called FaceIt, from New Jersey–based Visionics Corporation. FaceIt scans the visages of people and searches for matches in a video library of known criminals. When the system spots one of those faces, the authorities are contacted. A military version might work the same way. Over the past year, according to a DARPA document recently sent to Congress, "several new technical approaches have been identified" that could provide improved face recognition at longer distances, as well as extend the range of iris-recognition systems.

DARPA believes, however, that combining several types of technologies could form a network that is more capable than a single system. New concepts it is exploring include the thermal signature of the blood vessels in the head, which some researchers suspect is as unique to a person as his or her fingerprints; the shape of a person's ear; and even "the kinetics of their gait," in DARPA's words. "There are some unique characteristics to how people move that allow you to recognize them," explains DARPA's David Gunning. After conducting a "thorough analysis" of existing technologies, the agency says it is "ready to begin immediately with the new developments." The Pentagon hopes to spend $11.7 million in 2000 on the IUFP program—a good deal of money for a DARPA effort.

The potential for an integrated network of identification techniques has understandably generated significant interest among defense and intelligence agencies that are prime targets for terrorists. "There's a lot of enthusiasm," Gunning says—after all, through the marriage of recognition systems and surveillance technologies, DARPA thinks it has a handle on how to keep track of "one of the few detectable precursors" to terrorist attacks. *—Daniel G. Dupont*

DANIEL G. DUPONT is the editor of Inside the Pentagon *in Washington, D.C. He described unmanned aerial vehicles in the September issue.*

INFORMATION POLICY

NO SECRETS

Data produced in federally supported studies are now part of the public record

Scientists are bracing for a deluge of demands for their research records after a fiercely controversial law extending the Freedom of Information Act (FOIA) came into effect in November.

The law, sponsored by Senator Richard Shelby of Alabama, allows members of the public to use FOIA to request any research data generated with federal support, including information gathered in ongoing, long-term studies. Over the past year, industry groups, which see an opportunity to challenge studies used to develop environmental and other regulations, have fought draft rules for implementing the Shelby amendment, which would make the access conditional. Scientific organizations, on the other hand, have protested that without such restrictions the legislation could be used to harass researchers and force them to violate promises of confidentiality made to research participants.

The Office of Management and Budget received more than 12,000 comments on its proposals for implementing the law, close to a record. The final rules, which the OMB published on October 8, include some of the protections that researchers wanted; for example, the law will not apply to data that have never been cited in a publication or used by an agency to justify a regulation. And it will cover only information gathered after November 6 of this year. But William L. Kovacs of the U.S. Chamber of Commerce, which represents three million businesses, says his organization is "disappointed" that the administration's rules fail to provide access to data that have already been gathered.

Wendy Baldwin, director of extramural research at the National Institutes of Health, acknowledges that it is hard to argue against public disclosure of publicly funded research data. But representatives of research universities point to complexities that FOIA was not designed to deal with. For instance, although FOIA allows the names and addresses of individuals to be redacted from records that are to be released, data remaining after redaction may make it possible for a sleuth to identify individuals participating in a study. Baldwin cites a fictional but plausible case involving "the only female rabbi in Rapid City" whose brother learned details of her medical problems from reading survey data disclosed under FOIA: the data revealed the number and age of her children as well as her occupation. Once research data are obtained through FOIA, there are no restrictions on the uses to which it can be put, notes Richard M. Suzman of the NIH.

True-life stories are not reassuring. In 1992 R. J. Reynolds, the tobacco company, subpoenaed records of academic research on children's recognition of the Joe Camel advertising character that included the participants' names and addresses. Reynolds later dropped its request for the identifying information but got everything else. Pharmaceutical giant Pfizer used FOIA in 1995 to request correspondence and unpublished research of an investigator whose studies questioned the value of a Pfizer drug. (The company eventually withdrew its request.)

Under the new law, researchers will be able to group or otherwise mask data to protect the confidentiality of individuals. But Baldwin notes that the Shelby amendment could pose serious problems for the many studies that depend on the participation of local governments or commercial entities such as clinics, because FOIA's confidentiality exemptions apply only to individuals. Agencies and companies often provide sensitive information to researchers with the understanding that its precise source will not be disclosed. Researchers will probably have to modify consent agreements to make clear that some information they gather could come to light, which might deter some participants. International data-sharing agreements that pledge confidentiality to collaborating organizations could also be imperiled. Many details affecting how agencies will implement the new law have still to be settled. But the data-access train is coming fast down the track.

—Tim Beardsley in Washington, D.C.

To Your On-line Health

In the Norman Rockwell days of health care, your "family doctor" knew your medical history because he knew you. And if he forgot something, there was always a manila file filled with scrawled notes from previous visits. That was before privatized health management organizations and the information age reduced medical records to a series of check-boxes and red tape.

Recently, though, a segment of on-line industry has promised to empower individuals with control of their own health records on secure Web sites. The idea is that users visiting a health site on the Web or on a corporate intranet establish lifelong personal medical records for free; companies advocating the idea would make money by licensing their software to on-line portals, corporations and health plan providers. Eventually, these companies predict, the personal medical record will become a collaboration between physician and patient and would be readily available on-line to any health care provider you happen to visit.

Building a lifelong personal medical record that's useful to the patient, the physician and the firm that is footing the bill is no small task, though. And even if logistical nightmares are on the verge of resolution, patient demand for personal health care records remains uncertain. Ultimately, these companies' predictions and prescriptions may prove to be way off target.

"I don't think consumers are going to find these products exceedingly attractive today," says Calvin Wiese, CEO of HealthMagic, who reported abysmal interest in his firm's HealthCompass personal medical record system when it was tested in 1998 in Celebration, Fla. HealthCompass is also available via the high-traffic drkoop.com health portal. "What [the personal medical records] are today are things consumers can put information into, but they don't hook up to the world," Wiese says. "I do believe that personal medical record space is the center of the universe for the health care information infrastructure of the 21st century, but it's a long way to the center."

And along the way, health care's infamous Tower of Babel must be toppled. "There are 100 ways of saying 'high blood pressure,' " says Philip Marshall, an architect of WellMed Personal Health Manager, offered by firms such as General Electric and Goldman Sachs to their employees. "That disparate array of information, which on any given individual can sit on a wide variety of databases in a number of health care offices, needs to be summarized in some format."

A standardized record, however, requires a doctor's diagnosis not only to be legible but also to be quantified into percentages, codes and precise wording understandable by a computer. "If you put in that you had a 'busted ankle,' does that mean you had a twisted or sprained

DAVID SUTER

ankle or broken ankle?" asks WellMed president and CEO Craig Froude. WellMed believes they have this problem solved via software that probes the patient for details. "We allow you to describe yourself in your own words and interpret that," Froude explains.

The benefits of a standardized and centralized system of on-line medical records are clearest for the bean counters. It's easier for administrative tasks (read: billing) if a patient's entire medical history is all in one place. Again, though, worries arise for the patient when a lifelong history of every ingrown toenail or malignant polyp is laid out in front of the person who typically foots your premiums: your employer. WellMed has this rather unsettling statement in its marketing materials: "In a typical organization, 10–15% of the employees will account for 80% of a company's health care claims. [Our risk-profiling product] serves as an affordable, highly accurate tool to identify those employees with abnormally high health risks."

And fire them? Absolutely not, Froude insists. "I guess the phrasing there may be confusing. The corporation itself just gets group-level data." If they received individual data, the corporation could be "liable for prejudice or wrongful termination," Froude adds.

Of course, those individuals are the ones to be most affected by on-line medical records. Certainly the service is a step in the right direction. Appointment reminders can be automatically e-mailed, for instance, and health risk assessment tests can keep you abreast of potential conditions to watch out for based on your diet, or you could be notified of emerging treatments as they become available.

But there's the rub. In the future, these firms hope to garner advertising revenue from companies targeting specific niches of personal health record users. Putting yourself in the center of a target market necessitates that you forgo at least a bit of privacy—even if it's not as drastic as revealing your medical conditions directly to the drug vendors. "We're like a direct-mail house," Froude says. "If you choose to participate—and this is an opt-in situation for consumers—we'll allow marketing in. But we're the ones who control that."

Whether or not even that kind of consumer-requested advertising will fly is, at the moment, up to Congress. "Federal law does more today to guarantee the privacy of our choice of video rentals than it does our personal medical histories," wrote Donna Shalala, secretary of the U.S. Department of Health and Human Services, in a recent *Los Angeles Times* editorial. At press time, Congress was to vote on legislation guaranteeing the privacy of personal medical records. If no laws are handed down by February 21, 2000, the regulation becomes the responsibility of the DHHS, a stern advocate for patient privacy.

Clearly, while numerous companies race to put physicians at ease with the digitization of their duties, the wants and needs of the end customer must be determined as well. After all, a personal medical record is only as useful as the information provided. *—David Pescovitz*

The Unexpected Science to Come

by Sir John Maddox

The most important discoveries of the next 50 years are likely to be ones of which we cannot now even conceive

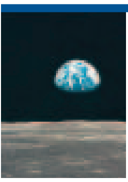
The questions we do not yet have the wit to ask will be a growing preoccupation of science in the next 50 years. That is what the record shows. Consider the state of science a century ago, in 1899. Then, as now, people were reflecting on the achievements of the previous 100 years. One solid success was the proof by John Dalton in 1808 that matter consists of atoms. Another was the demonstration (by James Prescott Joule in 1851) that energy is indeed conserved and the earlier surmise (by French physicist Sadi Carnot) that the efficiency with which one form of energy can be converted into another is inherently limited: jointly, those developments gave us what is called thermodynamics and the idea that the most fundamental laws of nature incorporate an "arrow of time."

There was also Charles Darwin, whose *Origin of Species by Means of Natural Selection* (published in 1859) purported to account for the diversity of life on Earth but said nothing about the mechanism of inheritance or even about the reasons why different but related species are usually mutually infertile. Finally, in the 19th century's catalogue of self-contentment, was James Clerk Maxwell's demonstration of how electricity and magnetism can be unified by a set of mathematical equations on strictly Newtonian lines. More generally, Newton's laws had been so well honed by practice that they offered a solution for any problem in the real world that could be accurately defined. What a marvelous century the 1800s must have been!

Only the most perceptive people appreciated, in 1899, that there were flaws in that position. One of those was Hendrik Antoon Lorentz of Leiden University in the Netherlands, who saw that Maxwell's theory implicitly embodied a contradiction: the theory supposed that there must be an all-pervading ether through which

NASA JOHNSON SPACE CENTER

Earth viewed from the moon portends a new way of seeing our world and its inhabitants but gives few hints of the paths future discoveries will take.



Our understanding of the human brain is incomplete in one conspicuous way: nobody understands how decisions are made or how imagination is set free.

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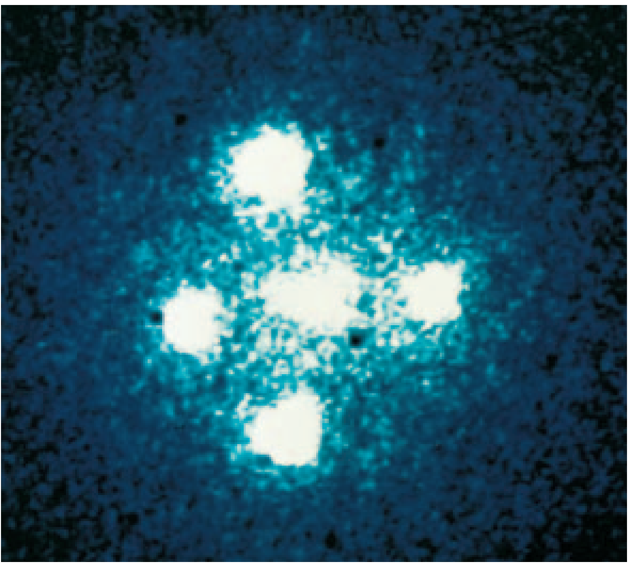
electromagnetic disturbances are propagated, but it is far simpler to suppose that time passes more slowly on an object moving relative to an observer. It was a small step from there (via Henri Poincaré of the University of Paris) to Albert Einstein's special theory of relativity, published in 1905. The special theory, which implies that relative velocities cannot exceed the speed of light, falsifies Newton only philosophically: neither space nor time can provide a kind of invisible grid against which the position of an object, or the time at which it attains that position, can be measured. A century ago few people seem to have appreciated that A. A. Michelson and E. W. Morley, in the 1880s, had conducted an experiment whose simplest interpretation is that Maxwell's ether does not exist.



One of the landmarks of 20th-century science, Einstein's general theory of relativity reformulated gravity as a warping of space and time, predicting effects such as the bending of light by large masses. A graphic example is provided by this image of a so-called Einstein Cross, obtained with the Hubble Space Telescope. Four images of a quasar surround the central image of the galaxy, which acts as a gravitational lens.

For those disaffected from, or even offended by, the prevailing complacency of 1899, ample other evidence should have hinted that accepted fundamental science was heading into trouble. Atoms were supposed to be indivisible, so how could one explain what seemed to be fragments of atoms, the electrons and the "rays" given off by radioactive atoms, discovered in 1897? Similarly, although Darwin had supposed that the inheritable (we would now say "genetic") changes in the constitution of individuals are invariably small ones, the rediscovery of Gregor Mendel's work in the 1850s (chiefly by Hugo de Vries in the Netherlands) suggested that spontaneous genetic changes are, rather, discrete and substantial. That development led, under the leadership of Thomas Hunt Morgan, to the emergence of Columbia University in New York City as the citadel of what is now called classical genetics (a phrase coined only in 1906) and to the recognition in the 1930s that the contradiction between Darwinism and "Mendel-Morganism" (as the Soviets in the 1950s came to call Columbia's work) is not as sharp as it first seemed.

Now we marvel at how these contradictions have been resolved and at much else. Our own contentment with our own century surpasses that of 1899. Not least important is the sense of personal liberation we enjoy that stems from applications of science in the earliest years of the 20th century—Marconi's bridging of the Atlantic with radio waves and the Wright brothers' measured mile of flight in a heavier-than-air machine. (Wilbur and Orville had built a primitive wind tunnel at their base in Ohio before risking themselves aloft.) The communications and aviation industries have grown from those beginnings. Our desks are cluttered with powerful computing machines that nobody foresaw in 1900. And we are also much healthier: think of penicillin!

A Catalogue of Contentment

In fundamental science, we have as much as or more to boast about than did the 19th century. Special relativity is no longer merely Newton made philosophically respectable. Through its implication that space and time must be dealt with on an equal footing, it has become a crucial touchstone of the validity of theories in fundamental physics.

The other three landmarks in fundamental science this century were hardly foreseen. Einstein's general theory of relativity in 1915, which would have been better called his "relativistic theory of gravitation," would have been a surprise to all but close readers of Ernst Mach, the Viennese physicist and positivist philosopher. By positing that gravitational forces everywhere are a consequence of a gravitational field that reaches into the farthest corners of the cosmos, Einstein launched the notion that the structure and evolution of the universe are ineluctably linked. But even Einstein was surprised when Edwin Hubble discovered in 1929 that the universe is expanding.

Quantum mechanics was another bolt from the blue, even though people had been worrying about the properties of the radiation from hot objects for almost half a century. The problem was to explain how it arises that the radiation from an object depends crucially on its temperature such that the most prominent frequency in the emission is directly proportional to the temperature, at least when the temperature is measured from the absolute zero (which is 273 degrees Celsius below the freezing point of water, or –459 degrees Fahrenheit, and which had itself been defined by 19th-century thermodynamics). The solution offered by Max Planck in 1900 was that energy is transferred between a hot object and its surroundings only in finite (but very small) amounts, called quanta. The actual amount of energy in a quantum depends on the frequency of the radiation and, indeed, is proportional to it. Planck confessed at the time that he did not know what this result meant and guessed that his contemporaries would also be perplexed.

As we know, it took a quarter of a century for Planck's difficulty to be resolved, thanks to the efforts of Niels Bohr, Werner Heisenberg, Erwin

Schrödinger and Paul Dirac, together with a small army of this century's brightest and best. Who would have guessed, in 1900, that the outcome of the enterprise Planck began would be a new system of mechanics, as comprehensive as Newton's in the sense that it is applicable to all well-posed problems but applies only to atoms, molecules and the parts thereof—electrons and so on?

Even now there are people who claim that quantum mechanics is full of paradoxes, but that is a deliberate (and often mischievous) reading of what happened in the first quarter of this century. Our intuitive understanding of how objects in the macroscopic world behave (embodied in Newton's laws) is based on the perceptions of our senses, which are themselves the evolutionary products of natural selection in a world in which the avoidance of macroscopic objects (predators) or their capture (food) would have favored survival of the species. It is difficult to imagine what selective advantage our ancestors would have gained from a capacity to sense the behavior of subatomic particles. Quantum mechanics is therefore not a paradox but rather a discovery about the nature of reality on scales (of time and distance) that are very small. From that revelation has flowed our present understanding of how particles of nuclear matter may be held to consist of quarks and the like—an outstanding intellectual achievement, however provisional it may be.

The third surprise this century has followed from the discovery of the structure of DNA by James D. Watson and Francis Crick in 1953. That is not to suggest that Watson and Crick were unaware of the importance of their discovery. By the early 1950s it had become an embarrassment that the genes, which the Columbia school of genetics had shown are arranged in a linear fashion along the chromosomes, had not been assigned a chemical structure of some kind. The surprise was that the structure of DNA accounted not just for how offspring inherit their physical characteristics from their parents but also for how individual cells in all organisms survive from millisecond to millisecond in the manner in which natural selection has shaped them. The secret of life is no longer hidden.

A Catalogue of Ignorance

Both quantum mechanics and the structure of DNA have enlarged our understanding of the world to a degree that their originators did not and could not have foretold. There is no way of telling which small stone overturned in the next 50 years will lead to a whole new world of science. The best that one can do is make a catalogue of our present ignorance—of which there is a great deal—and then extrapolate into the future current trends in research. Yet even that procedure suggests an agenda for science in the next half a century that matches in its interest and excitement all that has happened in the century now at an end. Our children and grandchildren will be spellbound.

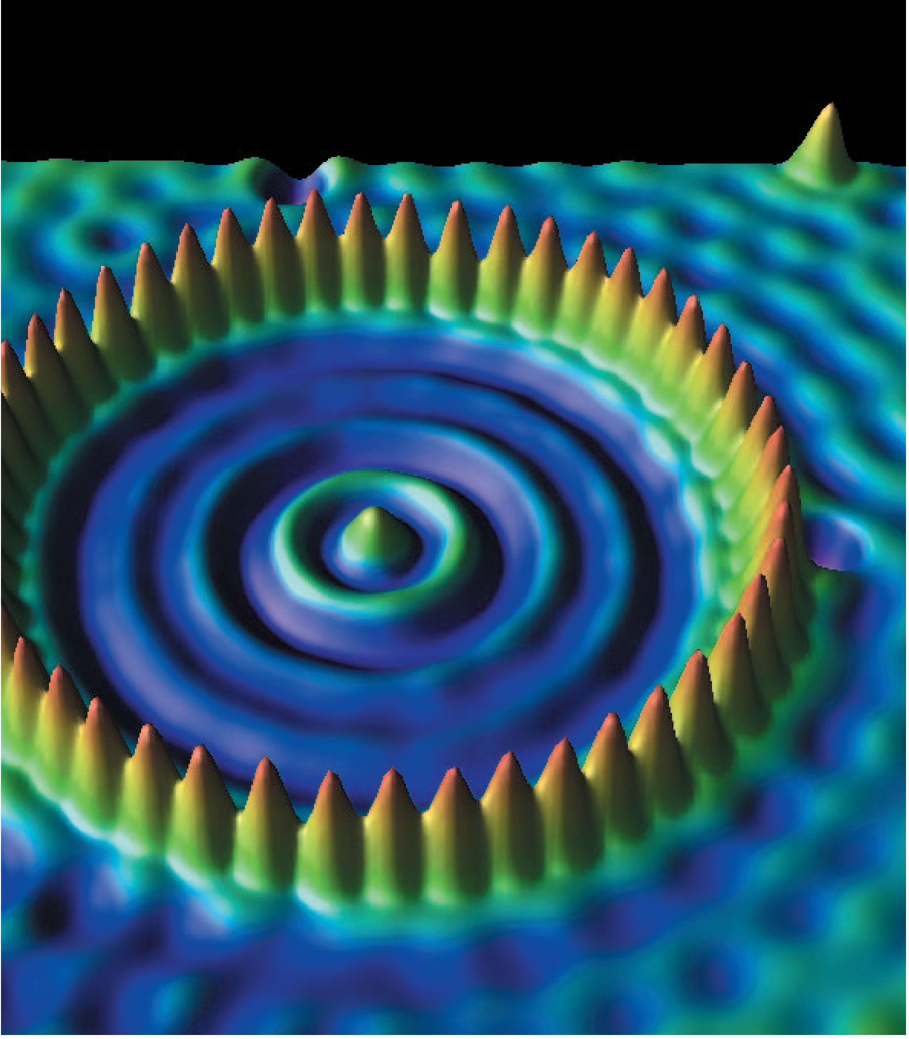
One prize now almost ready for the taking is the reconstruction of the genetic history of the human race, *Homo sapiens*. A triumph of the past decade has been the unraveling of the genetics of ontogeny, the transformation of a fertilized embryo into an adult in the course of gestation and infancy. The body plans of animals and plants appear initially to be shaped by genes of a common family (called *Hox* genes) and then by species-specific developmental genes. Although molecular biologists are still struggling to understand how the hierarchical sequence of developmental genes is regulated and how genes that have done their work are then made inactive, it is only a matter of time before the genes involved in the successive stages of human development are listed in the order in which they come into play.

Then it will be possible to tell from a comparison between human and, say, chimpanzee genes when and in what manner the crucial differences between humans and the great apes came into being. The essence of the tale is known from the fossil record: the hominid cerebral cortex has steadily increased in size over the past 4.5 million years; hominids were able to walk erect with *Homo erectus* 2.1 million years ago; and the faculty of speech probably appeared with mitochondrial Eve perhaps as recently as 125,000 years ago. Knowing the genetic basis of these changes will give us a more authentic history of our species and a deeper understanding of our place in nature.

That understanding will bring momentous by-products. It may be possible to infer why some species of hominids, of which the Neanderthals are only one, failed to survive to modern times. More important is that the genetic history of *H. sapiens* is likely to be a test case for the mechanism of speciation. Despite the phrase "Origin of Species" in the title of Darwin's great book, the author had nothing to say about why members of different species are usually mutually infertile. Yet the most striking genetic difference between humans and the great apes is that humans have 46 chromosomes (23 pairs), whereas our nearest relatives have 48. (Much of the missing ape chromosome seems to be at the long end of human chromosome 2, but other fragments appear else-

Discovery of the structure of DNA in 1953 by James D. Watson (*left*) and Francis Crick unveiled the secret of life and spawned spectacular advances in medicine and molecular biology. Their model of this structure—the double helix—has become a universal symbol of science.

A. BARRINGTON BROWN *Science Source/Photo Researchers, Inc.*



Quantum mechanics—another monumental intellectual achievement of the 20th century—revealed the nature of reality on microscopic size scales. We can now manipulate and view individual atoms and quantum waves. This scanning tunneling microscope image shows a "quantum corral" of 48 iron atoms on a copper surface enclosing quantum waves of electrons.

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where in the human genome, notably on the X chromosome.) It will be important for biology generally to know whether this rearrangement of the chromosomes was the prime cause of human evolution or whether it is merely a secondary consequence of genetic mutation.

The 50 years ahead will also see an intensification of current efforts to identify the genetic correlates of evolution more generally. Comparison of the amino acid sequences of similar proteins from related species or of the sequences of nucleotides in related nucleic acids—the RNA molecules in ribosomes are a favorite—is in principle a way of telling the age of the common ancestor of the two species. It is simply necessary to know the rate at which mutations naturally occur in the molecules concerned.

But that is not a simple issue. Mutation rates differ from one protein or nucleic acid molecule to another and vary from place to place along their length. Constructing a more reliable "molecular clock" must be a goal for the near future. (The task is similar to, but if anything more daunting than, cosmologists' effort to build a reliable distance-scale for the universe.) Then we shall be able to guess at the causes of the great turning points in the evolution of life on Earth—the evolution of the Krebs cycle by which all but bacterial cells turn chemicals into energy, the origin of photosynthesis, the appearance of the first multicellular organisms (now firmly placed more than 2,500 million years ago).

With luck, the same effort will also tell us something about the role of viruslike agents in the early evolution of life. The human genome is crammed with DNA sequences that appear to be nucleic acid fossils of a time when genetic information was readily transferred between different species much as bacteria in the modern world acquire certain traits (such as resistance to antibiotics) by exchanging DNA structures called plasmids. We shall not know our true place in nature until we understand how the apparently useless DNA in the human genome (which Crick was the first to call "junk") contributed to our evolution.

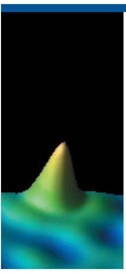
Understanding all the genomes whose complete structure is known will not, in itself, point back to the origin of life as such. It should, however, throw more light on the nature of living things in the so-called RNA world that is supposed to have preceded the predominantly DNA life that surrounds us. It is striking and surely significant of something that modern cells still use RNA molecules for certain basic functions—as the editors of DNA in the nucleus, for example, and as the templates for making the structures called telomeres that stabilize the ends of chromosomes.

At some stage, but probably more than half a century from now, someone will make a serious attempt to build an organism based on RNA in the laboratory. But the problem of the origin of life from inorganic chemicals needs understanding now lacking—not least an understanding of how flux of radiation such as that from the sun can, over time, force the formation of complex from simpler chemicals. Something of the kind is known to occur in giant molecular clouds within our galaxy, where radioastronomers have been finding increasingly complex chemicals, most recently fullerenes (commonly called "buckyballs") such as C60. The need is for an understanding of the relation between complexity and the flux of radiation. This is a problem in irreversible thermodynamics to which too little attention has been paid.

Indeed, biologists in general have paid too little attention to the quantitative aspects of their work in the past few hectic decades. That is understandable when there are so many interesting (and important) data to be gathered. But we are already at the point where deeper understanding of how, say, cells function is impeded by the simplification of reality now commonplace in cell biology and genetics—and by the torrent of data accumulating everywhere. Simplification? In genetics, it is customary to look for (and to speak of) the "function" of a newly discovered gene. But what if most of the genes in the human genome, or at least their protein products, have more than one function, perhaps even mutually antagonistic ones? Plain-language accounts of cellular events are then likely to be misleading or meaningless unless backed up by quantitative models of some kind.

A horrendous example is the cell-division cycle, in which the number of enzymes known to be involved seems to have been growing for the past few years at the rate of one enzyme a week. It is a considerable success that a complex of proteins that functions as a trigger for cell division (at least in yeast) has been identified, but why this complex functions as a trigger and how the trigger itself is triggered by influences inside and outside a cell are questions still unanswered. They will remain so until researchers have built numerical models of cells in their entirety. That statement is not so much a forecast as a wish.

The catalogue of our ignorance must also include the understanding of the human brain, which is incomplete in one conspicuous way: nobody understands how decisions are made or how imagination is set free. What consciousness consists of (or how it should be defined) is equally a puzzle. Despite the marvelous successes of neuroscience in the past century (not to mention the disputed relevance of artificial intelligence), we seem as far from understanding cognitive process as we were a century ago. The essence of the difficulty is to identify what patterns of the behavior of neurons in the head signal making a decision or other cognitive activity. Perhaps decision making has several alternative neural correlates, which will complicate the search. Yet there is no reason to believe the problem is intractable. Even nonhuman animals (such as rats in a maze) make decisions, although they may not be conscious that they do so, which means that observation and experiment are possible. But it will be no shame on neuroscience if these questions are unanswered 50 years from now.



The central problem in fundamental physics is that quantum mechanics and Einstein's theory of gravitation are incompatible with each other.

That is also the case for the central problem in fundamental physics, which stems from the fact that quantum mechanics and Einstein's theory of gravitation are incompatible with each other. So much has emerged from failed attempts to "quantize" the gravitational field in the past two decades. Yet without a bridge of some kind between these two theories, two of the triumphs of our century, it will not be possible to describe the big bang with which the universe is supposed to have begun with anything like the customary rigor. Doubt has also infected particle physics, where for many years researchers have shared the goal that all four forces of nature should eventually be unified. Those laboring in the field of string theory believe their work provides an acceptable bridge, but others point to the waxing and waning of enthusiasm in the past 20 years and are less sanguine. At least the next 50 years should show which camp is correct.

Is that not a long time to wait for the resolution of what often seems to be a mere problem in mathematics? My forecast may be overlong, but we should not be surprised if a few more decades pass before it is clear whether string theory is a true description of the particles of matter or merely a blind alley. We should not forget that, in the 19th century, three decades passed between Faraday's experimental proof that electricity and magnetism are aspects of the same phenomenon and Maxwell's eventually successful theory of electromagnetism. Then, the mathematics Maxwell needed was amply described in textbooks; now, in string theory, it must be invented as people inch their way forward. Moreover, if string theory is successful in bridging gravitation and quantum mechanics, it will also provide a new picture of the pointlike elementary particles of matter, one that endows both space and time with a kind of microscopic structure on a scale so small that it cannot be probed by existing accelerator machines or any now in prospect. Yet as things are, there are no uniquely relevant experimental data. We must be patient.

Despite the illusion we enjoy that the pace of discovery is accelerating, it is important that, in some fields of science, many goals appear to be attainable only slowly and by huge collective effort. To be sure, the spacecraft now exploring the solar system are usually designed a decade or so before their launch. After a century of seismology, only now are measurement and analytical techniques sensitive enough to promise that we shall soon have a picture of the interior of the planet on which we live, one that shows the rising convection plumes of mantle rock that drive the tectonic plates across the surface of Earth. Since the 1960s, molecular biologists have had the goal of understanding the way in which the genes of living organisms are regulated, but not even the simplest bacterium has yet been comprehensively accounted for. And we shall be lucky if the neural correlates of thinking are identified in the half-century ahead. The application of what we know already will enliven the decades immediately ahead, but there are many important questions that will be answered only with great difficulty.

And we shall be surprised. The discovery of living things of some kind elsewhere in the galaxy would radically change the general opinion of our place in nature, but there will be more subtle surprises, which, of necessity, cannot be anticipated. They are the means by which the record of the past 500 years of science has been repeatedly enlivened. They are also the means by which the half-century ahead will enthrall the practitioners and change the lives of the rest of us. SA

The Author

COURTESY OF *NATURE*

SIR JOHN MADDOX was lecturer in theoretical physics at the University of Manchester from 1949 to 1956 and editor-in-chief of *Nature* from 1966 to 1973 and from 1980 to 1995. He was knighted for "services to science" in 1985.

A Unified Physics by 2050?

by Steven Weinberg

Experiments at CERN and elsewhere should let us complete the Standard Model of particle physics, but a unified theory of all forces will probably require radically new ideas

One of the primary goals of physics is to understand the wonderful variety of nature in a unified way. The greatest advances of the past have been steps toward this goal: the unification of terrestrial and celestial mechanics by Isaac Newton in the 17th century; of optics with the theories of electricity and magnetism by James Clerk Maxwell in the 19th century; of space-time geometry and the theory of gravitation by Albert Einstein in the years 1905 to 1916; and of chemistry and atomic physics through the advent of quantum mechanics in the 1920s [*see illustrations on pages 70 and 71*].

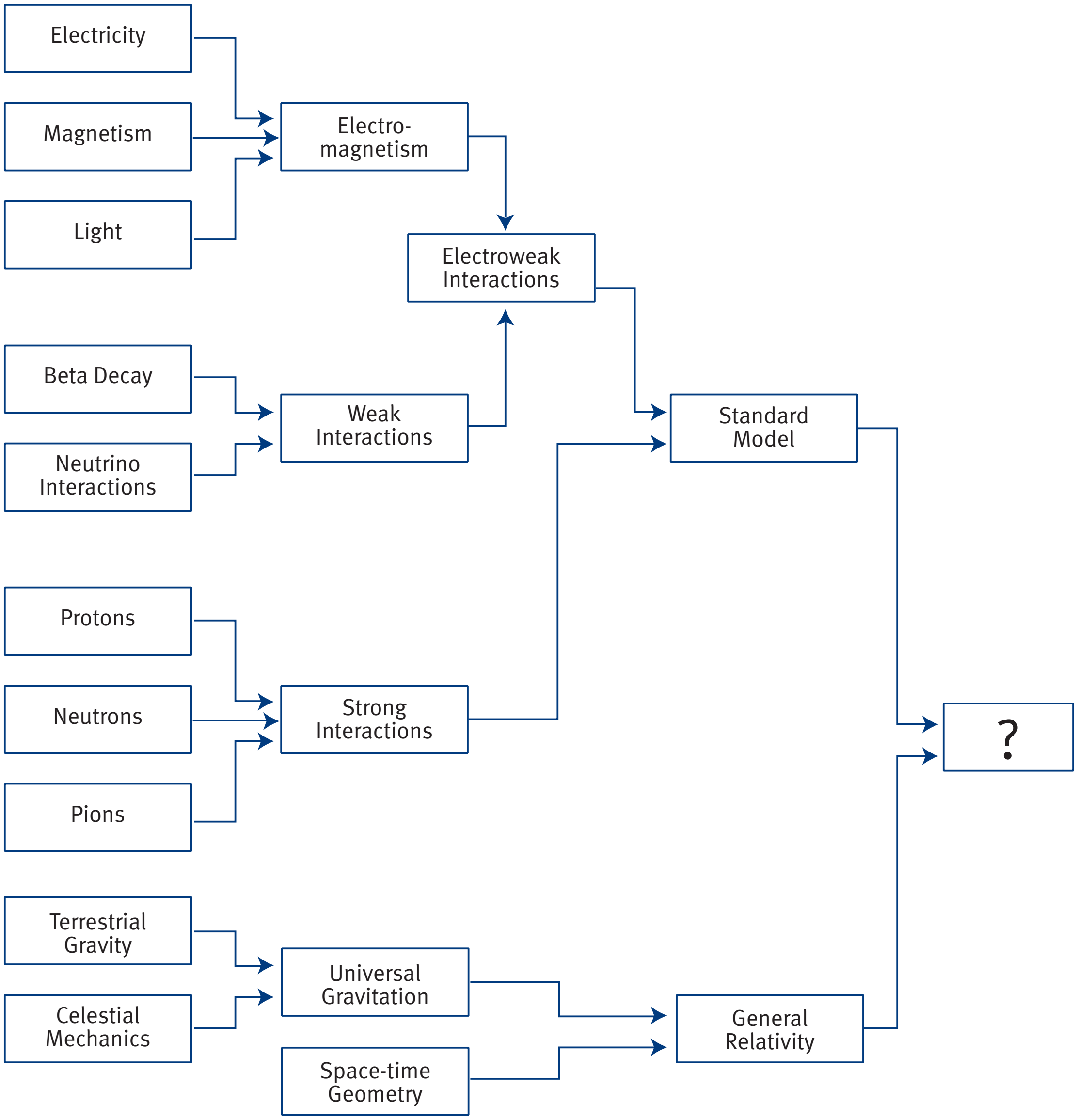
Einstein devoted the last 30 years of his life to an unsuccessful search for a "unified field theory," which would unite general relativity, his own theory of space-time and gravitation, with Maxwell's theory of electromagnetism. Progress toward unification has been made more recently, but in a different direction. Our current theory of elementary particles and forces, known as the Standard Model of particle physics, has achieved a unification of electromagnetism with the weak interactions, the forces responsible for the change of neutrons and protons into each other in radioactive processes and in the stars. The Standard Model also gives a separate but similar description of the strong interactions, the forces that hold quarks together inside protons and neutrons and hold protons and neutrons together inside atomic nuclei.

We have ideas about how the theory of strong interactions can be unified

ALFRED T. KAMAJIAN

The quantum nature of space and time must be dealt with in a unified theory. At the shortest distance scales, space may be replaced by a continually reconnecting structure of strings and membranes—or by something stranger still.

Unification of disparate phenomena within one theory has long been a central theme of physics. The Standard Model of particle physics successfully describes three (electromagnetism, weak and strong interactions) of the four known forces of nature but remains to be united definitively with general relativity, which governs the force of gravity and the nature of space and time.



JOHNNY JOHNSON

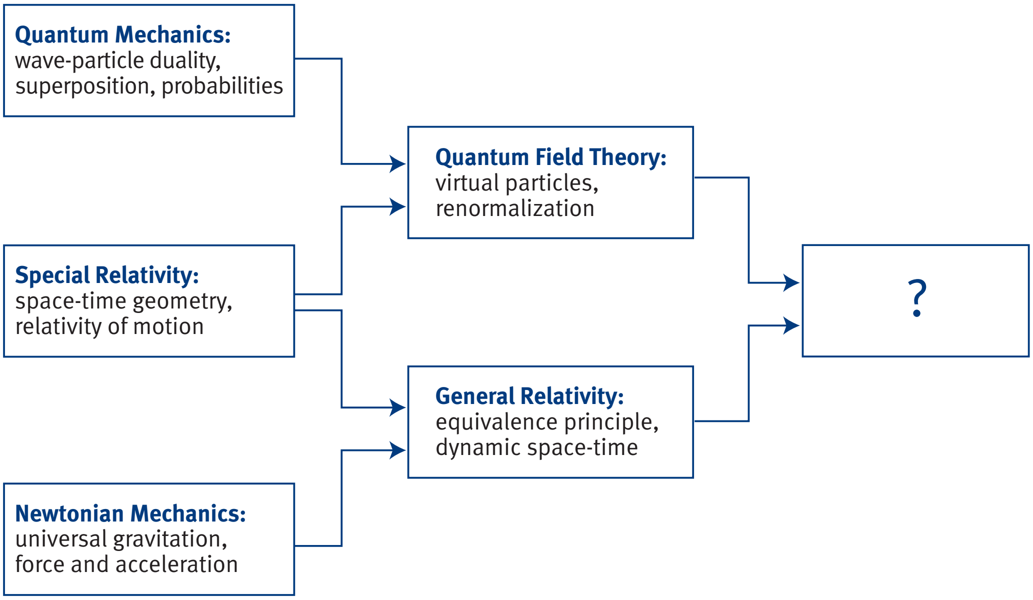
with the theory of weak and electromagnetic interactions (often called Grand Unification), but this may only work if gravity is included, which presents grave difficulties. We suspect that the apparent differences among these forces have been brought about by events in the very early history of the big bang, but we cannot follow the details of cosmic history at those early times without a better theory of gravitation and the other forces. There is a chance the work of unification will be completed by 2050, but about that we cannot be confident.

Quantum Fields

The Standard Model is a quantum field theory. Its basic ingredients are fields, including the electric and magnetic fields of 19th-century electrodynamics. Little ripples in these fields carry energy and momentum from place to place, and quantum mechanics tells us that these ripples come in bundles, or quanta, that are recognized in the laboratory as elementary particles. For instance, the quantum of the electromagnetic field is a particle known as the photon.

The Standard Model includes a field for each type of elementary particle that has been observed in high-energy physics laboratories [*see top illustration on page 72*]. There are the lepton fields: their quanta include the familiar electrons, which make up the outer parts of ordinary atoms, similar heavier particles known as muons and tauons, and related electrically neutral particles known as neutrinos. There are fields for quarks of various types, some of which are bound together in the protons and neutrons that make up the nuclei of ordinary atoms. Forces between these particles are produced by the exchange of photons and similar elementary particles: the W^+, W^- and Z^0 transmit the weak force, and eight species of gluon produce the strong forces.

These particles exhibit a wide variety of masses that follow no recognizable pattern, with the electron 350,000 times lighter than the heaviest quark, and neutrinos even lighter. The Standard



The profoundest advances in fundamental physics tend to occur when the principles of different types of theories are reconciled within a single new framework. We do not yet know what guiding principle underlies the unification of quantum field theory, as embodied in the Standard Model, with general relativity.

Model has no mechanism that would account for any of these masses, unless we supplement it by adding additional fields, of a type known as scalar fields. The word "scalar" means that these fields do not carry a sense of direction, unlike the electric and magnetic fields and the other fields of the Standard Model. This opens up the possibility that these scalar fields can pervade all space without contradicting one of the best established principles of physics, that space looks the same in all directions. (In contrast, if, for example, there were a significant magnetic field everywhere in space, then we could identify a preferred direction by using an ordinary compass.) The interaction of the other fields of the Standard Model with the all-pervasive scalar fields is believed to give the particles of the Standard Model their masses.

Beyond the Top

To complete the Standard Model, we need to confirm the existence of these scalar fields and find out how many types there are. This is a matter of discovering new elementary particles, often called Higgs particles, that can be recognized as the quanta of these fields. We have every reason to expect that this task will be accomplished before 2020, when the accelerator called the Large Hadron Collider at CERN, the European laboratory for particle physics near Geneva, will have been operating for over a decade.

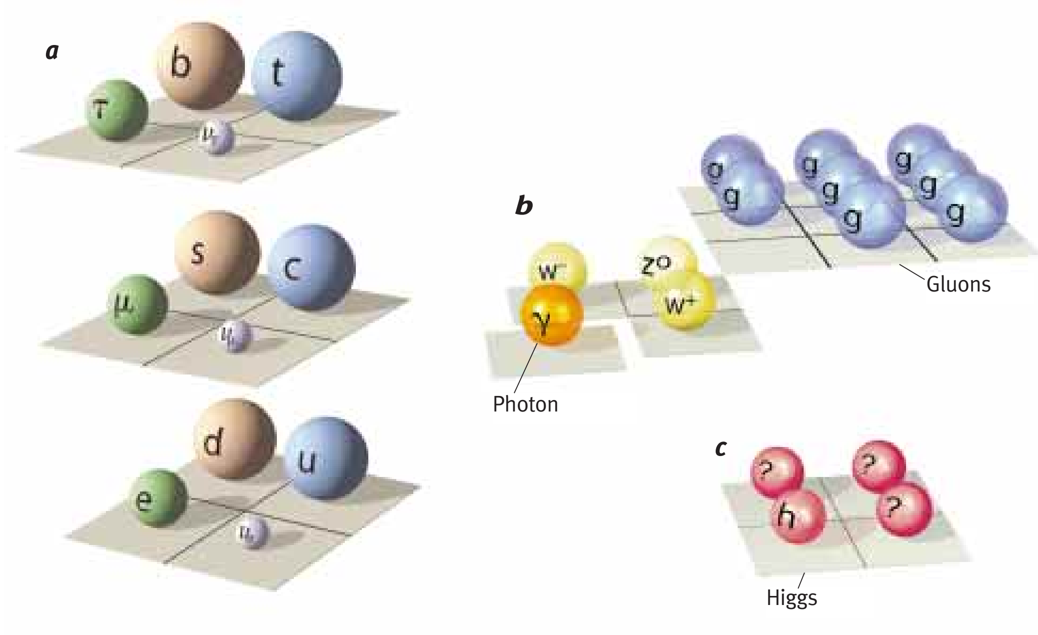
The very least new thing that will be discovered is a single electrically neutral scalar particle. It would be a disaster if this were all that were discovered by 2020, though, because it would leave us without a clue to the solution of a formidable puzzle regarding the characteristic energies encountered in physics, known as the *hierarchy problem*.

The heaviest known particle of the Standard Model is the top quark, with a mass equivalent to an energy of 175 gigaelectron volts (GeV). (One GeV is a little more than the energy contained in a proton mass.) [See "The Discovery of the Top Quark," by Tony M. Liss and Paul L. Tipton; Scientific American, September 1997.] The not yet discovered Higgs particles are expected to have similar masses, from 100 to several hundred GeV. But there is evidence of a much larger scale of masses that will appear in equations of the not yet formulated unified theory. The gluon, *W*, *Z* and photon fields of the Standard Model have interactions of rather different strengths with the other fields of this model; that is why the forces produced by exchange of gluons are about 100 times stronger than the others under ordinary conditions. Gravitation is vastly weaker: the gravitational force between the electron and proton in the hydrogen atom is about 10^{-39} the strength of the electric force.

How can we get the ideas we need to describe a realm where all intuitions derived from life in space-time become inapplicable?

But all these interaction strengths depend on the energy at which they are measured [*see top illustration on page 73*]. It is striking that when the interactions of the fields of the Standard Model are extrapolated, they all become equal to one another at an energy of a little more than 10^{16} GeV, and the force of gravitation has the same strength at an energy not much higher, around 10^{18} GeV. (Refinements to the theory of gravitation have been suggested that would even bring the strength of gravitation into equality with the other forces at about 10^{16} GeV.) We are used to some pretty big mass ratios in particle physics, like the 350,000 to 1 ratio of the top quark to the electron mass, but this is nothing compared with the enormous ratio of the fundamental unification energy scale of 10^{16} GeV (or perhaps 10^{18} GeV) to the energy scale of about 100 GeV that is typical of the Standard Model

The Standard Model of particle physics describes each particle of matter and each force with a quantum field. The fundamental particles of matter are fermions and come in three generations (*a*). Each generation of particles follows the same pattern of properties. The fundamental forces are caused by bosons (*b*), which are organized according to three closely related symmetries. In addition, one or more Higgs particles or fields (*c*) generate the masses of the other fields.



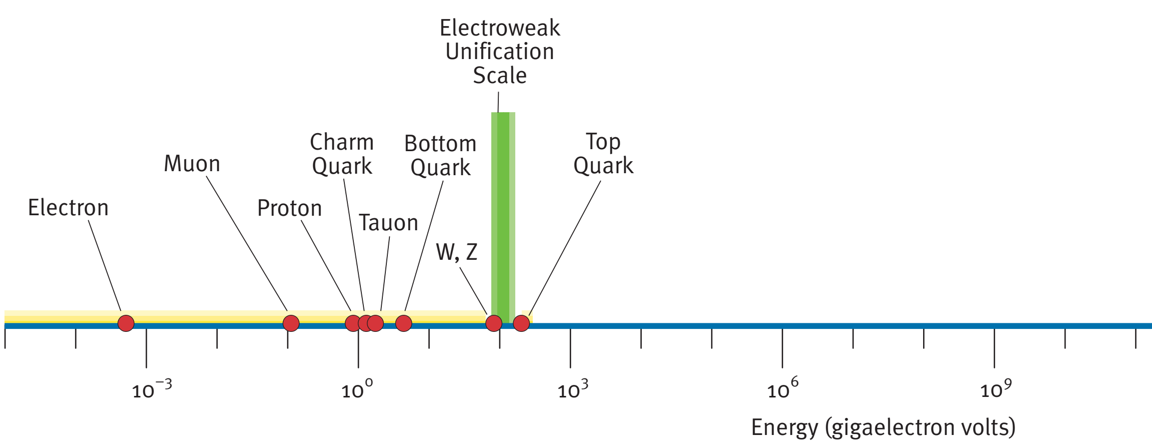
SLIM FILMS

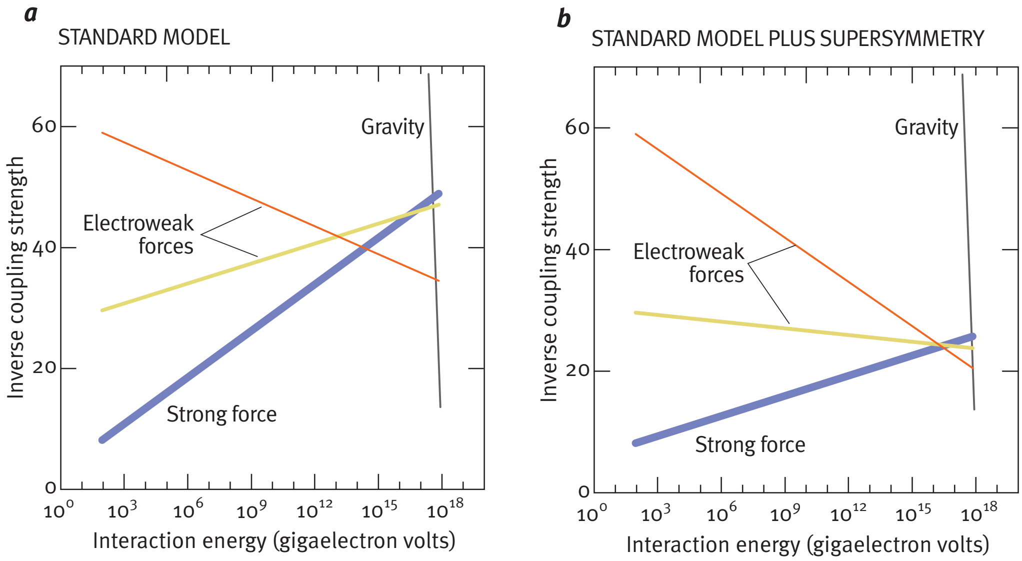
[*see illustration below*]. The crux of the hierarchy problem is to understand this huge ratio, this vast jump from one level to the next in the hierarchy of energy scales, and to understand it not just by adjusting the constants in our theories to make the ratio come out right but as a natural consequence of fundamental principles.

Theorists have proposed several interesting ideas for a natural solution to the hierarchy problem, incorporating a new symmetry principle known as supersymmetry (which also improves the accuracy with which the interaction strengths converge at 10^{16} GeV), or new strong forces known as technicolor, or both [*see illustration on page 74*]. All these theories contain additional forces that are unified with the strong, weak and electromagnetic forces at an energy of about 10^{16} GeV. The new forces become strong at some energy far below 10^{16} GeV, but we cannot observe them directly, because they do not act on the known particles of the Standard Model. Instead they act on other particles that are too massive to be created in our laboratories. These "very heavy" particles are nonetheless much lighter than 10^{16} GeV because they acquire their mass from the new forces, which are strong only far below 10^{16} GeV. In this picture, the known particles of the Standard Model would interact with the very heavy particles, and their masses would arise as a secondary effect of this relatively weak interaction. This mechanism would solve the hierarchy problem, making the known particles lighter than the very heavy particles, which are themselves much lighter than 10^{16} GeV.

All these ideas share another common feature: they require the existence of a zoo of new particles with masses not much larger than 1,000 GeV. If there is any truth to these ideas, then these particles should be discovered before 2020 at the Large Hadron Collider, and some of them may even show up before then at Fermilab or CERN, although it may take further decades and new accelerators to explore their properties fully. When these particles have been discovered and their properties measured, we will be able to tell whether any of them would have survived the early moments of the big bang and could now furnish the "dark matter" in intergalactic space that is

The hierarchy problem is a measure of our ignorance. Experiments (*yellow band*) have probed up to an energy of about 200 GeV and have revealed an assortment of particle masses (*red*) and interaction energy scales (*green*) that are remarkably well described by the Standard Model. The puzzle is the vast gap to two further energy scales, that of strong-electroweak unification near 10^{16} GeV and the Planck scale, characteristic of quantum gravity, around 10^{18} GeV.





Theoretical extrapolation shows that the three Standard Model forces (the strong force and the unified weak and electromagnetic forces) have roughly equal strength at very high energy (*a*), and the equality is improved by allowing for supersymmetry (*b*). Curve thickness indicates approximate uncertainty in the coupling strengths.

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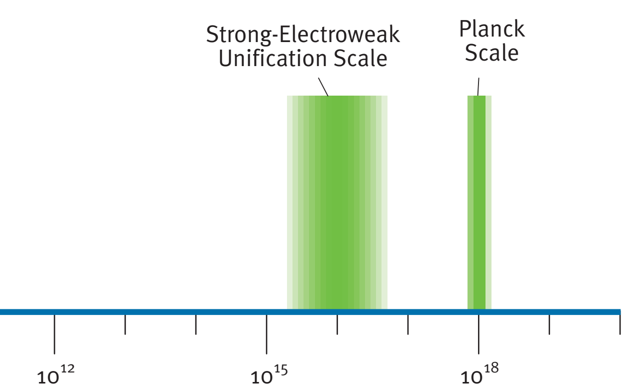
thought to make up most of the present mass of the universe. At any rate, it seems likely that by 2050 we will understand the reason for the enormous ratio of energy scales encountered in nature.

What then? There is virtually no chance that we will be able to do experiments involving processes at particle energies like 10^{16} GeV. With present technology the diameter of an accelerator is proportional to the energy given to the accelerated particles. To accelerate particles to an energy of 10^{16} GeV would require an accelerator a few light-years across. Even if someone found some other way to concentrate macroscopic amounts of energy on a single particle, the rates of interesting processes at these energies would be too slow to yield useful information. But even though we cannot study processes at energies like 10^{16} GeV directly, there is a very good chance that these processes produce effects at accessible energies that can be recognized experimentally because they go beyond anything allowed by the Standard Model.

The Standard Model is a quantum field theory of a special kind, one that is "renormalizable." This term goes back to the 1940s, when physicists were learning how to use the first quantum field theories to calculate small shifts of atomic energy levels. They found that calculations using quantum field theory kept producing infinite quantities, a situation that usually means a theory is badly flawed or is being pushed beyond its limits of validity. In time, they found a way to deal with the infinite quantities by absorbing them into a redefinition, or "renormalization," of just a few physical constants, such as the charge and mass of the electron. (The minimum version of the Standard Model, with just one scalar particle, has 18 of these constants.) Theories in which this procedure worked were called renormalizable and had a simpler structure than nonrenormalizable theories.



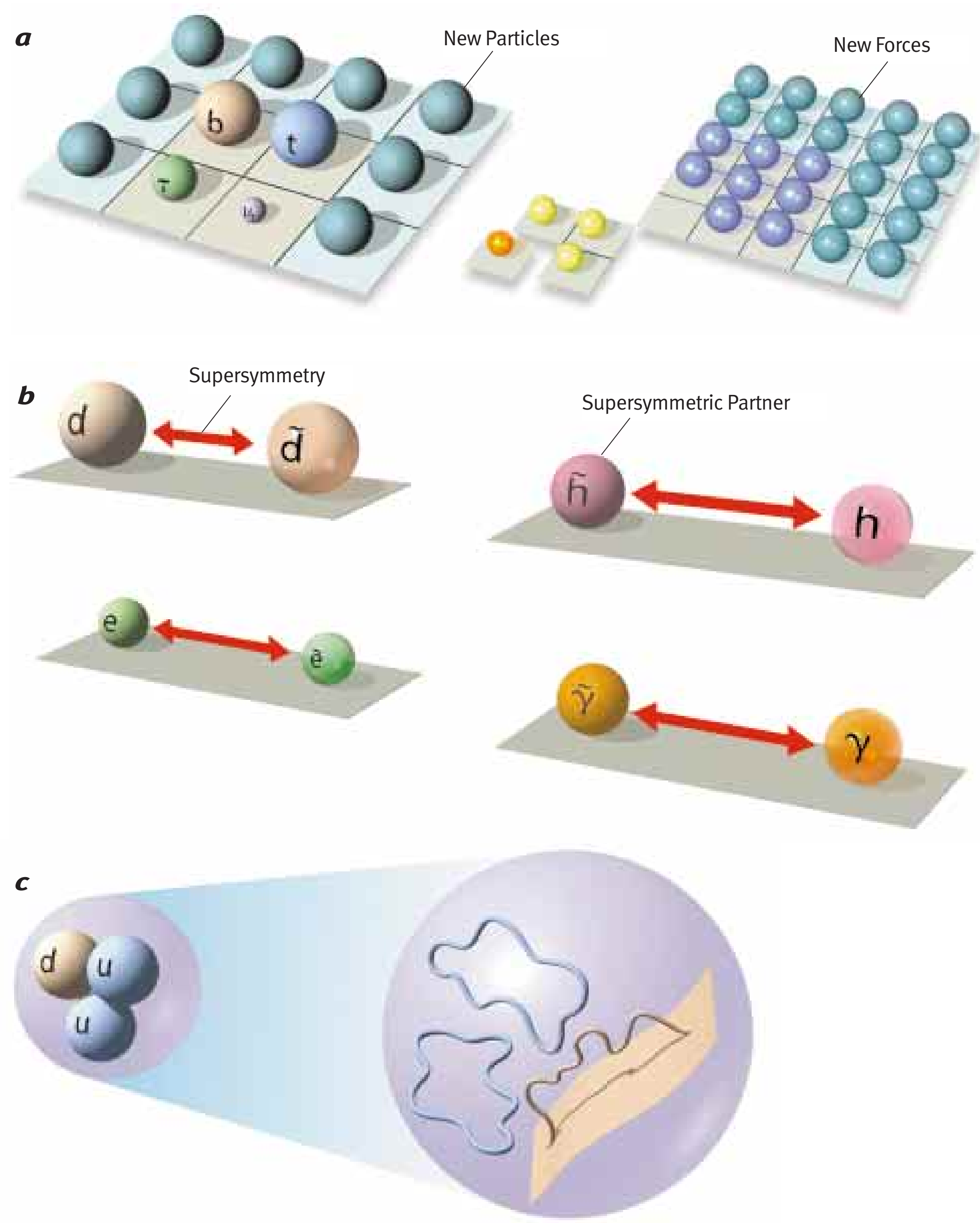
Suppressed Interactions

It is this simple renormalizable structure of the Standard Model that has let us derive specific quantitative predictions for experimental results, predictions whose success has confirmed the validity of the theory. In particular, the principle of renormalizability, together with various symmetry principles of the Standard Model, rules out unobserved processes such as the decay of isolated protons and forbids the neutrinos from having masses. Physicists commonly used to believe that for a quantum field theory to have any validity, it had to be renormalizable. This requirement was a powerful guide to theorists in formulating the Standard Model. It was terribly disturbing that it seemed impossible, for fundamental reasons, to formulate a renormalizable quantum field theory of gravitation.

Today our perspective has changed. Particle physics theories look different depending on the energy of the processes and reactions being considered. Forces produced by exchange of a very massive particle will typically be extremely weak at energies that are low compared with that mass.

JOHNNY JOHNSON

What comes next? There are several possibilities for the unified physics that lies beyond the Standard Model. Technicolor models (*a*) introduce new interactions analogous to the "color" force that binds quarks. Accompanying the interactions are new generations of particles unlike the three known generations. Supersymmetry (*b*) relates fermions to bosons and adds the supersymmetric partners of each known particle to the model. M-theory and string theory (*c*) recast the entire model in terms of new entities such as tiny strings, loops and membranes that behave like particles at low energies.



Other effects can be similarly suppressed, so that at low energies one has what is known as an effective field theory, in which these interactions are negligible. Theorists have realized that any fundamental quantum theory that is consistent with the special theory of relativity will look like a renormalizable quantum field theory at low energies. But although the infinities are still canceled, these effective theories do not have the simple structure of theories that are renormalizable in the classic sense. Additional complicated interactions are present; instead of being completely excluded, they are just highly suppressed below some characteristic energy scale.

Gravitation itself is just such a suppressed nonrenormalizable interaction. It is from its strength (or rather weakness) at low energies that we infer that its fundamental energy scale is roughly 10^{18} GeV. Another suppressed nonrenormalizable interaction would make the proton unstable, with a half-life in the range of 10^{31} to 10^{34} years, which might be too slow to be observed even by 2050 [see my article "The Decay of the Proton"; SCIENTIFIC AMERICAN, June 1981]. Yet another suppressed nonrenormalizable interaction would give the neutrinos tiny masses, about 10^{-11} GeV. There is already some evidence for neutrino masses of this order; this should be settled well before 2050 [see "Detecting Massive Neutrinos," by Edward Kearns, Takaaki Kajita and Yoji Totsuka; SCIENTIFIC AMERICAN, August 1999].

Observations of this kind will yield valuable clues to the unified theory of all forces, but the discovery of this theory will probably not be possible without radically new ideas. Some promising ones are already in circulation. There are five different theories of tiny one-dimensional entities known as strings, which in their different modes of vibration appear at low energy as various kinds of particles and apparently furnish perfectly finite theories of gravitation and other forces in 10 space-time dimensions. Of course, we do not live in 10 dimensions, but it is plausible that six of these dimensions could be rolled up so tightly that they could not be observed in processes at energies below 10^{16} GeV per particle. Evidence has appeared in the past few years that these five string theories (and also a quantum field theory in 11 dimensions) are all versions of a single fundamental theory (sometimes called M-theory) that apply under different approximations [see "The Theory Formerly Known as Strings," by Michael J. Duff; SCIENTIFIC AMERICAN, February 1998]. But no one knows how to write down the equations of this theory.

Outside of Space-time

Two great obstacles stand in the way of this task. One is that we do not know what physical principles govern the fundamental theory. In developing general relativity, Einstein was guided by a principle he had inferred from the known properties of gravitation, the principle of the equivalence of gravitational forces to inertial effects such as centrifugal force. The development of the Standard Model was guided by a principle known as gauge symmetry, a generalization of the well-known property of electricity that it is only differences of voltages that matter, not voltages themselves.

But we have not discovered any fundamental principle that governs M-theory. The various approximations to this theory look like string or field theories in space-times of different dimensionalities, but it seems probable that the fundamental theory is not to be formulated in space-time at all. Quantum field theory is powerfully constrained by principles concerning the nature of four-dimensional space-time that are incorporated in the special theory of relativity. How can we get the ideas we need to formulate a truly fundamental theory, when this theory is to describe a realm where all intuitions derived from life in space-time become inapplicable?

The other obstacle is that even if we were able to formulate a fundamental theory, we might not know how to use it to make predictions that could confirm its validity. Most of the successful predictions of the Standard Model have been based on a method of calculation known as perturbation theory. In quantum mechanics the rates of physical processes are given by sums over all possible sequences of intermediate steps by which the process may occur. Using perturbation theory, one first considers only the simplest intermediate steps, then the next simplest, and so on. This works only if increasingly complicated intermediate steps make decreasingly large contributions to the rate, which is usually the case if the forces involved are sufficiently weak. Sometimes a theory with very strong forces is equivalent to another theory with very weak forces, which can be solved by the methods of perturbation theory. This seems to be true of some pairs of the five string theories in 10 dimensions and the field theory in 11 dimensions mentioned earlier. Unfortunately, the forces of the fundamental theory are probably neither very strong nor very weak, ruling out any use of perturbation theory.

Recognizing the Answer

It is impossible to say when these problems will be overcome. They may be solved in a preprint put out tomorrow by some young theorist. They may not be solved by 2050, or even 2150. But when they are solved, even though we cannot do experiments at 10^{16} GeV or look into higher dimensions, we will not have any trouble in recognizing the truth of the fundamental unified theory. The test will be whether the theory successfully accounts for the measured values of the physical constants of the Standard Model, along with whatever other effects beyond the Standard Model may have been discovered by then.

It is possible that when we finally understand how particles and forces behave at energies up to 10^{18} GeV, we will just find new mysteries, with a final unification as far away as ever. But I doubt it. There are no hints of any fundamental energy scale beyond 10^{18} GeV, and string theory even suggests that higher energies have no meaning.

The discovery of a unified theory that describes nature at all energies will put us in a position to answer the deepest questions of cosmology: Did the expanding cloud of galaxies we call the big bang have a beginning at a definite time in the past? Is our big bang just one episode in a much larger universe in which big and little bangs have been going on eternally? If so, do what we call the constants of nature or even the laws of nature vary from one bang to another?

This will not be the end of physics. It probably won't even help with some of the outstanding problems of today's physics, such as understanding turbulence and high-temperature superconductivity. But it will mark the end of a certain kind of physics: the search for a unified theory that entails all other facts of physical science. SA

THE AUTHOR

COURTESY OF STEVEN WEINBERG

STEVEN WEINBERG is head of the Theory Group at the University of Texas at Austin and a member of its physics and astronomy departments. His work in elementary particle physics has been honored with numerous prizes and awards, including the Nobel Prize for Physics in 1979 and the National Medal of Science in 1991. The third volume (*Supersymmetry*) of his treatise *The Quantum Theory of Fields* is due out this month from Cambridge University Press. The second volume (*Modern Applications*) was hailed as being "unmatched by any other book on quantum field theory for its depth, generality and definitive character."

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Exploring Our Universe and Others

by Martin Rees

In the 21st century cosmologists will unravel the mystery of our universe's birth—and perhaps prove the existence of other universes as well

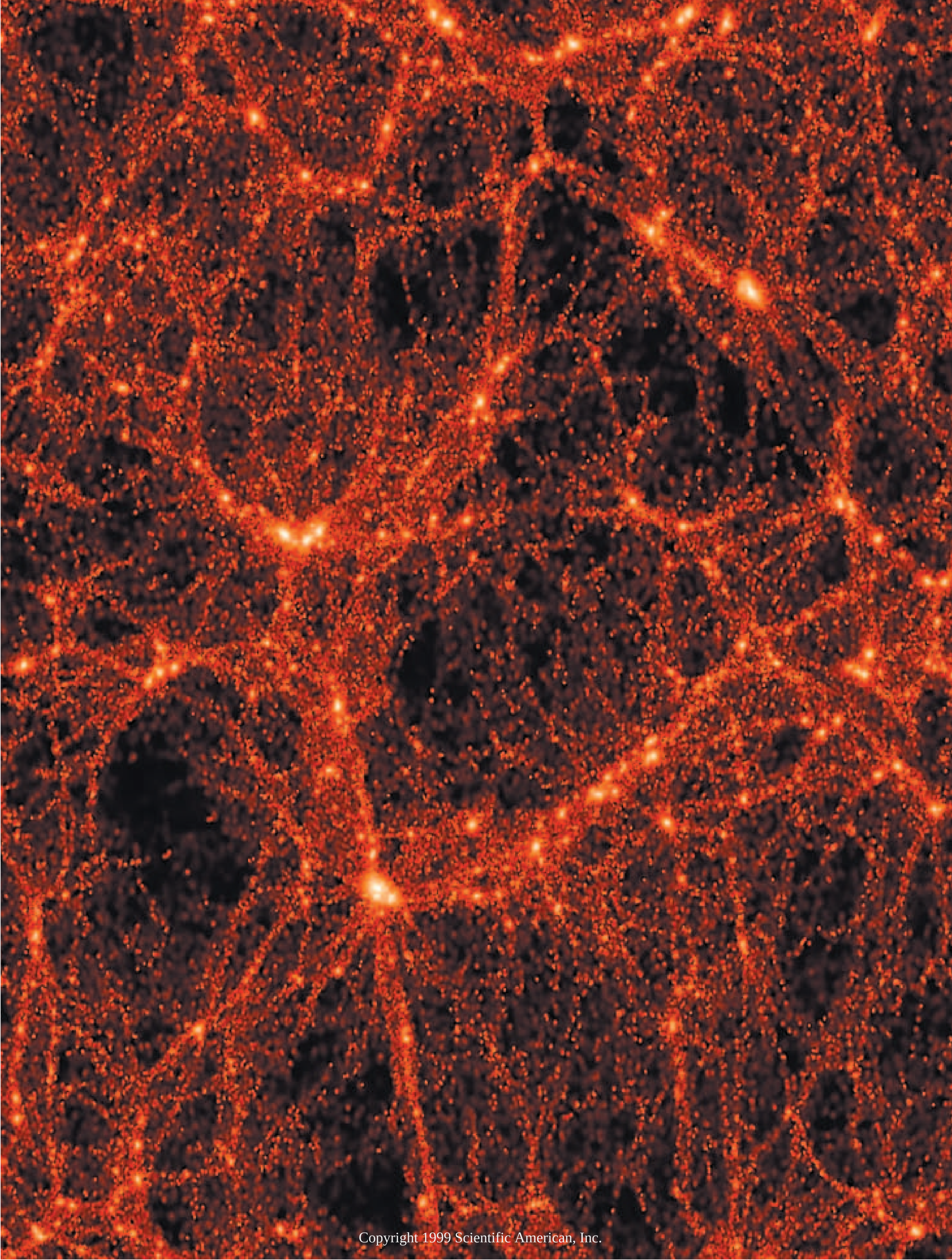
Cosmic exploration is preeminently a 20th-century achievement. Only in the 1920s did we realize that our Milky Way, with its 100 billion stars, is just one galaxy among millions. Our empirical knowledge of the universe has been accumulating ever since. We can now set our entire solar system in a grand evolutionary context, tracing its constituent atoms back to the initial instants of the big bang. If we were ever to discover alien intelligences, one thing we might share with them—perhaps the only thing—would be a common interest in the cosmos from which we have all emerged.

Using the current generation of ground-based and orbital observatories, astronomers can look back into the past and see plain evidence of the evolution of the universe. Marvelous images from the Hubble Space Telescope reveal galaxies as they were in remote times: balls of glowing, diffuse gas dotted with massive, fast-burning blue stars. These stars transmuted the pristine hydrogen from the big bang into heavier atoms, and when the stars died they seeded their galaxies with the basic building blocks of planets and life—carbon, oxygen, iron and so on. A Creator didn't have to turn 92 different knobs to make all the naturally occurring elements in the periodic table. Instead the galaxies act as immense ecosystems, forging elements and recycling gas through successive generations of stars. The human race itself is composed of stardust—or, less romantically, the nuclear waste from the fuel that makes stars shine.

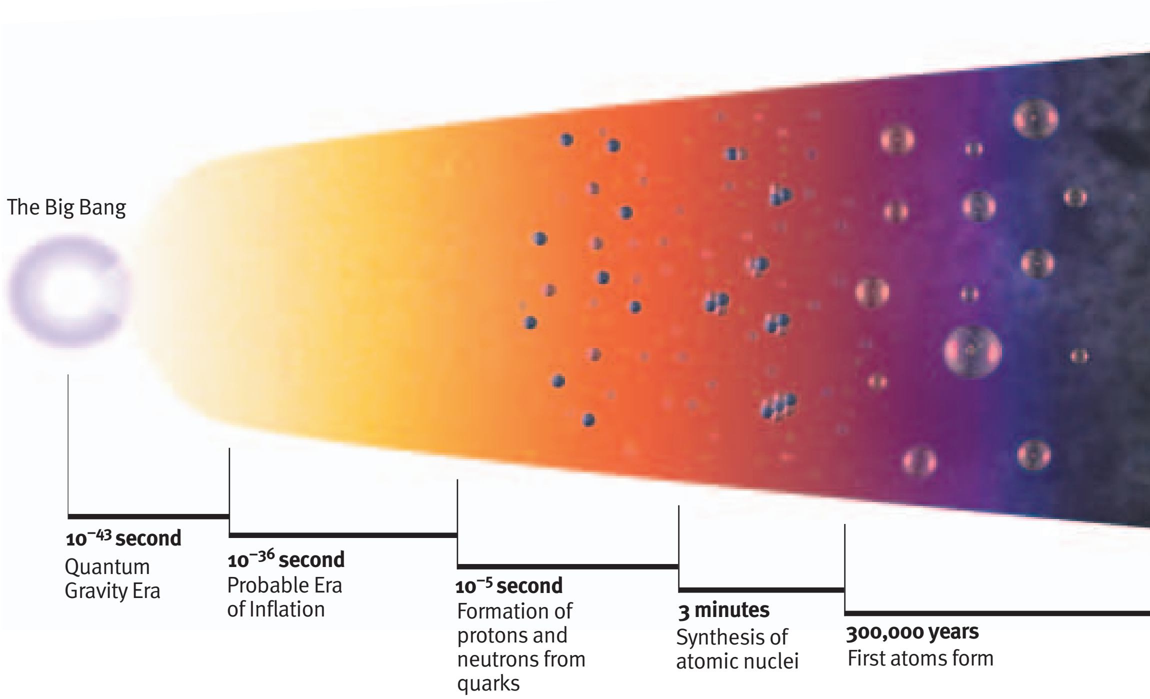
Astronomers have also learned much about the earlier, pregalactic era by studying the microwave background radiation that makes even intergalactic space slightly warm. This afterglow of creation tells us that the entire

Large-scale structure of the universe can be simulated by running cosmological models on a supercomputer. In this simulation, produced by the Virgo Consortium, each particle represents a galaxy.

VIRGO CONSORTIUM (J.M. COLBERG, H.M.P. COUCHMAN, G. EFSTATHIOU, C. S. FRENK, A. JENKINS, J. A. PEACOCK, F. R. PEARCE AND S.D.M. WHITE)



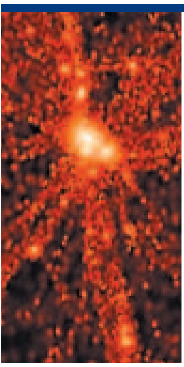
Cosmic timeline shows the evolution of our universe from the big bang to the present day. In the first instant of creation—the epoch of inflation—the universe expanded at a staggering rate. After about three minutes, the plasma of particles and radiation cooled enough to allow the formation of simple atomic nuclei; after another 300,000 years, atoms of hydrogen and helium began to form. The first stars and galaxies appeared about a billion years later. The ultimate fate of the universe—whether it will expand forever or recollapse—is still unknown, although current evidence favors perpetual expansion.



universe was once hotter than the centers of stars. Scientists can use laboratory data to calculate how much nuclear fusion would have happened during the first few minutes after the big bang. The predicted proportions of hydrogen, deuterium and helium accord well with what astronomers have observed, thereby corroborating the big bang theory.

At first sight, attempts to fathom the cosmos might seem presumptuous and premature, even in the closing days of the 20th century. Cosmologists have, nonetheless, made real progress in recent years. This is because what makes things baffling is their degree of complexity, not their sheer size—and a star is simpler than an insect. The fierce heat within stars, and in the early universe, guarantees that everything breaks down into its simplest constituents. It is the biologists, whose role it is to study the intricate multilayered structure of trees, butterflies and brains, who face the tougher challenge.

The progress in cosmology has brought new mysteries into sharper focus and raised questions that will challenge astronomers well into the next century. For example, why does our universe contain its observed mix of ingredients? And how, from its dense beginnings, did it heave itself up to such a vast size? The answers will take us beyond the physics with which we are familiar and will require new insights into the nature of space and time. To truly understand the history of the universe, scientists must discover the profound links between the cosmic realm of the very large and the quantum world of the very small.



The great mystery for cosmologists is the series of events that occurred less than one millisecond after the big bang.

It is embarrassing to admit, but astronomers still don't know what our universe is made of. The objects that emit radiation that we can observe—such as stars, quasars and galaxies—constitute only a small fraction of the universe's matter. The vast bulk of matter is dark and unaccounted for. Most cosmologists believe dark matter is composed of weakly interacting particles left over from the big bang, but it could be something even more exotic. Whatever the case, it is clear that galaxies, stars and planets are a mere afterthought in a cosmos dominated by quite different stuff. Searches for dark matter, mainly via sensitive underground experiments designed to detect elusive subatomic particles, will continue apace in the coming decade. The stakes are high: success would not only tell us what most of the universe is made of but would also probably reveal some fundamentally new kinds of particles.

Astronomers are also unsure how much dark matter there is. The ultimate fate of our universe—whether it continues expanding indefinitely or eventually changes course and collapses to the so-called big crunch—depends on the total amount of dark matter and the gravity it exerts. Current data indicate that the universe contains only about 30 percent of the matter that would be needed to halt the expansion. (In cosmologists' jargon, omega—the ratio of observed density to critical density—is 0.3.) The odds favoring perpetual growth have recently strengthened further: tantalizing observations of distant supernovae suggest that the expansion of the universe may be speeding up rather than slowing down. Some astronomers say the observations are evidence of an extra repulsive force that overwhelms gravity on cosmic scales—what Albert Einstein called the cosmological constant. The jury is still out on this

issue, but if the existence of the repulsive force is confirmed, physicists will learn something radically new about the energy latent in empty space.

Research is also likely to focus on the evolution of the universe's large-scale structure. If one had to answer the question "What's been happening since the big bang?" in just one sentence, the best response might be to take a deep breath and say, "Ever since the beginning, gravity has been amplifying inhomogeneities, building up structures and enhancing temperature contrasts—a prerequisite for the emergence of the complexity that lies around us now and of which we're a part." Astronomers are now learning more about this 10-billion-year process by creating "virtual universes" on their computers. In the coming years, they will be able to simulate the history of the universe with ever improving realism and then compare the results with what telescopes reveal.

Questions of structure have preoccupied astronomers since the time of Isaac Newton, who wondered why all the planets circled the sun in the same direction and in almost the same plane. In his 1704 work *Opticks* he wrote: "Blind fate could never make all the planets move one and the same way in orbits concentrick." Such a wonderful uniformity in the planetary system, Newton believed, must be the effect of divine providence.

Now astronomers know that the coplanarity of the planets is a natural outcome of the solar system's origin as a spinning disk of gas and dust. Indeed, we have extended the frontiers of our knowledge to far earlier times; cosmologists can roughly outline the history of the universe back to the very first second after the big bang. Conceptually, however, we're in little better shape than Newton was. Our understanding of the causal chain of events now stretches further back in time, but we still run into a barrier, just as surely as Newton did. The great mystery for cosmologists is the series of events that occurred less than one millisecond after the big bang, when the universe was extraordinarily small, hot and dense. The laws of physics with which we are familiar offer little firm guidance for explaining what happened during this critical period.

To unravel this mystery, cosmologists must first pin down—by improving and refining current observations—some of the characteristics of the universe when it was only one second old: its expansion rate, the size of its density fluctuations, and its proportions of ordinary atoms, dark matter and radiation. But to comprehend why our universe was set up this way, we must probe further back, to the very first tiny fraction of a microsecond. Such an effort will require theoretical advances. Physicists must discover a way to relate Einstein's theory of general relativity, which governs large-scale interactions in the cosmos, with the quantum principles that apply at very short distances [see "A Unified Physics by 2050?," by Steven Weinberg, on page 68]. A unified theory would be

Multiple universes are continually being born, according to some cosmologists. Each universe is shown here as an expanding bubble branching off from its "parent" universe. The changes in color represent shifts in the laws of physics from one universe to another.

ILLUSTRATIONS BY ALFRED T. KAMAJIAN

PAT RAWLINGS

Lunar observatories will greatly extend the reach of 21st-century astronomers. The far side of the moon is an ideal place for telescopes because of its absence of atmosphere and its utterly dark nights. (Sunlight reflected off Earth's surface cannot reach the far side, which never faces our planet.) Lunar ores can be used to build the instruments.

needed to explain what happened in the first crucial moments after the big bang, when the entire universe was squeezed into a space smaller than a single atom.

Astronomy is a subject in which observation is king. Now the same is true for cosmology—in contrast with the pre-1965 era, when speculation was largely unconstrained. The answers to many of cosmology's long-standing questions are most likely to come from the new telescopes now going into use. The two Keck Telescopes on Mauna Kea in Hawaii are far more sensitive than earlier observatories and thus can glimpse fainter objects. Still more impressive is the Very Large Telescope being built in northern Chile, which will be the world's premier optical facility when it is completed. Astronomers can take advantage of the Chandra X-ray Observatory, launched into orbit this past summer, and several new radio arrays on the ground. And a decade from now next-generation space telescopes will carry the enterprise far beyond what the Hubble can achieve.

Well before 2050 we are likely to see the construction of giant observatories in space or perhaps on the far side of the moon. The sensitivity and imaging power of these arrays will vastly surpass that of any instruments now in use. The new telescopes will target black holes and planets in other solar systems. They will also provide snapshots of every cosmological era going back to the very first light, when the earliest stars (or maybe quasars) condensed out of the expanding debris from the big bang. Some of these observatories may even be able to measure gravitational waves, allowing scientists to probe vibrations in the fabric of space-time itself.

The amount of data provided by all these instruments will be so colossal that the entire process of analysis and discovery will most likely be automated. Astronomers will focus their attention on heavily processed statistics for each population of objects they are studying and in this way find the best examples—for instance, the planets in other solar systems that are most like Earth. Researchers will also concentrate on extreme objects that may hold clues to physical processes that are not yet fully understood. One such object is the gamma-ray burster, which emits, for a few seconds, as much power as a billion galaxies. Increasingly, astronomers will use the heavens as a cosmic laboratory to probe phenomena that cannot be simulated on Earth.

Another benefit of automation will be open access to astronomical data that in the past were available only to a privileged few. Detailed maps of the sky will be available to anyone who can access or download them. Enthusiasts anywhere in the world will be able to check their own hunches, seek new patterns and discover unusual objects.

Intimations of a Multiverse?

Cosmologists view the universe as an intricate tapestry that has evolved from initial conditions that were imprinted in the first microsecond after the big bang. Complex structures and phenomena have unfolded from simple physical laws—we wouldn't be here if they hadn't. Simple laws, however, do not necessarily lead to complex consequences. Consider an analogue from the field of fractal mathematics: the Mandelbrot set, a pattern with an infinite depth of structure, is encoded by a short algorithm, but other simple algorithms that are superficially similar yield very boring patterns.

Our universe could not have become structured if it were not expanding at a special rate. If the big bang had produced fewer density fluctuations, the universe would have remained dark and featureless, with no galaxies or stars. And there are other prerequisites for complexity. If our universe had more than three spatial dimensions, planets could not stay in orbits around stars. If gravity were much stronger, it would crush living organisms of human size, and stars would be small and short-lived. If nuclear forces were a few percent weaker, only hydrogen would be stable: there would be no periodic table, no chemistry and no life. On the other hand, if nuclear forces were slightly stronger, hydrogen itself could not exist.

Some would argue that this fine-tuning of the universe, which seems so providential, is nothing to be surprised about, because we could not exist otherwise. There is, however, another interpretation: many universes may exist, but only some would allow creatures like us to emerge, and we obviously find ourselves in one of that subset. The seemingly designed features of our universe need then occasion no surprise.

Perhaps, then, our big bang wasn't the only one. This speculation dramatically enlarges our concept of reality. The entire history of our universe becomes just an episode, a single facet, of the infinite multiverse. Some universes might resemble ours, but most would be "stillborn." They would recollapse after a brief existence, or the laws governing them would not permit complex consequences.

Some cosmologists, especially Andrei Linde of Stanford University and Alex Vilenkin of Tufts University, have already shown how certain mathematical assumptions lead, at least in theory, to the creation of a multiverse. But such ideas will remain on the speculative fringe of cosmology until we really understand—rather than just guess at—the extreme physics that prevailed immediately after the big bang. Will the long-awaited unified theory uniquely determine the masses of particles and the strengths of the basic forces? Or are these properties in some sense accidental outcomes of how our universe cooled—secondary manifestations of still deeper laws governing an entire ensemble of universes?

This topic might seem arcane, but the status of multiverse ideas affects how we should place our bets in some ongoing cosmological controversies. Some theorists have a strong preference for the simplest picture of the cosmos, which would require an omega of 1—the universe would be just dense enough to halt its own expansion. They are unhappy with observations suggesting that the universe is not nearly so dense and with extra complications such as the cosmological constant. Perhaps we should draw a lesson from 17th-century astronomers Johannes Kepler and Galileo Galilei, who were upset to find that planetary orbits were elliptical. Circles, they thought, were simpler and more beautiful. But Newton later explained all orbits in terms of a simple, universal law of gravity. Had Galileo still been alive, he would have surely been joyfully reconciled to ellipses.

The parallel is obvious. If a low-density universe with a cosmological constant seems ugly, maybe this shows our limited vision. Just as Earth follows one of the few Keplerian orbits around the sun that allow it to be habitable, our universe may be one of the few habitable members of a grander ensemble.

A Challenge for the New Millennium

As the 21st century dawns, scientists are expanding humanity's store of knowledge on three great frontiers: the very big, the very small and the very complex. Cosmology involves them all. In the coming years, researchers will focus their efforts on pinning down the basic universal constants, such as omega, and on discovering what dark matter is. I think there is a good chance of achieving both goals within 10 years. Maybe everything will fit the standard theoretical framework, and we will successfully determine not only the relative abundance of ordinary atoms and dark matter in the universe but also the cosmological constant and the primordial density fluctuations. If that happens, we will have taken the measure of our universe just as, over the past few centuries, we have learned the size and shape of Earth and our sun. On the other hand, our universe may turn out to be too complicated to fit into the standard framework. Some may describe the first outcome as optimistic; others may prefer to inhabit a more complicated and challenging universe!

In addition, theorists must elucidate the exotic physics of the very earliest moments of the universe. If they succeed, we will learn whether there are many universes and which features of our universe are mere contingencies rather than the necessary outcomes of the deepest laws. Our understanding will still have limits, however. Physicists may someday discover a unified theory that governs all of physical reality, but they will never be able to tell us what breathes fire into their equations and what actualizes them in a real cosmos.

Cosmology is not only a fundamental science; it is also the grandest of the environmental sciences. How did a hot amorphous fireball evolve, over 10 to 15 billion years, into our complex cosmos of galaxies, stars and planets? How did atoms assemble—here on Earth and perhaps on other worlds—into living beings intricate enough to ponder their own origins? These questions are a challenge for the new millennium. Answering them may well be an unending quest. SA

The Author

COURTESY OF MARTIN REES

MARTIN REES is Royal Society Research Professor at the University of Cambridge and holds the honorary title of Astronomer Royal. He was previously director of the Cambridge Institute of Astronomy and before that a professor at the University of Sussex. His research interests include black holes, galaxy formation and high-energy astrophysics. He also lectures and writes extensively for general audiences. His recent books are *Gravity's Fatal Attraction* (Scientific American Library, 1996, with Mitchell C. Begelman), *Before the Beginning* (Perseus Books, 1998) and *Just Six Numbers* (Basic Books, in press).

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Deciphering the Code of Life

by Francis S. Collins
and Karin G. Jegalian

The study of all the genes of various organisms will yield answers to some of the most intriguing questions about life

When historians look back at this turning of the millennium, they will note that the major scientific breakthrough of the era was the characterization in ultimate detail of the genetic instructions that shape a human being. The Human Genome Project—which aims to map every gene and spell out letter by letter the literal thread of life, DNA—will affect just about every branch of biology. The complete DNA sequencing of more and more organisms, including humans, will answer many important questions, such as how organisms evolved, whether synthetic life will ever be possible and how to treat a wide range of medical disorders.

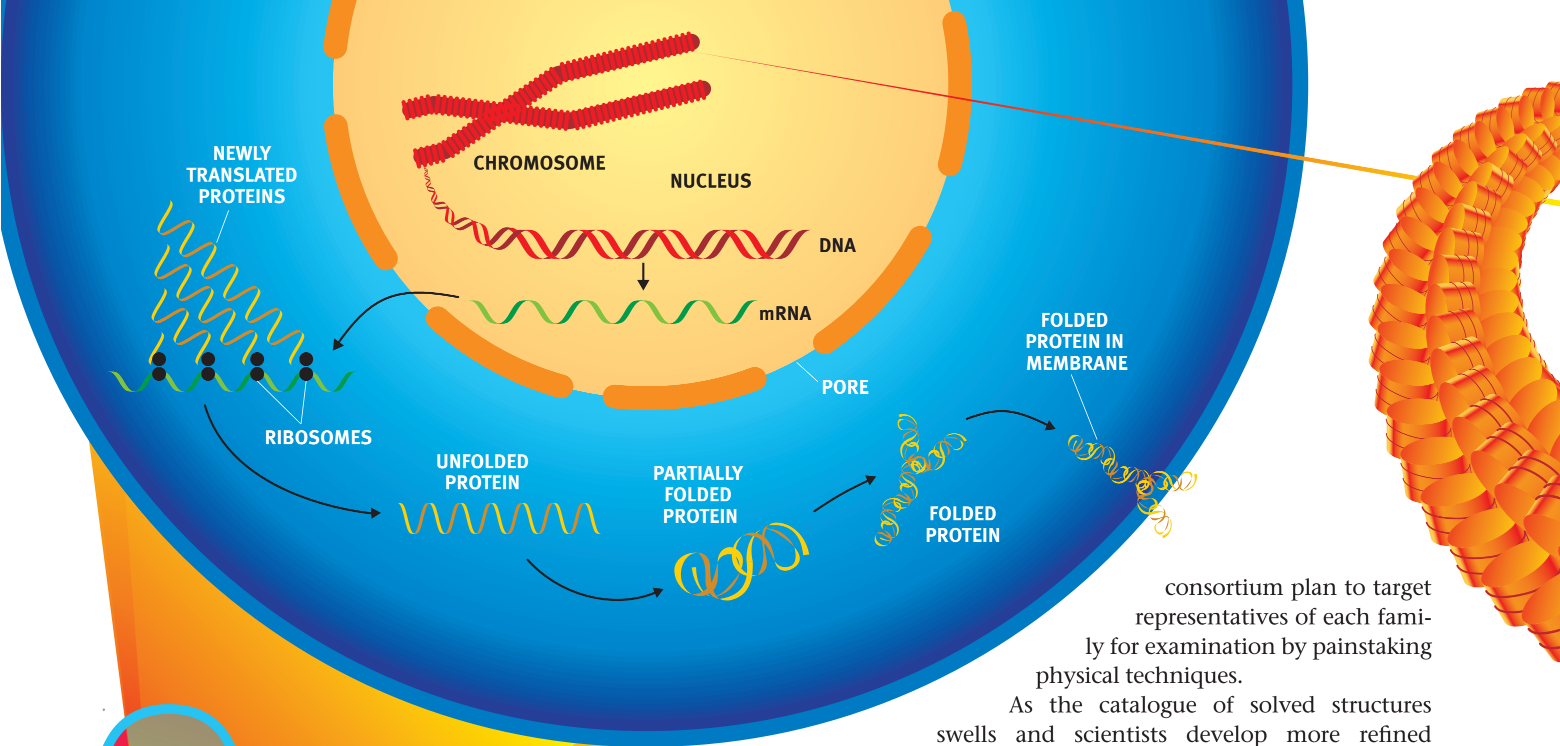
The Human Genome Project is generating an amount of data unprecedented in biology. A simple list of the units of DNA, called bases, that make up the human genome would fill 200 telephone books—even without annotations describing what those DNA sequences do. A working draft of 90 percent of the total human DNA sequence should be in hand by the spring of 2000, and the full sequence is expected in 2003. But that will be merely a skeleton that will require many layers of annotation to give it meaning. The payoff from the reference work will come from understanding the proteins encoded by the genes.

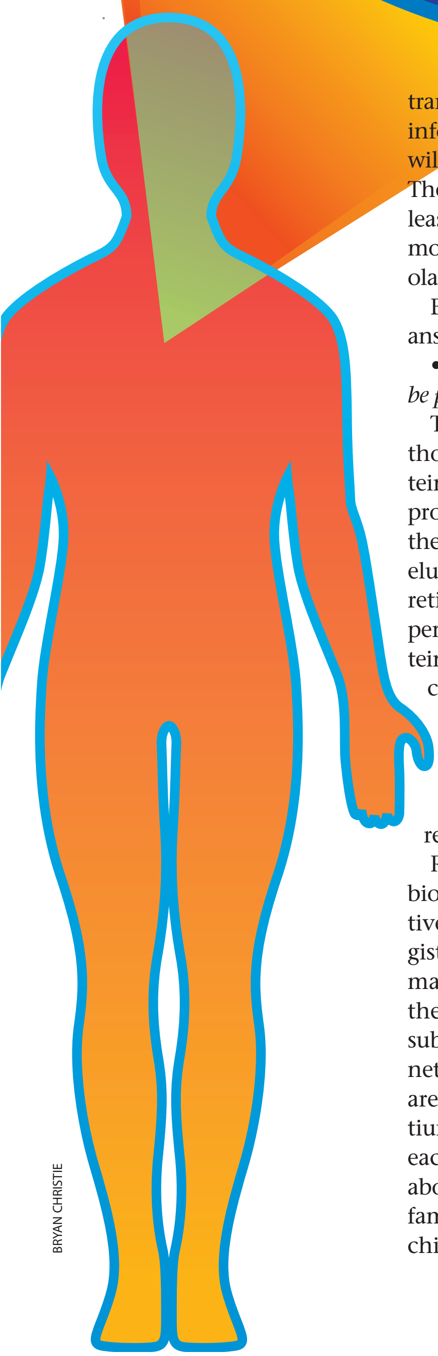
Proteins not only make up the structural bulk of the human body but also include the enzymes that carry out the biochemical reactions of life. They are composed of units called amino acids linked together in a long string; each string folds in a way that determines the function of a protein. The order of the amino acids is set by the DNA base sequence of the gene that encodes a given protein, through intermediaries called RNA; genes that actively make RNA are said to be "expressed."

EVERARD WILLIAMS, JR.

The Human Genome Project seeks not just to elucidate all the proteins produced within a human but also to comprehend how the genes that encode the proteins are expressed, how the DNA sequences of those genes stack up against comparable genes of other species, how genes vary within our species and how DNA sequences

Human genome contains all the biochemical instructions—in the form of combinations of the DNA bases *A, T, C* and *G*—for making and maintaining a human being.





BRYAN CHRISTIE

translate into observable characteristics. Layers of information built on top of the DNA sequence will reveal the knowledge embedded in the DNA. These data will fuel advances in biology for at least the next century. In a virtuous cycle, the more we learn, the more we will be able to extrapolate, hypothesize and understand.

By 2050 we believe that genomics will be able to answer the following major questions:

• *Will the three-dimensional structures of proteins be predictable from their amino acid sequences?*

The six billion bases of the human genome are thought to encode approximately 100,000 proteins. Although the sequence of amino acids in a protein can be translated in a simple step from the DNA sequence of a gene, we cannot currently elucidate the shape of a protein on purely theoretical grounds, and determining structures experimentally can be quite laborious. Still, a protein's structure is conserved—or maintained fairly constantly throughout evolution—much more than its amino acid sequence is. Many different amino acid sequences can lead to proteins of similar shapes, so we can infer the structures of various proteins by studying a representative subset of proteins in detail.

Recently an international group of structural biologists have begun a Protein Structure Initiative to coordinate their work. Structural biologists "solve" the shapes of proteins either by making very pure crystals of a given protein and then bombarding the crystals with x-rays or by subjecting a particular protein to nuclear magnetic resonance (NMR) analysis. Both techniques are time-consuming and expensive. The consortium intends to get the most information out of each new structure by using existing knowledge about related structures to group proteins into families that are most likely to share the same architectural features. Then the members of the consortium plan to target representatives of each family for examination by painstaking physical techniques.

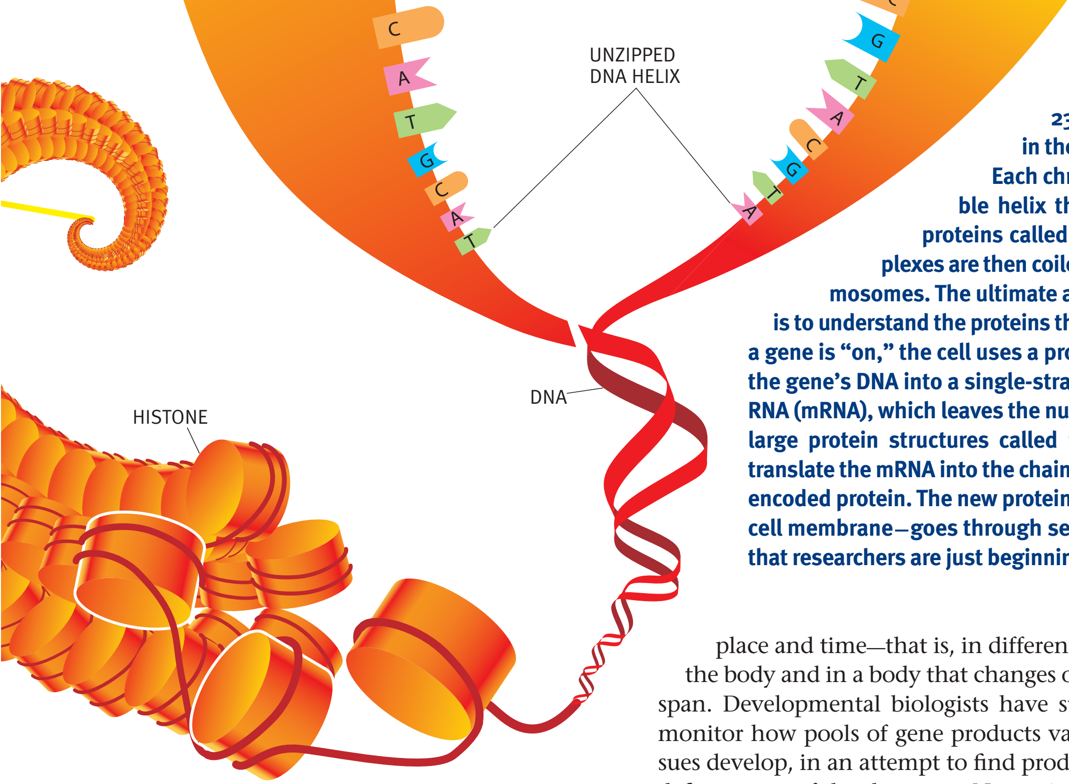
As the catalogue of solved structures swells and scientists develop more refined schemes for grouping structures into a compendium of basic shapes, biochemists will increasingly be able to use computers to model the structures of newly discovered—or even wholly invented—proteins. Structural biologists project that a total of about 1,000 basic protein-folding motifs exist; current models suggest that solving just 3,000 to 5,000 selected structures, beyond the ones already known, could allow researchers to deduce the structures of new proteins routinely. With structural biologists solving more than 1,000 protein structures every year and with their progress accelerating, they should be able to complete the inventory not long after the human genome itself is sequenced.

• *Will synthetic life-forms be produced?*

Whereas structural biologists work to group proteins into categories for the practical aim of solving structures efficiently, the fact that proteins are so amenable to classification reverberates with biological meaning. It reflects how life on the earth evolved and opens the door to questions central to understanding the phenomenon of life itself. Is there a set of proteins common to all organisms? What are the biochemical processes required for life?

Already, with several fully sequenced genomes available—mostly from bacteria—scientists have started to take inventories of genes conserved among these organisms, guided by the grand question of what constitutes life, at least at the level of a single cell.

If, within a few years, investigators can expect to amass a tidy directory of the gene products—RNA as well as proteins—required for life, they may well be able to make a new organism from scratch by stringing DNA bases together into an invented genome coding for invented products. If this invented genome crafts a cell around itself and the cell reproduces reliably, the exercise would prove that we had deciphered the basic



Human genome is contained in 23 pairs of chromosomes, which lie in the nucleus of every cell in the body. Each chromosome consists of a DNA double helix that is wrapped around spoollike proteins called histones. The DNA-histone complexes are then coiled and double-coiled to yield chromosomes. The ultimate aim of the Human Genome Project is to understand the proteins that are encoded by the DNA. When a gene is "on," the cell uses a process called transcription to copy the gene's DNA into a single-stranded molecule called messenger RNA (mRNA), which leaves the nucleus to associate with a series of large protein structures called ribosomes. The ribosomes then translate the mRNA into the chain of amino acids that makes up the encoded protein. The new protein—here a receptor destined for the cell membrane—goes through several folding steps in a sequence that researchers are just beginning to understand.

mechanisms of life. Such an experiment would also raise safety, ethical and theological issues that cannot be neglected.

• *Will we be able to build a computer model of a cell that contains all the components, identifies all the biochemical interactions and makes accurate predictions about the consequences of any stimulus given to that cell?*

In the past 50 years, a single gene or a single protein often dominated a biologist's research. In the next 50 years, researchers will shift to studying integrated functions among many genes, the web of interactions among gene pathways and how outside influences affect the system.

Of course, biologists have long endeavored to describe how components of a cell interact: how molecules called transcription factors bind to specific scraps of DNA to control gene expression, for example, or how insulin binds to its receptor on the surface of a muscle cell and triggers a cascade of reactions in the cell that ultimately boosts the number of glucose transporters in the cell membrane. But the genome project will spark similar analyses for thousands of genes and cell components at a time. Within the next half-century, with all genes identified and all possible cellular interactions and reactions charted, pharmacologists developing a drug or toxicologists trying to predict whether a substance is poisonous may well turn to computer models of cells to answer their questions.

• *Will the details of how genes determine mammalian development become clear?*

Being able to model a single cell will be impressive, but to understand fully the life-forms we are most familiar with, we will plainly have to consider additional levels of complexity. We will have to examine how genes and their products behave in place and time—that is, in different parts of the body and in a body that changes over a life span. Developmental biologists have started to monitor how pools of gene products vary as tissues develop, in an attempt to find products that define stages of development. Now scientists are devising so-called expression arrays that survey thousands of gene products at a time, charting which ones turn on or off and which ones fluctuate in intensity of expression. Techniques such as these highlight many good candidates for genes that direct development and establish the animal body plan.

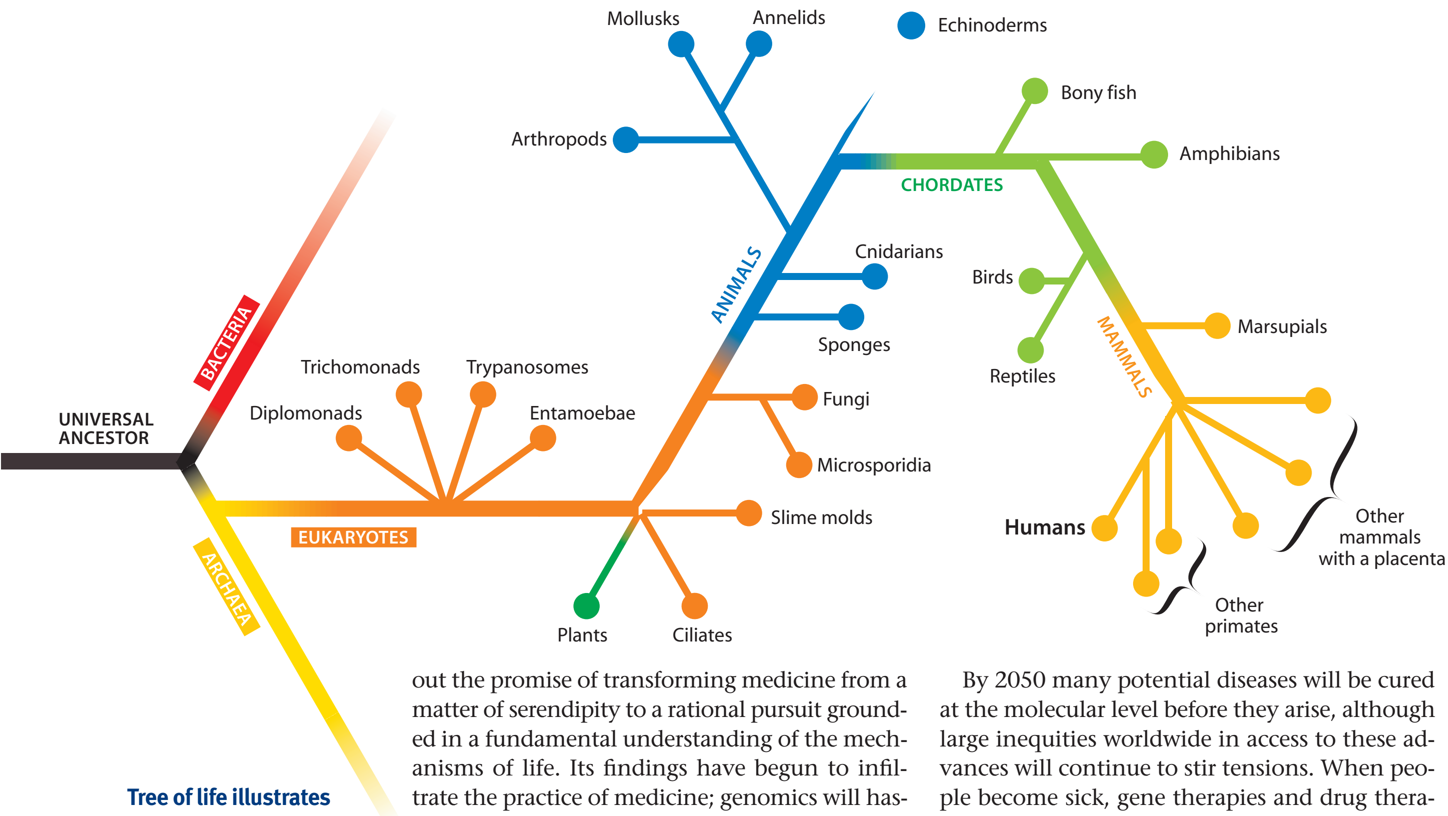
As in the past, model organisms—like the fruit fly *Drosophila,* the nematode *Caenorhabditis elegans* and the mouse—will remain the central workhorses in developmental biology. With the genome sequence of *C. elegans* finished, *Drosophila*'s near completion, the full human sequence on the way by 2003 and the mouse's likely within four to five years, sequence comparisons will become more commonplace and thorough and will give biologists many clues about where to look for the driving forces that fashion a whole animal. Many more complete genomes representing diverse branches of the evolutionary tree will be derived as the cost of sequencing decreases.

So far developmental biologists have striven to find signals that are universally important in establishing an animal's body plan, the arrangement of its limbs and organs. In time, they will also describe the variations—in gene sequence and perhaps in gene regulation—that generate the striking diversity of forms among different species. By comparing species, we will learn how genetic circuits have been modified to carry out distinct programs so that almost equivalent networks of genes fashion, for example, small furry legs in mice and arms with opposable digits in humans.

• *Will understanding the human genome transform preventive, diagnostic and therapeutic medicine?*

Molecular biology has long held

Researchers will shift to studying **the web of interactions among gene pathways** and how outside influences affect the system.



BRYAN CHRISTIE, WITH ASSISTANCE FROM JOHN LOGSDON *Dalhousie University*

Tree of life illustrates the current view of the relationships among all living things, including humans. Once the DNA sequence of the human genome is known, scientists will be able to compare the information to that produced by efforts to sequence the genomes of other species, yielding a fuller understanding of how life on the earth evolved.

out the promise of transforming medicine from a matter of serendipity to a rational pursuit grounded in a fundamental understanding of the mechanisms of life. Its findings have begun to infiltrate the practice of medicine; genomics will hasten the advance. Within 50 years, we expect comprehensive genomics-based health care to be the norm in the U.S. We will understand the molecular foundation of diseases, be able to prevent them in many cases, and design accurate, individual therapies for illnesses.

In the next decade, genetic tests will routinely predict individual susceptibility to disease. One intention of the Human Genome Project is to identify common genetic variations. Once a list of variants is compiled, epidemiological studies will tease out how particular variations correlate with risk for disease. When the genome is completely open to us, such studies will reveal the roles of genes that contribute weakly to diseases on their own but that also interact with other genes and environmental influences such as diet, infection and prenatal exposure to affect health. By 2010 to 2020 gene therapy should also become a common treatment, at least for a small set of conditions.

Within 20 years, novel drugs will be available that derive from a detailed molecular understanding of common illnesses such as diabetes and high blood pressure. The drugs will target molecules logically and therefore be potent without significant side effects. Drugs such as those for cancer will routinely be matched to a patient's likely response, as predicted by molecular fingerprinting. Diagnoses of many conditions will be much more thorough and specific than they are now. For example, a patient who learns that he has high cholesterol will also know which genes are responsible, what effect the high cholesterol is likely to have, and what diet and pharmacological measures will work best for him.

By 2050 many potential diseases will be cured at the molecular level before they arise, although large inequities worldwide in access to these advances will continue to stir tensions. When people become sick, gene therapies and drug therapies will home in on individual genes, as they exist in individual people, making for precise, customized treatment. The average life span will reach 90 to 95 years, and a detailed understanding of human aging genes will spur efforts to expand the maximum length of human life.

• *Will we reconstruct accurately the history of human populations?*

Despite what may seem like great diversity in our species, studies from the past decade show that the human species is more homogeneous than many others; as a group, we display less variation than chimps do. Among humans, the same genetic variations tend to be found across all population groups, and only a small fraction of the total variation (between 10 and 15 percent) can be related to differences between groups. This has led some population biologists to the conclusion that not so long ago the human species was composed of a small group, perhaps 10,000 individuals, and that human populations dispersed over the earth only recently. Most genetic variation predated that time.

Armed with techniques for analyzing DNA, population geneticists have for the past 20 years been able to address anthropological questions with unprecedented clarity. Demographic events such as migrations, population bottlenecks and expansions alter gene frequencies, leaving a detailed and comprehensive record of events in human history. Genetic data have bolstered the view that modern humans originated relatively recently, perhaps 100,000 to 200,000 years ago, in Africa and dispersed gradually into the rest of the world. Anthropologists have used DNA data to test cultural traditions about the origins of groups such as Gypsies and Jews, to track the migration of humans into the South Pacific islands and the Americas, and to glean insights into the spread of populations in Europe, among other examples. As DNA sequence data become increasingly easy to accumulate, relationships among groups of people will become clearer, revealing histories of intermingling as well as periods of separation and migration. Race and ethnicity will prove to be largely social and cultural ideas; sharp, scientifically based boundaries between groups will be found to be nonexistent.

By 2050, then, we will know much more than we do now about human populations, but a question remains: How much can be known? Human beings have mated with enough abandon that probably no one family tree will be the unique solution accounting for all human history. In fact, the history of human populations will emerge not as a tree but as a trellis where lineages often meet and mingle after intervals of separation. Still, in 50 years, we will know how much ambiguity remains in our reconstructed history.

• *Will we be able to reconstruct the major steps in the evolution of life on the earth?*

Molecular sequences have been indispensable tools for drawing taxonomies since the 1960s. To a large extent, DNA sequence data have already exposed the record of 3.5 billion years of evolution, sorting living things into three domains—Archaea (single-celled organisms of ancient origin), Bacteria and Eukarya (organisms whose cells have a nucleus)—and revealing the branching patterns of hundreds of kingdoms and divisions. One aspect of inheritance has complicated the hope of assigning all living things to branches in a single tree of life. In many cases, different genes suggest different family histories for the same organisms; this reflects the fact that DNA isn't always inherited in the straightforward way, parent to offspring, with a more or less predictable rate of mutation marking the passage of time. Genes sometimes hop across large evolutionary gaps. Examples of this are mitochondria and chloroplasts, the energy-producing organelles of animals and plants, both of which contain their own genetic material and descended from bacteria that were evidently swallowed whole by eukaryotic cells.

This kind of "lateral gene transfer" appears to have been common enough in the history of life, so that comparing genes among species will not yield a single, universal family tree. As with human lineages, a more apt analogy for the history of life will be a net or a trellis, where separated lines diverge and join again, rather than a tree, where branches never merge.

In 50 years, we will fill in many details about the history of life, although we might not fully understand how the first self-replicating organism came about. We will learn when and how, for instance, various lineages invented, adopted or adapted genes to acquire new sets of biochemical reactions or different body plans. The gene-based perspective of life will have taken hold so deeply among scientists that the basic unit they consider will very likely no longer be an organism or a species but a gene. They will chart which genes have traveled together for how long in which genomes. Scientists will also address the question that has dogged people since Charles Darwin's day: What makes us human? What distinguishes us as a species?

Undoubtedly, many other questions will arise over the next 50 years as well. As in any fertile scientific field, the data will fuel new hypotheses. Paradoxically, as it grows in importance, genomics itself may not even be a common concept in 50 years, as it radiates into many other fields and ultimately becomes absorbed as part of the infrastructure of all biomedicine.

• *How will individuals, families and society respond to this explosion in knowledge about our genetic heritage?*

This social question, unlike the preceding scientific, technological and medical ones, does not come down to a yes-or-no answer. Genetic information and technology will afford great opportunities to improve health and to alleviate suffering. But any powerful technology comes with risks, and the more powerful the technology, the greater the risks. In the case of genetics, people of ill will today use genetic arguments to try to justify bigoted views about different racial and ethnic groups. As technology to analyze DNA has become increasingly widespread, insurers and employers have used the information to deny workers access to health care and jobs. How we will come to terms with the explosion of genetic information remains an open question.

Finally, will antitechnology movements be quieted by all the revelations of genetic science? Although we have enumerated so many questions to which we argue the answer will be yes, this is one where the answer will probably be no. The tension between scientific advances and the desire to return to a simple and more "natural" lifestyle will probably intensify as genomics seeps into more and more of our daily lives. The challenge will be to maintain a healthy balance and to shoulder collectively the responsibility for ensuring that the advances arising from genomics are not put to ill use. SA

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FRANCIS S. COLLINS has been the director of the National Institutes of Health's National Human Genome Research Institute (NHGRI) since 1993. Before that, he was a research geneticist at the University of Michigan, where he and his colleagues were the first to clone the gene for cystic fibrosis. A practicing Christian, Collins is particularly interested in the ethical implications of human genetics research.

COURTESY OF KARIN G. JEGALIAN

KARIN G. JEGALIAN, who received her Ph.D. in biology from the Massachusetts Institute of Technology in 1998, is now a science writer at the NHGRI.

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The End of Nature versus Nurture

by Frans B. M. de Waal

THOMAS WANSTALL *The Image Works*

Twins reared apart have been studied for clues about the relative contributions of genes and environment to human behavior. These brothers rediscovered each other later in life when both were mustachioed firefighters.

Is human behavior determined by genetics or by environment? It may be time to abandon the dichotomy

The defenders of nature and nurture have been at each other's throats for as long as I can remember. Whereas biologists have always believed that genes have something to do with human behavior, social scientists have flocked en masse to the opposite position: that we are fully and entirely our own creation, free from the chains of biology.

I felt the heat of this debate in the 1970s whenever, in lectures for general audiences, I mentioned sex differences in chimpanzees, such as that males are more aggressive and more ambitious than females. There

CORBIS

SOVFOTO/EASTFOTO

Danger comes from extremes of both positions—the biological determinism of the Nazis and the social engineering of the Communists.

would be howls of protest. Wasn't I projecting my own values onto these poor animals? How rigorous were my methods? Why did I even bother to compare the sexes? Did I perhaps have a hidden agenda?

Nowadays the same sort of information makes people yawn! Even direct comparisons between human and ape behavior, something that used to be taboo, fail to get anyone excited. Everyone has heard that men are from Mars and women from Venus. Everyone has seen, in *Time* and *Newsweek,* PET scans of the human brain engaged in various tasks, with different areas lighting up in male and female brains.

This time, however, it is my turn to be troubled. Instead of celebrating the victory of the biological approach, I regard some of the contemporary dichotomies between men and women as gross simplifications rendered politically correct by a fashionable amount of male-bashing (for example, when normal hormonal effects are referred to as "testosterone poisoning"). We remain as far removed as ever from a sophisticated understanding of the interplay between genes and environment. Society has let the pendulum swing wildly back from nurture to nature, leaving behind a number of bewildered social scientists. Yet we still love to phrase everything in terms of one influence or the other, rather than both.

It is impossible to explore where we may be heading 50 years from now without looking back an equal number of years at the charged history of the nature/nurture controversy. The debate is so emotional because any stance one takes comes with serious political implications. Positions have ranged from an unfounded faith in human flexibility by reformists to an obsession with blood and race by conservatives. Each in their own way, these positions have caused incalculable human suffering in the past century.

Learning and Instinct

Fifty years ago the two dominant schools of thought about animal and human behavior had opposite outlooks. Teaching animals arbitrary actions such as lever-pressing, American behaviorists came to view all behavior as the product of trial-and-error learning. This process was considered so universal that differences among species were irrelevant: learning applied to all animals, including humans. As B. F. Skinner, the founder of behaviorism, bluntly put it: "Pigeon, rat, monkey, which is which? It doesn't matter."

In contrast, the ethological school in Europe focused on naturalistic behavior. Each animal species is born with a number of so-called fixed-action patterns that undergo little modification by the environment. These and other species-specific behaviors represent evolutionary adaptations. Thus, no one needs to teach humans how to laugh or cry: these are innate signals, universally used and understood. Similarly, the spider does not need to learn how to construct a web. She is born with a battery of spinnerets (spinning tubes connected to silk glands) as well as a behavioral program that "instructs" her how to weave threads together.

Because of their simplicity, both views of behavior had enormous appeal. And although both paid homage to evolution, they sometimes did so in a superficial, arm-waving sort of way. Behaviorists stressed the continuities between humans and other animals, attributing these to evolution. But because for them behavior was learned rather than inborn,they ignored the genetic side, which is really what evolution is all about. While it is true that evolution implies continuity, it also implies diversity: each animal is adapted to a specific way of life in a specific environment. As is evident from Skinner's statement, this point was blithely ignored.

Similarly, some ethologists had rather vague evolutionary notions, emphasizing phylogenetic descent rather than the processes of natural selection. They saw behavioral traits, such as the inhibition of aggression, as good for the species. The argument was that if animals were to kill one another in fights, the species would not survive. This may be true, but animals have perfectly selfish reasons to avoid the escalation of fights that may harm themselves and their relationships. Hence, these ideas have now been replaced by theories about how traits benefit the actor and its kin; effects on the species as a whole are considered a mere by-product.

Behaviorism started losing its grip with the discovery that learning is not the same for all situations and all species. For example, a rat normally links actions with effects only if the two immediately follow each other. So it would be very slow to learn to press a bar if a reward followed minutes later. When it comes to food that makes it sick, however, a delay of hours between consumption and the negative sensation still induces future food aversion. Apparently, animals are specialized learners, being best at those contingencies that are most important for survival.

At the same time that behaviorists were forced to adopt the premises of evolutionary biology and to consider the world outside the laboratory, ethologists and ecologists were laying the groundwork for the neo-Darwinian revolution of the 1970s. The pioneer here was Dutch ethologist Nikolaas Tinbergen, who conducted ingenious field experiments on the survival value of animal behavior. He understood, for instance, why many birds remove eggshells from the nest after the chicks have hatched. Because the outside of a shell is colored for camouflage but the inside is not, predators such as crows easily locate eggs if broken shells are placed next to them. Throwing out the pieces is an automatic response favored by natural selection because the birds that practice this behavior have more surviving offspring.

Others developed theories to explain behavior that at first sight does not seem to help the actor but someone else. Such "altruism" can be seen in ant soldiers giving their lives in defense of their colony or in dolphins lifting a drowning companion to the surface. Biologists assumed that natural selection will allow for assistance among relatives as a means of promoting the same genes. Or, if two animals are unrelated, the favor granted by one must be returned at some future time.

The scientists felt so confident about their explanations of cooperative animal societies that they could not resist extending these ideas to our own species. They saw the hugely cooperative enterprise of human society as based on the same premise of family values and economic tit-for-tat.

It fell to an American expert on ants, Edward O. Wilson, to deliver the news in 1975 that a great deal of human behavior was ripe for the Darwinian perspective and that the social sciences should prepare themselves to work together with biologists on this endeavor. Thus far the two disciplines had led separate lives, but from the perspective of a biologist social science is not much more than the study of animal behavior focused on a single species: ours. Because this is not how social scientists see their work, proposals for a united framework were not kindly received. One of Wilson's outraged opponents even poured cold water over Wilson's head after he gave a lecture. For reasons explained below, his new synthesis, dubbed "sociobiology," was equated with race policies of the past and ultimately with the Holocaust.

Although the criticism was patently unfair—Wilson was offering evolutionary explanations, not policy suggestions—we shouldn't be surprised that the topic of human biology arouses strong emotions.

Burdens of the Past

It is generally believed that some human behavior can easily be changed because it is learned, whereas other behavior resists modification because it is part of our biological heritage.

Ideologues of all colors have grasped this division to argue for the innate nature of certain human characteristics (for example, purported race differences in intelligence) and the plasticity of others (such as the ability to overcome gender stereotypes). Thus, Communism was founded on great confidence in human malleability. Because people, unlike social insects, resist submerging individuality for the greater good, some regimes accompanied their revolutions with massive indoctrination efforts. All of this proved in vain, however. Communism went under because of an economic incentive structure that was out of touch with human nature. Unfortunately, it did so only after having caused great misery and death.

Even more disastrous was the embrace of biology by Nazi Germany. Here, too, the collective (*das Volk*) was placed above the individual, but instead of relying on social engineering the method of choice was genetic manipulation. People were classified into "superior" and "inferior" types, the first of which needed to be protected against contamination by the second. In the horrible medical language of the Nazis, a healthy *Volk* required the cutting out of all "cancerous" elements. This idea was followed to its extreme in a manner that Western civilization has vowed never to forget.

Don't think that the underlying selectionist ideology was restricted to this particular time and place, however. In the early part of the 20th century, the eugenics movement—which sought to improve humanity by "breeding from the fitter stocks"—enjoyed widespread appeal among intellectuals in both the U.S. and Great Britain. Based on ideas going back to Plato's *Republic,* sterilization of the mentally handicapped and of criminals was considered perfectly acceptable. And social Darwinism—the idea that in a laissez-faire capitalist economy the strong will outcompete the weak, resulting in general improvement of the population—still inspires political agendas today. In this view, the poor should not be aided in their struggle for existence so as not to upset the natural order.

FRANS LANTING *Minden Pictures*

Our closest animal relatives—such as this bonobo family—share many human behaviors. Television nature programs have brought home to the general public the lesson of biology's influence on behavior.

Given these ideologies, it is understandable why suppressed categories of people, such as minorities and women, fail to see biology as a friend. I would argue, however, that the danger comes from both directions, from biological determinism as well as its opposite, the denial of basic human needs and the belief that we can be everything we want to be. The hippie communes of the 1960s, the Israeli kibbutzim and the feminist revolution all sought to redefine humans. But denial of sexual jealousy, the parent-child bond or gender differences can be carried only so far before a countermovement will seek to balance cultural trends with evolved human inclinations.

What makes the present era different is that the genocide of World War II is fading into memory while at the same time the evidence for a connection between genes and behavior is mounting. Studies of twins reared apart have reached the status of common knowledge, and almost every week newspapers report a new human gene. There is evidence for genes involved in schizophrenia, epilepsy and Alzheimer's and even in common behavioral traits such as thrill-seeking. We are also learning more about genetic and neurological differences between men and women, as well as between gay and straight men. For example, a small region of the brain in transsexual men (who dress and behave like women) resembles the same region in women's brains.

The list of such scientific advances is getting longer by the day, resulting in a critical mass of evidence that is impossible to ignore. Understandably, academics who have spent their life condemning the idea that biology influences human behavior are reluctant to change course. But they are being overtaken by the general public, which seems to have accepted that genes are involved in just about everything we do and are. Concurrently resistance to comparisons with other animals has dissipated because of a stream of television nature programs that has brought exotic wildlife into our homes while showing animals to be quite a bit smarter and more interesting than people used to believe.

Studies of chimpanzees and bonobos, such as those by Jane Goodall and myself, show that countless human practices and potentials, from politics and child-rearing to violence and even morality, have parallels in the lives of our closest animal relatives. How can we maintain the dualisms of the past—between humans and animals and between body and mind—in the face of all this evidence to the contrary? Current knowledge about our biological background simply doesn't permit a return to the tabula rasa views of the past.

This doesn't solve the problem of ideological abuse, however. If anything, it makes things worse. So long as people have political agendas, they will depict human nature one way or another for their own purposes. Conservatives like to point out that people are naturally selfish, whereas liberals argue that we have evolved to be social and cooperative. The obvious correctness of both inferences goes to show what is wrong with simple-minded genetic determinism.

The Best of Both Worlds

Because genetic language ("a gene for x") plays into our sound-bite culture, there is all the more reason to educate the public that genes, by themselves, are like seeds dropped onto the pavement: powerless to produce anything. When scientists say that a trait is inherited, all they mean is that part of its variability is explained by genetic factors. That the environment usually explains at least as much tends to be forgotten.

As Hans Kummer, a Swiss primatologist, remarked years ago, to try to determine how much of a trait is produced by genes and how much by the environment is as useless as asking whether the drumming that we hear in the distance is made by the percussionist or by his instrument. On the other hand, if we pick up distinct sounds on different occasions, we can legitimately ask whether the variation is caused by different drummers or by different drums. This is the only sort of question science addresses when it looks into genetic versus environmental effects.

I foresee a continued mapping of the links between genes and behavior, a much more precise knowledge of how the brain works and a gradual adoption of the evolutionary paradigm in the social sciences. Charles Darwin's portrait will finally decorate the walls of departments of psychology and sociology! But one would hope that all of this will be accompanied by continued assessment of the ethical and political implications of behavioral science.

Traditionally, scientists have acted as if it is none of their business how the information they produce is being used. During some periods they have even actively assisted in political abuse. One notable exception was, of course, Albert Einstein, who may serve as a model of the kind of moral awareness needed in the behavioral and social sciences. If history teaches us anything, it is that it is critical that we remain on the alert against misinterpretations and simplifications. No one is in a better position than the scientists themselves to warn against distortions and to explain the complexities.

In which direction the thinking may develop can perhaps be illustrated with an example from the crossroads between cultural and evolutionary anthropology. Sigmund Freud and many traditional anthropologists, such as Claude Lévi-Strauss, have assumed that the human incest taboo serves to suppress sexual urges between family members. Freud believed that "the earliest sexual excitations of youthful human beings are invariably of an incestuous character." Hence, the incest taboo was seen as the ultimate victory of culture over nature.

In contrast, Edward Westermarck, a Finnish sociologist who lived at about the same time as Freud, hypothesized that early familiarity (such as between mother and child and between siblings) kills sexual desire. Little or no sexual attraction is found, he argued, between individuals who have grown up together. A fervent Darwinian, Westermarck proposed this as an evolved mechanism designed to prevent the deleterious consequences of inbreeding.

In the largest-scale study on this issue to date, Arthur P. Wolf, an anthropologist at Stanford University, examined the marital histories of 14,400 women in a "natural experiment" carried out in Taiwan. Families in this region used to adopt and raise future daughters-in-law, which meant that intended marriage partners grew up together from early childhood. Wolf compared these marriages with those arranged between men and women who did not meet until the wedding day. Using divorce and fertility rates as gauges of marital happiness and sexual activity, respectively, the data strongly supported the Westermarck effect: association in the first years of life appeared to compromise adult marital compatibility. Nonhuman primates are subject to the same mechanism. Many primates prevent inbreeding through migration of one sex or the other at puberty. The migratory sex meets new, unrelated mates, whereas the resident sex gains genetic diversity from the outside. But close kin who stay together also generally avoid sexual intercourse.

Kisaburo Tokuda first observed this in a group of Japanese macaques at the Kyoto zoo in the 1950s. A young adult male that had risen to the top rank made full use of his sexual privileges, mating frequently with all the females except for one: his mother. This was not an isolated case: mother-son matings are strongly suppressed in all primates. Even in bonobos—probably the most sexually active primates on the earth—this is the one partner combination in which sex is extremely rare or absent. Incest avoidance has now been convincingly demonstrated in a host of primates, and the mediating mechanism is thought to be early familiarity.

The Westermarck effect serves as a showcase for Darwinian approaches to human behavior because it so clearly rests on a combination of nature and nurture. The framework includes a developmental component (learned sexual aversion), an innate component (the effect of early familiarity), a cultural component (some cultures raise unrelated children together, others raise siblings of the opposite sex apart, but most have family arrangements that automatically lead to sexual inhibitions among relatives), a sound evolutionary reason (suppression of inbreeding) and direct parallels with animal behavior. On top of this comes the cultural taboo, which is unique to our species. An intriguing question is whether the incest taboo merely serves to formalize and strengthen the Westermarck effect or whether it adds a substantially new dimension.

The unexpected richness of a research program that integrates developmental, genetic, evolutionary and cultural approaches to a well-circumscribed phenomenon demonstrates the power of breaking down old barriers between disciplines. Most likely what will happen in the next millennium is that evolutionary approaches to human behavior will become more and more sophisticated by explicitly taking cultural flexibility into account. Hence, the traditional either/or approach to learning and instinct will be replaced by a more integrated perspective. In the meantime, students of animal behavior will become more interested in environmental effects on behavior and especially—in animals such as primates and marine mammals—the possibility of cultural transmission of information and habits. For example, some chimpanzee communities use stones to crack nuts in the forest, whereas other communities have the same nuts and stones available but don't do anything with them. Such differences are unexplained by genetic variation.

These two developments together will weaken the dichotomies popular today to the point of eliminating them. Rather than looking at culture as the antithesis of nature, we will be gaining a much more profound understanding of human behavior by silently carrying the old nature/nurture debate to its grave. SA

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CATHERINE MARIN

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The Human Impact on Climate

by Thomas R. Karl and
Kevin E. Trenberth

How much of a disruption do we cause? The much-awaited answer could be ours by 2050, but only if nations of the world commit to long-term climate monitoring now

The balance of evidence suggests a discernible human influence on global climate." With these carefully chosen words, the Intergovernmental Panel on Climate Change (jointly supported by the World Meteorological Organization and the United Nations Environmental Program) recognized in 1995 that human beings are far from inconsequential when it comes to the health of the planet. What the panel did not spell out—and what scientists and politicians dispute fiercely—is exactly when, where and how much that influence has and will be felt.

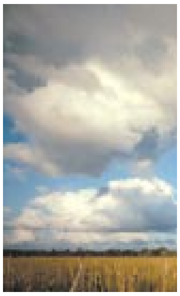
So far the climate changes thought to relate to human endeavors have been relatively modest. But various projections suggest that the degree of change will become dramatic by the middle of the 21st century, exceeding anything seen in nature during the past 10,000 years. Although some regions may benefit for a time, overall the alterations are expected to be disruptive or even severe. If researchers could clarify the extent to which specific activities influence climate, they would be in a much better position to suggest strategies for ameliorating the worst disturbances. Is such quantification possible? We think it is and that it can be achieved by the year 2050—but only if that goal remains an international priority.

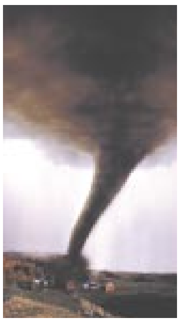
Despite uncertainties about details of climate change, our activities clearly affect the atmosphere in several troubling ways. Burning of fossil fuels in power plants and automobiles ejects particles and gases that alter the composition of the atmosphere. Visible pollution from sulfur-rich fuels includes micron-size particles called aerosols, which often cast a milky haze in the sky.

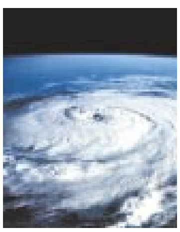
CORBIS/AFP

A New York City pedestrian fights heavy rains from Hurricane Floyd, which hit the area this past September. Downpours associated with tropical storms are just one type of severe weather that worsens with global warming.

These aerosols temporarily cool the atmosphere because they reflect some of the sun's rays back to space, but they stay in the air for only a few days before rain sweeps them to the planet's surface.







Climate simulation and prediction will come of age only with an **ongoing record of changes** as they happen.

Certain invisible gases deliver a more lasting impact. Carbon dioxide remains in the atmosphere for a century or more. Worse yet, such greenhouse gases trap some of the solar radiation that the planet would otherwise radiate back to space, creating a "blanket" that insulates and warms the lower atmosphere.

Indisputably, fossil-fuel emissions alone have increased carbon dioxide concentrations in the atmosphere by about 30 percent since the start of the Industrial Revolution in the late 1700s. Oceans and plants help to offset this flux by scrubbing some of the gas out of the air over time, yet carbon dioxide concentrations continue to grow. The inevitable result of pumping the sky full of greenhouse gases is global warming. Indeed, most scientists agree that the earth's mean temperature has risen at least 0.6 degree Celsius (more than one degree Fahrenheit) over the past 120 years, much of it caused by the burning of fossil fuels.

The global warming that results from the greenhouse effect dries the planet by evaporating moisture from oceans, soils and plants. Additional moisture in the atmosphere provides a swollen reservoir of water that is tapped by all precipitating weather systems, be they tropical storms, thundershowers, snowstorms or frontal systems. This enhanced water cycle brings on more severe droughts in dry areas and leads to strikingly heavy rain or snowfall in wet regions, which heightens the risk of flooding. Such weather patterns have burdened many parts of the world in recent decades.

Human activities aside from burning fossil fuels can also wreak havoc on the climate system. For instance, the conversion of forests to farmland eliminates trees that would otherwise absorb carbon from the atmosphere and reduce the greenhouse effect. Fewer trees also mean greater rainfall runoff, thereby increasing the risk of floods.

It is one thing to have a sense of the factors that can bring about climate change. It is another to know how the human activity in any given place will affect the local and global climate. To achieve that aim, those of us who are concerned about the human influence on climate will have to be able to construct more accurate climate models than have ever been designed before. We will therefore require the technological muscle of supercomputers a million times faster than those in use today. We will also have to continue to disentangle the myriad interactions among the oceans, atmosphere and biosphere to know exactly what variables to feed into the computer models.

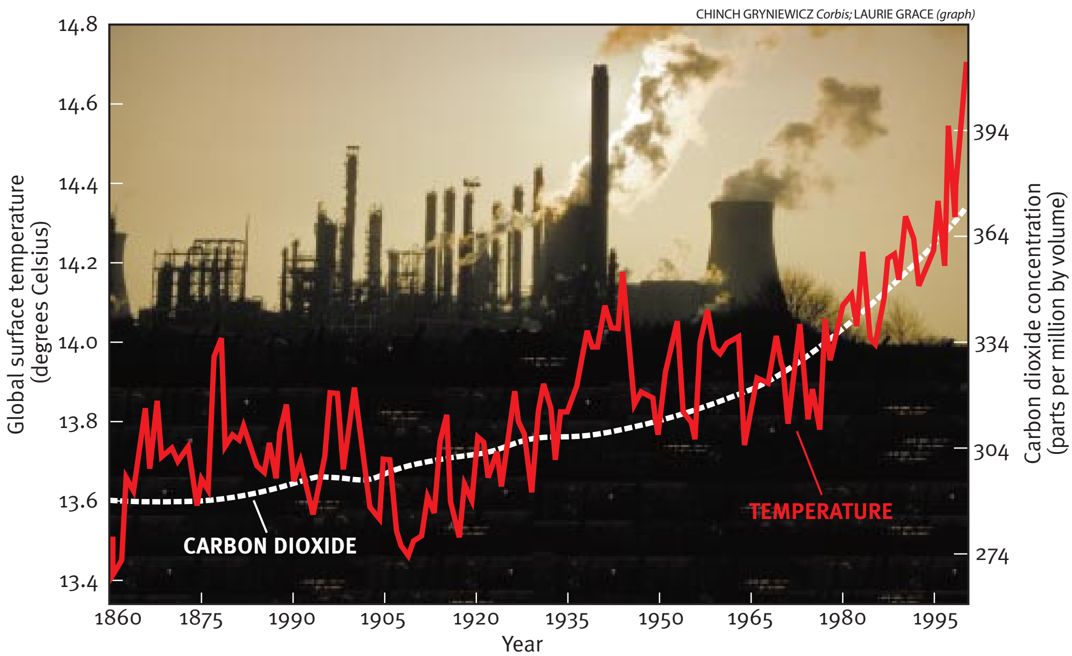
Most important, we must be able to demonstrate that our models accurately simulate past and present climate change before we can rely on models to predict the future. To do that, we need long-term records. Climate simulation and prediction will come of age only with an ongoing record of changes as they happen.

Computers and Climate Interactions

For scientists who model climate patterns, everything from the waxing and waning of ice ages to the desertification of central Africa plays out inside the models run on supercomputers. Interactions among the components of the climate system—the atmosphere, oceans, land, sea ice, freshwater and biosphere—behave according to

CORBIS (*hurricane*); JIM ZUCKERMAN *Corbis* (*tornado*); DAVID MUENCH *Corbis* (*clouds*); ROBERT PICKETT *Corbis* (*snowflake*)

CHINCH GRYNIEWICZ *Corbis*; LAURIE GRACE (*graph*)



Burning fossil fuels (*photograph*) has increased atmospheric concentrations of carbon dioxide (*white dashes*) and has contributed to a rise in global surface temperatures during the past 140 years (*red line*).

physical laws represented by dozens of mathematical equations. Modelers instruct the computers to solve these equations for each box in a three-dimensional grid that covers the globe. Because nature is not constrained by boxes, the chore is not only to incorporate the correct mathematics within each box but also to describe appropriately the transfer of energy and mass into and out of the boxes.

The computers at the world's preeminent climate-modeling facilities can perform between 10 and 50 billion operations per second, but with so many evolving variables, the simulation of a single century can take months. The time it takes to run a simulation, then, limits the resolution (or number of boxes) that can be included within climate models. For typical models designed to mimic the detailed evolution of weather systems, boxes in the three-dimensional grid measure about 250 kilometers (156 miles) square in the horizontal direction and one kilometer in the vertical. Tracking patterns within smaller areas thus proves especially difficult.

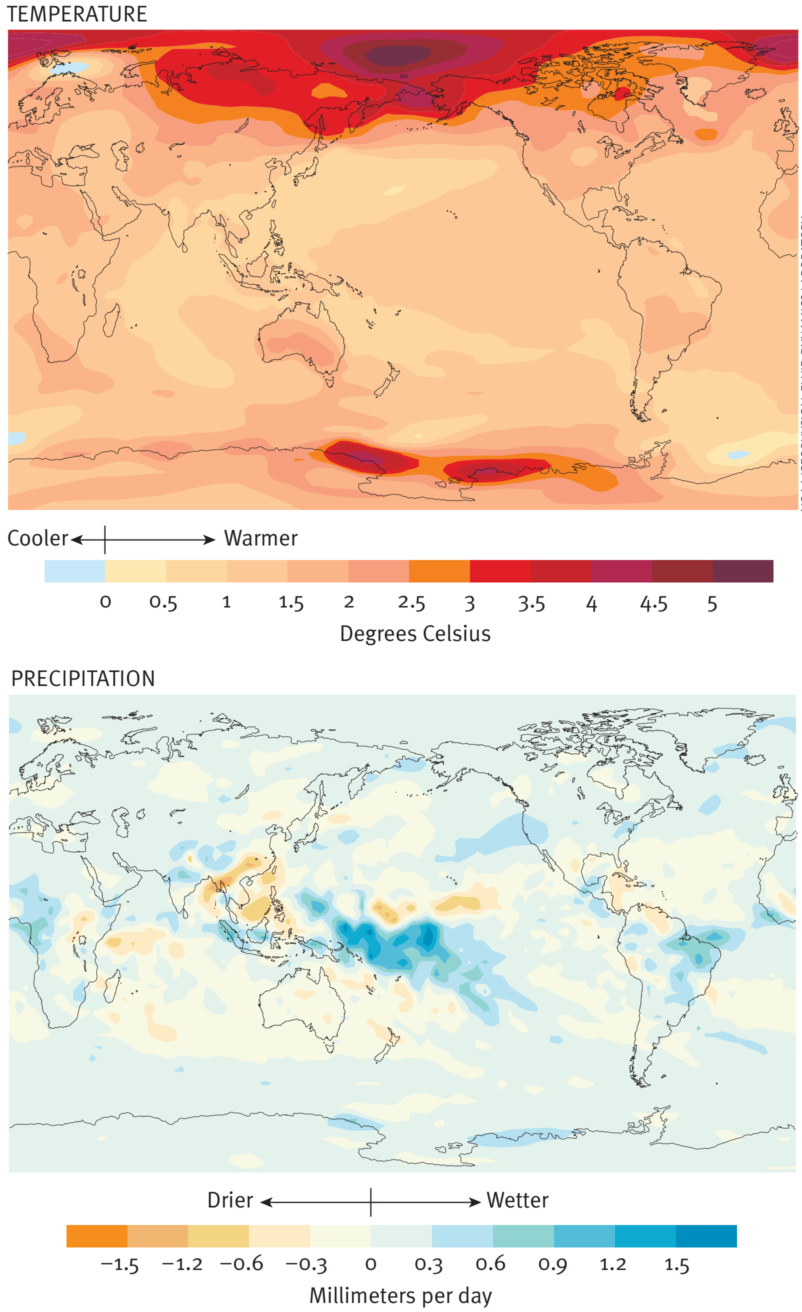
Even the most sophisticated of our current global models cannot directly simulate conditions such as cloud cover and the formation of rain. Powerful thunderstorm clouds that can unleash sudden downpours often operate on scales of less than 10 kilometers, and raindrops condense at submillimeter scales. Because each of these events happens in a region smaller than the volume of the smallest grid unit, their characteristics must be inferred by elaborate statistical techniques.

Such small-scale weather phenomena develop randomly. The frequency of these random events can differ extensively from place to place, but most agents that alter climate, such as rising levels of greenhouse gases, affect all areas of the planet much more uniformly. The variability of weather will increasingly mask large-scale climate activity as smaller regions are considered. Lifting that mask thus drains computer time, because it requires running several simulations, each with slightly different starting conditions. The climate features that occur in every simulation constitute the climate "signal," whereas those that are not reproducible are considered weather-related climate "noise."

Conservative estimates indicate that computer-processing speed will have increased by well over a million times by 2050. With that computational power, climate modelers could perform many simulations with different starting conditions and better distinguish climate signals from climate noise. We could also routinely run longer simulations of hundreds of years with less than one-kilometer horizontal resolution and an average of 100-meter vertical resolution over the oceans and atmosphere.

Faster computers help to predict climate change only if the mathematical equations fed into them perfectly describe what happens in nature. For example, if a model atmosphere is simulated to be too cold by four degrees C (not uncommon a decade ago), the simulation will indicate that the atmosphere can hold about 20 percent less water than its actual capacity—a significant error that renders meaningless any subsequent estimates of evaporation and precipitation. Another problem is that we do not yet know how to replicate adequately all the processes that influence climate, such as hiccups in the carbon cycle and modifications in land use. What is more, these changes can initiate feedback cycles that, if ignored, can lead the model astray. Raising temperature, for example, sometimes enhances another variable, such as moisture content of the atmosphere, which in turn amplifies the original perturbation. (In this case, more moisture in the air causes in-

CLIMATE CHANGE BY 2050



NOAA/GEOPHYSICAL FLUID DYNAMICS LABORATORY

Global warming of up to five degrees Celsius (*top*) could enhance precipitation (*bottom*) in much of the world by the middle of the 21st century. These simulations use 1992 estimates by the Intergovernmental Panel on Climate Change for emissions of greenhouse gases and sulfate aerosols between the years 2000 and 2050.

NEIL RABINOWITZ *Corbis*

Deforestation changes climate in more than one way: Cutting down trees makes the forest less able to scrub carbon dioxide out of the air. Dark-colored forests also absorb more solar energy and keep the region warmer and more moist than do the light-colored areas left when the trees are gone.

creased warming because water vapor is a powerful greenhouse gas.)

Researchers are only beginning to realize how much some of these positive feedbacks influence the planet's life-giving carbon cycle. The 1991 eruption of Mount Pinatubo in the Philippines, for instance, belched out enough ash and sulfur dioxide to cause a temporary global cooling as those compounds interacted with water droplets in the air to block some of the sun's incoming radiation. This depleted energy can inhibit carbon dioxide uptake in plants.

Using land in a different way can perturb continental and regional climate systems in ways that are difficult to translate into equations. Clearing forests for farming and ranching brightens the land surface. Croplands are lighter-colored than dark forest and thus reflect more solar radiation, which tends to cool the atmosphere, especially in autumn and summer.

Dearth of Data

Climate simulations can never move out of the realm of good guesses without accurate observations to validate them and to show that the models do indeed reflect reality. In other words, to reduce our uncertainty about the sensitivity of the climate system to human activity, we need to know how the climate has changed in the past. We must be capable of adequately simulating conditions before the Industrial Revolution and especially since that time, when humans have altered irrevocably the composition of the atmosphere.

To understand climate from times prior to the development of weather-tracking satellites and other instruments, we rely on indicators such as air and chemicals trapped in ice cores, the width of tree rings, coral growth, and sediment deposits on the bottoms of oceans and lakes. These snapshots provide us with information that aids in piecing together past conditions. To truly understand the present climate, however, we require more than snapshots of physical, chemical and biological quantities; we also need the equivalent of long-running videotape records of the currently evolving climate. Ongoing measurements of sea ice, snow cover, soil moisture, vegetative cover, and ocean temperature and salinity are just some of the variables involved.

But the present outlook is grim: no U.S. or international institution has the mandate or resources to monitor long-term climate. Scientists currently compile their interpretations of climate change from large networks of satellites and surface sensors such as buoys, ships, observatories, weather stations and airplanes that are being operated for other purposes, such as short-term weather forecasting. As a result, depictions of past climate variability are often equivocal or missing.

The National Oceanic and Atmospheric Administration operates many of these networks, but it does not have the resources to commit to a long-term climate-monitoring program. Even the National Aeronautics and Space Administration's upcoming Earth Observing System, which entails launching several sophisticated satellites to monitor various aspects of global systems, does not include the continuity of a long-term climate observation program in its mission statement.

Whatever the state of climate monitoring may be, another challenge in the next decade will be to ensure that the quantities we do measure actually represent real multidecadal changes in the environment. In other words, what happens if we use a new camera or point it in a different direction? For instance, a satellite typically lasts only four years or so before it is replaced with another in a different orbit. The replacement usually has new instruments and observes the earth at a different time of day. Over a period of years, then, we end up measuring not only climate variability but also the changes introduced by observing the climate in a different way. Unless precautions are taken to quantify the modifications in observing technology and sampling methods before the older technology is replaced, climate records could be rendered useless because it will be impossible to compare the new set of data with its older counterpart.

Future scientists must be able to evaluate their climate simulations with unequivocal data that are properly archived. Unfortunately, the data we have archived from satellites and critical surface sensors are in jeopardy of being lost forever. Long-term surface observations in the U.S. are still being recorded on outdated punched paper tapes or are stored on decaying paper or on old computer hardware. About half the data from our new Doppler radars are lost because the recording system relies on people to deal with the details of data preservation during severe weather events, when warnings and other critical functions are a more immediate concern.

Can We Realize the Vision?

Over the next 50 years we can broadly understand, if we choose to, how human beings are affecting the global, regional and even small-scale aspects of climate. But waiting until then to take action would be foolhardy. Long lifetimes of carbon dioxide and other greenhouse gases in the atmosphere, coupled with the climate's typically slow response to evolving conditions, mean that even if we cut back on harmful human activities today, the planet very likely will still undergo substantial change.

Glaciers melting in the Andes highlands and elsewhere are already confirming the reality of a warming planet. Rising sea level—and drowning coastlines—testify to the projected global warming of perhaps two degrees C or more by the end of the next century. Climate change will in all likelihood capture the most attention when its effects exacerbate other pressures on society. The spread of settlements into coastal regions and low-lying areas vulnerable to flooding is just one of the initial difficulties that we will most likely face. But as long as society can fall back on the uncertainty of human impact on climate, legislative mandates for changing standards of fossil-fuel emissions or forest clear-cutting will be hard fought.

The need to foretell how much we influence our world argues for doing everything we can to develop comprehensive observing and data-archiving systems now. The resulting information could feed models that help make skillful predictions of climate several years in advance. With the right planning we could be in a position to predict, for example, exactly how dams and reservoirs might be better designed to accommodate anticipated floods and to what extent greenhouse gas emissions from new power plants will warm the planet.

Climate change is happening now, and more change is certain. We can act to slow it down, and we can sensibly plan for it, but at present we are doing neither. To anticipate the true shape of future climate, scientists must overcome the obstacles we have outlined above. The need for greater computer power and for a more sophisticated understanding of the nuances of climate interactions should be relatively easy to overcome. The real stumbling block is the long-term commitment to global climate monitoring. How can we get governments to commit resources for decades of surveys, particularly when so many governments change hands with such frequency?

If we really want the power to predict the effects of human activity by 2050—and to begin addressing the disruption of our environment—we must pursue another path. We have a tool to clear such a path: the United Nations Framework Convention on Climate Change, signed by President George Bush in 1992. The convention binds together 179 governments with a commitment to remedy damaging human influence on global climate. The alliance took a step toward stabilizing greenhouse gas emissions by producing the Kyoto Protocol in 1997, but long-term global climate-monitoring systems remain unrealized. SA

Further Information

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The United Nations Framework Convention on Climate Change and Kyoto Protocol updates are available at www.unfccc.org/ on the World Wide Web.

The Authors

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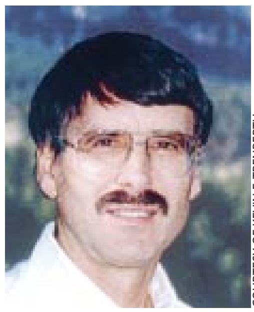
THOMAS R. KARL has directed the National Climatic Data Center (NCDC) in Asheville, N.C., since March 1998. The center is part of the National Oceanic and Atmospheric Administration and serves as the world's largest active archive of climate data. Karl, who has worked at the center since 1980, has focused much of his research on climate trends and extreme weather. He also writes reports for the Intergovernmental Panel on Climate Change (IPCC), the official science source for international climate change negotiations.



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KEVIN E. TRENBERTH directs the Climate Analysis section at the National Center for Atmospheric Research (NCAR) in Boulder, Colo., where he studies El Niño and climate variability. After several years in the New Zealand Meteorological Service, he became a professor of atmospheric sciences at the University of Illinois in 1977 and moved to NCAR in 1984. Trenberth also co-writes IPCC reports with Karl.

Can Human Aging Be Postponed?

by Michael R. Rose

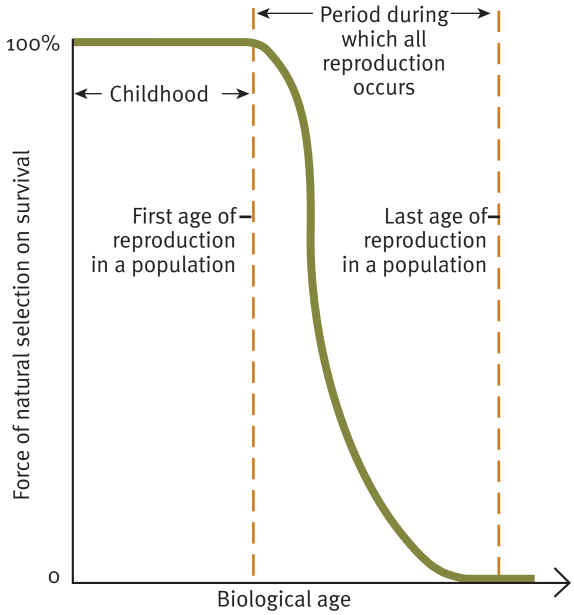
In theory, it certainly can. Yet no single elixir will do the trick. Antiaging therapies of the future will undoubtedly have to counter many destructive biochemical processes at once

Aging remains inevitable, but scientists now have a strategy in place for figuring out how to retard the process.

Cultures throughout history have aspired to postpone aging, thereby prolonging vitality and life itself. Today macrobiotic diets, recycled Hindu health practices, the latest fashions in gray-market hormone therapy and other forms of chicanery continue to fan the flames of hope. All these attempts to restore or sustain youthful vigor have just one thing in common: failure to achieve their goal. People who survive past 65 these days are only slightly more likely to enjoy a robust old age than their counterparts were 2,000 years ago.

Medical researchers have devised useful therapies for disorders that become more common with advancing age, such as cancer and heart disease. And over the past 120 years, sanitation systems and drugs that combat infectious disease have increased life expectancy in the developed nations by reducing premature death. But nothing delays or

JERRY GAY *Tony Stone Images*



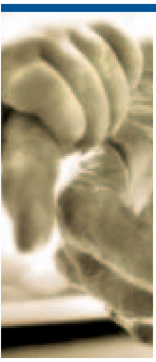
Discovery by evolutionary biologists explains why we age. Calculations show that the force of natural selection on survival in sexually reproducing populations drops soon after the earliest age of reproduction is reached. Aging has evolved because genes that produce deleterious effects late in life meet little or no opposition from natural selection and thus become rampant in the gene pool.

LAURIE GRACE

slows the innate processes that cause adults to age, to suffer a decline in physiological functioning as they grow older. Consequently, successful treatment of one illness late in life often means that another age-related problem soon takes its place. Infirmity remains the lot of those older than 80, however much the media may dote on the 90-year-old marathon runner.

None of this means that postponing aging will be impossible forever. Since 1980 many studies have achieved that feat in animals, albeit by methods that cannot be applied to humans. The situation of aging research in 1999 is thus like that of atomic physics in 1929. Physicists by then had discovered previously unimagined quantum forces. The question was, Could they harness those forces? Aging research has made great progress recently, but has it advanced enough to defer our years of infirmity?

Not yet. To meet that goal, investigators need a much better understanding of the physiological processes that underlie senescence and influence life span. I am, however, optimistic that these processes can be discerned, because a more fundamental mystery has been solved: Why has aging evolved in the first place? The answer has enabled researchers to develop a rational strategy for unearthing the biochemical pathways that might be manipulated to extend our years of vigor.



What lies beyond the first significant postponement of aging? Further postponement. **Delaying human aging is not an all-or-none objective,** like putting a person on the moon.

Natural Selection Snoozes

Aging does not occur because of some universal defect in all cell types. If some singular, unavoidable flaw caused every cell to fail eventually, no animal would escape aging. But some do. For example, asexual sea anemones kept for decades in aquariums do not show failing health. Nor does aging derive from a genetic program designed by nature to block overpopulation. Instead senescence is the by-product of a pattern of natural selection that afflicts humans and other vertebrates but not vegetative sea anemones. More specifically, aging arises in sexually reproducing species because the force of natural selection declines after the start of adulthood.

This concept follows logically from general evolutionary theory. Heritable traits persist and become prevalent in a population—they are selected, in evolutionary terms—if those properties help their bearers to survive into reproductive age and produce offspring. The most useful traits result in the most offspring and hence in the greatest perpetuation of the genes controlling those properties. Meanwhile traits that diminish survival in youth become uncommon—are selected against—because their possessors often die before reproducing.

In contrast to deleterious genes that act early, those that sap vitality in later years would be expected to accumulate readily in a population, because parents with those genes will pass them to the next generation before their bad effects interfere with reproduction. (The later the genes lead to disability, the more they will spread, because the possessors will be able to reproduce longer.) Aging, then, creeps into populations because natural selection, the watchdog that so strongly protects traits ensuring hardiness during youth, itself becomes increasingly feeble with adult age.

Two devastating genetic diseases dramatize this point. Progeria, caused by a chance mutation in one copy of one gene in a new embryo, leads to nightmarish deterioration during childhood. Many systems degenerate so quickly that the youngsters soon come to look as old as their grandparents. They commonly die of heart disease or stroke before their 15th birthday. Huntington's disease, which is also caused by a defect in one copy of a gene, manifests itself in middle age. In this case, the nervous system degenerates, eventually leading to death.

Progeria is rare, whereas Huntington's is relatively common among genetic disorders. Why? People with progeria die before reproducing. In this way, intense natural selection readily removes the progeria mutation from the gene pool whenever it arises. The mutation for Huntington's, on the other hand, does not interfere significantly with reproduction, because it does not yield disability until after people have produced all or most of their children. It manifests at a stage when the force of natural selection is weak.

In the 1940s and 1950s J.B.S. Haldane and Nobelist Peter B. Medawar, both at University College London, were the first to introduce this evolutionary explanation of aging. W. D. Hamilton

MARK WEXLER *Woodfin Camp and Associates*

PETER GINTER *Bilderberg Photo Archive*

Two genetic disorders illustrate how weakened natural selection can allow deleterious late-acting genes to spread in a population. The person at the left had progeria, which causes rapid deterioration of the body during childhood; he looked old but was really a youngster. The man at the right had Huntington's disease, a neurodegenerative disorder that typically arises in middle age. Progeria is rare because natural selection is strong in childhood and weeds out the causative gene; disease sufferers do not reproduce and so do not pass the gene to future generations. Huntington's is more common because natural selection is powerless against it; by the time victims become symptomatic, they have usually bequeathed the destructive gene to half their offspring.

of Imperial College and Brian Charlesworth of the University of Sussex then made the thesis mathematically rigorous in the 1960s and 1970s.

In their most important result, Hamilton and Charlesworth established that for organisms that do not reproduce by splitting in two, the force of natural selection on survival falls with adult age and then disappears entirely late in life. Because natural selection is the source of all adaptation, and thus of health, the hardiness of older organisms declines as natural selection fades out. Eventually, with the continued absence of natural selection at later ages, survival may be so imperiled that optimal conditions and medical care may be unable to keep the older individual alive.

Since the 1970s the original mathematical proofs have been confirmed experimentally many times, most often by manipulations that deliberately prolong the period of intense natural selection in laboratory animals. Investigators extend this period by delaying the age at which reproduction begins; they discard all fertilized eggs produced by young animals and use only those produced late in life. As a result, only individuals who are robust enough to reproduce at an advanced age will pass their genes to the next generation.

If the declining strength of natural selection after the start of reproduction really does explain the evolution of aging, then progressively retarding this drop for a number of generations in a test population should lead to the evolution of significantly postponed aging in that lineage. This prediction has been shown to be true in fruit flies of the genus *Drosophila* that have had reproduction delayed across 10 or more generations. As a result of these experiments, scientists now have stocks that live two to three times longer than normal and are healthy longer as well.

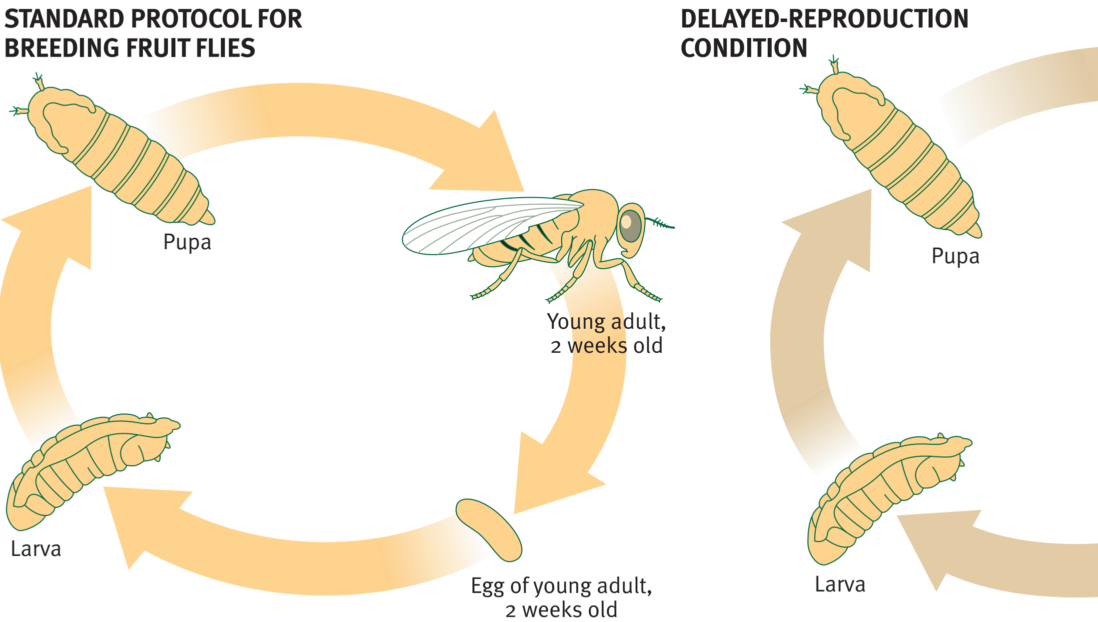
The flies that display postponed aging are surprisingly perky. They do not merely sustain normal biological functions for longer periods; they display superior capabilities at all adult ages. In youth and later, they are better able to resist such normally lethal stresses as acute desiccation and starvation. They also show more athletic prowess than their like-aged counterparts do, being able to walk and fly for longer periods.

If people could be treated in the same way as fruit flies, the problem of postponing human aging could be solved by forcibly delaying childbirth over many generations. Such practices would be barbaric, however, as well as extremely slow in producing results. Those who wish to delay aging must therefore find other methods, ones that would essentially mimic the physiological changes brought about by generations of postponed breeding. (A note to those who are tempted to try postponing breeding: the practice will not yield any immediate benefit to you or your future children. It would probably take about 10 generations to increase longevity at all and centuries to yield a significant increase in life span.)

Clues to Biochemical Causes

Evolutionary theory and some crude experiments suggest that hundreds of genetically determined biochemical pathways—cascades of molecular interactions—influence longevity and might thus be manipulated to postpone aging. So far, however, only a handful of genes that could be involved have been discovered, principally in the nematode worm *Caenorhabditis elegans* and in the fruit fly *Drosophila melanogaster*. Whether results in these organisms apply to humans remains to be determined.

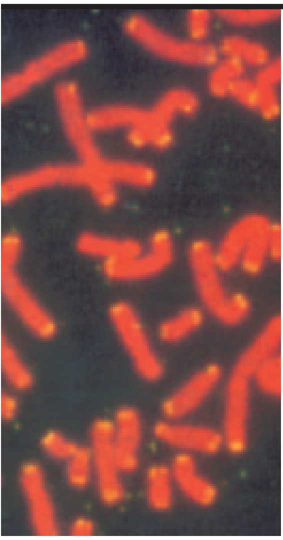
Fruit fly experiments support the notion that aging is caused by the declining power of natural selection during adulthood. Scientists allowed a control group (*left*) to reproduce soon after reaching maturity, thereby keeping the period of intense natural selection short. At the same time, they delayed reproduction in another group (*right*), thereby prolonging the period of intense natural selection. After many generations, such manipulation delayed aging in both males and females in the second group and led to greater longevity (*graphs*).



A few studies have been done in people as well. For instance, genetic analyses of French centenarians have identified two variable genes that might participate in postponing aging in people: one codes for apolipoprotein E (a protein involved in cholesterol transport), the other for angiotensin-converting enzyme (involved in blood pressure regulation). In each case, particular alleles, or variants, of the genes have been found to be more common in the centenarians than in younger adults.

The French results do not point to any antiaging therapies, however. No one knows exactly how the alleles common in long-lived people might combat aging. Moreover, even if those alleles, or ones first uncovered in worms and fruit flies, were linked to extended health in people, the discovery would still constitute only one step toward delaying senescence. Alteration of the multifactorial aging process is likely to require manipulation of several, perhaps many, biochemical pathways.

A useful way to find alleles that might affect aging in people would be to compare the genetic makeup of normal animals and of those displaying deferred aging. Fortunately, the same approach



ROBERT K. MOYZIS

Telomeres that cap chromosomes are highlighted by fluorescence.

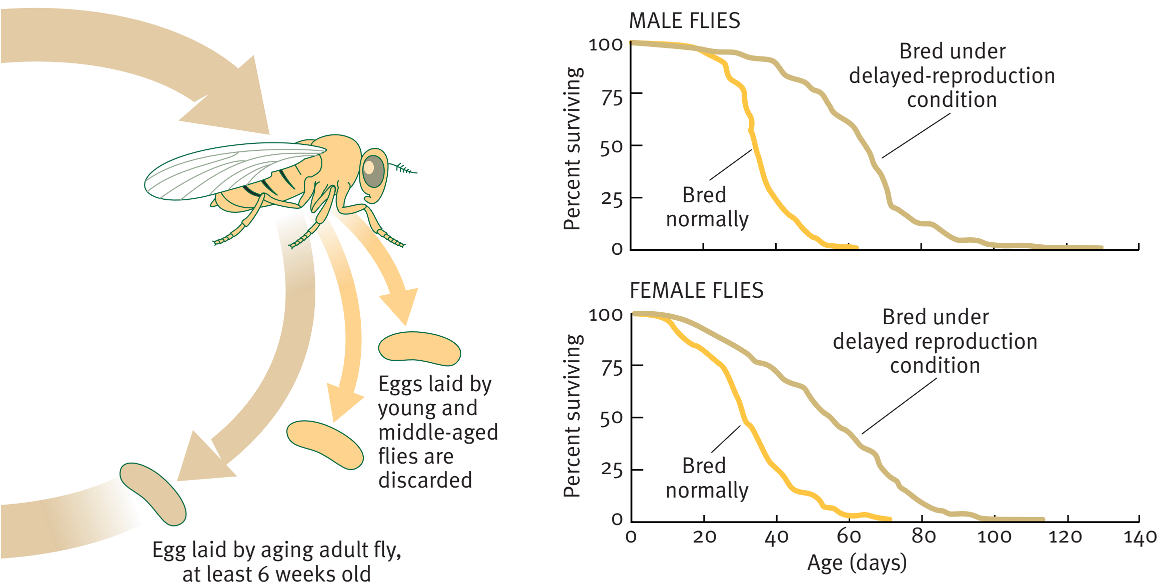
No Easy Fixes

Homo sapiens are already relatively long-lived, at least for organisms that are not trees. But many of us would like to live even longer, especially if we can do so in good health. That desire, however, may sometimes blind us to the reality that any promises of easy fixes are sure to be empty.

Among the potential therapies that have been publicized in recent years are exercise, diet restriction, and delivery of such substances as growth hormone, the enzyme telomerase and antioxidants. Exercise improves functioning for as long as it is pursued diligently, but it has not been shown to increase long-term survival; in addition, its beneficial physiological effects do not persist very long after a person returns to a more sedentary way of life. Diet restriction works in rodents but has not been studied systematically in humans and is not practical for most people. And arbitrarily cranking up the levels of any hormone in the body is potentially dangerous.

Many news reports have focused on the ability of telomerase to delay senescence of human cells in the test tube. This enzyme acts on structures called telomeres, which cap the ends of chromosomes. Telomeres shrink a bit every time a cell divides; when the length drops below a set threshold, cells stop dividing. Some investigators have suggested that drug therapies that preserve telomeres might enable dividing cells to reproduce and remain healthy indefinitely; they also have proposed that such preservation might retard aging in whole organisms. They have not, however, managed to prove their case by holding off the aging of any living creature. Further, anything that contributes to the immortality of cells runs the risk of promoting cancer.

Research in fruit flies and other organisms does seem to implicate free radicals—highly destructive, oxidizing molecules made by the body itself—in aging. Indeed, in fruit flies, a gene variant giving rise to an unusually active form of superoxide dismutase, a scavenger of destructive free radicals, is associated with robust longevity. If oxidation reactions are involved in human aging, then blocking the production of free radicals or scavenging them might help to delay senescence. Despite claims to the contrary, though, scientists do not yet know how to achieve those effects safely in people, and no studies have determined whether such interventions would, in fact, be successful. *—M.R.R.*



CHRISTOPH BLUMRICH (*illustration*); LAURIE GRACE (*graphs*)

that tested the evolutionary theory of aging can be applied to reveal large suites of genes with an influence on life span. Fruit flies that have had their longevity extended by delayed reproduction turn out to have a different mix of alleles than occurs in run-of-the-mill fruit flies. These alleles were not selected in advance and delivered to the long-lived flies. Rather, in response to delayed reproduction, natural selection constructed organisms that exhibited postponed aging.

Identifying the specific alleles that differ in long-lived and normal animals will help those of us who study aging to develop treatments that emulate or enhance the effects of beneficial alleles and that counter the effects of deleterious ones. Candidate therapies will, of course, have to be tested successfully in laboratory animals before being evaluated in people.

Technology Will Set the Pace

Whether fruit flies, rodents or other animals are the subjects of comparative studies, the work will not be easy. Scientists will not only have to identify hundreds or thousands of alleles that occur most frequently in long-lived subjects, they will also have to decipher the biological functions and unique features of the corresponding proteins. The collected technologies needed to perform these tasks fall under the rubric of "functional genomics," which is very much a work in progress. Only if that progress is rapid enough will we see human aging postponed significantly by 2050.

This statement may seem puzzling in light of never-ending publicity about the potential anti-aging effects of any number of interventions. Yet, as I said earlier, no proposed therapy has yet been proved to work, and none is likely to have a dramatic impact on its own [*see box on opposite page*].

What lies beyond the first significant postponement of human aging, sometime in the next century? Further postponement. Delaying human aging is not an all-or-none objective, like putting a person on the moon. Our survival and function in later life will be improved cumulatively, much as cars have been improved progressively over the past century of manufacturing. I see no limit to how long human life can be extended if scientists learn how to turn on antiaging genes in the young or how to prepare cocktails of drugs that serve the same purpose as genetic engineering. Yet no one knows even the basic features that successful interventions will need to have.

The postponement of human aging raises difficult issues for public policy and personal ethics. How will Social Security fare in a postponed-aging future? What will happen to retirement at 65? What of our children's expectation that we will die and leave them a beneficence? Will there be even more overpopulation? Isn't there something immoral about the elderly clinging to life? These difficult questions concern many thoughtful people.

Still a conjectural achievement, the postponement of human aging poses no direct threat to anyone in 1999. But in 2050 it may be a reality that gives headaches to Congress and high spirits to the middle-aged. SA

The Author

THERESA HANSEN

MICHAEL R. ROSE is professor of evolutionary biology at the University of California, Irvine. He concentrates on experimental tests, mainly in fruit flies, of evolutionary theories of aging, fitness and life histories. He says it has been at least 10 years since he has been openly ridiculed for explaining aging in terms of evolution.

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How the Brain Creates the Mind

by Antonio R. Damasio

Philosophers, neuroscientists and laypeople have long wondered how the conscious mind comes to be. A more complete understanding of the workings of the brain ought to lead to an eventual solution

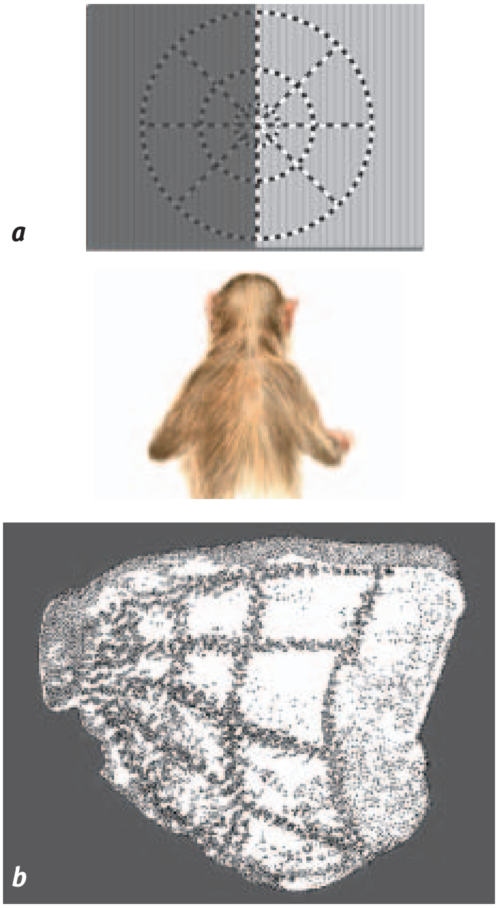
As the millennium draws to a close, it is apparent that one question towers above all others in the life sciences: How does the set of processes we call mind emerge from the activity of the organ we call brain? The question is hardly new. It has been formulated in one way or another for centuries. Once it became possible to pose the question and not be burned at the stake, it has been asked openly and insistently. Recently the question has preoccupied both the experts—neuroscientists, cognitive scientists and philosophers—and others who wonder about the origin of the mind, specifically the conscious mind.

The question of consciousness now occupies center stage because biology in general and neuroscience in particular have been so remarkably successful at unraveling a great many of life's secrets. More may have been learned about the brain and the mind in the 1990s—the so-called decade of the brain—than during the entire previous history of psychology and neuroscience. Elucidating the neurobiological basis of the conscious mind—a version of the classic mind-body problem—has become almost a residual challenge.

Contemplation of the mind may induce timidity in the contemplator, especially when consciousness becomes the focus of the inquiry. Some thinkers, expert and amateur alike, believe the question may be unanswerable in principle. For others, the relentless and exponential increase in new knowledge may give rise to a vertiginous feeling that no problem can resist the assault of science if only the theory is right and the techniques are powerful enough. The debate is intriguing and even unexpected, as no comparable doubts have been raised over the likelihood of explaining how the brain is responsible for processes such as vision or memory, which are obvious components of the larger process of the conscious mind.

SLIM FILMS

The multimedia mind-show occurs constantly as the brain processes external and internal sensory events. As the brain answers the unasked question of who is experiencing the mind-show, the sense of self emerges.



a

b

The brain's business is representing other things. Studies with macaques show a remarkable fidelity between a seen shape (*a*) and the shape of the neural activity pattern (*b*) in one of the layers of the primary visual cortex.

DIMITRY SCHIDLOVSKY; SOURCE: Tootell et al., *Journal of Neuroscience*, May 1988.

I am firmly in the confident camp: a substantial explanation for the mind's emergence from the brain will be produced and perhaps soon. The giddy feeling, however, is tempered by the acknowledgment of some sobering difficulties.

Nothing is more familiar than the mind. Yet the pilgrim in search of the sources and mechanisms behind the mind embarks on a journey into a strange and exotic landscape. In no particular order, what follows are the main problems facing those who seek the biological basis for the conscious mind.

The first quandary involves the perspective one must adopt to study the conscious mind in relation to the brain in which we believe it originates. Anyone's body and brain are observable to third parties; the mind, though, is observable only to its owner. Multiple individuals confronted with the same body or brain can make the same observations of that body or brain, but no comparable direct third-person observation is possible for anyone's mind. The body and its brain are public, exposed, external and unequivocally objective entities. The mind is a private, hidden, internal, unequivocally subjective entity.

How and where then does the dependence of a first-person mind on a third-person body occur precisely? Techniques used to study the brain include refined brain scans and the measurement of patterns of activity in the brain's neurons. The naysayers argue that the exhaustive compilation of all these data adds up to *correlates* of mental states but nothing resembling an *actual mental state*. For them, detailed observation of living matter thus leads not to mind but simply to the details of living matter. The understanding of how living matter generates the sense of self that is the hallmark of a conscious mind—the sense that the images in my mind are mine and are formed in my perspective—is simply not possible. This argument, though incorrect, tends to silence most hopeful investigators of the conscious mind.

To the pessimists, the conscious-mind problem seems so intractable that it is not even possible to explain why the mind is even *about* something—why mental processes represent internal states or interactions with external objects. (Philosophers refer to this representational quality of the mind with the confusing term "intentionality.") This argument is false.

The final negative contention is the reminder that elucidating the emergence of the conscious mind depends on the existence of that same conscious mind. Conducting an investigation with the very instrument being investigated makes both the definition of the problem and the approach to a solution especially complicated. Given the conflict between observer and observed, we are told, the human intellect is unlikely to be up to the task of comprehending how mind emerges from brain. This conflict is real, but the notion that it is insurmountable is inaccurate.

In summary, the apparent uniqueness of the conscious-mind problem and the difficulties that complicate ways to get at that problem generate two effects: they frustrate those researchers committed to finding a solution and confirm the conviction of others who intuitively believe that a solution is beyond our reach.

Evaluating the Difficulties

Those who cite the inability of research on the living matter of the brain to reveal the "substance of mind" assume that the current knowledge of that living matter is sufficient to make such judgment final. This notion is entirely unacceptable. The current description of neurobiological phenomena is quite incomplete, any way you slice it. We have yet to resolve numerous details about the function of neurons and circuits at the molecular level; we do not yet grasp the behavior of populations of neurons within a local brain region; and our understanding of the large-scale systems made up of multiple brain regions is also incomplete. We are barely beginning to address the fact that interactions among many noncontiguous brain regions probably yield highly complex biological states that are vastly more than the sum of their parts.

In fact, the explanation of the physics related to biological events is still incomplete. Consequently, declaring the conscious-mind problem insoluble because we have studied the brain to the hilt and have not found the mind is ludicrous. We have not yet fully studied either neurobiology or its related physics. For example, at the finest level of description of mind, the swift construction, manipulation and superposition of many sensory images might require explanation at the quantum level. Incidentally, the notion of a possible role for quantum physics in the elucidation of mind, an idea usually associated with mathematical physicist Roger Penrose of the University of Oxford, is not an endorsement of his specific proposals, namely, that consciousness is based on quantum-level phenomena occurring in the microtubules—constituents of neurons and other cells. The quantum level of operations might help explain how we have a mind, but I regard it as unnecessary to explain how we *know* that we own that mind—the issue I regard as most critical for a comprehensive account of consciousness.

The strangeness of the conscious-mind problem mostly reflects ignorance, which limits the imagination and has the curious effect of making the possible seem impossible. Science-fiction writer Arthur C. Clarke has said, "Any sufficiently advanced technology is indistinguishable from magic." The "technology" of the brain is so complex as to appear "magical," or at least unknowable. The appearance of a gulf between mental states and physical/biological phenomena comes from the large disparity between two bodies of knowledge—the good understanding of mind we have achieved through centuries of introspection and the efforts of cognitive science versus the incomplete neural specification we have achieved through the efforts of neuroscience. But there is no reason to expect that neurobiology cannot bridge the gulf. Nothing indicates that we have reached the edge of an abyss that would separate, in principle, the mental from the neural.

Therefore, I contend that the biological processes now presumed to correspond to mind processes in fact *are* mind processes and will be seen to be so when understood in sufficient detail. I am not denying the existence of the mind or saying that once we know what we need to know about biology the mind ceases to exist. I simply believe that the private, personal mind, precious and unique, indeed *is* biological and will one day be described in terms both biological and mental.

The other main objection to an understanding of mind is that the real conflict between observer and observed makes the human intellect unfit to study itself. It is important, however, to point out that the brain and mind are not a monolith: they have multiple structural levels, and the highest of those levels creates instruments that permit the observation of the other levels. For example, language endowed the mind with the power to categorize and manipulate knowledge according to logical principles, and that helps us classify observations as true or false. We should be modest about the likelihood of ever observing our entire nature. But declaring defeat before we even make the attempt defies Aristotle's observation that human beings are infinitely curious about their own nature.

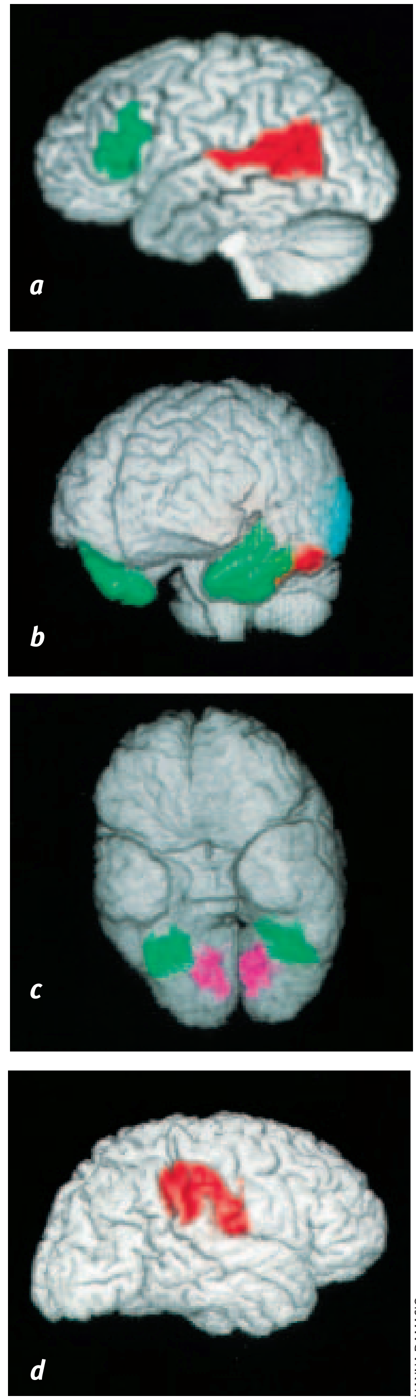
Reasons for Optimism

My proposal for a solution to the conundrum of the conscious mind requires breaking the problem into two parts. The first concern is how we generate what I call a "movie-in-the-brain." This "movie" is a metaphor for the integrated and unified composite of diverse sensory images—visual, auditory, tactile, olfactory and others—that constitutes the multimedia show we call mind. The second issue is the "self" and how we automatically generate a sense of ownership for the movie-in-the-brain. The two parts of the problem are related, with the latter nested in the former. Separating them is a useful research strategy, as each requires its own solution.

Neuroscientists have been attempting unwittingly to solve the movie-in-the-brain part of the conscious-mind problem for most of the history of the field. The endeavor of mapping the brain regions involved in constructing the movie began almost a century and a half ago, when Paul Broca and Carl Wernicke first suggested that different regions of the brain were involved in processing different aspects of language. More recently, thanks to the advent of ever more sophisticated tools, the effort has begun to reap handsome rewards.

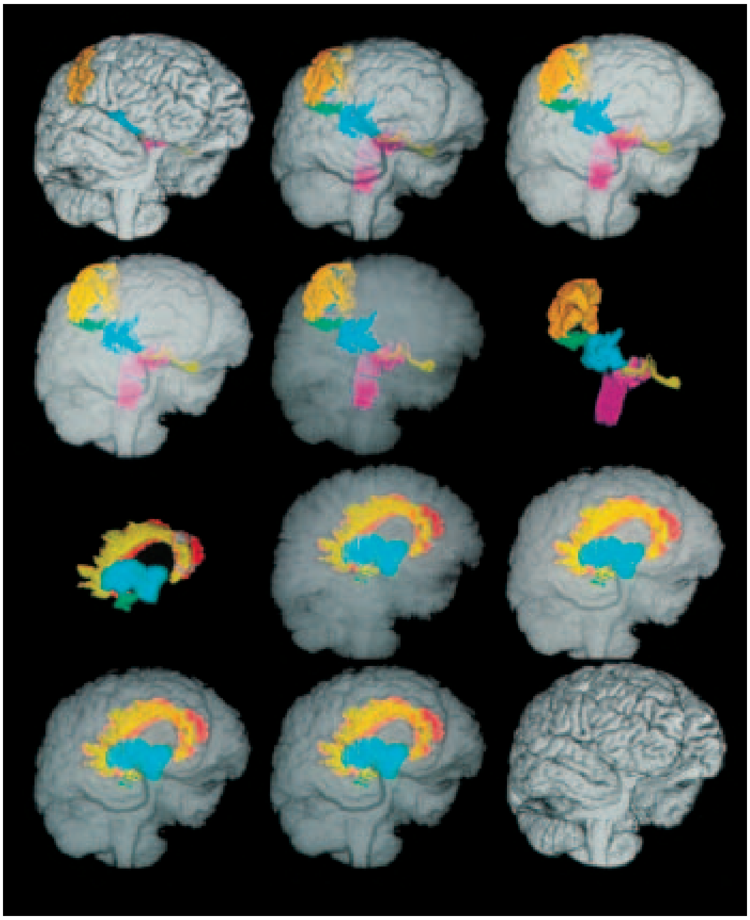
Researchers can now directly record the activity of a single neuron or group of neurons and relate that activity to aspects of a specific mental state, such as the perception of the color red or of a curved line. Brain-imaging techniques such as PET (positron emission tomography) scans and fMR (functional magnetic resonance) scans reveal how different brain regions in a normal, living person are engaged by a certain mental effort, such as relating a word to an object or learning a particular face. Investigators can determine how molecules within microscopic neuron circuits participate in such diverse mental tasks, and they can identify the genes necessary for the production and deployment of those molecules.

Progress in this field has been swift ever since David H. Hubel and Torsten Wiesel of Harvard University provided the first clue for how brain circuits represent the shape of a given object, by demonstrating that neurons in the primary visual cortex were selectively tuned to respond to edges oriented in varied angles. Hubel and Margaret S. Livingstone, also at Harvard, later showed that other neurons in the primary visual cortex respond selectively to color but not shape. And Semir Zeki of University College London found



HANNA DAMASIO

Neuroscience continues to associate specific brain structures with specific tasks. Some language regions are highlighted in *a* and *b*. Color-processing (*red*) and face-processing (*green*) regions are shown in *c*. One's own body sense depends on the region shown in *d*.



HANNA DAMASIO

The sense of self has a seat in the brain's core. Stripping away the external anatomy of a human brain shows a number of deep-seated regions responsible for homeostatic regulation, emotion, wakefulness and the sense of self.

that brain regions that received sensory information after the primary visual cortex did were specialized for the further processing of color or movement. These results provided a counterpart to observations made in living neurological patients: damage to distinct regions of the visual cortices interferes with color perception while leaving discernment of shape and movement intact.

A large body of work, in fact, now points to the existence of a correspondence between the structure of an object as taken in by the eye and the pattern of neuron activity generated within the visual cortex of the organism seeing that object [*see illustration on page 114*].

Further remarkable progress involving aspects of the movie-in-the-brain has led to increased insights related to mechanisms of learning and memory. In rapid succession, research has revealed that the brain uses discrete systems for different types of learning. The basal ganglia and cerebellum are critical for the acquisition of skills, for example, learning to ride a bicycle or play a musical instrument; the hippocampus is integral to the learning of facts pertaining to such entities as people, places or events. And once facts are learned, the long-term memory of those facts relies on multicomponent brain systems, whose key parts are located in the vast brain expanses known as cerebral cortices.

Moreover, the process by which newly learned facts are consolidated in long-term memory goes beyond properly working hippocampi and cerebral cortices. Certain processes must take place, at the level of neurons and molecules, so that the neural circuits are etched, so to speak, with the impressions of a newly learned fact. This etching depends on strengthening or weakening the contacts between neurons, known as synapses. A provocative recent finding by Eric R. Kandel of Columbia University and Timothy P. Tully of Cold Spring Harbor Laboratory is that etching the impression requires the synthesis of fresh proteins, which in turn rely on the engagement of specific genes within the neurons charged with supporting the consolidated memory.

These brief illustrations of progress could be expanded with other revelations from the study of language, emotion and decision making. Whatever mental function we consider, it is possible to identify distinct parts of the brain that contribute to the production of a function by working in concert; a close correspondence exists between the appearance of a mental state or behavior and the activity of selected brain regions. And that correspondence can be established between a given macroscopically identifiable region (for example, the primary visual cortex, a language-related area or an emotion-related nucleus) and the microscopic neuron circuits that constitute the region.

Most exciting is that these impressive advances in the study of the brain are a mere beginning. New analytical techniques continuously improve the ability to study neural function at the molecular level and to investigate the highly complex large-scale phenomena arising from the whole brain. Revelations from those two areas will make possible ever finer correspondences between brain states and mental states, between brain and mind. As technology develops and the ingenuity of researchers grows, the fine grain of physical structures and biological activities that constitute the movie-in-the-brain will gradually come into focus.

Confronting the Self

The momentum of current research on cognitive neuroscience, and the sheer accumulation of powerful facts, may well convince many doubters that the neural basis for the movie-in-the-brain can be identified. But the skeptics will still find it difficult to accept that the second part of the conscious-mind problem—the emergence of a sense of self—can be solved at all. Although I grant that solving this part of the problem is by no means obvious, a possible solution has been proposed, and a hypothesis is being tested.

The main ideas behind the hypothesis involve the unique representational ability of the brain. Cells in the kidney or liver perform their assigned functional roles and do not represent any other cells or functions. But brain cells, at every level of the nervous system, represent entities or events occurring elsewhere in the organism. Brain cells are assigned by design to be *about* other things and other doings. They are born cartographers of the geography of an organism and of the events that take place within that geography. The oft-quoted mystery of the "intentional" mind relative to the representation of external objects turns out to be no mystery at all. The philosophical despair that surrounds this "intentionality" hurdle alluded to earlier—why mental states represent internal emotions or interactions with external objects—lifts with the consideration of the brain in a Darwinian context: evolution has crafted a brain that is in the business of directly representing the organism and indirectly representing whatever the organism interacts with.

The brain's natural intentionality then takes us to another established fact: the brain possesses devices within its structure that are designed to manage the life of the organism in such a way that the internal chemical balances indispensable for survival are maintained at all times. These devices are neither hypothetical nor abstract; they are located in the brain's core, the brain stem and hypothalamus. The brain devices that regulate life also represent, of necessity, the constantly changing states of the organism as they occur. In other words, the brain has a natural means to represent the structure and state of the *whole* living organism.

But how is it possible to move from such a biological self to the sense of ownership of one's thoughts, the sense that one's thoughts are constructed in one's own perspective, without falling into the trap of invoking an all-knowing homunculus who interprets one's reality? How is it possible to know about self and surroundings? I have argued in my book *The Feeling of What Happens* that the biological foundation for the sense of self can be found in those brain devices that represent, moment by moment, the continuity of the same individual organism.

Simply put, my hypothesis suggests that the brain uses structures designed to map both the organism and external objects to create a fresh, second-order representation. This representation indicates that the organism, as mapped in the brain, is involved in interacting with an object, also mapped in the brain. The second-order representation is no abstraction; it occurs in neural structures such as the thalamus and the cingulate cortices.

Such newly minted knowledge adds important information to the evolving mental process. Specifically, it *presents* within the mental process the information that the organism is the owner of the mental process. It volunteers an answer to a question never posed: To whom is this happening? The sense of a self in the act of knowing is thus created, and that forms the basis for the first-person perspective that characterizes the conscious mind.

Again from an evolutionary perspective, the imperative for a sense of self becomes clear. As Willy Loman's wife says in Arthur Miller's *Death of a Salesman*: "Attention must be paid!" Imagine a self-aware organism versus the same type of organism lacking it. A self-aware organism has an incentive to heed the alarm signals provided by the movie-in-the-brain (for instance, pain caused by a particular object) and plan the future avoidance of such an object. Evolution of self rewards awareness, which is clearly a survival advantage.

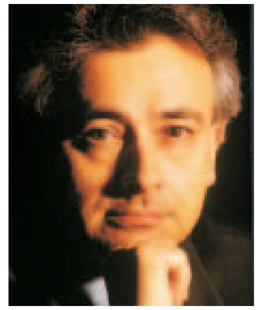
With the movie metaphor in mind, if you will, my solution to the conscious-mind problem is that the sense of self in the act of knowing emerges *within* the movie. Self-awareness is actually part of the movie and thus creates, within the same frame, the "seen" and the "seer," the "thought" and the "thinker." There is no separate spectator for the movie-in-the-brain. The idea of spectator is constructed within the movie, and no ghostly homunculus haunts the theater. Objective brain processes knit the subjectivity of the conscious mind out of the cloth of sensory mapping. And because the most fundamental sensory mapping pertains to body states and is imaged as feelings, the sense of self in the act of knowing emerges as a special kind of feeling—the feeling of what happens in an organism caught in the act of interacting with an object.

The Future

I would be foolish to make predictions about what can and cannot be discovered or about when something might be discovered and the route of a discovery. Nevertheless, it is probably safe to say that by 2050 sufficient knowledge of biological phenomena will have wiped out the traditional dualistic separations of body/brain, body/mind and brain/mind.

Some observers may fear that by pinning down its physical structure something as precious and dignified as the human mind may be downgraded or vanish entirely. But explaining the origins and workings of the mind in biological tissue will not do away with the mind, and the awe we have for it can be extended to the amazing microstructure of the organism and to the immensely complex functions that allow such a microstructure to generate the mind. By understanding the mind at a deeper level, we will see it as nature's most complex set of biological phenomena rather than as a mystery with an unknown nature. The mind will survive explanation, just as a rose's perfume, its molecular structure deduced, will still smell as sweet. SA

The Author



REMI BENALI *Gamma Liaison Network*

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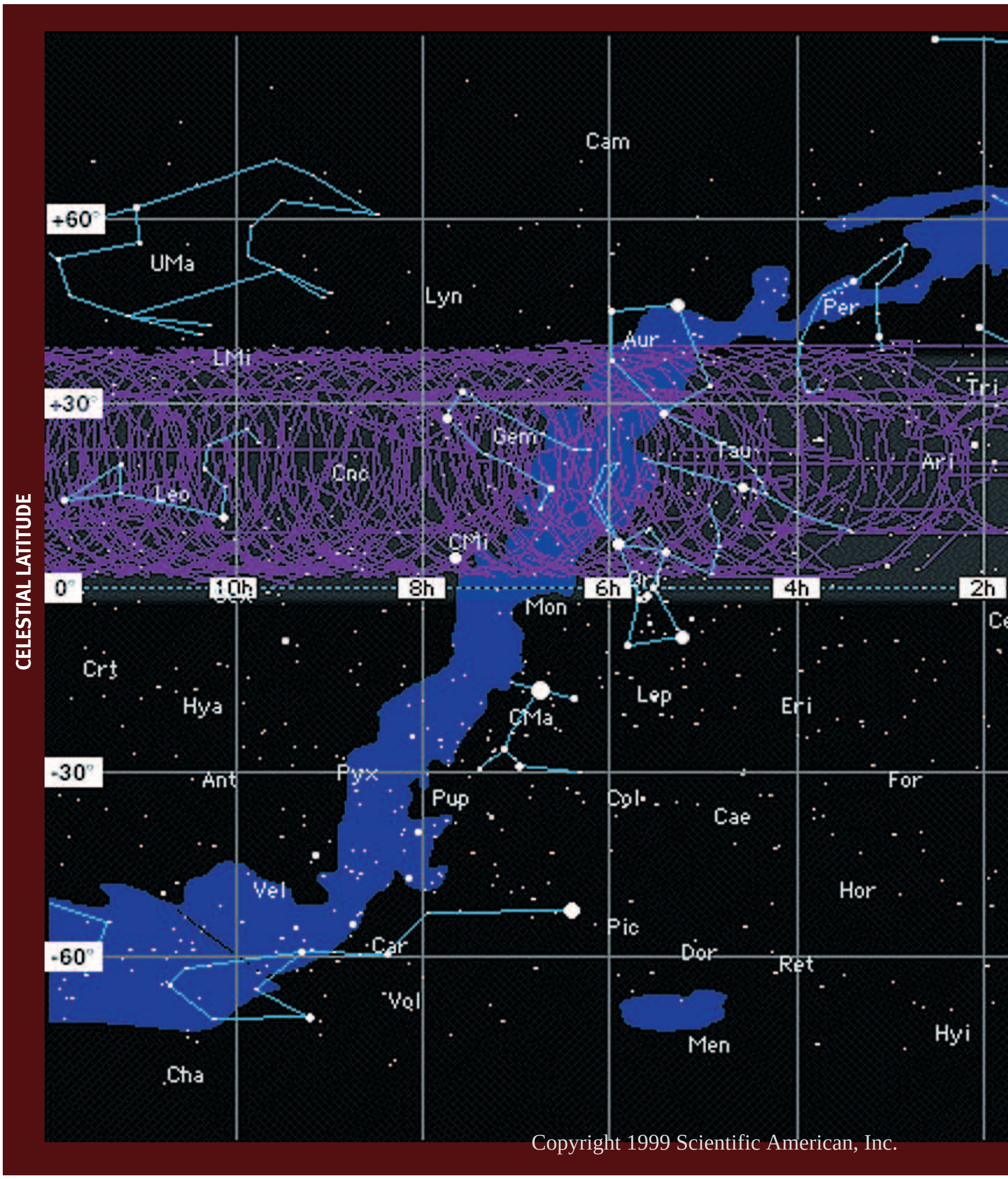
The answer is: nobody knows. Scientists' search for life beyond Earth has been less thorough than commonly thought. But that is about to change

Is There Life Elsewhere in the Universe?

by Jill C. Tarter and Christopher F. Chyba



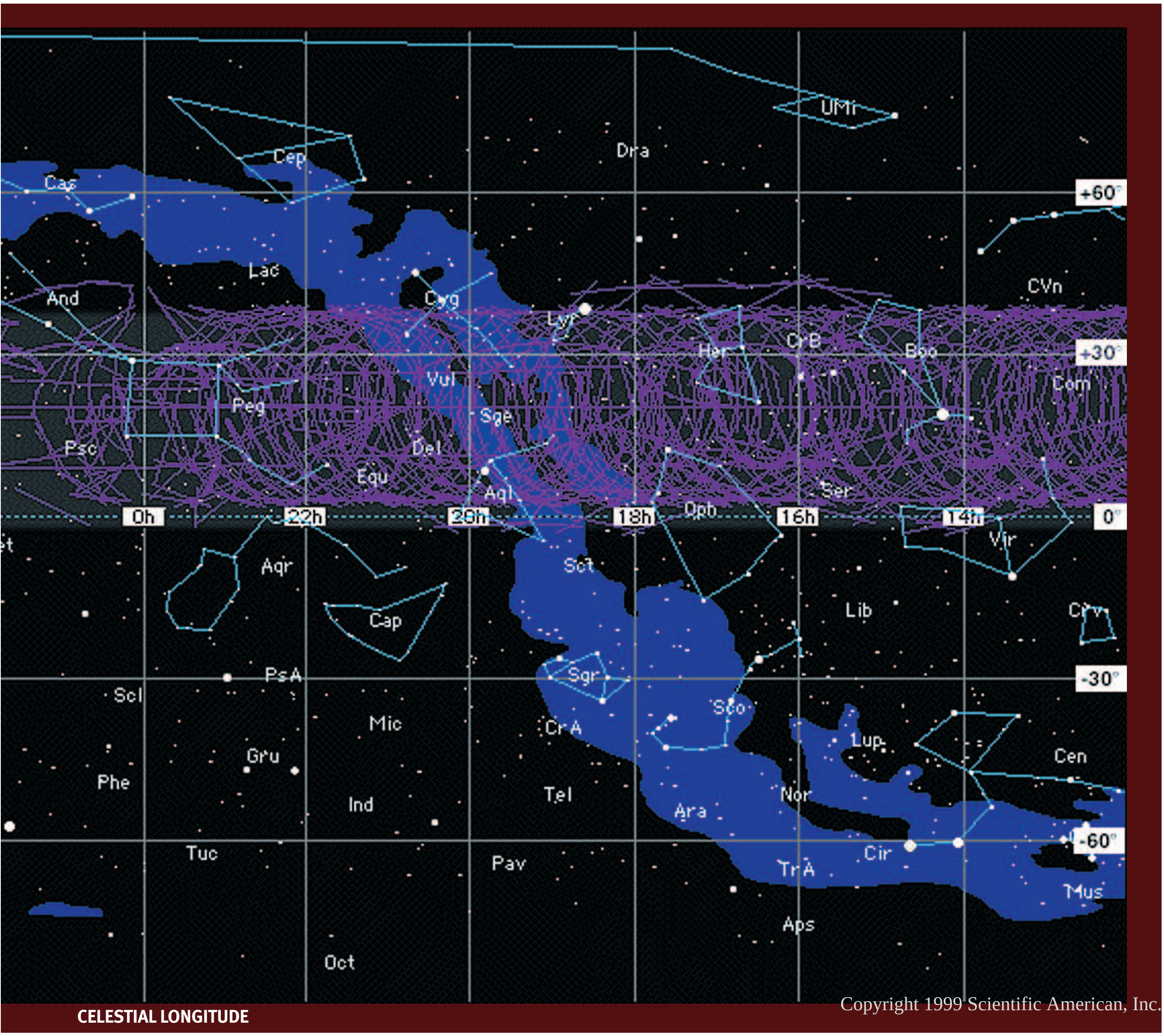
One of the ongoing searches for alien radio signals, SETI@home, scans a stripe across the sky. Because the Arecibo Observatory in Puerto Rico has only a limited ability to steer, the stripe extends from the celestial equator up to a declination (celestial latitude) of 35 degrees—which fortuitously includes many of the recently discovered planetary systems. To observe year-round and avoid interfering with other astronomical observations, SETI@home simply tags along wherever the telescope happens to be pointing. Over time, it sweeps across the band.

For 40 years, scientists have conducted searches for radio signals from an extraterrestrial technology, sent spacecraft to all but one of the planets in our solar system, and greatly expanded our knowledge of the conditions in which living things can survive. The public perception is that we have looked extensively for signs of life elsewhere. But in reality, we have hardly begun to search.

Assuming our current, comparatively robust space program continues, by 2050 we may finally know whether there is, or ever was, life elsewhere in our solar system. At a minimum we will have thoroughly explored the most likely candidates, something we cannot claim today. We will have discovered whether life dwells on Jupiter's moon Europa or on Mars. And we will have undertaken the systematic exobiological exploration of planetary systems around other stars, looking for traces of life in the spectra of planetary atmospheres. These surveys will be complemented by expanded searches for intelligent signals.

We may find that life is common but technical intelligence is extremely rare or that both are common or rare.

SETI@HOME, UNIVERSITY OF CALIFORNIA, BERKELEY



For now, we just don't know. The Milky Way galaxy is vast, and we have barely stirred its depths. Indeed, we have so poorly explored our own solar system that we cannot even rule out exotic possibilities such as the existence of a small robotic craft sent here long ago to await our emergence as a technological species. Over the next 50 years, our searches for extraterrestrial intelligence will perhaps meet with success. Or the situation may remain the same as it was in 1959, when astrophysicists Giuseppe Cocconi and Philip Morrison concluded, "The probability of success is difficult to estimate, but if we never search, the chance of success is zero."

SETH SHOSTAK *SETI Institute* (*Arecibo Observatory*)

Radio-frequency interference might force us to take our search to the **far side of the moon,** maybe to the Saha crater.

A search for life elsewhere must by guided by a practical definition of life. Many researchers studying the origins of life have adopted a "Darwinian" definition, which holds that life is a self-sustained chemical system capable of undergoing Darwinian evolution by natural selection. By this definition, we will have made living systems of molecules in the laboratory well before 2050. The extent to which these systems will inform us about the early history of life here or elsewhere is unclear, but at least they will give us some examples of the diversity of plausible biological styles.

Unfortunately, the Darwinian definition is not terribly useful from the point of view of spacecraft exploration. How long should one wait to see whether a chemical system is capable of undergoing evolution? As a practical matter, the Darwinian approach must give way to less precise but operationally more useful definitions. Consider the biology experiments that the twin Viking spacecraft carried to Mars in 1976. Researchers implicitly adopted a metabolic definition: they hoped to recognize Martian life through its consumption of chemicals. One of the tests they conducted, the labeled-release experiment (which checked whether a soil sample fed with nutrients gave off gaseous carbon), did in fact suggest the presence of organisms. In the words of Viking biology team leader Chuck Klein, its findings "would almost certainly have been interpreted as presumptive evidence for biology" were it not for contradictory data from other experiments.

Lessons from Viking

Foremost among these other experiments was the Viking gas chromatograph and mass spectrometer, which searched for organic molecules. None were found; consequently, scientists explained the labeled-release results as unanticipated chemistry rather than biology [see "The Search for Life on Mars," by Norman H. Horowitz; Scientific American, November 1977]. In effect, they adopted a biochemical definition for life: Martian life, like that on Earth, would be based on organic carbon.

The Viking experience holds important lessons. First, although we should search for life from the perspective of multiple definitions, the biochemical definition seems likely to trump others whenever the sensing is done remotely; in the absence of organic molecules, biologically suggestive results will probably be distrusted. Second, researchers

SETH SHOSTAK *SETI Institute*

Large arrays of small dishes will conduct the next generation of searches for extraterrestrial intelligence. The plans call for hundreds or even thousands of satellite-television antennas, which collectively offer higher sensitivity, broader frequency coverage and better resilience to interference. The first such instrument, the 1hT (which will have a total collecting area of one hectare, or 2.5 acres), is projected to cost $25 million.

must establish the chemical and geological context in order to interpret putative biological findings. Finally, life detection experiments should be designed to provide valuable information even in the case of a negative result. All these conclusions are being incorporated into thinking about future missions, such as the experiments to be flown on the first Europa lander.

In addition to a biochemical instrument, a valuable life detection experiment might involve a microscope. The advantage of a microscope is that it makes so few assumptions about what might be found. But the recent controversy over Allan Hills 84001, the Martian meteorite in which some researchers have claimed to see microfossils, reminds us that the shape of microscopic features is unlikely to provide unambiguous evidence for life. There are just too many nonbiological ways of producing structures that appear biological in origin.

Europa may be the most promising site for life elsewhere in the solar system. Growing evidence indicates that it harbors the solar system's second extant ocean—a body of water that has probably lasted for four billion years underneath a surface layer of ice. The exploration of Europa will begin with a mission, scheduled for launch in 2003, designed to prove whether or not the ocean is really there [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; Scientific American, October]. A positive answer will inspire a program of detailed exploration—including landers and perhaps, ultimately, ice-penetrating submarines—that will check whether the ocean is home to life. Whatever the outcome, we will certainly learn a great deal more about the limits of life's adaptability and the conditions under which it can arise. On Earth, wherever there is liquid water, there is life, even in unexpected places, such as deep within the crust.

Another Jovian satellite, Callisto, also shows signs of a sea. In fact, subsurface oceans might be standard features of large icy satellites in the outer solar system. Saturn's moon Titan could be another example. Because Titan is covered with a kind of atmospheric organic smog layer, we have not yet seen its surface in any detail [see "Titan," by Tobias Owen; Scientific American, February 1982]. In 2004 the Huygens probe will drop into its atmosphere, floating down for two hours and sending back images. Some models suggest that there may be liquid hydrocarbons flowing on Titan's surface. If these organics mix with subsurface liquid water, what might be possible?

Inter(pla)net

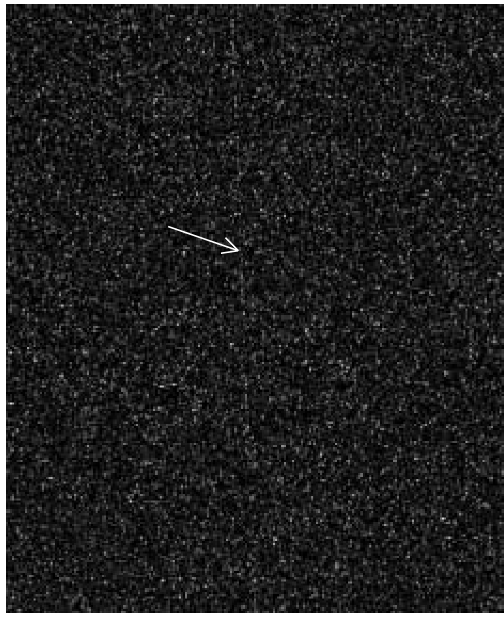
By 2050 we will have scoured the surface and some of the subsurface of Mars. Already the National Aeronautics and Space Administration is launching two spacecraft to Mars each time it and Earth are suitably aligned, every 26 months. In addition, researchers now plan a series of Mars micromissions: infrastructure and technology demonstrations that take advantage of surplus payload available on launches of the European Space Agency's Ariane 5 rocket. By 2010 we expect to have established a Mars global positioning system and computer network. Computer users on Earth will be able to enjoy continuous live video returned from robot rovers exploring Mars on the ground and in the air. In a virtual sense, hundreds of millions of people will visit Mars regularly, and it will come to seem a familiar place. As the Internet becomes interplanetary, we will inevitably come to think of ourselves as a civilization that spans the solar system.

Within a decade, we will begin returning samples from Mars to Earth. But the best places to look for extant life—Martian hot springs (if they exist) and deep niches containing liquid water—may well be the most demanding for robot explorers. In the end, we will probably need to send human explorers. Despite the difficulties, we foresee the first permanent human outposts on Mars, with regularly rotating crews, by 2050. Humans will work closely with robots to explore in detail those sites identified as the most likely venues for life or its fossil remains.

If researchers discover life on Mars, one of the first questions they will ask is: Is it related to us? An important realization of the past 10 years is that the planets of the inner solar system may not have been biologically isolated. Viable organisms could have moved among Mars, Earth and Venus enclosed in rocks ejected by large impacts. Thus, whichever world first developed life may have then inoculated the others. If life exists on Mars, we may share a common ancestor with it. If so, DNA comparison could help us determine the world of origin. Of course, should Martian life be of independent origin from life on Earth, it may lack DNA altogether. The discovery of a second genesis within our solar system would suggest that life develops wherever it can; such a finding would buttress arguments for the ubiquity of life throughout the universe [see "The Search for Extraterrestrial Life," by Carl Sagan; Scientific American, October 1994].

An essential part of our exploration of Mars and other worlds will be planetary protection. NASA now has guidelines to protect the worlds that it visits against contamination with microorganisms carried from Earth. We have much to learn about reducing the bioload of spacecraft we launch elsewhere. Progress is demanded—scientifically by the requirement of not introducing false positives, legally by international treaty and, we believe, ethically by the imperative to protect any alien biospheres.

And what about other planetary systems? Already we know of more planets outside our solar



SETI INSTITUTE

An extraterrestrial signal shows up as a slightly tilted streak on a plot such as this one. Each dot denotes the detection of radio energy at a given frequency (*horizontal axis*) and time (*vertical axis*). Scattered dots are noise; a line represents a regular signal. For an extraterrestrial signal, the line is slanted, because Earth's rotation shifts the frequency. In this case, the transmission (*arrow*) comes from a spaceship—one of ours, Pioneer 10, which is now 73 times as far from the sun as Earth is.

system than within it. Well before 2050 the first truly interstellar missions will be flying out of our solar system, perhaps sent on the wings of giant solar sails. They will directly sample the prolific organic chemistry (already revealed by radio telescopes) present between the stars. They will not reach the nearest systems by 2050—with present technology, the trip would take tens of thousands of years—so we will have to study those systems remotely.

Window on the Worlds

By 2050 we will have catalogues of extrasolar planetary systems analogous to our current catalogues of stars. We will know whether our particular planetary system is typical or unusual (we suspect it will prove to be neither). Currently the only worlds our technology routinely detects are giant planets more massive than Jupiter. But advanced space-based telescopes will regularly detect Earth-size worlds around other stars, if they exist, and analyze their atmospheres for hints of biological processes. Such worlds would then become compelling targets for additional observations, including searches for intelligent signals.

Although we talk of searching for extraterrestrial intelligence (SETI), what we are seeking is evidence of extraterrestrial technologies. It might be better to use the acronym SET-T (pronounced the same) to acknowledge this. To date, we have concentrated on a very specific technology—radio transmissions at wavelengths with weak natural backgrounds and little absorption [see "The Search for Extraterrestrial Intelligence," by Carl Sagan and Frank Drake; Scientific American, May 1975]. No one has yet found any verified signs of a distant technology. But the null result may have more to do with limitations in range and sensitivity than with actual lack of civilizations. The most distant star probed directly is still less than 1 percent of the distance across our galaxy.

SETI, like all of radio astronomy, now faces a crisis. Humanity's voracious appetite for technologies that utilize the radio spectrum is rapidly obscuring the natural window with curtains of radio-frequency interference. This trend might eventually force us to take our search to the far side of the moon, the one place in the solar sys-

Lurking in the depths of Mars (*bottom*) or Europa (*top*) could be our fellow inhabitants of the solar system. The surface of Mars, crosscut by canyons, hints at a watery past. The surface of Europa, mishmashed by icebergs, hints at a subterranean ocean. Life survives deep in Earth's crust and oceans. Could it survive on these worlds, too?

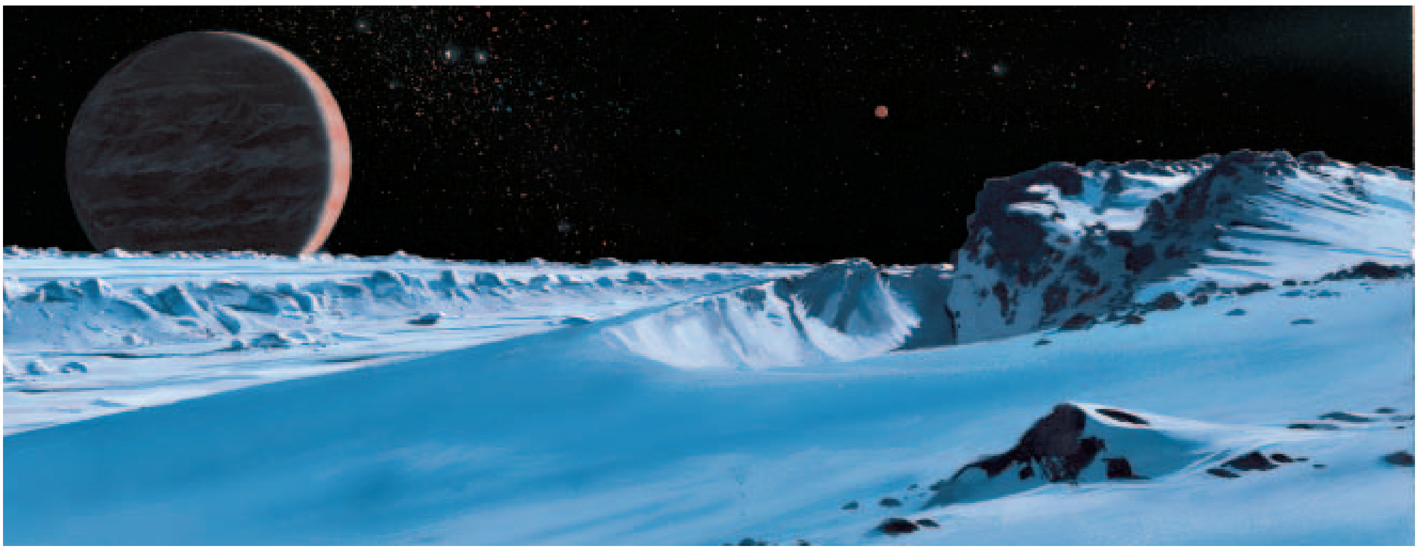
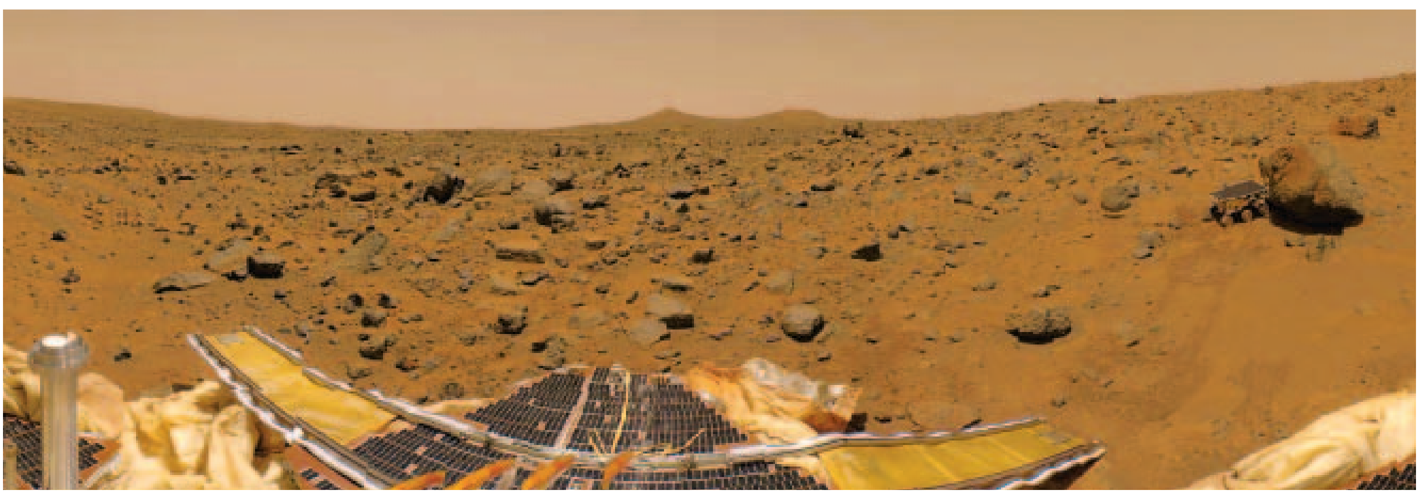


ILLUSTRATION BY RON MILLER



NASA/JET PROPULSION LABORATORY

tem that never has Earth in its sky. International agreements have already established a "shielded zone" on the moon, and some astronomers have discussed reserving the Saha crater for radio telescopes. If the path for human exploration of Mars proceeds via the moon, then by 2050 the necessary infrastructure may be in place.

Plans for the next few decades of SETI also envision the construction of a variety of ground-based instruments that offer greater sensitivity, frequency coverage and observing time. Currently all these plans rely on private philanthropic funding. For searches at radio frequencies, work has commenced on the One Hectare Telescope (1hT), which will permit simultaneous access to the entire microwave window. A large field of view—and a large amount of computational power—will enable dozens of objects to be observed at the same time, a mix of SETI targets and natural astronomical bodies. Radio astronomy and SETI will thus be able to share telescope resources, rather than compete for them, as is frequently the case now. The 1hT will also demonstrate one affordable way to build a still larger Square Kilometer Array (SKA) that could improve sensitivity by a factor of 100 over anything available today. For SETI, this factor of 100 translates into a factor of 10 in distance and 1,000 in the number of stars explored.

These arrays will be affordable because their hardware will derive from recent consumer products. To the extent possible, complexity will be transferred from concrete and steel to silicon and software. We will be betting on Moore's Law—the exponential increase in computing power over time. The SETI@home screensaver, which more than a million people around the globe have downloaded (from www.setiathome.ssl.berkeley.edu), illustrates the kind of parallel computation available even today. By 2050 we may have built many SKAs and used them to excise actively the growing amount of interference. If successful, such instruments will certainly be more affordable than an observatory on the lunar far side.

Recently other wavelength bands besides the radio have been receiving attention. Generations of stargazers have scanned the heavens with naked eyes and telescopes without ever seeing an artifact of astroengineering. But what if it flashed for only a billionth of a second? Limited searches for optical pulses have just begun. In the coming decades, optical SETI searches may move on to larger telescopes. If these initial searches do not succeed in finding other civilizations, they will at least probe astrophysical backgrounds at high time resolution.

The increased pace of solar system exploration will provide additional opportunities for SETI. We should keep our robotic eyes open for probes or other artifacts of an extraterrestrial technology. Despite tabloid reports of aliens and artifacts everywhere, scientific exploration so far has revealed no good evidence for any such things.

Sharing the Universe

Although we cannot state with confidence what we will know about other intelligent occupants of the universe in 2050, we can predict that whatever we know, everyone will know. Everyone will have access to the process of discovery. Anyone who is curious will be able to keep score of what searches have been done and which groups are looking at what, from where, at any given moment. The data generated by the searches will flow too quickly for humans to absorb, but the interesting signals, selected by silicon sieves, will be available for our perusal. In this way, we hope to supplant the purveyors of pseudoscience who attract the curious and invite them into a fantastic (and lucrative) realm of nonsense. Today the real data are too often inaccessible, whereas the manufactured data are widely available. The real thing is better, and it will be much easier to access in the future.

If by 2050 we have found no evidence of an extraterrestrial technology, it may be because technical intelligence almost never evolves, or because technical civilizations rapidly bring about their own destruction, or because we have not yet conducted an adequate search using the right strategy. If humankind is still here in 2050 and still capable of doing SETI searches, it will mean that our technology has not yet been our own undoing—a hopeful sign for life generally. By then we may begin considering the active transmission of a signal for someone else to find, at which point we will have to tackle the difficult questions of who will speak for Earth and what they will say. SA

The Authors

SETI INSTITUTE

JILL C. TARTER participated in her first search for extraterrestrial intelligence in 1976 while an astrophysics graduate student at the University of California, Berkeley. Her current effort is over 1,000 times as sensitive. Tarter's career bears a striking resemblance to that of Ellie Arroway, the heroine of Carl Sagan's novel *Contact*. Today she is the director of research for the SETI Institute in Mountain View, Calif. When not observing, lecturing or fund-raising, she enjoys flying a private plane and dancing the samba.

SETI INSTITUTE

CHRISTOPHER F. CHYBA is a planetary scientist whose research focuses on the origins of life and exobiology. He recently led the Science Definition Team for NASA's 2003 Orbiter mission to Europa. He now chairs the space agency's Solar System Exploration Subcommittee, which recommends priorities for solar system exploration. Chyba is a former director for international environmental affairs on the National Security Council staff at the White House. At the SETI Institute, he holds the endowed chair named for his graduate school adviser, Carl Sagan.

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Rise of the Robots

by Hans Moravec

By 2050 robot "brains" based on computers that execute 100 trillion instructions per second will start rivaling human intelligence

In recent years the mushrooming power, functionality and ubiquity of computers and the Internet have outstripped early forecasts about technology's rate of advancement and usefulness in everyday life. Alert pundits now foresee a world saturated with powerful computer chips, which will increasingly insinuate themselves into our gadgets, dwellings, apparel and even our bodies.

Yet a closely related goal has remained stubbornly elusive. In stark contrast to the largely unanticipated explosion of computers into the mainstream, the entire endeavor of robotics has failed rather completely to live up to the predictions of the 1950s. In those days, experts who were dazzled by the seemingly miraculous calculational ability of computers thought that if only the right software were written, computers could become the artificial brains of sophisticated autonomous robots. Within a decade or two, they believed, such robots would be cleaning our floors, mowing our lawns and, in general, eliminating drudgery from our lives.

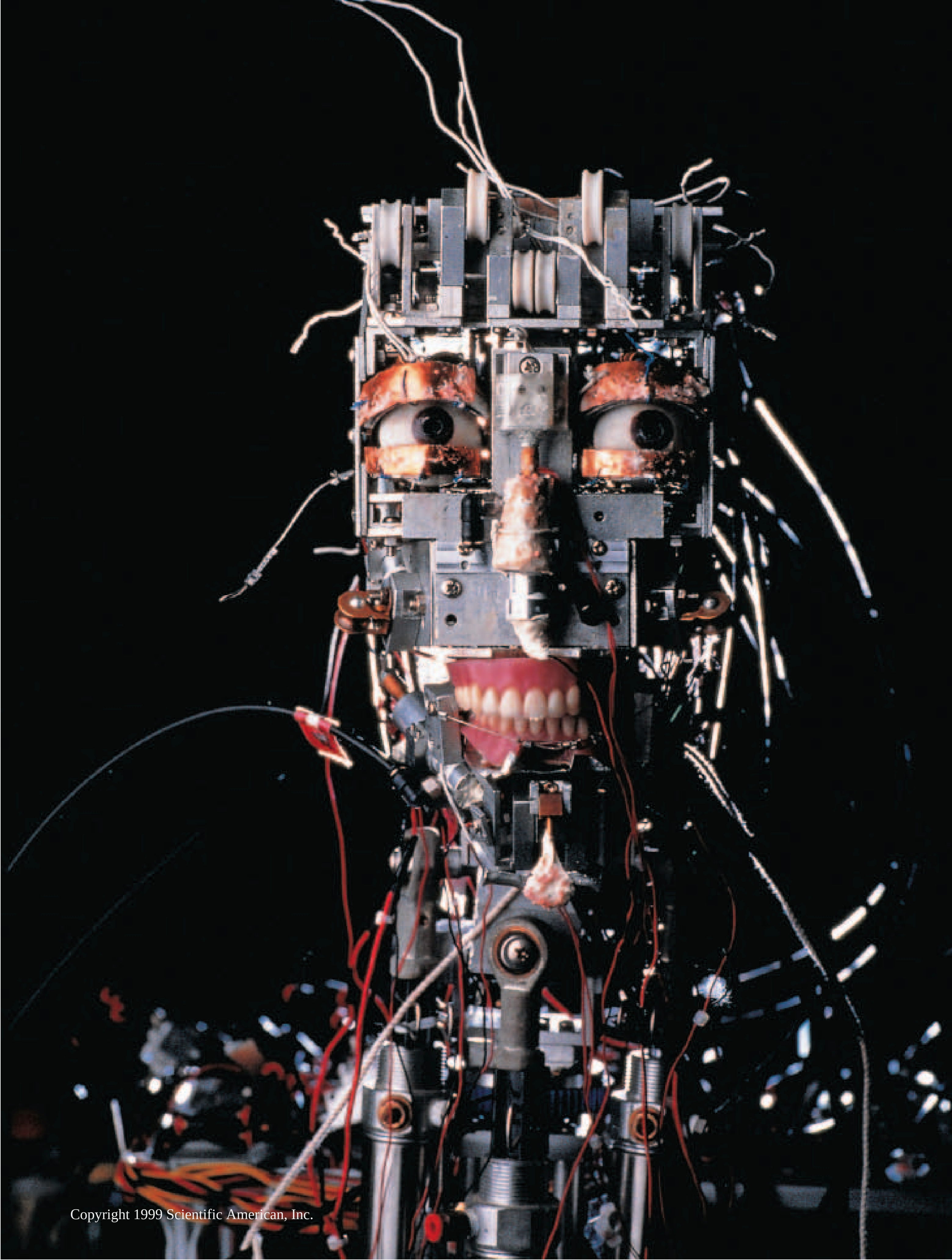
Obviously, it hasn't turned out that way. It is true that industrial robots have transformed the manufacture of automobiles, among other products. But that kind of automation is a far cry from the versatile, mobile, autonomous creations that so many scientists and engineers have hoped for. In pursuit of such robots, waves of researchers have grown disheartened and scores of start-up companies have gone out of business.

It is not the mechanical "body" that is unattainable; articulated arms and other moving mechanisms adequate for manual work already exist, as the industrial robots attest. Rather it is the computer-based artificial brain that is still well below the level of sophistication needed to build a humanlike robot.

Nevertheless, I am convinced that the decades-old dream of a useful, general-purpose autonomous robot will be realized in the not too distant future.

PETER MENZEL

Face robot at the Science University of Tokyo is used in research on how machines can show and respond to emotional expressions. Nonverbal communication will be important in later generations of robots because it will enable them to interact more smoothly with humans.



By 2010 we will see mobile robots as big as people but with cognitive abilities similar in many respects to those of a lizard. The machines will be capable of carrying out simple chores, such as vacuuming, dusting, delivering packages and taking out the garbage. By 2040, I believe, we will finally achieve the original goal of robotics and a thematic mainstay of science fiction: a freely moving machine with the intellectual capabilities of a human being.

Reasons for Optimism

In light of what I have just described as a history of largely unfulfilled goals in robotics, why do I believe that rapid progress and stunning accomplishments are in the offing? My confidence is based on recent developments in electronics and software, as well as on my own observations of robots, computers and even insects, reptiles and other living things over the past 30 years.

The single best reason for optimism is the soaring performance in recent years of mass-produced computers. Through the 1970s and 1980s, the computers readily available to robotics researchers were capable of executing about one million instructions per second (MIPS). Each of these instructions represented a very basic task, like adding two 10-digit numbers or storing the result in a specified location in memory.

JESSE EASUDES

Within a decade or two, experts believed, robots would be cleaning our floors, mowing our lawns and, in general, **eliminating drudgery from our lives.**

In the 1990s computer power suitable for controlling a research robot shot through 10 MIPS, 100 MIPS and has lately reached 1,000 in high-end desktop machines. Apple's new iBook laptop computer, with a retail price at the time of this writing of $1,600, achieves more than 500 MIPS. Thus, functions far beyond the capabilities of robots in the 1970s and 1980s are now coming close to commercial viability.

For example, in October 1995 an experimental vehicle called Navlab V crossed the U.S. from Washington, D.C., to San Diego, driving itself more than 95 percent of the time. The vehicle's self-driving and navigational system was built around a 25-MIPS laptop based on a microprocessor by Sun Microsystems. The Navlab V was built by the Robotics Institute at Carnegie Mellon University, of which I am a member. Similar robotic vehicles, built by researchers elsewhere in the U.S. and in Germany, have logged thousands of highway kilometers under all kinds of weather and driving conditions.

In other experiments within the past few years, mobile robots mapped and navigated unfamiliar office suites, and computer vision systems located textured objects and tracked and analyzed faces in real time. Meanwhile personal computers became much more adept at recognizing text and speech.

Still, computers are no match today for humans in such functions as recognition and navigation. This puzzled experts for many years, because computers are far superior to us in calculation. The explanation of this apparent paradox follows from the fact that the human brain, in its entirety, is not a true programmable, general-purpose computer (what computer scientists refer to as a universal machine; almost all computers nowadays are examples of such machines).

To understand why this is requires an evolutionary perspective. To survive, our early ancestors had to do several things repeatedly and very well: locate food, escape predators, mate and protect offspring. Those tasks depended strongly on the brain's ability to recognize and navigate. Honed by hundreds of millions of years of evolution, the brain became a kind of ultrasophisticated—but special-purpose—computer.

The ability to do mathematical calculations, of course, was irrelevant for survival. Nevertheless, as language transformed human culture, at least a small part of our brains evolved into a universal machine of sorts. One of the hallmarks of such a machine is its ability to follow an arbitrary set of instructions, and with language, such instructions could be transmitted and carried out. But because we visualize numbers as complex shapes, write them down and perform other such functions, we process digits in a monumentally awkward and inefficient way. We use hundreds of billions of neurons to do in minutes what hundreds of them, specially "rewired" and arranged for calculation, could do in milliseconds.

A tiny minority of people are born with the ability to do seemingly amazing mental calculations. In absolute terms, it's not so amazing: they calculate at a rate perhaps 100 times that of the average person. Computers, by comparison, are millions or billions of times faster.

Can Hardware Simulate Wetware?

The challenge facing roboticists is to take general-purpose computers and program them to match the largely special-purpose human brain, with its ultraoptimized perceptual inheritance and other peculiar evolutionary traits. Today's robot-controlling computers are much too feeble to be applied successfully in that role, but it is only a matter of time before they are up to the task.

Implicit in my assertion that computers will eventually be capable of the same kind of perception, cognition and thought as humans is the idea that a sufficiently advanced and sophisticated artificial system—for example, an electronic one—can be made and programmed to do the same thing as the human nervous system, including the brain. This issue is controversial in some circles right now, and there is room for brilliant people to disagree.

At the crux of the matter is the question of whether biological structure and behavior arise entirely from physical law and whether, moreover, physical law is computable—that is to say, amenable to computer simulation. My view is that there is no good scientific evidence to negate either of these propositions. On the contrary, there are compelling indications that both are true.

Molecular biology and neuroscience are steadily uncovering the physical mechanisms underlying life and mind but so far have addressed mainly the simpler mechanisms. Evidence that simple functions can be composed to produce the higher capabilities of nervous systems comes from programs that read, recognize speech, guide robot arms to assemble tight components by feel, classify chemicals by artificial smell and taste, reason about abstract matters and so on. Of course, computers and robots today fall far short of broad human or even animal competence. But that situation is understandable in light of an analysis, summarized in the next section, that concludes that today's computers are only powerful enough to function like insect nervous systems. And, in my experience, robots do indeed perform like insects on simple tasks.

Ants, for instance, can follow scent trails but become disoriented when the trail is interrupted. Moths follow pheromone trails and also use the moon for guidance. Similarly, many commercial robots today follow guide wires installed beneath the surface they move over, and some orient themselves using lasers that read bar codes on walls.

If my assumption that greater computer pow-

Third-generation robots will have computer "brains" that process around five million million instructions per second, giving them intelligence similar to that of monkeys. They will perform a variety of routine domestic and manual chores.

SPACE CHANNEL/PHILIP SAUNDERS/ GORDON CHAPMAN

Shuttle robot moves people over a predefined area, locating itself with respect to magnets in a grid pattern on the ground. Based in Utrecht, the Netherlands, the company that built the machine, Frog, took its name from the acronym for "free ranging on grid."

er will eventually lead to human-level mental capabilities is true, we can expect robots to match and surpass the capacity of various animals and then finally humans as computer-processing rates rise sufficiently high. If on the other hand the assumption is wrong, we will someday find specific animal or human skills that elude implementation in robots even after they have enough computer power to match the whole brain. That would set the stage for a fascinating scientific challenge—to somehow isolate and identify the fundamental ability that brains have and that computers lack. But there is no evidence yet for such a missing principle.

The second proposition, that physical law is amenable to computer simulation, is increasingly beyond dispute. Scientists and engineers have already produced countless useful simulations, at various levels of abstraction and approximation, of everything from automobile crashes to the "color" forces that hold quarks and gluons together to make up protons and neutrons.

Nervous Tissue and Computation

If we accept that computers will eventually become powerful enough to simulate the mind, the question that naturally arises is: What processing rate will be necessary to yield performance on a par with the human brain? To explore this issue, I have considered the capabilities of the vertebrate retina, which is understood well enough to serve as a Rosetta stone roughly relating nervous tissue to computation. By comparing how fast the neural circuits in the retina perform image-processing operations with how many instructions per second it takes a computer to accomplish similar work, I believe it is possible to at least coarsely estimate the information-processing power of nervous tissue—and by extrapolation, that of the entire human nervous system.

The human retina is a patch of nervous tissue in the back of the eyeball half a millimeter thick and approximately two centimeters across. It consists mostly of light-sensing cells, but one tenth of a millimeter of its thickness is populated by image-processing circuitry that is capable of detecting edges (boundaries between light and dark) and motion for about a million tiny image regions. Each of these regions is associated with its own fiber in the optic nerve, and each performs about 10 detections of an edge or a motion each second. The results flow deeper into the brain along the associated fiber.

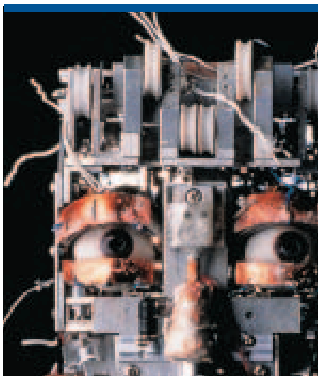
From long experience working on robot vision systems, I know that similar edge or motion detection, if performed by efficient software, requires the execution of at least 100 computer instructions. Thus, to accomplish the retina's 10 million detections per second would require at least 1,000 MIPS.

The entire human brain is about 75,000 times heavier than the 0.02 gram of processing circuitry in the retina, which implies that it would take, in round numbers, 100 million MIPS (100 trillion instructions per second) to emulate the 1,500-gram human brain. Personal computers in 1999 beat certain insects but lose to the human retina and even to the 0.1-gram brain of a goldfish. A typical PC would have to be at least a million times more powerful to perform like a human brain.

Brainpower and Utility

Though dispiriting to artificial-intelligence experts, the huge deficit does not mean that the goal of a humanlike artificial brain is unreachable. Computer power for a given price doubled each year in the 1990s, after doubling every 18 months in the 1980s, and every two years before that. Prior to 1990 this progress made possible a great decrease in the cost and size of robot-controlling computers. Cost went from many millions of dollars to a few thousand, and size went from room-filling to handheld. Power, meanwhile, held steady at about 1 MIPS. Since 1990 cost and size reductions have abated, but power has risen to near 1,000 MIPS per computer. At the present pace, only about 30 or 40 years will be needed to close the millionfold gap. Better yet, useful robots don't need full human-scale brainpower.

Commercial and research experiences convince me that the mental power of a guppy—about 1,000 MIPS—will suffice to guide mobile utility robots reliably through unfamiliar surroundings, suiting them for jobs in hundreds of thousands of



Asked why there are candles on the table, **a third-generation robot might reply** that it put them there because its owner likes candlelit dinners and it likes to please its owner.

industrial locations and eventually hundreds of millions of homes. Such machines are less than a decade away but have been elusive for so long that only a few dozen small research groups are now pursuing them.

Commercial mobile robots—the smartest to date, barely insectlike at 10 MIPS—have found few jobs. A paltry 10,000 work worldwide, and the companies that made them are struggling or defunct. (Makers of robot manipulators are not doing much better.) The largest class of commercial mobile robots, known as Automatic Guided Vehicles (AGVs), transport materials in factories and warehouses. Most follow buried signal-emitting wires and detect end points and collisions with switches, a technique developed in the 1960s.

It costs hundreds of thousands of dollars to install guide wires under concrete floors, and the routes are then fixed, making the robots economical only for large, exceptionally stable factories. Some robots made possible by the advent of microprocessors in the 1980s track softer cues, like magnets or optical patterns in tiled floors, and use ultrasonics and infrared proximity sensors to detect and negotiate their way around obstacles.

The most advanced industrial mobile robots, developed since the late 1980s, are guided by occasional navigational markers—for instance, laser-sensed bar codes—and by preexisting features such as walls, corners and doorways. The costly labor of laying guide wires is replaced by custom software that is carefully tuned for each route segment. The small companies that developed the robots discovered many industrial customers eager to automate transport, floor cleaning, security patrol and other routine jobs. Alas, most buyers lost interest as they realized that installation and route changing required time-consuming and expensive work by experienced route programmers of inconsistent availability. Technically successful, the robots fizzled commercially.

In failure, however, they revealed the essentials for success. First, the physical vehicles for various jobs must be reasonably priced. Fortunately, existing AGVs, forklift trucks, floor scrubbers and other industrial machines designed for human riders or for following guide wires can be adapted for autonomy. Second, the customer should not have to call in specialists to put a robot to work or to change its routine; floor cleaning and other mundane tasks cannot bear the cost, time and uncertainty of expert installation. Third, the robots must work reliably for at least six months before encountering a problem or a situation requiring downtime for reprogramming or other alterations. Customers routinely rejected robots that after a month of flawless operation wedged themselves in corners, wandered away lost, rolled over employees' feet or fell down stairs. Six months, though, earned the machines a sick day.

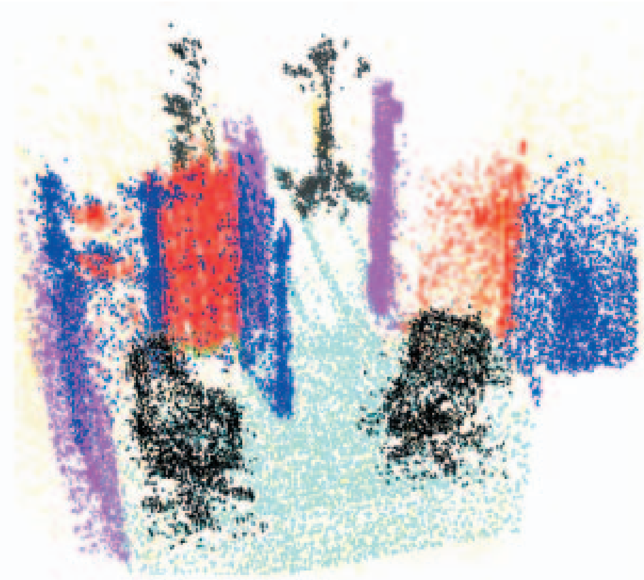
Robots exist that have worked faultlessly for years, perfected by an iterative process that fixes the most frequent failures, revealing successively rarer problems that are corrected in turn. Unfortunately, that kind of reliability has been achieved only for prearranged routes. An insectlike 10 MIPS is just enough to track a few handpicked landmarks on each segment of a robot's path. Such robots are easily confused by minor surprises such as shifted bar codes or blocked corridors (not unlike ants thrown off a scent trail or a moth that has mistaken a streetlight for the moon).

P3 Robot cost several million dollars to build and is one of the most advanced self-contained robots in existence today. Its primary skill is walking, which it can do up and down stairs and on flat, sloped ground. Unfortunately, it can stroll for only about 25 minutes before its battery is exhausted. The robot was built at Honda Motors of Japan.

PETER MENZEL

A Sense of Space

Robots that chart their own routes emerged from laboratories worldwide in the mid-1990s, as microprocessors reached 100 MIPS. Most build two-dimensional maps from sonar or



HANS MORAVEC

Robot vision would convey the key elements of a scene in a map useful for navigation. The latest maps, such as the one at the right, are three-dimensional and convey details down to centimeter-scale. The map was made from 20 stereoscopic images.

laser rangefinder scans to locate and route themselves, and the best seem able to navigate office hallways for days before becoming disoriented. Of course, they still fall far short of the six-month commercial criterion. Too often different locations in the coarse maps resemble one another. Conversely, the same location, scanned at different heights, looks different, or small obstacles or awkward protrusions are overlooked. But sensors, computers and techniques are improving, and success is in sight.

My small laboratory is in the race. In the 1980s we devised a way to distill large amounts of noisy sensor data into reliable maps by accumulating statistical evidence of emptiness or occupancy in each cell of a grid representing the surroundings. The approach worked well in two dimensions and guides many of the robots described above.

Three-dimensional maps, 1,000 times richer, promised to be much better but for years seemed computationally out of reach. In 1992 we used economies of scale and other tricks to reduce the costs of three-dimensional maps 100-fold. We now have a test program that accumulates thousands of measurements from stereoscopic camera glimpses to map a room's volume down to centimeter-scale. With 1,000 MIPS, the program digests over a glimpse per second, adequate for slow indoor travel.

Robot, Version 1.0

One thousand MIPS is only now appearing in high-end desktop PCs. In a few years it will be found in laptops and similar smaller, cheaper computers fit for robots. To prepare for that day, we recently began an intensive three-year project to develop a prototype for commercial products based on such a computer. We plan to automate learning processes to optimize hundreds of evidence-weighing parameters and to write programs to find clear paths, locations, floors, walls, doors and other objects in the three-dimensional maps. We will also test programs that orchestrate the basic capabilities into larger tasks, such as delivery, floor cleaning and security patrol.

The initial testbed will be a small camera-studded mobile robot. Its intelligence will come from two computers: an Apple iBook laptop on board the robot, and an off-board Apple G4–based machine with about 1,000 MIPS that will communicate wirelessly with the iBook. Tiny mass-produced digital camera chips promise to be the cheapest way to get the millions of measurements needed for dense maps.

As a first commercial product, we plan a basketball-size "navigation head" for retrofit onto existing industrial vehicles. It would have multiple stereoscopic cameras, generic software for mapping, recognition and control, a different program for its specific application (such as floor cleaning), and a hardware connection to vehicle power, controls and sensors. Head-equipped vehicles with transport or patrol programs could be taught new routes simply by leading them through once. Floor-cleaning programs would be shown the boundaries of their work area.

Introduced to a job location, the vehicles would understand their changing surroundings competently enough to work at least six months without debilitating mistakes. Ten thousand AGVs, 100,000 cleaning machines and, possibly, a million forklift trucks are candidates for retrofit, and robotization may greatly expand those markets.

Fast Replay

Income and experience from spatially aware industrial robots would set the stage for smarter yet cheaper ($1,000 rather than $10,000) consumer products, starting probably with small robot vacuum cleaners that automatically learn their way around a home, explore unoccupied rooms and clean whenever needed. I imagine a machine low enough to fit under some furniture, with an even lower extendable brush, that returns to a docking station to recharge and disgorge its dust load. Such machines could open a true mass market for robots.

Commercial success will provoke competition and accelerate investment in manufacturing, engineering and research. Vacuuming robots ought to beget smarter cleaning robots with dusting, scrubbing and picking-up arms, followed by larger multifunction utility robots with stronger, more dexterous arms and better sensors. Programs will be written to make such machines pick up clutter, store, retrieve and deliver things, take inventory, guard homes, open doors, mow lawns, play games and so on. New applications will expand the market and spur further advances when robots fall short in acuity, precision, strength, reach, dexterity, skill or processing power. Capability, numbers sold, engineering and manufacturing quality, and cost-effectiveness will increase in a mutually reinforcing spiral. Perhaps by 2010 the process will have produced the first broadly competent "universal robots," as big as people but with lizardlike 5,000-MIPS minds that can be programmed for almost any simple chore.

Like competent but instinct-ruled reptiles, first-generation universal robots will handle only contingencies explicitly covered in their application programs. Unable to adapt to changing circumstances, they will often perform inefficiently or not at all. Still, so much physical work awaits them in businesses, streets, fields and homes that robotics could begin to overtake pure information technology commercially.

A second generation of universal robot with a mouselike 100,000 MIPS will adapt as the first generation does not and will even be trainable. Besides application programs, such robots would host a suite of software "conditioning modules" that would generate positive and negative reinforcement signals in predefined circumstances. For example, doing jobs fast and keeping its batteries charged will be positive; hitting or breaking something will be negative. There will be other ways to accomplish each stage of an application program, from the minutely specific (grasp the handle underhand or overhand) to the broadly general (work indoors or outdoors). As jobs are repeated, alternatives that result in positive reinforcement will be favored, those with negative outcomes shunned. Slowly but surely, second-generation robots will work increasingly well.

A monkeylike five million MIPS will permit a third generation of robots to learn very quickly from mental rehearsals in simulations that model physical, cultural and psychological factors. Physical properties include shape, weight, strength, texture and appearance of things, and how to handle them. Cultural aspects include a thing's name, value, proper location and purpose. Psychological factors, applied to humans and robots alike, include goals, beliefs, feelings and preferences. Developing the simulators will be a huge undertaking involving thousands of programmers and experience-gathering robots. The simulation would track external events and tune its models to keep them faithful to reality. It would let a robot learn a skill by imitation and afford a kind of consciousness. Asked why there are candles on the table, a third-generation robot might consult its simulation of house, owner and self to reply that it put them there because its owner likes candlelit dinners and it likes to please its owner. Further queries would elicit more details about a simple inner mental life concerned only with concrete situations and people in its work area.

Fourth-generation universal robots with a humanlike 100 million MIPS will be able to abstract and generalize. They will result from melding powerful reasoning programs to third-generation machines. These reasoning programs will be the far more sophisticated descendants of today's theorem provers and expert systems, which mimic human reasoning to make medical diagnoses, schedule routes, make financial decisions, configure computer systems, analyze seismic data to locate oil deposits and so on.

Properly educated, the resulting robots will become quite formidable. In fact, I am sure they will outperform us in any conceivable area of endeavor, intellectual or physical. Inevitably, such a development will lead to a fundamental restructuring of our society. Entire corporations will exist without any human employees or investors at all. Humans will play a pivotal role in formulating the intricate complex of laws that will govern corporate behavior. Ultimately, though, it is likely that our descendants will cease to work in the sense that we do now. They will probably occupy their days with a variety of social, recreational and artistic pursuits, not unlike today's comfortable retirees or the wealthy leisure classes.

The path I've outlined roughly recapitulates the evolution of human intelligence—but 10 million times more rapidly. It suggests that robot intelligence will surpass our own well before 2050. In that case, mass-produced, fully educated robot scientists working diligently, cheaply, rapidly and increasingly effectively will ensure that most of what science knows in 2050 will have been discovered by our artificial progeny! SA

The Author

PETER MENZEL

HANS MORAVEC is a principal research scientist at the Robotics Institute at Carnegie Mellon University. Over the past 40 years he has worked on eight mobile robots, the first of which—an assemblage of tin cans, batteries, lights and a motor—he constructed at age 10. His current work focuses on enabling robots to determine their position and to navigate by a three-dimensional awareness of their surroundings.

Further Information

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MATHEMATICAL RECREATIONS

by Ian Stewart

Defend the Roman Empire!

During World War II, when General Douglas MacArthur was conducting military operations in the Pacific theater, he adopted a strategy of "island-hopping"—moving troops from one island to a nearby one, but only when he could leave behind a large enough garrison to keep the first island secure. A similar deployment problem faced the Roman emperor Constantine in the fourth century A.D., only his task was to maintain the security of an entire empire. He decided on what appears to be the first recorded use of the strategy that MacArthur later adopted in the Pacific.

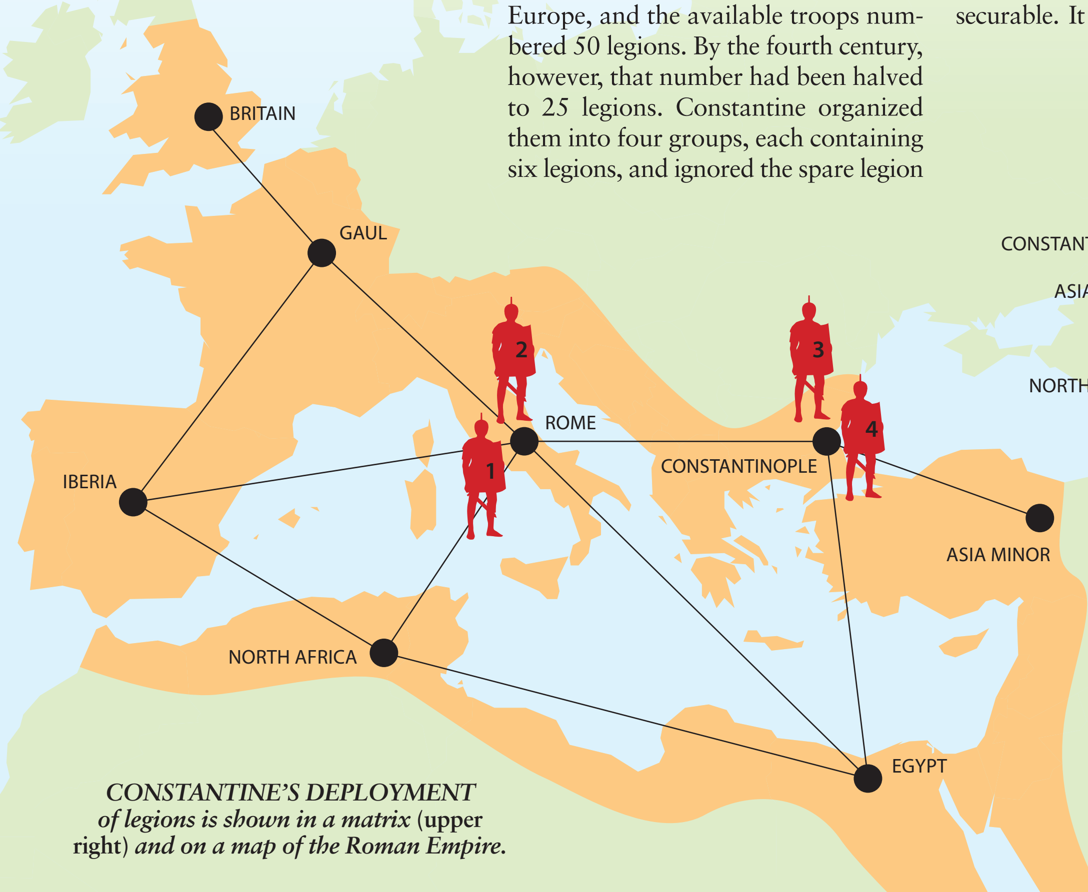
Is it possible, however, that Constantine could have deployed his legions more effectively? In 1997 Charles S. ReVelle of Johns Hopkins University and Kenneth E. Rosing of Erasmus University in Rotterdam, the Netherlands, applied a mathematical technique called zero-one programming to study Constantine's problem. Their work is a beautiful example—simple but instructive—of this technique in action, and it also forms the basis of an enjoyable game. Their analysis was published in the *Johns Hopkins Magazine* in April 1997 and will appear in the *American Mathematical Monthly* next year. Problems of this type, though usually far more complex, often arise in commercial and military decision making.

As a warm-up puzzle, consider a simplified version of the Roman Empire at the time of Constantine [*see illustration below*]. This "game board" shows eight regions (circles) from Asia Minor to Britain, together with the routes (lines) that link the regions. In the third century the empire's forces dominated most of Europe, and the available troops numbered 50 legions. By the fourth century, however, that number had been halved to 25 legions. Constantine organized them into four groups, each containing six legions, and ignored the spare legion left over (which in practice made one group contain seven legions, not six). He devised some simple rules for deploying and moving troops, aimed at producing adequate security, and then worked out the logical consequences of those rules.

Think of each group of six legions as a single piece, to be placed on the circles marked on the game board. Here are Constantine's rules:

- A region is securable if a piece can be moved to it in a single step from an adjacent region.
- At least two pieces must occupy a region before a piece can move out of it (that is, at least one piece must remain behind).

Given these rules, how can you allocate your groups to secure the entire empire—or, failing that, as much of it as possible? The illustration shows Constantine's solution: two groups at Rome and two at his newly founded capital, Constantinople. Notice that with this deployment, one region—Britain—is not securable. It takes four moves to get a



	PIECE 1	2	3	4
ROME	1	1	0	0
EGYPT	0	0	0	0
CONSTANTINOPLE	0	0	1	1
ASIA MINOR	0	0	0	0
IBERIA	0	0	0	0
NORTH AFRICA	0	0	0	0
GAUL	0	0	0	0
BRITAIN	0	0	0	0

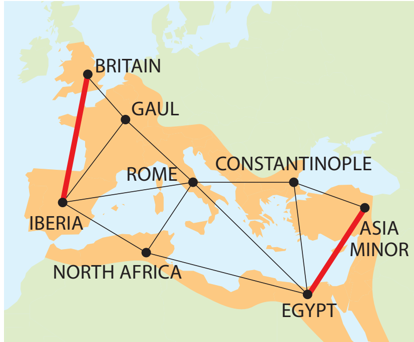
***CONSTANTINE'S DEPLOYMENT** of legions is shown in a matrix* (upper right) *and on a map of the Roman Empire.*

ILLUSTRATIONS BY BRYAN CHRISTIE

group to Britain. Here's one way: First, move a piece from Rome to Gaul (thereby securing Gaul, which would doubtless have been much more important to the Romans than distant, cold, wet Britain). Then move a piece from Constantinople to Rome, then to Gaul, and finally to Britain itself.

Is it possible to improve on Constantine's deployment? Yes, in the sense that a deployment exists in which every region can be secured in only one move. Simply place two pieces in Rome, one in Britain and one in Asia Minor. Why did Constantine not do this? After all, it gives Rome sufficient protection—12 legions—just like the emperor's solution. It seems likely that he felt dissatisfied with this deployment because it would leave the empire seriously weakened if trouble arose on two different fronts. Once one piece has left Rome, all the pieces are stuck in place, disallowing the possibility of a second move.

A more complex version of the problem is shown in the illustration above, which depicts two extra routes: one between Iberia and Britain and another between Egypt and Asia Minor. In this



***MORE COMPLEX VERSION** of Constantine's problem includes extra routes between regions* (red).

case, our improved solution—two pieces in Rome, one in Britain and one in Asia Minor—still secures the entire empire in only one move. We now have new connections that make further troop movements possible, however, and we can ask whether there are any other solutions. I will answer that question toward the end of this column.

Let me say a little about the mathematics that can be used to solve more complex puzzles of this kind. The general area is known as programming and involves representing all such problems in an algebraic form. One way is to make a table (the fancy term is matrix) whose rows correspond to regions and whose columns correspond to pieces. The matrix for Constantine's problem has eight rows and four columns. We can use a 1 to indicate that a given piece is in a given region and a 0 to show that it is not in any other region. The illustration on the opposite page shows the matrix corresponding to Constantine's solution. His rules can be restated as rules for changing the entries of such matrices, and so the puzzle can be reformulated algebraically. For obvious reasons, questions such as this are known as zero-one programming problems.

I won't go into technical details, but it's worth observing that ReVelle and Rosing's method breaks the problem up into two different ones. The first is the Set Covering Deployment Problem. This ignores the constraint that there are four pieces and instead asks for the smallest number of pieces that can be placed so that all regions can be secured in only one move. (If the answer is more than four, then Constantine's problem can't be solved.) The second problem is complementary to the first and is known as the Maximal Covering Deployment Problem. This asks for the largest number of regions that can be secured (in one move or none) with four pieces.

ReVelle and Rosing invented general methods, embodied as software, to solve each of these problems. The two methods together bracket Constantine's problem, telling us whether a solution exists with four pieces (yes) and whether fewer pieces would work (no). Moreover, these methods make it possible to solve any allocation puzzle of this kind.

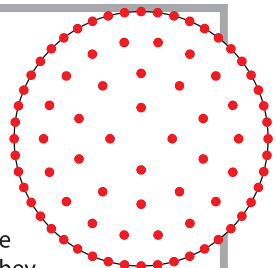
Now I will reveal the solutions to Constantine's problem. There are six. The figures in parentheses show how many pieces to put in the named regions:

1. Iberia (2), Egypt (2).
2. Iberia (2), Constantinople (2).
3. Iberia (2), Asia Minor (2).
4. Britain (2), Egypt (2).
5. Britain (1), Rome (2), Asia Minor (1).
6. Gaul (2), Egypt (2).

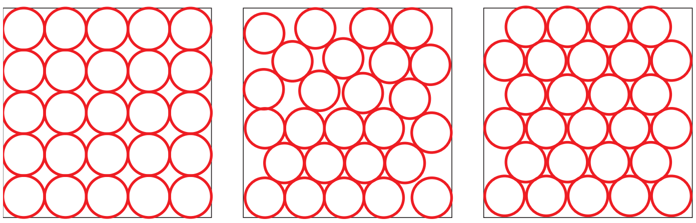
As it happens, Constantine's successors lost control of Britain. The causes were surely more complex than anything that can be explained by this simple model. Nevertheless, one might argue that if Constantine had been a better mathematician, the Roman Empire might have lasted a little longer than it did. SA

FEEDBACK

In "Tight Tins for Round Sardines" [February 1998], I discussed how to pack as many circles as possible into containers of various shapes—square, circular and triangular. Since then, Kari J. Nurmela of the Helsinki University of Technology has sent me four research papers on the subject (two written with Patric R. J. Östergård). One paper provides computer-assisted proofs of the optimal packings of a square by up to 27 circles (three packings are shown below). Another paper discusses a subtly different problem: how to distribute point charges in a circular disk so as to minimize the total energy. Because the charges repel one another, they tend to space themselves in concentric rings (*above*). Readers can e-mail Kari.Nurmela@hut.fi for further details. —*I.S.*



25 CIRCLES 26 CIRCLES 27 CIRCLES



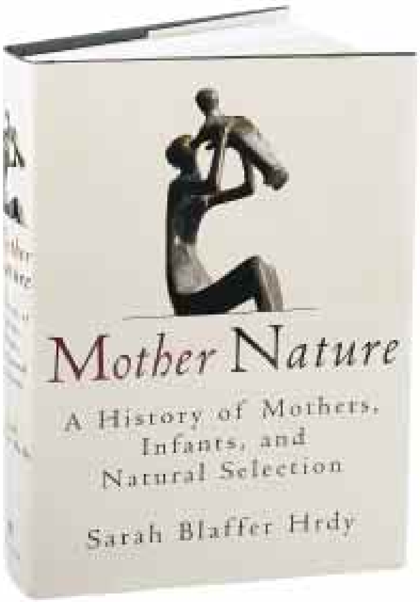
Editors' note: Correspondence for Feedback is welcome, but it is not always possible to send a reply, and materials included cannot be returned.

BRYAN CHRISTIE

MOTHER NATURE IS AN OLD LADY WITH BAD HABITS

Review by Helen Fisher

Mother Nature: A History of Mothers, Infants, and Natural Selection
SARAH BLAFFER HRDY
Pantheon Books, New York ($35)



BETH PHILLIPS

"I am the family face; flesh perishes, I live on, projecting trait and trace through time to times anon." Thomas Hardy was talking about our heredity—all those physical attributes and behavior patterns that distinguish us as human beings. But, as Sarah Blaffer Hrdy reminds us in her impressive new book, *Mother Nature,* the distinction between the human animal and other creatures is far from absolute. We share some 98 percent of our DNA with chimpanzees. We share basic bodily substances such as the endorphins, natural opiates that contribute to the "runner's high," with earthworms. In fact, only a mere 50 or so genes (as well as several regulatory genes that control the timing of gene expression) account for our humanness. Much of our "family face" stems from others who swam, crawled or brachiated in aeons past.

And our feminine forebears were busy. Be they beetles or rhinos, all creatures must adhere to a basic principle if they are to spread their genes into tomorrow. Either they bear young themselves and see that those infants live, or they help their relatives rear offspring—individuals who share some of their DNA. So under every rock, in every tree, in burrows, reefs and tenements, mothers have always worked to win the only game in town, reproduction. Passive, egg-making machines? Hardly. Ambitious? Absolutely. Hrdy has assimilated a cornucopia of data and ideas about the biology and behavior of mothers great and small to shed light on this venerable occupation: mothering.

Fundamental to her argument is the proposition that mothers are "flexible, manipulative opportunists." How much a mother—of any species, including our own—invests in her newborns depends on the number in her litter, the ratio of sons to daughters, her infants' health, their size and weight, and all the social conditions that will abet or deter her from parenting. Spiders, fish, birds, mice, wolves, lions, tigers, hippos: mothers of all varieties size up the perquisites and deficits of rearing babies. And when they sense that they cannot rear their offspring to maturity, they cull their litters or abandon or cannibalize their young. Mothers are "pro-choice"; family planning is much older than humanity.

Mother golden hamsters, for example, eat their runts when food is scarce. Mother gulls, eagles and herons lay their eggs about a day apart; the first-laid eggs hatch several days before the last ones. This way the mother keeps potentially lethal predators—her elder young—on hand in the nest. If food supplies begin to dwindle, she lets these stronger offspring dominate the less mature ones; with time her own infants trim her brood. When a strange, potentially infanticidal male wanders into the territory of a pregnant house mouse or lemming, the expectant mother reabsorbs her embryos. Pregnant female monkeys sometimes spontaneously abort when a new male usurps command of their troop. Maternal infanticide, abortion and infant abandonment—seen in human societies everywhere—are traditions in the natural world.

In fact, human babies have evolved strategies to win their mothers' hearts. Why, for example, are infants plump? Hrdy notes that no other primate infants are fat; hence, this peculiar trait must have appeared during human evolution. She then reviews four possibilities. Insulation cannot be the answer; other primates huddle to stay warm. The stored baby fat could be an insurance policy, a reserve for emergencies. But monkeys and apes have not employed this mechanism to counter the vicissitudes of infancy. This baby fat could have provided ancestral infants with larders to feed their rapidly expanding, fat-guzzling brains instead. But such provisions could have been stockpiled after birth so this lipid baggage would not jeopardize the infant as it squeezed through the treacherously narrow birth canal. Hrdy concludes that babies put on their fat before birth to advertise to mothers that they are, if I may use the term, "keepers," that they are healthy, that they can survive. Babies are plump in order to be loved.

Mother Knows Best

Once convinced that they should expend their precious parental energy, mothers go to great lengths to rear their young. Most impressive is the Australian social spider. As her spiderlings mature, she begins to turn into mush. As she liquefies, her children suck her up. Sated from this sacrificial meal of mother, they exercise better manners and forgo eating one another as well.

Mothers also engage other females to assist them in mothering. These helpers are known as allomothers. For example, female elephants share nursing duties with maternal kin. This strategy has been popular with women, too. From medieval times until recently, elite women of Europe, Asia and the Near East enlisted wet nurses. But our species has also acquired a singular kind of allomother: postmenopausal women. Many scientists now believe that menopause—a uniquely human biological attribute—probably evolved so that ancestral women could conserve their energy in middle age and help daughters rear young instead.

"The dark, uneasy world of family life—where the greatest can fail and the humblest succeed," wrote poet Randall Jarrell. Everywhere mothers strive to win. But, as Hrdy reminds us, all must balance familial chores with another demand: the need to work, to provide for themselves.

Take Flo. Flo was a member of a chimp community at the Gombe Stream Reserve in Tanzania when Jane Goodall arrived in the 1960s to study ape behavior. Hrdy reports that Flo was confident, gentle, intelligent—and popular with the males. She worked to build a powerful web of local connections and carved out a bountiful, safe personal territory in the heart of her homeland. When she died, she bequeathed to her daughter, Fifi, a strong network of local kin contacts that enabled her to remain in her natal home. (Some 50 percent of pubescent females must emigrate to another community to reproduce.) Flo's work paid off. Fifi thrives. Her two sons became the highest-ranking members of the group. And her daughter, Fanni, had the earliest anogenital swelling on record, at age 8.5 years, an indication that she will probably bear many young. Hrdy's point is that industrious mothers of many species are able to translate their hard work into reproductive payoffs. This may be one reason, conscious or otherwise, that many modern women work so hard to succeed in their careers.

Sarah Hrdy, an emeritus professor of anthropology at the University of California at Davis and the author of *The Woman That Never Evolved,* has made important contributions to anthropology. She is well known for her work in southern India, where she began studying langur monkeys in 1971. She soon noticed that after male interlopers stole control of the troop, they seized and killed the infants. Curiously, the infantless mothers soon became sexually receptive again. Thus, by eliminating the young, triumphant males acquired the opportunity to spread their seed. Moreover, the mothers willingly mated with the conquerors, grabbing the chance to bear new young. After learning this, I noticed that this phenomenon is seen even in Shakespeare. In *Richard III,* soon after Richard slaughters the husband of Lady Anne, he begins to woo her. To his amazement, she succumbs. Richard muses, "Was ever woman in this humor woo'd? Was ever woman in this humor won?" Yes. Hrdy tells us that females in 35 species breed with their conquerors—even after their infants have been massacred.

Mothers are "flexible, manipulative opportunists."

"Studying infanticide in other primates turned out to be only the beginning of my quest to understand female nature and motherhood in particular," Hrdy writes. "This quest lured me to do research in seven countries over thirty years, drawing on extremely unlikely sources of information—last wills and testaments, documents from foundling homes, folktales, even the pages of phone books—in my effort to learn about parental attitudes in my own species. Along the way, I have come to understand just how flexible parental emotions in humans can be. Whatever maternal *instincts* are, they are not automatic in the sense that most people use that term. Most important, I have learned that even though the world has undergone immense change since our ancestors lived by foraging, many of the basic outlines of the dilemmas mothers confront remain remarkably constant."

Hrdy's book is thorough, thoughtful and clearly written. It is also a trove of factual treasures. Did you know that fresh mother's milk can kill a common form of dysentery-causing amoebas? This may be why the Swedish rub mother's milk on babies to curb diaper rash. Moreover, as mother mammals lick their babies, they ingest the pathogens residing on their young. Then they manufacture antibodies to these killers and secrete these antibodies in the teat milk they feed their offspring.

One comes away from this book with a vital message: we have much in common with other living creatures on earth. As Wendell Berry put it, we are part of "the larger circle of all creatures, passing in and out of life, who move also in a dance, to a music so subtle and vast that no ear hears it except in fragments." Hrdy has caught the beat—and elegantly exposed some of nature's secrets. As I look around during my morning jog at the earthworms that cross my trail and the pigeons that waddle through New York City's Central Park, I feel some sympathy for all creatures struggling to survive. At the throat of this timeless process are billions on billions of mothers who want their children to succeed.

HELEN FISHER, an anthropologist at Rutgers University, is the author of The First Sex: The Natural Talents of Women and How They Are Changing the World *(Random House, 1999) and* Anatomy of Love: The Natural History of Monogamy, Adultery, and Divorce *(W. W. Norton, 1992).*

THE EDITORS RECOMMEND

HOW WE BELIEVE: THE SEARCH FOR GOD IN AN AGE OF SCIENCE. Michael Shermer. W. H. Freeman and Company, New York, 1999 ($24.95).

Shermer marches bravely into the arena where theists, atheists and agnostics argue their views, usually without convincing anyone not on their side. As editor of *Skeptic* and director of the Skeptics Society and a man (trained in psychology) who has been successively a theist, an atheist and an agnostic, he might seem to the religious to have a bias against their convictions. But he says his "primary focus in addressing readers is not whether they believe or disbelieve, but *how* and *why* they have made their particular belief choice." He has asked the question of many people, and he summarizes their reasoning. His discussion ranges eloquently and learnedly over broad areas of philosophy, theology and science. In the end, whatever the reader's own thinking, she will probably discover that she has learned a lot about the opinions other people have on "the God Question" and why they hold those opinions.

FROM *HOW WE BELIEVE*

Virus: The Co-discoverer of HIV Tracks Its Rampage and Charts the Future. Luc Montagnier. Translated from the French by Stephen Sartarelli. W. W. Norton and Company, New York, 1999 ($24.95).

French virologist Montagnier presents here what amounts to a basic course on AIDS for the layman. He describes the first manifestations of the disease in humans 20 years ago and tells of the intense microbiological detective work involved in the search for the causative virus—work in which he played a leading role. Then he discusses AIDS treatments and the probable future of the disease. He also recounts his side of the conflict he and American researcher Robert Gallo have had over who discovered what, and when.

Along the way the reader learns of the events that led Montagnier to virology and something of the frustrations of research. ("The day-to-day life of researchers consists mostly of disappointments.... One must have the mentality of a gambler or fisherman. As for me, I am only interested in big fish.") Although there is as yet no treatment that will eradicate the HIV virus and enable a patient to recover fully from AIDS, he writes, "researchers and clinicians have made great strides toward turning AIDS into a chronic, treatable, and perhaps one day curable, disease." But the epidemic cannot be stopped "until a global prevention policy is implemented and an effective vaccine made available to all, especially the third world."

Greetings, Carbon-Based Bipeds! Collected Essays 1934–1998. Arthur C. Clarke. Edited by Ian T. Macauley. St. Martin's Press, New York, 1999 ($35).

"During the last sixty years," Clarke says, "I must have written at least a thousand pieces of nonfiction of every possible length, from a few paragraphs to entire books." (Not to mention his many works of fiction, including the famous *2001: A Space Odyssey*.) Here he collects 110 of his nonfiction pieces, mostly short and having to do with his prophecies for science and technology. He has organized the entries by decade, and for each decade he provides an introduction intended to "serve as a reminder of the profound cultural, political, and scientific revolutions that were taking place while the pieces were being written and that are, of course, being reflected in them." Among his topics, suggesting the breadth of his range, are space exploration, thinking machines, the uses of the moon and his adventures in scuba diving. Looking back over his work, he finds that it has often "been more interesting to see where (and why) I went wrong than where I happened to be right." Serious in his thinking, lighthearted in his approach, he has composed his own epitaph: "He never grew up, but he never stopped growing."

The Search for Life on Mars. Malcolm Walter. Perseus Books, Reading, Mass., 1999 ($23).

"There will be people on Mars long before the end of the twenty-first century," says Walter, a paleobiologist at the University of Sydney who is also involved with the U.S. National Aeronautics and Space Administration's program for seeking life on Mars. "It's inevitable, and irresistible. It might happen before 2020. It could happen by 2011. Mars is our next frontier." Thus boldly introducing his subject, he proceeds to lay a solid scientific foundation for his claim. He discusses what is known about early life on Earth, the controversial evidence of Mars life from Martian meteorites, the past and present conditions on Mars, and finally the possible strategies for seeking evidence of life there. He is aware that, as biologist Jared Diamond has said, astrobiology "is the sole scientific field whose subject matter has not yet been shown to exist." ("I could quibble with this and suggest that theoretical scientists often work with objects or processes that are inferred but not observed," Walter says.) But he sees reasons to think that microbial life has existed on Mars and that if it has, "there is a good chance it is still there."

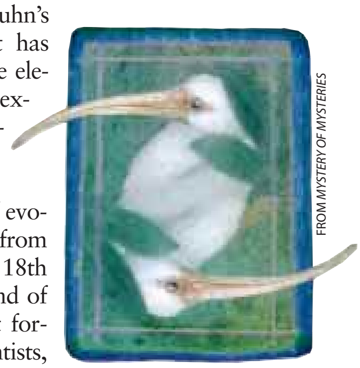
The Biology of Doom: The History of America's Secret Germ Warfare Project. Ed Regis. Henry Holt and Company, New York, 1999 ($25).

Regis, a former professor of philosophy, interested himself in what the U.S. and other countries did during and after World War II to develop methods of biological warfare. With the aid of the Freedom of Information Act, he obtained more than 2,000 pages of formerly secret U.S. government documents on the subject. They form the foundation of this account, which traces the U.S. biological weapons program from its inception in 1942 to its termination by President Richard Nixon in 1969 on the grounds that "biological weapons have massive, unpredictable, and potentially uncontrollable consequences." By then, according to Regis, "the U.S. Army had officially standardized and weaponized two lethal biological agents, *Bacillus anthracis* [anthrax] and *Francisella tularensis* [tularemia], and three incapacitating biological agents, *Brucella suis* [brucellosis], *Coxiella burnetii* [Q fever], and Venezuelan equine encephalitis virus (VEE). The Army had also weaponized one lethal toxin, botulinum, and one incapacitating toxin, staphylococcal enterotoxin B (SEB)."

The U.S. had also stockpiled several other biological agents and toxins. Notwithstanding all this activity—and similar work by the U.K., Canada, Germany and Japan—nations have so far avoided serious biological warfare. Regis thinks the reason is that biological weapons lack "the single most important ingredient of any effective weapon, an immediate visual display of overwhelming power and brute strength."

Mystery of Mysteries: Is Evolution a Social Construction? Michael Ruse. Harvard University Press, Cambridge, Mass., 1999 ($27.50).

Ruse is that rarity, a professor of two subjects, holding chairs in philosophy and zoology at the University of Guelph in Ontario. Here he is mostly the philosopher, examining a deep question: "Does science obey certain disinterested norms or rules, designed or guaranteed to tell us something about the real world, or is it a reflection of personal preference, the things in culture that people hold dear?" He frames the debate in terms of Karl Popper's view of science as objective and Thomas Kuhn's assertion that it has a large subjective element. Then he examines the question by way of 10 chapters on the history of evolutionary theory from the middle of the 18th century to the end of the 20th, as put forward by 10 scientists, beginning with Erasmus Darwin and ending with paleontologist J. John Sepkoski, Jr., of the University of Chicago. Ruse lays out his argument eloquently. His conclusion is that both Popper and Kuhn were right. In the evolution of evolutionary theory, he finds "that cultural values were important—all important—at the beginning, and that within science we have seen a gradual diminution or restriction of their importance."



FROM *MYSTERY OF MYSTERIES*

Evolving Brains. John Morgan Allman. Scientific American Library, New York, 1999 ($34.95).

"Brains exist because the distribution of resources necessary for survival and the hazards that threaten survival vary in space and time," Allman writes. Even single-celled organisms such as bacteria have brainlike functions that enable them to find food and avoid toxins. Starting with the brainlike activity of *Escherichia coli,* the populous bacterial tenants of our intestines, Allman (professor of biology at the California Institute of Technology) traces the development of brains from small to large, simple to complex. His account focuses on three themes: "that the essential role of brains is

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to serve as a buffer against environmental variation; that every evolutionary advance in the nervous system has a cost; and that the development of the brain to the level of complexity we enjoy—and that makes our lives so rich—depended on the establishment of the human family as a social and reproductive unit." From that level of complexity he asks an intriguing question: Why has the human brain become smaller in the past 35,000 years? His answer: "The domestication of plants and animals as sources of food and clothing served as major buffers against environmental variability. Perhaps humans, through the invention of agriculture and other cultural means for reducing the hazards of existence, have domesticated themselves."

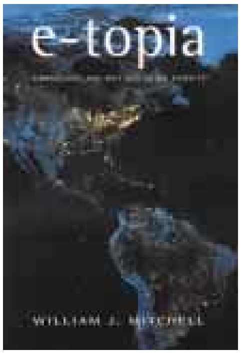
ANTS AT WORK: HOW AN INSECT SOCIETY IS ORGANIZED. Deborah Gordon. Free Press, New York, 1999 ($25).

"The basic mystery about ant colonies is that there is no management," Gordon writes. How, then, does a colony function in what seems to be such an organized way? "Each ant scratches and prods its way through the tiny world of its immediate surroundings. Ants meet each other, separate, go about their business. Somehow these small events create a pattern that drives the coordinated behavior of colonies." Gordon, professor of biological sciences at Stanford University, has for many summers studied colonies of red harvester ants (*Pogonomyrmex barbatus*) in a small patch of the Arizona desert.

Being a meticulous and resourceful experimenter, she has found ways to excavate a colony, to count a colony's population and to learn something about how the ants divide the work. The results lead her to think that "perhaps the ants have something general to teach us, at least by analogy, about how nature works. Any system of units that lack identity or agency, whose behavior arises from the interactions of these components, has something in common with ant colonies. It may be that the same kinds of relations that link ants and colonies allow neurons to produce the behavior of brains, a host of different cells to produce immune responses, and a few dividing cells eventually to produce a developed embryo."

E-TOPIA: URBAN LIFE, JIM—BUT NOT AS WE KNOW IT. William J. Mitchell. MIT Press, Cambridge, Mass., 1999 ($22.50).

As urban places have changed successively with the advent of such advances as piped water, printing, electricity and the Industrial Revolution, so they will change again with the advent of the digital revolution, Mitchell says from his perspective as dean of the school of architecture and planning at the Massachusetts Institute of Technology. In what way? “The resulting new urban tissues will be characterized by live/work dwellings, twenty-four-hour



neighborhoods, loose-knit, far-flung configurations of electronically mediated meeting places, flexible, decentralized production, marketing and distribution systems, and electronically summoned and delivered services.” Urban places will become “e-topias—lean, green cities that work smarter, not harder.”

Mitchell fills out this sketch in considerable detail with predictions of the alterations the digital revolution will bring to buildings, neighborhoods, communications, travel and other aspects of urban life. “We will,” he writes, “characterize cities of the twenty-first century as systems of interlinked, interacting, silicon- and software-saturated *smart* places.”

From Brains to Consciousness? Essays on the New Sciences of the Mind. Edited by Steven Rose. Princeton University Press, 1999 ($29.95).

“The vast sweep of advances in biological knowledge of the past half century has made the brain, and its ambiguous relationship to mind, science’s last frontier,” Rose writes. “Questions which for most of humanity’s existence have been the province of philosophy and religion are now the stuff of day-to-day laboratory experiment.” Rose, as director of the Brain and Behaviour Research Group at the Open University in England, was asked to organize a symposium on “Minds, Brains and Consciousness” at the 1996 meeting of the British Association for the Advancement of Science. He did that and then went a step further, inviting the participants to rewrite their talks, in a way accessible to a general audience, as chapters for this book.

The authors treat such intriguing subjects as memory, schizophrenia, consciousness and the aging of the brain. The work they describe has great portent for humanity. As Rose puts it: “To uncover the secrets of brain function offers the prospect of treating brain dysfunction, from the seemingly irreversible mental decline of Huntington’s or Alzheimer’s disease to the existential despair of schizophrenia. And if these conditions yield to molecular explanation, why should not also an even greater swath of problems in which there seems to be an uneasy fit between the individual mind and the society in which it is embedded?”

The Los Angeles River: Its Life, Death, and Possible Rebirth. Blake Gumprecht. Johns Hopkins University Press, Baltimore, 1999 ($39.95).

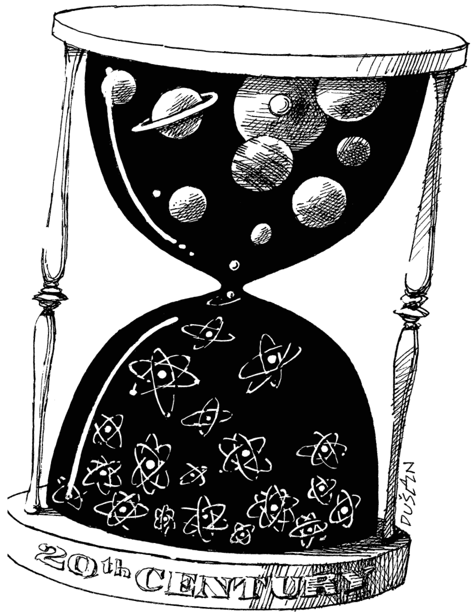
It is a sorry thing now, corseted in graffiti-splotched concrete over most of its 82-kilometer (51-mile) length, carrying mostly treated sewage and storm drainage and pocked with discarded shopping carts, refrigerators and other detritus of the big population that surrounds it. Yet as recently as 1877, the river was described by William Mulholland, an engineer who became superintendent of the Los Angeles water department, as a “beautiful, limpid little stream with willows on its banks.” But it had to supply the burgeoning city with water, and it sometimes produced damaging floods, and so it gradually took its present form through extensive flood-control works. Gumprecht, a former newspaperman who now teaches geography at the University of Oklahoma, relates the history of the river with graceful thoroughness. “We can learn much about urban rivers everywhere from the story of the Los Angeles River,” he says. Taking note of recent efforts to improve the riverside scene with bikeways and small parks, he is mildly optimistic about revitalizing the river. “Only a fool would bet on its future. But a few years ago, only a fool would have cared.” SA

COMMENTARY

WONDERS

by Philip and Phylis Morrison

A Century of Physics



DUSAN PETRICIC

The American Physical Society, with 40,000 members worldwide, celebrates 1999 as its centennial year. We can all enjoy the party. Physicists regard 20th century physics as born a few years ahead of the century itself, on that New Year's Day of 1896 when Wilhelm Röentgen mailed off his first paper on x-rays. Later that same spring radioactivity was discovered, in 1897 the electron was definitely characterized, and by 1899 wireless waves had usefully leapt the English Channel. The 1899 arrival of the American Physical Society (APS) was right on time. We sketch here our view of what followed in only a couple of frames. (Like every cartoonist we neglect plenty, yet what we do catch is indeed wonderful.)

Infrared and ultraviolet were familiar "colors," next-door neighbors of the visible and part of earlier physics. A new rainbow appeared with x-rays; they opened our way to high-energy colors beyond our inborn retinal powers, registered by a growing variety of detectors. The electromagnetic rainbow now extends over some 80 octaves. Radio belongs to the teeming world of less and less energetic photons, from the thermal emissions of a snowball to giant waves of continental scale.

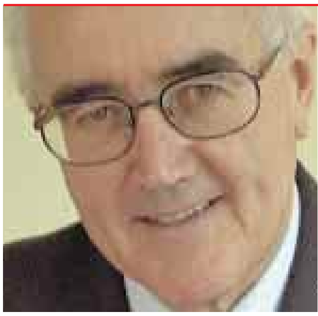
A new golden thread appeared within that tapestry of light. Quantum theory dawned on physicist Max Planck in the year 1900: all radiation can be assigned an energy intrinsic to its wavelength, not to be accounted for simply by counting radiative events taking place but answering to their quality as well. Each photon of light carries its own quantum of energy, the blue having more energy than the red. No one had doubted since Newton's time that a material particle, be it proton, dust mote or star, acquired more energy of motion as it was set going faster and faster. The surprise was that light and its kin include discrete entities, called photons, whose energy increases with frequency, their speed of motion unchanged. Radiation shares certain other particle behaviors: in free space, rays—narrow beams—move straight ahead. It was clear that in truly open space particles and light move alike in almost straight lines at almost steady speed. (Christiaan Huygens knew this by 1700). Both descriptions were seen for a long time as logically sharp alternatives, to be chosen by experiments. For Newton's time, particles; for Maxwell, clearly waves; for Einstein, particles again, but by then there were valid experiments pointing both ways. In the 1930s the quantum theory of fields arrived and has now matured: many properties are subtly shared by all the fundamental entities we know, call them waves or particles. Of course, they are neither exactly the one nor the other; we cannot expect our metaphors to describe the quantum world, probabilistic at its core yet structured in matchless precision.

Quantum theory dawned on physicist Max Planck in the year 1900.

Among the treasures unearthed is the intimate relation between the cosmically large and the subatomically small. Phil, an eager graduate student at Berkeley in 1937, heard a set of public lectures by Niels Bohr, largely on quantum measurements. We students, aided by his eye-catching drawings, grasped some of the subtlety, the public much less. But one well-read questioner brought out of the great man a marvelous answer on a topic Bohr had ignored: What did Bohr think of the embryonic cosmology of expanding space? His prescient answer is as fresh as today's news: we can hope to understand the cosmos only as we understand the elementary particles. But in 1937 there appeared no context yet that linked the two. Until that domain was probed, Bohr would remain silent. Since then, cosmic data have hinted at copious new kinds of matter in early times, and the unfinished theories that order the events in our high-energy labs wink in response. Sixty-odd years ago only Bohr's few sentences joined large and small.

This past March the American Physical Society published its timeline, *A Century of Physics,* graphic, colorful and good-humored. Big wall posters—perhaps the most popular format of our times—tell the story, each treating a decade. The mural narrative in 11 posters can be placed along 23 feet of wall space at eye height, the overall text and pictures filling an area about that of 100 ample book pages. Some 200 photographs overlay the background images. For each notable experiment or concept we read a brief paragraph; each poster has a longer header that seeks to sum up its decade. Enlarged images on three posters show handsomely the one curved track that first

Continued on page 148



CONNECTIONS
by James Burke

The O Zone

DUSAN PETRICIC

I was on the beach a few months back (wearing sunscreen and hat, of course), whiffing the tang of the sea air and thinking (as one does) about Christian Schönbein, who first discovered ozone (as the tang used to be called) in 1839 when he was playing around with electricity and water. Six years later he was to make a much bigger impression on the world with his other discovery. Arrived at by dipping cotton wool into a mixture of fuming nitric and sulfuric acids, then squeezing, washing and drying it. The impressive outcome of which was that when you set light to it, the stuff had much more bang than gunpowder did. Schönbein called the substance "guncotton," and despite the instant interest expressed by every military budget within earshot, one year later it was off the market for over a decade. Reason: the first time an attempt was made to mass-manufacture it, the cotton blew up and totally obliterated the factory (and damaged large bits of the town of Faversham, England, a mile away).

The best billiards balls came from a perfect tusk, for which you need a plentiful supply of dead elephants.

In 1867 Schönbein's fatal fluff was destined to make a comeback as a result of the Great Disappearing Elephant Scare, when the *New York Times* predicted almost certain extinction if hunters went on bagging the beasts at the rate they were going. Billiards players faced a particularly grim future, because the best balls came from a perfect tusk, dead center. For which you need a plentiful supply of dead elephants. Harrumph. Which was why the firm of Phelan & Collander was offering $10,000 for an ivory substitute, thus exciting the imagination of John Hyatt, a young printer in Albany, N.Y. In 1870 Hyatt mixed guncotton with alcohol and camphor, molded the result, and scooped the pool (well, you can't say "scooped the billiards"). The wonder material he came up with became false teeth, stiff collars and cuffs, vases, combs, fountain pens, dominoes, and about 1,000 other things. I'm sure you've already guessed that it was also bound to find its way into cameras; in 1889 an ex-banker named Eastman patented photographic film made of "celluloid" (Hyatt's brother's name for fake ivory).

Here the plot thickens. Back in 1877 an English photographic weirdo who called himself Eadweard Muybridge (real name: Ed. Muggeridge) had taken a series of stills of a horse at the gallop. These first action pix really turned on a Paris physiologist, Étienne Jules Marey, who was interested in the way anything that moved, moved. In 1887 he produced his *fusil chronophotographique,* which used a shutter to expose a roll of sensitized paper-based film to 12 shots a second. In 1889 Marey showed this gizmo to Edison, who promptly bought some of Eastman's new celluloid. And in 1891 "invented" the cine camera. Or (more probable) one of his unsung backroom noodlers did it (working according to Edison's helpful laboratory motto: "There's a better way. Find it.").

It was another Edisonian egghead who also apparently came across an amazing high-vacuum pump developed a few years earlier by a German chemist, Hermann Sprengel. Word had also reached a Brit inventor, Joseph Swan, who was seeking the same kind of enlightenment as Edison: an incandescent bulb whose carbon filament wouldn't burn out if the vacuum inside the bulb were good enough. Which, thanks to good old Hermann, it now would be. And before we get into the "Edison or Swan" debate, I should note that some other guy, in Cincinnati, had suggested incandescence as early as 1845. Anyway, in 1880 Swan installed the first of his lamps in the residence of Sir William Armstrong, a local politico, legal eagle, hydraulics engineer, field-gun designer, ship builder and general manufacturing big cheese. The house was a spare-no-expense extravaganza designed by Armstrong himself and built in the middle of rave scenic surroundings as barons of industry were wont to in the days before zoning laws. All the place lacked (in common with everywhere else on earth except Swan's or Edison's labs) was an electric lightbulb.

In 1843 Armstrong had been elected to the Royal Society with the help of one Charles Wheatstone. And here's the primacy thing again. With a guy named Cooke, Wheatstone was the fellow who invented a telegraph in 1837, well before Morse (as, in some form or other, did about a dozen people, too). Wheatstone's contraption worked by causing an incoming signal to deflect two magnetic needles to point at letters.

Like all Victorians, Wheatstone did a lot more besides electromagnetics. He invented a coding machine, a way of indicating the sun's position from the polarization of its rays, and the rheostat. But his real obsession was with acoustics. Not surprising since he came from a family of instrument makers, and in 1829 he had invented the concertina.

Without a doubt one of the greatest

squeezebox exponents of all time (according to his family) was Lord Balfour, British prime minister from 1902 and later foreign secretary (when in a letter to Lord Rothschild he stated what became known as the Balfour Declaration, which gave official blessing to the plan for setting up what would eventually become the state of Israel). In 1921 Balfour became president of the Society for Psychical Research, joining such table-rapping pillars of the science establishment as physics professor Oliver Lodge.

Prior to attempts at communication with the dead, Lodge also did much to improve the radio-telegraphic variety, when he developed (as did Frenchman Édouard Branly—here we go *again*) the "coherer." This device used metal filings to help detect radio waves, because they stuck together when even a very weak electromagnetic signal passed through them. Marconi used the coherer to make possible the 1901 Newfoundland reception of his very first (very weak) transatlantic dots and dashes.

The question of how those signals had traveled round the bulge of the earth was theoretically explained a year after the event by Wheatstone's nephew, Oliver Heaviside. And, simultaneously, by American electrical engineer Arthur Kennelly (this is getting out of hand!). Both men postulated some kind of stratospheric layer, off which radio signals might be bouncing. In 1912 one of Marconi's ex-assistants, a physicist named William Eccles who had been involved in preparing the original transatlantic transmission, worked out a theory to show that a layer of ionized air would do that reflecting trick. In 1924 Edward Appleton would prove Eccles right with the discovery of the ionosphere, caused by the effect on the atmosphere of incoming solar x-ray and ultraviolet radiation.

In 1913, only one year after Eccles had done his thing, Frenchman Charles Fabry was already fingering something *else* stratospheric and ionized—and caused by the incoming ultraviolet radiation. It was a layer of gas that effectively shields life on the earth from the lethal effects of the same radiation. The shield is a little less effective today than in Fabry's time, thanks to the hole in it. Which is why I was wearing all that protective gear on the beach. Because Fabry found the same gas, up there, that Schönbein had discovered down here: ozone. SA

Wonders, continued from page 146

disclosed antimatter, a ring of single atoms emplaced like game pieces, and the tiny deviations from utter blandness over the entire skyful of the oldest celestial radiation. Many pictures of investigators worldwide who led the work add a human touch: young Marie and Pierre Curie going cycling, a dapper teenaged Einstein, Lise Meitner, Richard Feynman, on to the Nobelists of the 1990s.

The timeline, too, notes what Bohr foresaw: the wondrous loop where microcosm and macrocosm begin to explain each other step by step. A photograph of an electric nanoguitar only 10 microns long, carved in silicon, adds a closing whimsy. The last poster looks to the future: all its named personalities are a youthful real sample of the American Physical Society—of tomorrow. We hope a sequel will follow (another poster every 10 years ahead?) with help from friends overseas. There is much to be done by students and teachers alike in augmenting and questioning this narrative, with more resources provided in support than we have room to name. Its strength is in its connectedness. Art, architecture and popular culture are well sampled as a kind of subtext, from Paul Cézanne to I. M. Pei; technology and biology are not forgotten. Many classroom and corridor walls already tell this tale.

About 20,000 copies have been sent free of charge countrywide to science teachers in high schools that responded to the offer. Others who represent schools, universities or science museums may request a free copy. Those who want to have it for home, workplace, camp, club or waiting room may simply order the heavy roll, delivered in a prism-shaped carton for $35 in the U.S. (Details can be learned from www.aps.org/timeline on the World Wide Web.)

Generous support for the endeavor came from Lucent Technologies and also the National Science Foundation, the U.S. Department of Energy and United Parcel Service. IBM has sponsored an extended version at www.timeline.aps.org on the Web. Among many, many others, three physicists merit special mention: the originators were Sidney Perkowitz of Emory University and Hans C. von Baeyer of William and Mary College, and at the hub at APS was Brian B. Schwartz. The designer was Albert Gregory of Boston. SA

ANNUAL INDEX 1999

AUTHORS

ARTICLES, BY KEY WORDS

THE AMATEUR SCIENTIST
by Shawn Carlson

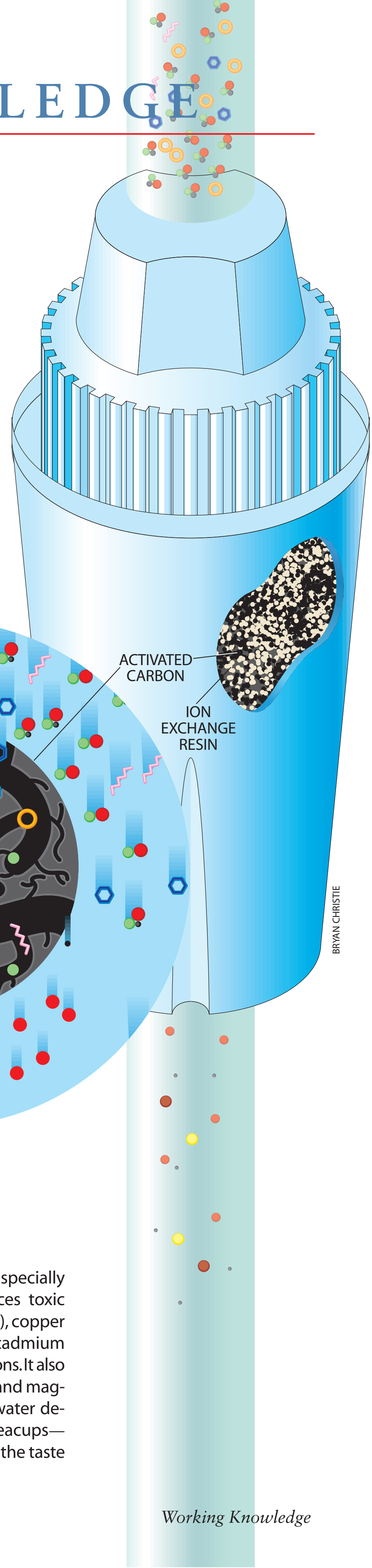
MATHEMATICAL RECREATIONS
by Ian Stewart

WORKING KNOWLEDGE

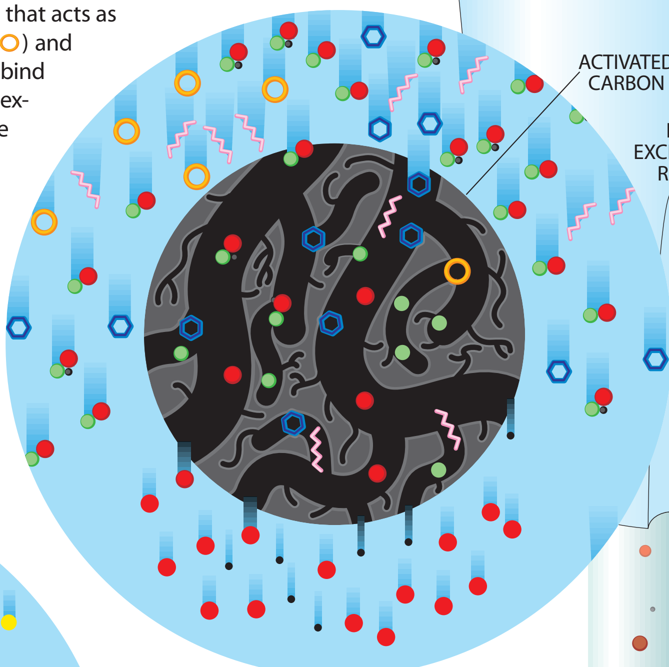
WATER FILTERS

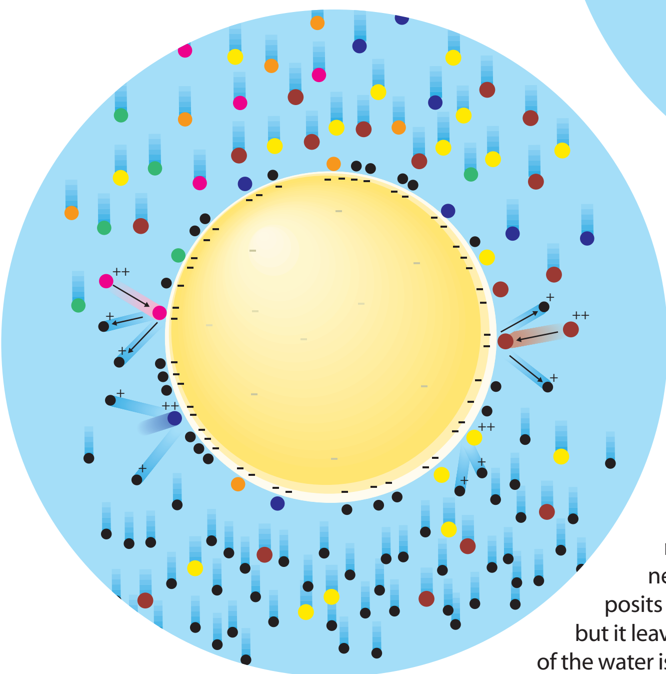
by Louis A. Bloomfield
Department of Physics, University of Virginia
Author of How Things Work: The Physics of Everyday Life

Despite the name, the most common type of water filter does not produce chemically pure water. If it did, the water would not taste right to us. Instead the filter's activated carbon and its ion exchange resin remove unwanted ions and molecules from water, leaving those that make it pleasant to drink. This selectivity has a practical aspect: it extends the life of the filter. The filter's capacity for chemicals is limited by the laws of thermodynamics. As the water becomes more pure and orderly, the filter becomes more impure and disorderly. This accumulating disorder and the associated consumption of the filter's potential energy lessen its effectiveness. By leaving innocuous and desirable chemicals, such as fluoride, in the water, the filter avoids an early demise.



ACTIVATED CARBON is a highly porous material that acts as a sponge for unwanted molecules like benzene (○) and some pesticides (⬡) and oils (〰). Such molecules bind chemically and physically to surfaces in the carbon's extensive network of large and small pores. A single gram (0.04 ounce) of activated carbon may have more than 1,000 square meters (about 11,000 square feet) of surface area inside it—nearly the size of a football or soccer field—so its pores can trap countless molecules before running out of room. The activated carbon also initiates a chemical reaction that converts free chlorine—HOCl (●●) and OCl^- (●●)—which utilities put in water to kill germs, into chloride (●$^-$) and hydrogen (●$^+$) ions, which are safe and taste all right.





ION EXCHANGE RESIN is a specially prepared plastic that replaces toxic metal ions such as lead (●$^{++}$), copper (●$^{++}$), mercury (●$^{++}$) and cadmium (●$^{++}$) with harmless hydrogen ions. It also removes enough calcium (●$^{++}$) and magnesium (●$^{++}$) ions to stop hard-water deposits from forming in kettles and teacups—but it leaves some of those ions in so that the taste of the water is not spoiled.