SEEING GRAVITY WAVES

21ST-CENTURY SLAVERY

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april 2002

contents

features

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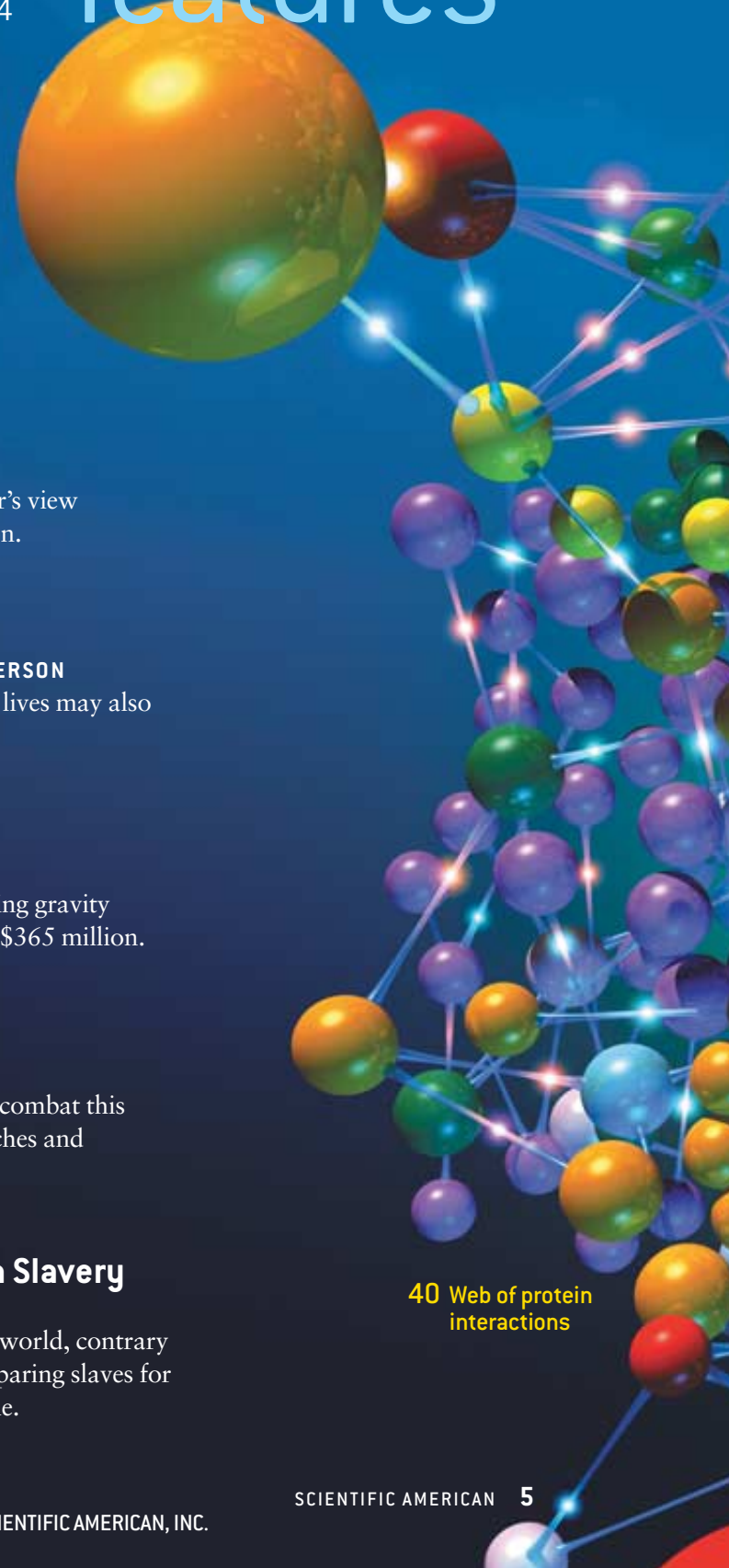

40 Web of protein interactions

SCIENTIFIC AMERICAN Volume 286 Number 4

departments

columns

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The Peculiar Institution

Most Americans probably assume that slavery ended in 1865. Unfortunately, they are wrong. Potentially millions of people around the world still live and toil in involuntary servitude: Slavic women in European brothels, bonded laborers in South Asia, cocoa plantation workers in West Africa. Their plight has drawn occasional attention from newspapers and magazines. But does discussion of it belong in a science magazine? The editors have been debating this question since we began to consider an article on the topic a year and a half ago. Ultimately we decided that the answer is yes [see "The Social Psychology of Modern Slavery," on page 80].

Whenever we run articles on social topics, some readers protest that we should stick to "real" science. A number also claim that the magazine has become "more politicized" in recent years. We understand: the social sciences lack the precision of the physical or biological sciences, and they are more likely to have political implications.

Ironically, we seldom hear these complaints from working physical or biological scientists. They are the first to point out that the natural universe, for all its complexity, is easier to understand than the human being. If social science seems mushy, it is largely because the subject matter is so difficult, not because humans are somehow unworthy of scientific inquiry.

That has been the position of *Scientific American* since its founding. The goals articulated by the editors who remade the magazine in 1948 included extensive coverage of "social sciences, taking in such specialties as anthropology, archaeology, economics and even political science." Our mission statement commits us to promoting "a deeper understanding of how science and technology influence human affairs—social, political, economic and personal."

When considering whether to publish an article, we always ask, What would this article contribute that no other has? In this case, the author, sociologist Kevin Bales, answers that past articles have treated slavery in a piecemeal fashion; he advocates a global perspective. His findings certainly meet one criterion of valuable research: they tell us things we might not have expected or liked to hear. It turns out, for instance, that slaveholders can be highly regarded by their community and that many freed slaves say they are more miserable than when they were slaves. For want of a nuanced understanding of psychology and social context, plenty of well-intentioned antislavery efforts have failed.

That said, we worry that the study of contemporary slavery is more of a protoscience than a science. Its data are uncorroborated, its methodology unsystematic. Few researchers work in the area, so the field lacks the give and take that would filter out subjectivity. Bales himself acknowledges all this. As we debated his definitions of slavery, he told us, "There is a part of me that looks forward to being attacked by other researchers for my interpretations, because then a viable field of inquiry will have developed."

During our preparation of this article, several staff members related their own encounters with contemporary slavery. One had met freed slaves in Gabon; another knew two women kidnapped by human traffickers in Taiwan. It is far more prevalent a practice than many of us suppose. Bales's article, notwithstanding our concerns, fulfills the basic aim of any *Scientific American* article: to offer insight into an important and little-understood aspect of our world.

THE EDITORS editors@sciam.com

INDENTURED CALL GIRL in Bangkok says her parents sold her into prostitution.

STEVE LEHMAN *SABA*

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Letters

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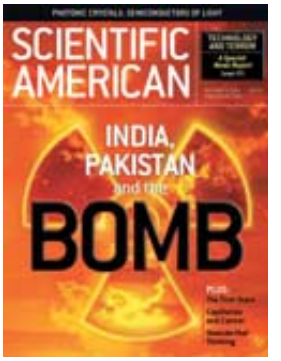
"IN 'EVALUATING THE THREAT' **[News Scan, December 2001], Ed Regis confuses the threat of biological weapons to public health with their threat to national security," writes C. Allen Black of the University of Pittsburgh. "The fact that bioweapons are not likely to be used for mass destruction is of no comfort or even practical relevance when our government and the entire U.S. infrastructure is vulnerable to one or a few men that the police and government seem powerless to find or stop. Perhaps after the anthrax attack, there is no justification for mass vaccinations based on the public health threat. From now on, though, an oath of office should be preceded by vaccination."**



Below, readers respond to this and other topics from the December 2001 issue.

PRIVACY, ANONYMITY AND THE DIFFERENCE BETWEEN THEM

"Here's Looking at You" [SA Perspectives] described electronic surveillance in public places as a matter of privacy versus security. What is unsettling, though, is the loss not of privacy but of anonymity. No one who is in a public place or engaging in transactions or entry that requires identification has any expectation of privacy. Now, however, we are losing the illusion of anonymity. Welcome to the real world.

What troubles me is the recording and storing of these identifications. I don't mind if someone can identify me walking down the street, going to a ball game or entering a national park. I do mind if these events are recorded and filed with no restrictions on the duration of storage or accessed without just cause. Without such restrictions, this would indeed be an invasion of my privacy.

CLAY W. CRITES
West Chester, Pa.

WHEN SAGE WASN'T

When SAGE was first deployed in the early 1950s, I was a U.S. Air Force fighter pilot flying F-86D all-weather interceptors in the Air Defense Command ["The Origins of Personal Computing," by M. Mitchell Waldrop]. Ours was one of the first squadrons to be equipped with Datalink, a feature that enabled SAGE to transmit steering commands directly to the autopilot in our aircraft. After getting airborne, establishing voice and data contact, and engaging the autopilot, the fighter pilot essentially became a passenger (a somewhat reluctant and skeptical passenger, I might add) in an aircraft being directed toward an intercept by SAGE.

Sometimes the process worked reasonably well, but there were frequent problems, including sudden, unexpected and often violent episodes of pitching or rolling that required immediate disengagement of the autopilot to prevent losing control of the aircraft. As you might imagine, these incidents could be a bit startling, especially at night or in bad weather, and did little to increase my confidence in SAGE or the Datalink remote-control system.

At the time, we usually attributed these problems to faulty equipment. In retrospect I came to realize that what I was actually experiencing were programming bugs! I still encounter computer bugs, but none quite so memorable as in the early days of SAGE.

R. O. WHITNEY
San Jose, Calif.

INVENTING LANGUAGE, EXAPTING MONEY

Ian Tattersall argues in "How We Came to Be Human" that language was a cultural innovation that occurred around 70,000 years (70 kyr) ago. This assumes that language is a generalized ability that arose from our capacity for symbolic

thought; however, Noam Chomsky and his successors have shown that modules for specific aspects of language acquisition are hardwired into the brain.

Such complex abilities specifically directed at language must have evolved during a long period, possibly the two million years over which the vocal tract developed. If language was until very recently used only for practical and social purposes, it is unlikely to have left any trace in the fossil record. It seems more reasonable to turn Tattersall's argument on its head and propose that fully modern humans arose as a result of exaptations in the brain around 70 kyr ago that allowed language to be used for symbolic thought.

Tattersall's idea of cultural innovation is a more pleasant explanation for the emergence of modern humans than the carnage of wholesale replacement. Unfortunately, the disappearance of the Neanderthals and the human record since then make replacement all too plausible.

DUDLEY MILES
London

I don't understand how Tattersall could conclude that language was invented between 60 and 70 kyr ago. Luigi Luca Cavalli-Sforza and others claim that genetic and linguistic evidence suggests that African and Eurasian languages diverged from a common source about 50 to 70 kyr ago and that Eurasian and Southeast Asian languages diverged 40 to 60 kyr ago. If so, was there enough time for language to become established and diverge into what we see today? Also, language is not purely cultural; there is much that is inborn. Wouldn't this prevent cultural diffusion or at least dramatically slow diffusion?

Let us consider another scenario: the purely cultural exaptation of stone toolmaking to body ornamentation to money. There is evidence that the Neolithic emergence was accompanied by the beginnings of body ornamentation and long-distance trade. Money, in the form of beads and such, would have led to trade, role specialization and new technologies. Money, too, is an adaptation that would have easily spread by cultural diffusion. To "exapt" the language of thermodynamics, perhaps money (stored work) facilitated the rise of novel dissipative systems.

LLOYD ANDERSON
Chicago

TATTERSALL REPLIES: In light of what we know about evolution, it seems most likely that our extraordinary cognitive capacity was somehow acquired as a unit, rather than in a gradual process of modular accretion, for it is plainly wrong to regard natural selection as a long-term fine-tuning of specific characteristics, however much we like the resulting stories. And it's important to remember that even today we are still testing the limits of this generalized capacity that makes so much possible. As for Miles's dismal view of human proclivities toward other species (let alone other people), I can only, if reluctantly, agree.

BURIED IN STYLE: One of the earliest (about 28,000 years ago) and most ornamented human burials in Europe; beads are mammoth ivory.

Anderson's point about language is equally well taken, although languages tend to change so fast and unpredictably that any uncalibrated chronology has to be suspect. Yes, language seems to be tied up quite intimately with all kinds of other behaviors that are linked in some way to our core cognition, and the invention of money is one more expression of that unique capacity. Money as we are familiar with it today is actually a rather recent innovation and has certainly brought problems in its wake, but the exchange of goods over long distances seems to be a behavior that was established very early in human prehistory.

AMERICAN BIOWARFARE

One biological-warfare tactic has deep roots in American soil ["Evaluating the Threat," by Ed Regis; News Scan]. In 1763 Lord Jeffrey Amherst, the British commander in chief for America, maliciously distributed smallpox-infested blankets and handkerchiefs to Native Americans living near Fort Pitt, Pa., and the U.S. Army did the same in the 19th century.

ALEXANDER S. WEGMANN
Port Angeles, Wash.

EDITORS' NOTE: Regis's reference to this fact in the original draft of the article was cut for space.

ERRATA In the map of South Asia in "India, Pakistan and the Bomb," by M. V. Ramana and A. H. Nayyar, the scale should have extended from 0 to roughly 500 kilometers, with each tick mark representing an increment of about 80 kilometers.

In "Photonic Crystals: Semiconductors of Light," by Eli Yablonovitch, the major credit for the theoretical discovery of a photonic band gap in face-centered cubic structures and in the scaffold structure should have gone to H. Sami Sözüer, now at Izmir Institute of Technology in Turkey. The creation of the smallest laser should have been credited jointly to Amnon Yariv's group as well as Axel Scherer's group, both at the California Institute of Technology.

NOVOSTI *Photo Researchers, Inc.*

50, 100 & 150 Million Years Ago

FROM *SCIENTIFIC AMERICAN*

Feets Don't Fail Me Now ▪ Danger from Above ▪ Bug Zapper

50,000,000 YEARS AGO

HUGE SHOES FOR SALE—"Standing at the podium, Lionel B. Ambulocetus, the president of the International League of Whales, was brief in his remarks, but there was no mistaking his anger. 'That's it, we're getting out of here,' he proclaimed. 'Life on land has no future, so we're returning to the seas. I've urged all our members to begin spending more time at the beach and to look for mates with shorter legs. We know it's not going to happen overnight, but we're going back to the oceans where we belong.' Staring down at his own feet, he said, 'A day will come when I need these like a hole in the head.'

"Mr. Ambulocetus was not shy about explaining the reasons for the whales' planned migration. 'Quite frankly, it's the primates. I know they're small and there aren't very many of them, but they make an unbelievable amount of noise, and their little grasping forefeet give me the creeps. We are convinced that the primates are going to cause a lot of trouble for everyone, and we don't want to be around when it happens. At least in the oceans, we'll be safe.' "

100,000,000 YEARS AGO

WATCH THE SKIES?—"At a recent interdisciplinary meeting on the campus of Pangaea University, researchers discussed with some alarm the mounting evidence that each of the known mass extinction events may have been caused by a titanic collision of a comet or asteroid with the earth. According to recent speculations, such impacts could envelop our planet in a dense cloud of dust and ash, blocking out the sun, with disastrous consequences for most life-forms.

"Massive impact scenarios should be of more than academic interest, many of the gathered scientists said, because a similarly calamitous collision could occur yet again. 'It's difficult to predict how bad it could be,' remarked geologist Edward Deinonychus of Gondwana Polytechnic. 'It would surely cause a huge loss of saurian life, maybe even amounting to 10 percent of the population. What's more, even aside from its climatic effects, the impact could ignite a gigantic firestorm. It might destroy every last trace of our magnificent papier-mâché cities.'

"Some of the participants at the meeting argued that a future mass extinction could be averted. 'Our space science is now sufficiently advanced for us to identify an incoming asteroid decades before its arrival and to change its course,' said Margaret Dimetrodon of Mount Ararat Observatory. 'I know it sounds like science fiction. But if we can put a sauropod on the moon, then we can do this.'

"But support within the government for investing in an asteroid-blasting scheme remains weak. Echoing sentiments heard throughout Congress, junior senator Strom Thurmond declared, 'Even if it is a good idea, a big collision like this might not occur for tens of millions of years. That's more than enough time for us to get it done. Right now we'd be better off putting our science funding to more worthwhile uses, like fusion research.' "

150,000,000 YEARS AGO

PEST CONTROL—"A new patent has been issued to Mr. Rufus Porter, an ichthyosaur, for the eradication of unwanted trilobites. The device emits a high-pitched tone that resonates with the exoskeletal chitin of the arthropods, setting up vibrations that the animals would presumably find painful.

"Issuance of this patent was held up for some time when one of the examiners questioned the need for such an invention insofar as trilobites are widely considered to be extinct, none having been seen for approximately 70 million years. Mr. Porter's answer was that this absence of trilobites only demonstrated the effectiveness of his invention. Copies of the patent can be obtained as of April 1."

TRILOBITES FLEE from invention, 149,997,998 B.C.

PATRICIA J. WYNNE

50, 100 & 150 Years Ago

FROM SCIENTIFIC AMERICAN

Age of Antibiotics ▪ Hollerith Number Cruncher ▪ African Missionary

APRIL 1952

THE ANTIBIOTIC ERA—"Although more than 300 antibiotic substances have now been discovered, only five (penicillin, streptomycin, chloromycetin, aureomycin and terramycin) have attained the stature of major drugs. A handful of others have important, though limited, uses or are considered promising. All the rest have fallen short for one reason or another. Some are too weak; some work only in the test tube or on subhuman animals; most are too toxic. Naturally the search for potential new 'wonder' drugs goes on with undiminished fervor. The field for searching is very wide. There is hardly an area in the plant kingdom that has not yielded antibiotic substances: they have come from seed plants, lichen, many groups of fungi, the actinomycetes and bacteria."

APRIL 1902

FRESH FOOD IN WINTER—"Science has deliberately set at defiance of all the laws which govern the seasons of growth, and in the conflict it has proved a great triumph for man. Winter gardening and farming in the southern belt of States where the climate is warm enough to produce out of doors have spread with phenomenal rapidity in recent years. Our whole system of living and diet have been transformed by this industry, and our winter season is supplied with fruits and vegetables almost as freely as the summer. The expansion has been due to the railroads and steamship companies operating lines along the coast or through the belt of southern States. There are some 60,000 refrigerator cars engaged in this traffic in the winter season."

COMPUTER PRECURSOR—"The Hollerith system of mechanical punching and tabulation had its inception in the preceding (eleventh) census. The system, however, has been greatly improved and extended to meet the larger want of the present time for the twelfth census. The two main features of the system are, first, a punched card, and second, means for transferring its legend mechanically to registers which add the units thereof [*see illustration*]. The latest development of the system is that the work of separately placing each card beneath the pin-box, depressing the pin-box and removing the card is performed automatically by a machine instead of by hand. If an improperly punched or distorted card happens to be in the lot, it is automatically thrown out." [*Editors' note: Herman Hollerith's Tabulating Machine Company eventually became IBM.*]

HOLLERITH SYSTEM card tabulator, 1902

A TASTE OF MONEY—"According to Count Gleichen in 'Mission to Menelik,' the people of Abyssinia use the Maria Theresa 1780 dollars. But for small change a very different coin is used: a bar of hard, crystallized salt, about ten inches long, slightly tapering toward the end. Five of these bars go for a dollar. People are very particular about the standard of fineness of the currency. If it does not ring like metal when struck with the finger-nail, or if it is cracked or chipped, they will not take it. It is a token of affection when friends meet to give each other a lick of their respective *amolis* (bars), and in this way the value of the bar is decreased."

APRIL 1852

DR. LIVINGSTONE IN AFRICA—"At the American Geographical Society, Mr. Leavitt read a very interesting paper from the Rev. Mr. Livingston [David Livingstone], a missionary in South Africa. The Rev. gentleman had made two excursions into the central part of the continent. From the maps exhibited, we perceive that 700 miles from the ocean the western branch of the Zambesi receives the Chobe, which is the largest of its tributaries; and that none of the sources of these rivers are as yet known. The Portuguese slave traders begin to penetrate there, not themselves, but by the black tribes who are in their employ. About two years ago some traders well supplied with English cloths, guns, etc., came into the Chobe region, but the people were not inclined to the business."

SPACEFLIGHT

Has the Space Age Stalled?

ROCKET SCIENCE PROVES HARDER THAN ROCKET SCIENTISTS HAD THOUGHT **BY MARK ALPERT**

Two abandoned spacecraft are hidden in California's Mojave Desert, and they're not crashed UFOs. These relics were built by hopeful human engineers. Inside a storage building at Edwards Air Force Base is the partially assembled X-33, a prototype space plane conceived by NASA and Lockheed Martin. About 20 miles away, in a building at Mojave Airport, is the Roton, a six-story-tall test vehicle constructed by the now defunct Rotary Rocket Company. Just a few years ago these machines were hailed as the forerunners of a revolutionary new generation of reusable launch vehicles. But these days they're merely sad reminders of a dream unfulfilled.

ROTON TEST VEHICLE, unveiled in 1999, is now gathering dust.

DAMIAN DOVARGANES *AP Photo*

The dream is a cheap, reliable way to carry people and payloads into orbit. The space shuttle falls far short of that goal: each flight costs about $500 million. The X-33 program was intended to produce a more cost-effective, fully reusable craft that could reach orbit with just one rocket stage. (The shuttle, in contrast, is a two-stage vehicle that jettisons a pair of solid-fuel boosters during its ascent to lessen the mass lifted into space.) But such a craft would have to carry 10 times its weight in fuel, and the technologies needed to reach that goal—such as the use of lightweight composite materials for fuel tanks—proved more troublesome than expected. After five years of effort, NASA canceled the program last year (the total cost: $912 million for NASA, $357 million for Lockheed). Several months later the U.S. Air Force turned down a chance to finish assembling the X-33 but agreed to store the vehicle's parts to save them from the scrap heap.

Private-sector space initiatives have fared no better. In the late 1990s half a dozen small companies tried to grab a share of the satellite launch business by building reusable rockets of their own. Perhaps the most ambitious design was Rotary Rocket's Roton, a single-stage craft that looked like a giant traffic cone with helicopter blades on top. A spinning engine at the base of the Roton was supposed to lift it into orbit, and the rotor blades would control its descent. Other companies, such as Kistler Aerospace and Kelly Space and Technology, drew up plans for low-cost, two-stage vehicles. But funding for all these projects dried up by the end of the decade as investors realized that the demand for satellite launches wouldn't grow as much as predicted.

Now NASA is going back to the drawing

THREE-STAGE CRAFT proposed by Boeing has two large boosters that could fly back to the launch site.

NEW PROJECT, SAME PLAYERS

NASA has long relied on defense contractors to design and build its spacecraft. Five large aerospace companies account for more than two thirds of the $886 million in contracts awarded so far in the Space Launch Initiative.

Company	Contract award (millions of dollars)
Boeing	143.7
Rocketdyne (subsidiary of Boeing)	128.4
Pratt & Whitney (subsidiary of United Technologies)	125.8
Northrop Grumman	110.1
Lockheed Martin	94.3

board. Under its Space Launch Initiative (SLI), the agency plans to spend $4.8 billion by 2006 to develop the technologies required to build a replacement for the shuttle. NASA has already awarded nearly $900 million in contracts to 22 companies and universities, with much of the work focused on rocket engines and airframes. The agency is reviewing preliminary vehicle designs proposed by Lockheed, Boeing and a joint team consisting of Northrop Grumman and Orbital Sciences.

Burned by its experience with the X-33, NASA has relegated the idea of a single-stage craft to the far future (that is, around 2025). The successor to the shuttle will most likely have one or more liquid-fuel boosters that would be able to fly or glide back to the launch site after separating from the upper stage. Because liquid-fuel rockets can be throttled up and down by varying the flow of fuel, they have an inherent safety advantage over the shuttle's solid-fuel boosters. Intriguingly, several of the proposals call for a three-stage craft: two large fly-back boosters would lift a relatively small crew-transfer vehicle into orbit. Minimizing the size of the upper stage makes the launch system more flexible, allowing it to be used for unmanned missions and even military strikes.

Some of the lesser players in the space industry have disparaged SLI, noting that the $4.8-billion program will not actually produce a spacecraft; NASA will merely choose a design by 2006 and then spend six more years building the vehicle. "What good are technology studies if they don't result in an operational system?" asks Michael J. Gallo, president of Kelly Space and Technology. Last year NASA rejected Kelly's proposal to spend part of the SLI money on developing a two-stage vehicle that would be towed by a 747 to an altitude of 20,000 feet and then launched horizontally. "We have a solution that can be implemented today," Gallo says. "But NASA just wants to play in the technology sandbox."

FERTILITY

Looking at ART

IS IT TIME TO SCRUTINIZE ASSISTED REPRODUCTION?

BY TABITHA M. POWLEDGE

When a National Academy of Sciences study group in January called for outlawing the creation of babies via cloning, the world's media took notice, and so did the U.S. Senate, where a few days later the NAS report formed the centerpiece of a hearing. Largely ignored, however, was a recommendation in the report that could have much wider impact. The NAS panel concluded that it's time to consider imposing more regulations on the field of assisted reproduction.

Assisted reproductive technology (ART) exploded into public consciousness in 1978 with the birth of Louise Brown, the first successful product of in vitro fertilization. In IVF, sperm and egg are mated in a lab dish, and a few days later the resulting embryo is transferred into a woman's carefully prepared uterus. IVF accounts for most ART business, but lately other procedures have emerged, among them intracytoplasmic sperm injection, in which sperm is inserted directly into an egg, and preimplantation genetic diagnosis, in which an embryo is vetted for genetic defects before transfer into a waiting womb.

In mannerly language, the NAS conveyed that it wasn't happy with what it saw, pointing out that ART procedures "have generally been subject to minimal oversight and regulation." As a result, "important data needed for assessing novel ART procedures are in some cases lacking, in other cases incomplete and hard to find," the report stated.

Indeed, over the years, assisted reproduction has been called the Wild West of medicine, and its short history is crowded with

TRACKING TEST TUBES

Success rates in assisted reproduction depend on several factors, including whether the eggs are frozen, the quality of donor eggs and the age of the mother. The Centers for Disease Control and Prevention compiles the data. The CDC's December 2001 report, providing information for the latest available year (1999), covers 370 clinics; 29 clinics, including the well-known Genetics and IVF Institute in Fairfax, Va., declined to report their numbers.

COURTESY OF BOEING

baroque cautionary tales. The most notorious is a series of horror stories in the early 1990s from the Center for Reproductive Health at the University of California at Irvine. Eggs and embryos were stolen from some women and implanted into others or turned over to zoologists; fertility drugs were sold illegally; records went missing. There were also cover-ups, fired whistle-blowers and fraudulent insurance claims. Two of three physicians who ran the place fled to Mexico and South America.

This episode and other concerns led in 1992 to the only major federal law governing ART. It asks that clinics report success rates and other data. The Society for Assisted Reproductive Technology (SART), a trade group that helps patients locate fertility clinics, collects that information and sends it to the Centers for Disease Control and Prevention.

Critics say current ART oversight is a feeble patchwork that allows abuses to slip through. "The whole field of reproductive technology is a case study in what commercialized biomedicine is," says Arthur Caplan, director of the Center for Bioethics at the University of Pennsylvania. "It's a mess and always has been." Caplan points to Internet bidding wars for eggs, a lack of standards in genetic screening of embryos, and unenforceable contracts with surrogate mothers.

Among his and other critics' gravest concerns, though, is the well-being of the patients themselves. Given the newness of some procedures, some of them may in effect be acting as research subjects. U.S. abortion politics have resulted in a decades-long ban on federal funding for human embryo research; thus, most of the science that underlies ART has been done with private money and out of the public eye. That means the researchers are almost never required to observe federal regulations governing human experimentation.

The existing self-regulation has also left societal and ethical concerns unaddressed. Legal cases in New Jersey, New York, Illinois, Massachusetts and Tennessee have posed perplexing questions about the fate of frozen embryos after their "parents" divorce. Ethicists still debate the case of Molly Nash, who was born with an inherited blood disease and whose parents used preimplantation genetic diagnosis to create an immunologically compatible brother who could serve as a tissue donor for her. Preimplantation screening also raises the issue of whether parents could try to select for characteristics of their progeny, such as intelligence, height or physical prowess.

Other groups besides the NAS are arguing that questions like these need systematic investigation. The California Advisory Committee on Human Cloning has urged the creation of a state agency to advise the governor and legislature on "related issues of human biotechnology." The Food and Drug Administration has also weighed in, asserting that it can regulate certain types of ART, such as cytoplasmic transfer, as developing biological treatments. In cytoplasmic transfer, a single sperm and donated cytoplasm from one woman's egg are injected into another woman's egg.

The Hastings Center, a bioethics think tank based in Garrison, N.Y., will soon recommend a broad federal oversight approach that applies to both publicly and privately funded work. According to Lori Knowles, principal investigator for the project, the group would like to see something akin to the 1984 Warnock commission in the U.K., which suggested that certain areas of human embryo manipulation be prohibited and other procedures be regulated. The Warnock report formed the basis for 1990 legislation that now governs embryo work in the U.K.

Not surprisingly, practitioners of ART resist additional laws. "No other branch of medicine has the kind of oversight that we have," states SART past president David Hoffman of the Northwest Center for Infertility and Reproductive Endocrinology in Margate, Fla. "We report our data set. Do you see cardiovascular surgeons reporting their data set for the results of bypass surgery?"

Despite a growing chorus to regulate ART, Hoffman's views are likely to prevail for a while. Caplan notes that "there are no lobbying groups saying, 'Let's go!' And there are plenty of interest groups saying, 'Let's not do anything.' "

Tabitha M. Powledge writes frequently about genetics, science policy, archaeology and the brain.

PHILLIP HAYSON *Photo Researchers, Inc.*

CHILLING FOR CHILDREN: Freezing with liquid nitrogen keeps sperm ready for use.

DEVELOPING A CULTURED LIFE

Number of babies resulting from assisted reproductive technologies (ART) in the U.S. in 1999: 30,285

Percent of ART attempts using fresh (nonfrozen), nondonor eggs that result in a live birth for women:

Younger than 35 years: 32.2

Between 41 and 42: 9.7

Average of all age groups: 25.2

Number of live births: 16,588

Percent that result in multiple infants for women:

Younger than 35: 41

Between 41 and 42: 14.4

Percent of clients who try ART more than once: 45.6

Percent who try five or more times: 6.5

Estimated cost of an uncomplicated in vitro fertilization procedure using fresh, nondonor gametes: $10,000

AVIATION

Heads on Tails

SAFETY INVESTIGATORS TRY TO FIND OUT IF COMPOSITES FOR AIRCRAFT ARE STRONG ENOUGH **BY PHIL SCOTT**

The November 12 crash of Flight 587 in New York City, in which the tail fin, or vertical stabilizer, of an Airbus A300 fell off, raised concerns about the increasing use of composites over metal. Composites consist of layers of carbon-fiber sheets impregnated with resin, making them lighter and stronger than the traditional aluminum. Preliminary crash reports from the National Transportation Safety Board indicate that composite layers on the Airbus had come apart, or delaminated, near the point where the stabilizer attaches to the aircraft body. When pilots attempted to maneuver with the tail's rudder in the wake turbulence from a preceding aircraft, the entire vertical stabilizer separated from the airplane, sending the A300 into a death spiral.

DIAGNOSTIC TOOLS of nondestructive evaluation are important in aircraft maintenance. Here an electromagnetic probe is used to look for flaws in metal parts; composites would require nonmagnetic probes.

Aviation experts found the falling tail fin extremely strange. Unlike metal, composites don't "fatigue" with use—assuming no construction flaws, they remain as good as new over the years as long as the structure doesn't encounter forces greater than its design limit. The Airbus tail was made to withstand 50 percent more force than is typically encountered, although in February NTSB officials concluded that sudden back-and-forth movements of the rudder could damage the tail. Crash investigators now plan to use technologies for "nondestructive evaluation" to conduct a postmortem on the tail, in the hopes of determining whether the breakage stemmed from undetected, preexisting damage or whether composites contain some inherent flaw.

To evaluate the integrity of metal parts, inspectors use a so-called self-nulling probe, which induces a magnetic field in the metal; structural flaws produce a detectable break in the magnetic field. (Such exhaustive reviews are done every few years, as well as when an aircraft experiences some trouble.) The probe won't work on composites, however, because they are not metallic and cannot generate a magnetic field.

One method for the nondestructive evaluation of composites is familiar, at least to expectant parents: ultrasound. "We can detect flaws by interrogating the speed of the sound as it goes through the material," explains Mark Shuart, director for structures and materials at the NASA Langley Research Center. Ultrasound sensors usually rely on small transducers housed inside a handheld device. With the pulse sound, "we can detect changes in the content of the material and detect delamination, fiber breakages and different sorts of failure mechanisms," Shuart adds.

NASA has also developed a thermographic camera, which sends a pulse of high-intensity light to the material's surface. A void in the structure acts as an insulator and remains cooler than the surrounding material. Such a camera can detect changes in temperature as small as 0.02 degree Celsius. It is also used on metal structures to find, for instance, leaks in the space shuttle's main engine. NASA engineers quickly pressurize the shuttle's nozzle to 40 pounds per square inch, which forces air through any leaks and thus slightly alters its temperature. Then the camera snaps a picture. "Nozzles cost more than $5 million apiece," explains Samuel S. Russell, chief of Langley's nondestructive evaluation team. "So if you can save a nozzle and not replace it, it's kind of nice."

Engineers can also use acoustic emission sensors on composite structures. Each sensor incorporates a piezoelectric crystal that transmits a high-frequency sound between 75 and 200 kilohertz. At the same time, investigators put a load on the structure and triangulate the location of its creaks and groans, which signify structural flaws.

Such nondestructive analyses could become a necessary routine to test composites in aircraft. Visual inspection once every five

MAKING DO WITH COMPOSITES

Composite surfaces can be repaired, but the patch must have a stiffness equivalent to the rest of the surface. If it's too stiff, the patch might induce loads in other areas.

Percentage of composites by weight in:

Airbus A300: 4 to 5

Boeing 777: 10

Airbus A310: 10 to 15

U.S. Air Force's F-22: up to 40

JEFF CAPLAN *NASA Langley Research Center*

years has been the maintenance rule for composite parts, but such eyeballing will not detect any microscopic or deeply buried flaws. "I wish I could have gotten hold of it before it went down," Russell says of the ill-fated A300. "That's exactly the sort of thing we look for."

Phil Scott, based in New York City, specializes in aviation technology.

TRENDS

Mind the Gap

IS THE U.S. STARTING TO LOSE ITS EDGE IN BASIC RESEARCH? BY SERGIO PISTOI

Science is growing faster in the European Union than in the U.S., according to recent findings by the European Commission. The report, issued as a first step toward a systematic benchmarking of European research, consists of a collection of 15 indicators related to human resources, investment and scientific productivity measured in terms of the number of scientific publications—specifically, articles, notes, reviews and letters. Whereas the number of publications in the E.U. is steadily increasing, the rate is declining in the U.S. The average annual growth has risen, on average, by 3 percent from 1995 to 1999 in the E.U., while it has essentially flatlined in the U.S. Citations for these papers (a proxy for measuring their impact) also lessened in the U.S. In 1996, the last year for which these data are available, citations were higher in the E.U. for all research fields.

"We now see that the gap is widening" in terms of the citations and the number of publications, affirms Yvan Capouet, a member of the E.U. research commissioner's cabinet. Rolf F. Lehming, program director of the division of science resources statistics at the National Science Foundation, concurs: "There has been a decline in U.S. number of publications since 1995, following years of almost linear growth."

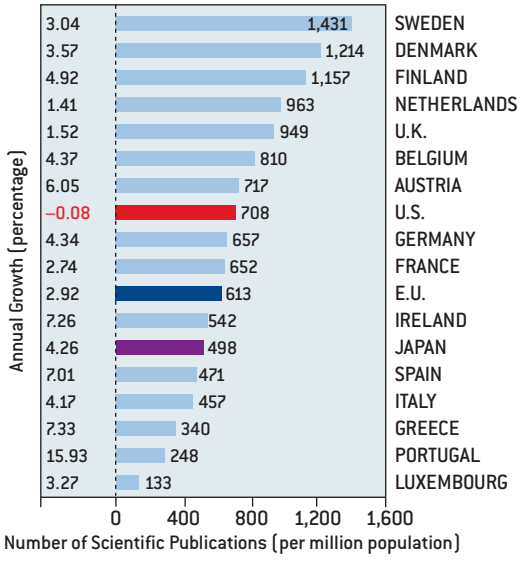
Leading the way in Europe is Scandinavia. On a per capita basis, Swedish, Danish and Finnish researchers produce up to twice the number of papers as the U.S., Japan or the E.U. as a whole. Sweden and Finland have also stood out in recent years for investments by both government and industry to attract scientists. In Sweden, for example, 3.7 percent of the gross domestic product is spent on research and development, more than in any other country (the U.S. spends 2.62 percent). And a quarter of foreign researchers' income is tax-free for up to three years.

A possible reason for the comparative decline in U.S. science output may be related to commercialization. The number of patents is still overwhelmingly higher in the U.S. than in the Old World, which suggests that U.S. researchers may be more likely to seek a patent than to divulge their results immediately.

In any case, Europe is not about to displace the U.S. as the world's research behemoth. In total numbers, the U.S. has more researchers and more frequently cited research papers. Moreover, E.U. countries are still a long way from achieving a unified scientific research terrain. Each country has a distinct science and technology infrastructure, and the competition for funds is mainly within national borders, not across member states.

And there is the issue of brain drain that afflicts Europe, to the benefit of the U.S.: researchers represent only 5.3 percent of the overall workforce in Europe, compared with 8.1 percent in the U.S., whose corporate and private laboratories are a more attractive destination for young investigators. "We are taking measures to increase the mobility of scientists between member states, [and] we need to reinforce the visibility and attractiveness of European research," says E.U. commissioner for research Philippe Busquin.

Sergio Pistoi is based in Arezzo, Italy.



SCIENTIFIC OUTPUT per capita is highest in Scandinavia. The rate of new papers from 1995 to 1999 (*numbers in left column*) has grown in Europe but not in the U.S. More data and a clickable map with statistics are available at **www.cordis.lu/rtd2002/indicators/**

IMMUNOLOGY

Drink Your Shots

GETTING RID OF THE STICKING POINT IN ALLERGY THERAPY **BY BRENDA GOODMAN**

For one out of five unlucky souls in the U.S., there's no mistaking the red, swollen eyes, drippy nose, sore throat and angry, inflamed nasal passages. The average person battles the scourge of allergy season with a small arsenal of pills, drops and inhalers, to the tune of $120 a year. And that's merely to stifle symptoms. Worse yet, such treatments won't stop about 20 percent of cases of allergic rhinitis from progressing to full-blown asthma—a condition that, despite improvements in drug therapies, now kills twice as many people in the U.S. every year as it did in 1980.

One weapon to tame the overreacting immune system is immunotherapy—gradual delivery of the substances that trigger allergies to acclimate the body to the world around it. In children it has been proved to prevent the development of new allergies and even asthma. For adults it can reduce the sneezing and wheezing of rhinitis by 80 percent and reduce the need for medications by an impressive 88 percent. This approach, however, requires the patient to assume the role of pincushion—doses must be delivered via a large needle twice weekly for the first few months and then monthly for up to five years. That's a total of at least 100 shots. No wonder the American College of Allergy, Asthma and Immunology found immunotherapy to be seriously underused.

But immunotherapy may soon be much more patient-friendly, thanks to the renaissance of an idea that has been around since the early 1980s—placing drops of the allergen extracts under patients' tongues. Mainstream medicine has been slow to embrace the latest incarnation of sublingual-swallow immunotherapy, or SLIT, but growing evidence from various clinical trials in Europe and a recent endorsement by the World Health Organization have made the idea much more palatable.

David Morris of Allergy Associates in La Crosse, Wis., is the most vocal advocate of SLIT in the U.S. He's leading an online campaign at allergychoices.com to educate other physicians and patients about the benefits, although skeptics argue he's no Jonas Salk. When asked to explain how the delicate allergens can survive the harsh environment of the digestive tract long enough to influence the immune system—the most common criticism of oral administration—Morris sighs and says, "I don't have to explain how it works. I have 60,000 patients who've had relief with the drops."

Luckily, research has begun to validate his campaign. Of 18 double-blind, placebo-controlled clinical trials in the past 15 years, 16 confirmed the effectiveness of SLIT in reducing patients' reactivity to grass pollen, house dust mites or birch pollen. Thus far studies have found that drops were as effective as shots and, not surprisingly, were better accepted by patients and were safer—though rare, a fatal systemic reaction to the shots is possible.

This trickle of scientific support has prompted Richard F. Lockey, director of the Division of Allergy and Immunology at the University of South Florida College of Medicine, to put at least one foot on the SLIT bandwagon. "I'm a very skeptical person, and if I'm starting to believe it works, there might be something to it," Lockey says.

He concurs with the latest recommendations offered in "Allergic Rhinitis and Its Impact on Asthma," a position paper published last November for the World Health Organization by an international consortium of 34 allergy experts. The group cautiously backs the use of sublingual therapy, especially for people who have experienced reactions to injections or who are not likely to comply with a regimen of shots. Immunotherapy "should be a first-line therapy," Lockey says. "We need the drops, and we need them soon."

Brenda Goodman is a science writer based in Orlando, Fla.

WHEN CO-WORKERS SAY GESUNDHEIT

You can be allergic to your job. Occupational rhinitis is caused by any of the approximately 250 allergens that are either native to your workplace or have hitched a ride on your office mates' hair or clothing, according to Emil J. Bardana, past president of the American College of Allergy, Asthma and Immunology. These allergens are also responsible for 5 percent of adult asthma cases.

One of the worst allergens of late is latex. After threats of bioterrorism, many employers rushed to protect their employees with powdered latex gloves. Anecdotal reports from allergists have noted a concurrent spike in complaints of sensitivity to latex, even from people who did not wear the gloves. That's because the latex allergen easily becomes airborne on the glove dusting powder.

MEET THE ENEMY: Weed pollen under the scanning electron microscope.

SCIENCE PICTURES *Photo Researchers, Inc.*

HUMOR

Joke Hunter of Science

FUNNYMAN MARC ABRAHAMS TACKLES AN IMPROBABLE ROLE AND AN IG NOBEL CAUSE **BY STEVE NADIS**

When April Fools' Day rolls around, many people look for little jokes to play on their friends. Marc Abrahams casts his net far wider, searching for the biggest jokes in the science world. April is when planning for the Ig Nobel prize ceremony "kicks into high gear," Abrahams explains. He has much to do before the event is held this October at Harvard University. In addition to settling on a list of winners, he'll write the libretto for a mini opera on jargon that will premiere at the prize ceremony, finish a book on the event's illustrious heritage, and continue to edit and publish the science humor magazine the *Annals of Improbable Research*, or *AIR*.

WATCH YOUR COCONUT: Marc Abrahams demonstrates the research of a 2001 Ig Nobel prizewinner.

His other activities include leading an international campaign to prevent the desecration of the plastic pink flamingo (invented by former Ig winner Don Featherstone), boosting membership in the Luxuriant Flowing Hair Club for Scientists (a group founded in honor of the Massachusetts Institute of Technology's Steven Pinker) and reviewing lunchrooms at various research hot spots for *AIR*. Such is the improbable life of one of science humor's most visible champions and possibly the only person in the world to pursue this line of work full-time.

"Marc holds a singular place in the science world," says Dudley Herschbach, a Harvard chemist and Nobel laureate who publishes in *AIR* and participates regularly in the Ig ceremony. Herschbach thinks Abrahams's biggest contribution—through both the Igs and the magazine—is to "poke fun at the silly things scientists do and show that science should not be taken as a sacred cow." He personally got involved "because it can stimulate interest in science by showing we aren't a bunch of super-nerds with no sense of humor."

Al Teich, director of science policy at the American Association for the Advancement of Science, made a similar case to AAAS officials six years ago, when he persuaded them to let Abrahams speak at the group's annual meetings. "Initially some board members felt this stuff was so frivolous it might detract from the stature of the meeting," Teich says. "But it's now obvious that Abrahams adds a dimension that people seem to enjoy. He always fills the room."

Not everyone is so enthusiastic. University of Bristol physicist Michael Berry, who shared the 2000 Ig prize in physics for his research on magnetically levitated frogs, was not sorry to have missed the ceremony: "From other people's descriptions and from what I saw on the Web, it's silly in a slightly embarrassing way that has no good effects as far as I can tell."

In his own defense, Abrahams points out that he always gives working scientists like Berry a chance to turn down the prize, and almost nobody does. Some participants, such as Peter Barss of McGill University, who took home the 2001 Ig Nobel in medicine for documenting the hazards posed by falling coconuts and other large fruits, believes his career and his cause have benefited from the award. Within a few months of winning the prize, Barss says, "I received more requests for interviews than in the past decade." Physicist Len Fisher, also at Bristol, remarks that his winning an Ig Nobel prize was partly responsible for his being approached by a major publisher to write a book tentatively entitled *How to Dunk a Donut*.

Abrahams is pleased to hear about such positive repercussions but says his number-one goal is still to make people laugh. Ultimately he hopes to show that "science humor" is not a contradiction in terms or a dangerous juxtaposition. The two words can sit together quite comfortably, and sometimes the results are curious indeed.

Steve Nadis, a writer based in Cambridge, Mass., has recurrent nightmares about winning an Ig Nobel prize in literature.

SAM OGDEN

THE START OF SOMETHING IG NOBEL

In 1990, before founding the *Annals of Improbable Research* in 1995, Marc Abrahams became editor of the *Journal of Irreproducible Results*. Soon after accepting the post, he was besieged by amateur scientists who wanted his help in winning a Nobel Prize. "I explained that I had no influence on these matters, but they invariably told me in great detail what they'd done and why they deserved a prize," Abrahams recalls. "In some cases, they were right. They deserved a prize, but not a Nobel Prize." A year later the Ig Nobel prizes were born—honoring "achievements that cannot or should not be reproduced."

Greenhouse Follies

PROSPERITY AND FERTILITY LIE AT THE ROOT OF GLOBAL WARMING, BUT NO ONE AGREES ON THE BEST FIX **BY RODGER DOYLE**

A quick and sure way to slow global warming is to arrange a really deep depression like the one that occurred in eastern Europe after the breakup of the Soviet empire. As the bottom left chart shows, such disintegration resulted in a steep decline in carbon dioxide emissions in that region. This episode illustrates that prosperity is a driving force behind the growing level of greenhouse gases. As incomes rise, people increasingly spend their money on autos, air-conditioning and other energy-intensive technologies, thus contributing to global warming.

Rising population is another prime contributor. Had population not changed since 1950, carbon emissions would now be 40 percent of their current level.

Of course, the world community will not be reducing the population or striving to cap prosperity. Instead it has focused on getting international agreements to lower emissions. The latest effort in this direction, the Kyoto Protocol, would set legally binding national targets for emission reductions. The Kyoto process, however, is in trouble, because not all countries (notably, the U.S.) will ratify it. Other efforts—such as the U.S. movement to impose higher mileage standards on sport-utility vehicles and the European Union plan to levy a tax on energy—have floundered.

In the absence of political action, many governments and private organizations have pinned their hopes on renewable sources of energy. The hydrogen fuel cell promoted by the Bush administration may not be a viable, near-term alternative to the internal-combustion engine because of its cost. Wind, solar, geothermal and biomass power now account for perhaps 2 percent of global energy needs and could supply 10 to 20 percent by midcentury.

The one reasonably sure way to cut emissions substantially over the next 50 years or so is through a massive proliferation of nuclear power plants. Expansion of nuclear power, which currently provides about 5 percent of the world's energy, is unlikely at this time in view of public distrust. In any case, it would take perhaps 40 years to build a sufficient number of plants to supply half of U.S. energy needs. China and India, the principal polluters among developing nations, would presumably take longer to hit the 50 percent mark.

What will happen if no serious effort is made to curtail fossil-fuel emissions? The Intergovernmental Panel on Climate Change has tried to answer the question by making a projection of emission levels through 2100 based on the assumption that fossil fuels will continue to supply most of the world's energy. The bottom right chart shows this calculation, along with two more optimistic scenarios. Such projections are, of course, no more than informed guesswork.

Rodger Doyle can be reached at rdoyle2@adelphia.net

news SCAN

NEED TO KNOW: WHO'S SPEWING?

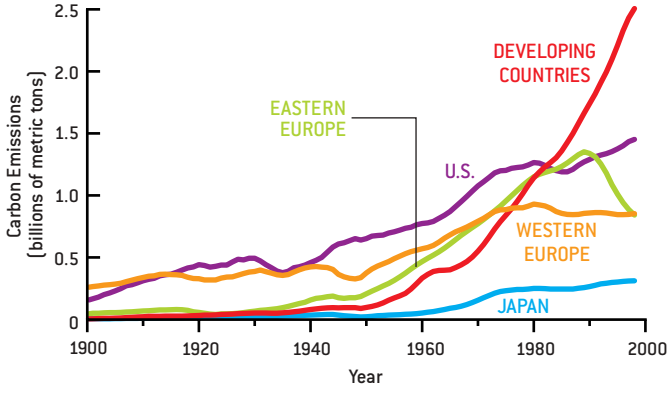
World Carbon Emissions from Fossil Fuels

	Percent of world emissions	Emissions per capita (metric tons)
U.S.	24	5.4
China	14	0.7
Russia	6	2.7
Japan	5	2.5
India	5	0.3
Germany	4	2.8
Canada	2	4.2
U.K.	2	2.5
South Korea	2	2.2
Italy	2	2.0
France	2	1.7
Mexico	2	1.1

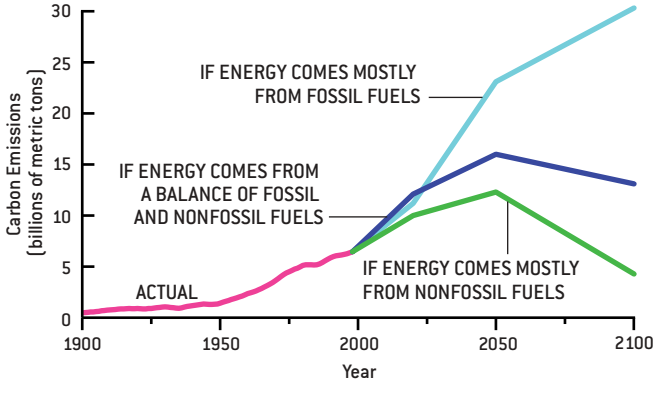
FURTHER READING

Climate Change: Science, Strategies and Solutions. Edited by Eileen Claussen, Vicki Arroyo Cochran and Debra P. Davis. Pew Center on Global Climate Change. Brill, Boston, 2001.

WORLDWIDE EMISSIONS, BY REGION



PROJECTED WORLDWIDE EMISSIONS



SOURCES: Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory; Emissions Scenarios, 2000: Special Report of the Intergovernmental Panel on Climate Change

RODGER DOYLE; GRAPHS BY LAURIE GRACE

DATA POINTS: FISH TALES

Using a statistical modeling program that incorporates oceanographic factors and historical production figures, Reg Watson and Daniel Pauly of the Fisheries Center in Vancouver, B.C., suggest that world fisheries are in more trouble than previously thought. Some countries—China in particular—have vastly overstated their catches.

Marine fish caught worldwide in 1999, millions of metric tons: 84.1

Marine fish produced through aquaculture: 13.1

Amount caught by China, as reported: 10.1

Amount caught by China, as indicated by statistical modeling: 5.5

Average annual change in fish catch since 1988, as suggested by reported figures: +330,000 metric tons

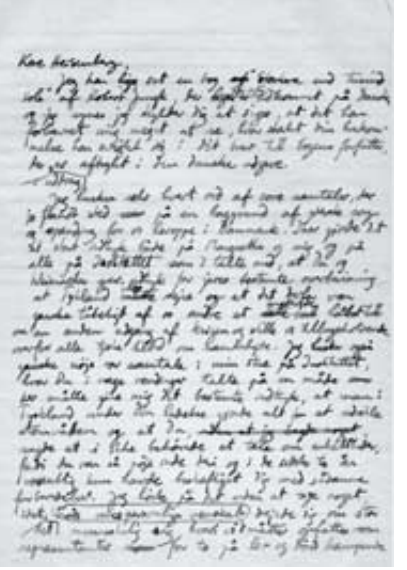
Change as suggested by statistical modeling: –360,000 metric tons

Percent of all fish caught or raised that is for human consumption: 74

SOURCES: Nature, *November 29, 2001;* State of World Fisheries and Aquaculture 2000, *by the Food and Agriculture Organization of the United Nations*

SCIENCE HISTORY

In No Uncertain Terms



RELEASED: A "Dear Werner" letter.

The Bohr family has finally released the mysterious letters that Niels Bohr wrote but never sent to Werner Heisenberg. They shed some light on the two physicists' mysterious meeting in 1941, which became the basis for Michael Frayn's play *Copenhagen*. In the letters, released in February, Bohr indicates that Heisenberg was not in fact stalling the Nazi atomic bomb program, as Heisenberg later claimed. "You spoke in a manner that could only give me the firm impression that, under your leadership, everything was being done in Germany to develop atomic weapons," Bohr wrote. The documents are not likely to be the last word, as some historians think Bohr could have misinterpreted Heisenberg's statements.

—Philip Yam

TRANSGENIC CROPS

Gene Fiends?

As genetically modified crops in North America grow, so does the debate over their use. A January report commissioned by the British conservation group English Nature showed that in Canada neighboring canola crops modified to be resistant to different kinds of herbicides have cross-pollinated and produced seeds that contain multiple resistances. If left behind after a harvest, the seeds could grow amid new crops or in field margins; English Nature argues that the offspring could become noxious weeds uncontrollable by existing chemicals. Keith Downey, research scientist emeritus at Canada's Saskatoon Research Center, disagrees. Canadian researchers expected resistance genes to accumulate, he says, and because there are more herbicides than resistance genes, the plants are just as easy to control as singly modified varieties. "The presence of the additional gene doesn't change it one little bit," Downey contends.

Indeed, genetically modified pollen may be less harmful than previously thought. In a September 14 *Proceedings of the National Academy of Sciences* report that was largely ignored, investigators showed that pollen shed by most types of corn engineered to secrete Bt insecticide harms monarch caterpillars only when at least 1,000 grains coat each square centimeter of caterpillar food. In nature, caterpillars encounter that much pollen less than 1 percent of the time.

—Alison McCook

CATERPILLARS of the monarch butterfly may not be truly threatened by transgenic crops.

NANOTECH

Falling in Line

To create nanoscale transistor junctions, engineers can criss-cross different types of semiconducting strands, thereby stacking the materials in layers crucial for manipulating electron flow. Three research teams recently managed to create a more complicated "superlattice" structure along a single wire.

One group, led by Charles M. Lieber of Harvard University, allowed vaporized semiconductor material to solidify behind gold molecules, then switched to different vapors midway through to link segments of different compounds, including gallium arsenide and gallium phosphide. The result was a nanowire consisting of alternating semiconductor bands capped by a gold contact. Such nanowires could serve as nanoscale lasers or bar codes that track proteins. Lieber's work appears in the February 7 *Nature;* researchers from the University of California at Berkeley and Lund University in Sweden present similar striped nanowires in the February *Nano Letters.*

—JR Minkel

NIELS BOHR INSTITUTE (*top*); ROD PLANCK *Photo Researchers, Inc.* (*bottom*); ILLUSTRATION BY MATT COLLINS

EPIDEMIOLOGY

Early to Rise

"You snooze, you lose" may be truer than anyone ever imagined. Based on a survey of more than 1.1 million people, an investigation led by Daniel F. Kripke of the University of California at San Diego found that people who slept at least eight hours a night had a higher risk of dying within six years than those who said they slept less, even as few as five hours. Women who clocked at least 10 hours a night were 41 percent more likely to die, and men 34 percent more, than subjects with the highest survival rates—those who reported nightly sleeps of between 6.5 and 7.4 hours. The results, however, could not indicate whether extended life span was a direct result of less sleep. Moreover, the researchers could not eliminate the influence of naps or every disease that might affect both sleep and mortality.

Most Americans get 6.5 hours of sleep nightly, Kripke says, and this study, appearing in the February 15 *Archives of General Psychiatry,* shows that they shouldn't feel guilty about not sleeping more. "What we can say to the average American is, 'You don't have to sleep eight hours. It isn't necessary for health.' " —*Alison McCook*

EYE-OPENER: A correlation between sleep and mortality.

EVOLUTION

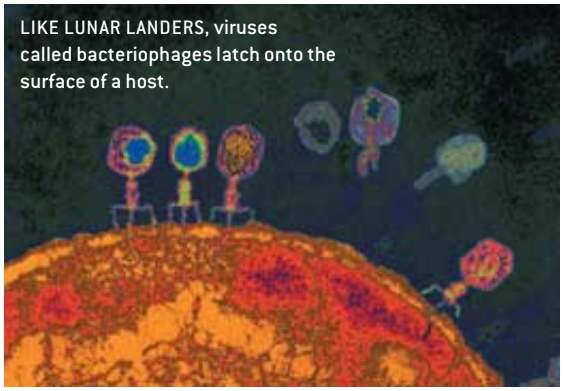
Score One for Natural Selection

Evolutionary biologists just got some genetic evidence they have been waiting for: a new study shows how simple genetic changes could have transformed multilimbed crustaceans into the six-limbed terrestrial insects that appeared around 400 million years ago. Experimenting with fruit flies, William McGinnis and two colleagues at the University of California at San Diego found that changing six amino acids in the protein Ubx, which normally helps to govern abdominal development, created embryos with fewer limbs. McGinnis says that a stepwise process of natural selection could have enabled this transition, with subsequent generations of crustacean ancestors carrying an additional amino acid change. These results, published online February 6 by *Nature,* counter arguments leveled by evolution critics who maintain that scientists lack genetic theories to explain how natural selection could induce radical changes in body designs. —*Alison McCook*

VIROLOGY

Breaking and Entering

Scientists have obtained atomic-level details of how a virus can infect and destroy bacterial cells more efficiently than any antibiotic can. Shuji Kanamaru of Purdue University and his colleagues found that the bacteriophage T4 virus takes over a cell using a needlelike structure protruding from its base. Once the virus recognizes a bacterial host, it undergoes a conformational change that pushes the needle into the bacterium. The virus's genetic information is injected through the tube into the host, where it proliferates and eventually bursts the cell. The T4 protrusion is quite stable, and the researchers speculate that it could one day refine atomic-force microscopes by replacing the larger stylus structures those instruments use to image surfaces. The results appeared in the January 31 *Nature*. —*Alison McCook*



LIKE LUNAR LANDERS, viruses called bacteriophages latch onto the surface of a host.

JOHN LAMB *Stone (top)*; MPI-TUBINGEN AND OLIVER MECKES *Photo Researchers, Inc. (bottom)*

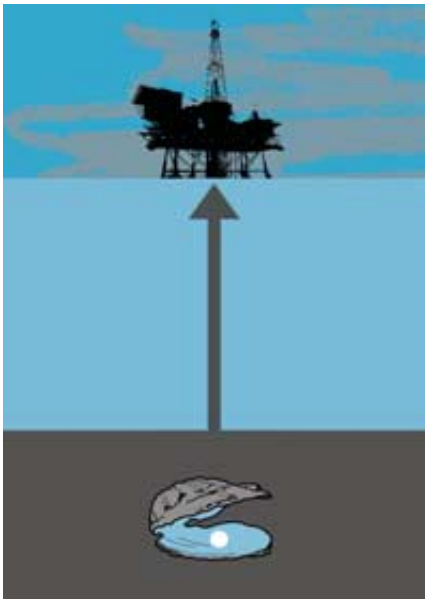
WWW.SCIAM.NEWS BRIEF BITS

- A study of Vietnam War veterans revealed that soldiers with high IQ scores fended off post-traumatic stress disorder better than those with lower scores. /013102/2.html
- Newly discovered in China, a fossil of a chicken-size dinosaur, dubbed *Sinovenator changii,* suggests that birdlike features arose earlier than previously thought. /021402/1.html
- In Kazakhstan, Soviet cold war aboveground atomic testing increased the genetic mutation rate among several generations living near the test site. /020802/2.html
- By splicing spider genes into mammal cells, a Canadian biotech firm has created synthetic spider silk that is almost as good as the real thing. /011802/1.html

It's Not Easy Being Green

Developing environmentally safe products is one thing; marketing them is another matter entirely By STEVEN ASHLEY

Larry Koskan's moment of inspiration arrived in the mid-1980s, when the organic chemist read a report by marine biologists at Clemson University and the University of South Alabama describing how oyster shells grow. Scientists knew that the mollusks secrete calcium carbonate as the essential constituent of their hardened exteriors. But what was new was the discovery that oysters also produce special protein-based agents that mold the mineral into their shells' characteristic shape. "When I realized that very low doses of the biopolymer they'd found—polyaspartate—inhibit the formation of calcium carbonate, the hair on the back of my neck rose up," Koskan recalls.



At the time, Koskan was employed by Nalco Chemical Company, where he was studying the properties of water-soluble polyacrylates (polyacrylics). Among other things, these widely used polymer additives help to stem the buildup of damaging mineral scale deposits (carbonate and sulfate compounds) on the surfaces of industrial water-treatment equipment. He realized that biodegradable polyaspartate could do the same job.

Polyaspartate mimics the scale-inhibiting activity of polyacrylate because it has a similar chemical morphology. Both molecules feature an active carboxylate chemical group directly attached to the polymer building blocks—a configuration that accounts for their chemical function, Koskan explains. But because the polymer backbone of polyaspartate is made of peptides (chains of amino acids) rather than the hydrocarbon compounds that constitute polyacrylate's backbone, it is degradable by bacterial action.

Polyacrylates, inexpensive and versatile chemicals that are easy to manufacture and process, have one drawback: they last virtually forever. "For years, the first question I'd hear when making customer calls in Germany and elsewhere in Europe was, 'Are your acrylic polymers biodegradable?'" Koskan says, noting that European governments were encouraging industry there to use environmentally friendly products. He suspected that he'd spotted an answer to their prayers as well as a potential winner in the then emerging "green chemistry" market.

The chemist's interest in the new polyaspartates was further piqued by the possibility that the biodegradable compounds could substitute for polyacrylics in other commercial roles. "In detergents, for example, water-soluble acrylates act as dispersants that keep dirt suspended in the wash water," Koskan says. Nowadays some half a billion pounds of polyacrylates are used in laundry detergents worldwide every year.

Even more enticing was the chance to enter another fast-growing market for polyacrylics: superabsorbent materials for disposable baby diapers and feminine-hygiene and adult-incontinence products, which currently account for around two billion pounds in annual production of polyacrylates. The polyacrylic chains crosslink into weblike configurations with a tremendous affinity for water. The trouble is, vast quantities of the highly stable substance are discarded in landfills.

When Koskan realized in ensuing years that Nalco Chemical had little interest in expending the considerable time and money it would take to pursue the polyaspartate technology, he decided to form his own company. Working with Ernst & Young, the accounting services firm, he developed a financial package for the start-up venture. In 1990 Donlar Corporation—now called Donlar Biosyntrex, after a recent merger—opened its doors in Bedford, Ill. (Today it has 17 employees.)

JOHN McFAUL

Around the same time, consumer products giant Procter & Gamble was removing phosphate water-softening additives from its popular laundry detergents. Such agents are environmentally undesirable because they can lead to the eutrophication (overenrichment) of surface waters, causing algae blooms.

"P&G started using significant quantities of polyacrylates as dispersants in its new detergents, as well as in disposable diapers and other superabsorbent products," notes Bob Pietrangelo, a veteran chemical industry executive who is now Donlar's chief operating officer. With the use of polyacrylates rising, P&G prodded the chemical industry to develop biodegradable substitutes for them. Soon thereafter, leading companies, including Rohm and Haas, BASF and Bayer, were researching the issue. "After six or seven years," Pietrangelo continues, "virtually everybody settled on polyaspartate as the most suitable replacement."

Unfortunately, the price of the substitute was estimated to be four to five times that of the high-volume-

"It's a funny thing about being environmentally friendly: everybody's in favor of it, but nobody wants to pay more for it."

production polyacrylates. "The problem for emerging technologies such as polyaspartates in securing a market niche is that the supporting infrastructure—particularly sufficient capacity to manufacture the product at a competitive price—is not generally available," Pietrangelo says. "As polyaspartates would be a costly product in small quantities, P&G lost interest and walked away from the technology, so the industry didn't run with it." Donlar, however, decided to stick with its core business and to focus on specialty application niches. "We spent the next five years after we set up Donlar developing the chemistry and the process technology for polyaspartates so we could offer competitive market pricing," Koskan recounts. So far the company has invested more than $50 million on development.

Donlar's patented production process starts with L-aspartic acid, a natural amino acid. It is heated on trays, causing the amino acid to polymerize as the constituent water is driven out. This reaction results in an intermediate powder product called polysuccinimide, a ring-shaped molecular compound. No solvents are required, and the only by-product is steam, which can be reused in the process. In the second step the polysuccinimide is hydrolyzed to polyaspartate through the addition of water, heat and a caustic base such as sodium hydroxide. Raising the pH of the mixture opens up the molecular rings, which form long polymer chains of sodium polyaspartate (a salt of alpha-beta-DL-polyaspartic acid). Donlar markets the result as thermal polyaspartate, or TPA. In 1997 the company completed a 50,000-square-foot manufacturing plant in Peru, Ill., with a production capacity of more than 30 million pounds a year.

Despite Donlar's success in developing the technology (and despite winning the first Green Chemistry Challenge Award from the U.S. Environmental Protection Agency in 1996), sales of the biodegradable product were not a sure bet. Says Pietrangelo: "It's a funny thing about being environmentally friendly: everybody's in favor of it, but nobody wants to pay more for it." Koskan agrees: "Though TPA is a tremendous technology, we had to forget about its green chemistry aspects and go with the idea that we've got a novel product that is competitive based on its merits."

By offering various technical advantages in certain applications, TPA has garnered increased sales in the oil and agricultural markets in recent years. (The company as a whole did $6.4 million in sales in 2000.) British Petroleum Exploration and other energy companies working the difficult North Sea offshore oil fields have achieved success with a TPA additive that helps to sustain the flow of crude from oil wells. In these operations, production is facilitated by injecting seawater under the ocean floor to maintain the pressure in the underlying oil formations. Because of the incompatibility of seawater with the water in the undersea geologic formation, mineral scales would otherwise form and block the flow of oil. Dual-purpose TPA not only inhibits mineral scale formation but checks oxidation as well.

In farming applications, the same TPA formulation is being added to fertilizers to keep them in the soil longer, allowing plant roots to absorb more nutrients. The result is greater crop yields and reduced nitrate runoff into groundwater. Donlar researchers have developed other products as well. For example, they have succeeded in cross-linking polyaspartate chains to produce a biodegradable superabsorbent material that could find widespread use at some point.

If Donlar can show continued success, it may help revive an environmental chemistry sector saddled with a reputation for ineffectiveness and high cost. And, as a profitable venture, it may finally lend an additional meaning to the "green" in green chemistry. SA

Steven Ashley is a staff editor and writer.

Tragedy of the Cyber Commons

A legal scholar issues a glum prognosis for future innovation on the Internet

Digital technology—of which the Internet is the most noteworthy exemplar—has enabled an extraordinary flourishing of creativity: people graduate from being passive consumers of music, video and other content to becoming publishers of their own works. Lawrence Lessig, a professor at Stanford Law School, suggests that the neutral platform, or commons, on which this newfound freedom thrives faces a mortal threat from entrenched telecommunications, cable and media interests. Lessig, who articulates these arguments in his recent book, *The Future of Ideas: The Fate of the Commons in a Connected World,* talked with SCIENTIFIC AMERICAN's Gary Stix about what lies ahead.

LAWRENCE LESSIG criticizes the Net's emerging power structure.

Describe the notion of a commons in relation to the Internet and how it might be endangered.

The Internet until now has been designed so that the network owner is not in a position to exercise control over the content or applications that run on it. The right to innovate is therefore held in common among all people who use the network and cannot be checked by the network owner. This freedom is increasingly under threat. The danger is that one class of property owners will use the legal system to veto certain kinds of innovation that no longer accord with its business interests. These owners will have the power to choose what kind of innovation is permitted—and that's inconsistent with the innovation commons.

How will this play out?

We're approaching a time in which cable will be a dominant mode of broadband access to the Internet. Cable companies will then have complete license to structure Internet access however they wish. That will have a very significant effect on certain kinds of innovation. Innovators, for instance, who want to stream lots of content over the Internet using the cable networks will find it very difficult to do so.

What has been the impact of the Napster case?

Napster symbolizes the failure of Congress to do what it has traditionally done to guarantee innovators access to content through compulsory licensing rights. The first real Napster in the past 50 years was not the Napster Corporation; the first real Napster was cable television, which was born by putting antennas on mountains that "stole" broadcasters' content, which was then sold to users. By the time Congress got around to dealing with the question, after lengthy court battles, it struck a balance. If you were a cable company that used broadcasting content, you had to pay for it, but you had a guaranteed right to get access to that content. This compulsory licensing meant that the broadcasters could not leverage their control of broadcasting into control over cable television. If Congress had done the same thing in the context of online music, we would see a completely different competitive horizon right now on the Internet. If it had established a compulsory licensing right from the record labels for online music, you'd have five or 10 new companies that would be in the business of innovating to find new ways to deliver content.

Should anything be done about software patents?

You begin to wonder: Where are the Republicans when you need them? Here's a clear example of government regulation of the innovation process. But who has done the regulatory impact statement to determine whether these regulations do any good? Nobody. In my view, we should not extend patents into fields like software until such an analysis is done. I don't believe we should regulate first and evaluate the new regulation later. SA

ELENA DORFMAN

Skepticism as a Virtue

An inquiry into the original meaning of the word "skeptic" By MICHAEL SHERMER

Poets often express deep insights into human nature with far less verbiage than scientists. Alexander Pope's *Essay on Man,* for example, is filled with pithy observations on the dualistic tensions of the human condition:

> Placed on this isthmus of a middle state,
> A Being darkly wise, and rudely great:
> With too much knowledge for the Sceptic side,
> With too much weakness for the Stoic's pride,
> He hangs between; in doubt to act, or rest,
> In doubt to deem himself a God, or Beast,
> In doubt his mind or body to prefer;
> Born but to die, and reasoning but to err.

Pope has packed a lot into this refrain, but the final clause is an important challenge to science: Is all our reasoning for naught, to end only in error? Such fear haunts us in our quest for understanding, and it is precisely why skepticism is a virtue. We must always be on guard against errors in our reasoning. Eternal vigilance is the watchword not just of freedom but of thought. That is the very nature of skepticism.

To my considerable chagrin, it was five years into the editing and publishing of *Skeptic* magazine before I realized I had never bothered to define the word or even examined how others had used it. Then Stephen Jay Gould, in the foreword to my book *Why People Believe Weird Things,* mentioned that it comes from the Greek *skeptikos,* for "thoughtful." Etymologically, in fact, its Latin derivative is *scepticus,* for "inquiring" or "reflective." Further variations in the ancient Greek include "watchman" or "mark to aim at." Hence, skepticism is thoughtful and reflective inquiry. To be skeptical is to aim toward a goal of critical thinking. Skeptics are the watchmen of reasoning errors, the Ralph Naders of bad ideas.

This is a far cry from modern misconceptions of the word as meaning "cynical" or "nihilistic," although a consideration of the word's history gives some insight into why its original definition has shifted. The *Oxford English Dictionary* offers this as its first definition of "sceptic": "one who, like Pyrrho and his followers in Greek antiquity, doubts the possibility of real knowledge of any kind; one who holds that there are no adequate grounds for certainty as to the truth of any proposition whatever." This may be true in philosophy, but not in science. There are more than adequate grounds for the probability of the truth of propositions—if we substitute "probability" for "certainty," because there are no incontrovertible facts in science if fact is a belief held with 100 percent certitude.

Superstring theory may be uncertain, but heliocentrism is not. Whether the history of life is best described by gradualism or punctuated equilibrium may still be in dispute, but the fact that life has evolved is not. The difference is one of probabilities, and this is reflected in a second usage of "sceptic": "one who doubts the validity of what claims to be knowledge in some particular department of inquiry." Okay, so we don't doubt everything, just some things—particularly those lacking in evidence and logic. Unfortunately, it is also true that some skeptics fall into a third usage of the word: "one who is habitually inclined rather to doubt than to believe any assertion or apparent fact that comes before him; a person of sceptical temper." Why some people are, by temperament, more skeptical than others is a subject for another essay. But suffice it to say that the reverse is also true—some folks are, by temperament, habitually inclined to believe rather than to doubt any assertion. Neither extreme is healthy.

Skepticism means finding a balance between orthodoxy and heresy.

Perhaps the closest fit to what we equate with a skeptical or scientific attitude is a fourth meaning: "a seeker after truth; an inquirer who has not yet arrived at definite convictions." Skepticism is not "seek and ye shall find"—a classic case of what is called the confirmation bias—but "seek and keep an open mind." What does it mean to have an open mind? It is to find the essential balance between orthodoxy and heresy, between a total commitment to the status quo and the blind pursuit of new ideas. SA

Michael Shermer is founding publisher of Skeptic *magazine (www.skeptic.com) and author of* The Borderlands of Science.

BRAD HINES

Father of the Impossible Children

Ignoring nearly universal opprobrium, Severino Antinori presses ahead with plans to clone a human being

By SERGIO PISTOI

A few hundred yards away from the Vatican, a fertility clinic has become both the top destination for desperate couples and the pope's most troublesome neighbor. As clients enter, they are greeted in the narrow corridor by a huge portrait of a pregnant Madonna. The towering image is an auspicious sign for the half a dozen couples who eagerly wait their turn for a consultation. As they sit, a man in a green surgical suit rushes from room to room, often yelling in a raspy voice on his mobile phone. His harried assistant witnesses the scene with dismay. "I'm going to die. I swear I'm going to die," she mutters.

The taskmaster in the scrubs is Severino Antinori, a physician whose reputation among infertile couples is far overshadowed by his international fame as the man who wants to clone a human being. Antinori's unapologetic stance has provoked worldwide condemnation that reached its crescendo last summer, when an eminent representative of the Catholic Church compared him to Adolf Hitler.

Cloning is Antinori's latest push on the ethics of assisted reproductive technology. In 1989 he made headlines for helping a 47-year-old woman become the first to give birth after menopause—a feat achieved via a donated egg and hormones. Five years later he enabled Rosanna Della Corte to set a world record as the oldest woman to give birth, at age 63. The Vatican labeled the experiment "grotesque" and "against the laws of Nature," but some researchers praised it as an admirable scientific achievement.

Some 6,600 infertile couples have signed up to be cloned, according to Antinori.

Antinori was born 56 years ago to small landowners in a village of Abruzzi, a region of central-southern Italy. The young Severino would watch with fascination while his uncle, a veterinarian, would artificially inseminate cows on surrounding farms. After his family moved to Rome, Antinori signed up for medical studies, where he soon discovered his intolerance for, as he puts it, the "academic mafia that was ruling the university." Still, he met Caterina Versaci there, and the two married shortly after they received their medical degrees. Specializing in gastroenterology and, later, in gynecology, Antinori worked in various posts around Italy before landing at Regina Elena, a public fertility hospital in Rome. In 1986, he says, he oversaw the birth of the first Italian child to be conceived in a publicly funded clinic through in vitro fertilization (IVF). But after clashing with some of his colleagues and hospital administrators, he resigned and, with his wife, set up the Associated Researchers for Human Reproduction (RAPRUI) clinic.

Antinori made his mark in the late 1980s, when he pioneered a technique called subzonal insemination (SUZI) to position sperm below the zona pellucida, the barrier around the egg, or oocyte. His work opened the way to intracytoplasmic sperm injection (ICSI), in which a single sperm is injected directly into the egg cell. He later introduced lasers to facilitate embryonic implantation. His résumé lists a professorship of human reproduction at the University of Rome as well as about 40 journal publications. In the past decade, however, he has become more involved with the judicial system than the peer-review one: he claims to have filed at least 36 libel suits, many still pending, against journalists, colleagues and his "Taliban" foes—his term for the Catholic Church.

"You know what the cardinals said when I invented SUZI?" Antinori asks. "That I was violating the barrier that God had put up to protect life. ICSI is routine today. It is the only option for millions of men who are subfertile"—that is, men who have low-motility sperm. Indeed, according to the Centers for Disease Control and Prevention, more than 90 percent of U.S. fertility labs offered the procedure in 1999, although geneticists warn that the technique

MASSIMO SAMBUCETTI *AP Photo*

SEVERINO ANTINORI: NO APOLOGIES

- **In 1994 published *My Impossible Children,* praising his own work.**
- **Reportedly threw an English television crew's equipment down some stairs because the crew brought along a critic of postmenopausal assisted reproduction.**
- **"She's a good biologist, but she's on the road to madness"—his opinion of cloning competitor Brigitte Boisselier, who works with the Raelian Movement, widely called the world's largest UFO religion.**

results in an alarming number of chromosomal abnormalities.

But ICSI is not enough to help all his patients. There are 100 million men who don't produce any sperm, and genetic reprogramming is the sole solution, he says. "Genetic reprogramming!" he emphasizes. "Not cloning. Cloning is a Hollywood-style term. It makes you think that you'll get a series of identical individuals. That's idiocy." Even if most of the clone's DNA comes from the donated nucleus, he argues, the oocyte still contributes a small percentage of genes from the mitochondria, meaning that cloning to produce two identical individuals is impossible.

The world glimpsed Antinori's flamboyance last August, when he, along with other would-be cloners, including Panayiotis Zavos and Brigitte Boisselier, took on the medical establishment at a colloquium organized by the National Academy of Sciences (NAS) in Washington, D.C. Most animal clones die before delivery or suffer from severe birth defects. Top experts, including the creator of Dolly the sheep, Ian Wilmut of the Roslin Institute in Edinburgh, Scotland, revealed that human clones could meet the same fate. Antinori and the other proponents were unfazed by such warnings. He dismissed the Dolly studies as "veterinary animal work."

According to Antinori, accurate prenatal screening can detect most defects, so bad embryos could be aborted. "Cloned sheep," he says, "have never been closely monitored for these defects." Even so, some sheep clones look perfectly healthy but suffer from nervous system disorders, respiratory ailments or other diseases after birth. Antinori admits that there is currently no way to test for these maladies. But he states that IVF and ICSI are much safer and more effective in humans than in livestock and that the same would hold true for cloning—a claim rejected by mainstream scientists. "Maybe they are culturing the animal embryos in an inappropriate way," he offers. "We have the expertise to do all that properly" in humans. (In January an NAS panel recommended a ban on human reproductive cloning but stood behind cloning to treat disease.)

Pinning Antinori down on specifics of his cloning bid—names, dates, places and such—is difficult: he becomes vague in his responses. His attempt, which has so far cost more than $300,000, will rely on anonymous private sources, mostly rich Asian and Arabian men, he says. The semiclandestine consortium, he insists, is a private agreement between him, Zavos and about 20 researchers of various nationalities whose identities and locations are kept secret as a precaution.

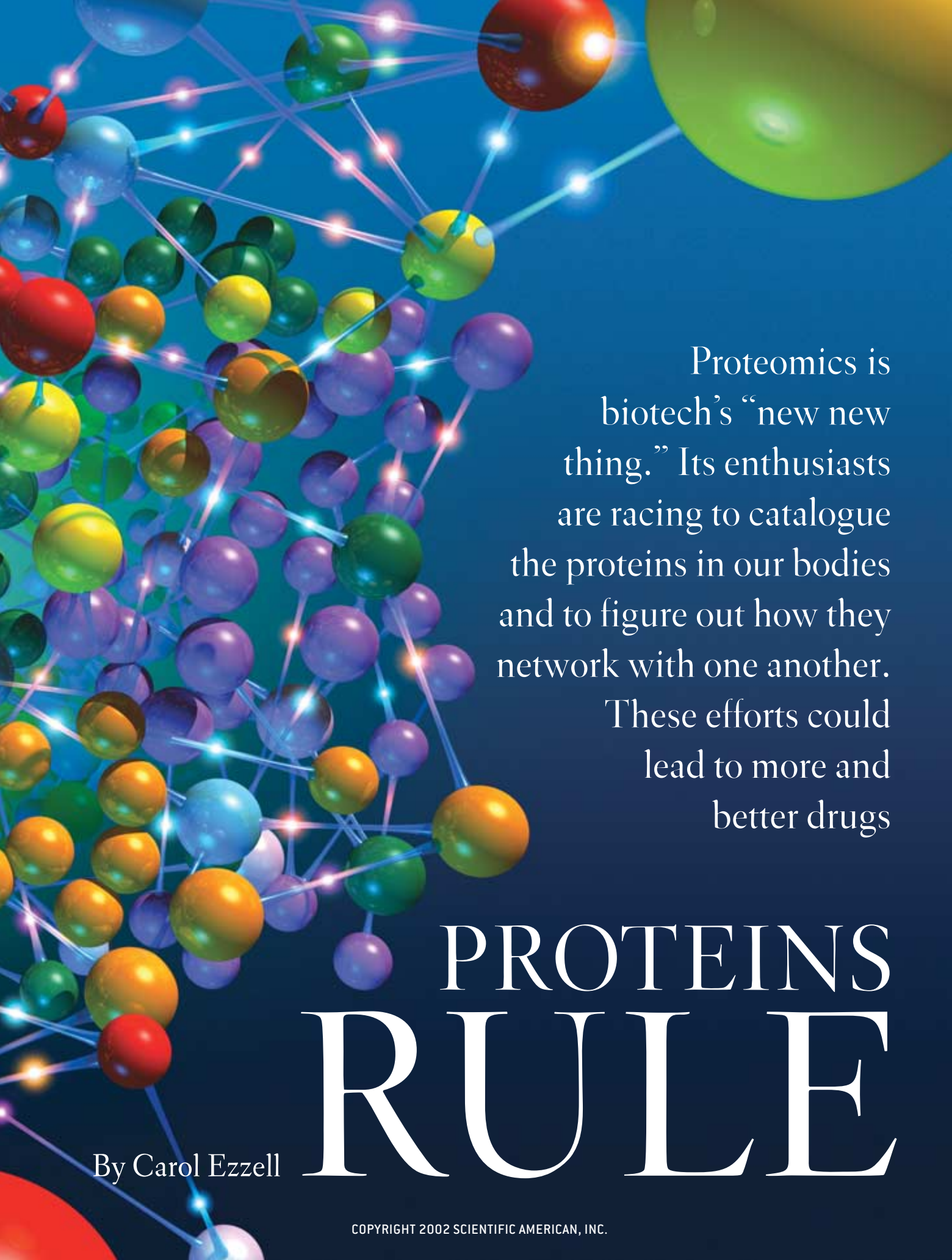
If Antinori is to be believed, he is far ahead of the rest of world. "We have obtained a cloned human embryo of 20 cells," he says, adding that the experiment was carried out somewhere in Asia. In contrast, Advanced Cell Technology in Worcester, Mass., which last November reported having cloned human embryos (for therapeutic, not reproductive, purposes), reached only six cells. The reason for the difference, Antinori suggests, is that his approach takes the nuclei from epidermal cells instead of from fibroblasts, as ACT researchers did, and uses oocytes at different stages of the cell cycle. Without any experimental data, it is hard to see whether these differences really can boost the success rate.

Antinori's determination to clone threatens his current livelihood. In September he was expelled from A PART, an international association of private fertility clinics of which he was once vice president; the reason, in part, was his "disreputable conduct [on] reproductive cloning." The Italian Medical Association says it might revoke his license should he push ahead with his cloning plans. (It could penalize him now, because its code prohibits postmenopausal assisted reproduction.)

Still, Antinori is not about to abandon reproductive cloning: about 600 infertile couples in Italy and more than 6,000 in the U.S. have already signed up for the procedure, he says. And the media buzz has so far helped his daily practice. "He is expensive, but we came here because they say he's the best," explains a patient waiting anxiously while his wife undergoes an IVF procedure. The human imperative to procreate is sure to keep Antinori's waiting room filled—and cloned babies on the agenda. SA

Sergio Pistoi, who is based in Arezzo, Italy, profiled war zone surgeon Gino Strada in the January issue.

NETWORKS of proteins pervade all cells.



Proteomics is biotech's "new new thing." Its enthusiasts are racing to catalogue the proteins in our bodies and to figure out how they network with one another. These efforts could lead to more and better drugs

PROTEINS RULE

By Carol Ezzell

Move over, human genome,

your day in the spotlight is coming to a close. Researchers are now concentrating on the human proteome, the collective body of proteins made by a person's cells and tissues. The genome—the full set of genetic information in the body—contains only the recipes for making proteins; it's the proteins that constitute the bricks and mortar of cells and that do most of the work. And it's proteins that distinguish the various types of cells: although all cells have essentially the same genome, they can differ in which genes are active and thus in which proteins are made; likewise, diseased cells often produce proteins that healthy cells don't, and vice versa.

Accordingly, corporate and academic scientists are looking to catalogue all human proteins and uncover their interactions with one another. The goal is to devise better drugs with fewer side effects.

Reaching that goal won't be a walk in the park, though: proteins are even more difficult to study than genes, and biotech companies are still struggling to come up with the best techniques and instruments for the task. Nevertheless, a race of sorts is on, with at least one company predicting that within three years it will have deciphered the human proteome, an important step in piecing together the myriad interactions among the individual proteins. Meanwhile federal programs are offering money to academic scientists to study the proteomes of cancer cells and serum, the watery component of human blood.

Researchers have already made some important strides: in January two groups reported that they had made maps of how all the proteins interact in baker's yeast, a popular model for studying cell biology. Other scientists announced in February that they had used proteomics techniques to devise an accurate early test for ovarian cancer.

Proteomics is set to become big business. According to investment analysts at Frost & Sullivan, the worldwide market for proteomics instruments, supplies and services will reach roughly $5.6 billion by 2005, up from only $700 million in 1999—and that doesn't include income generated from drugs or diagnostics developed as a result of proteomics approaches. Proteomics could also be vital to the future of the pharmaceutical industry, says Jessica Chutter, managing director and co-director of biotechnology for Morgan Stanley. The industry spent $30 billion on R&D in 2000, she states, but only 30 drugs were approved that year. "Pharmaceutical companies are dependent on proteomics and like technologies to overhaul their entire drug development process, or they will not survive," she claims.

Overview/*Proteomics*

- Now that the Human Genome Project is completed, scientists are turning to deciphering the networks of proteins within cells and tissues. But proteins are much more complex than genes and more difficult to study.
- Investors have poured hundreds of millions of dollars into companies that are devoted to producing proteomics equipment or to developing drugs or diagnostic tests based on proteomics techniques.
- Determining the three-dimensional structures of proteins allows researchers to find sites where proteins are most vulnerable to drugs.

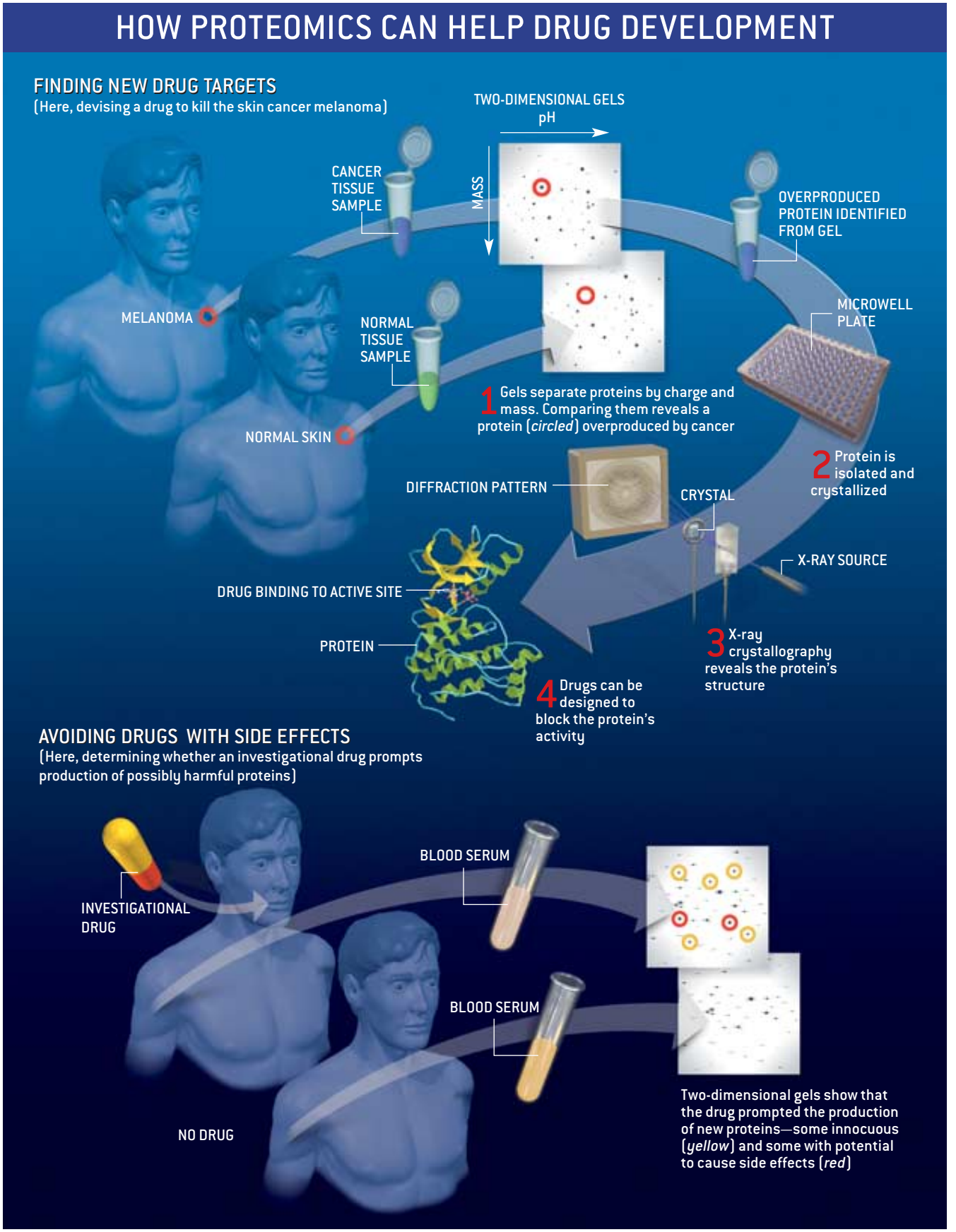
"Genes Were Easy"

THE TERM "PROTEOME" was coined in 1994 by Marc R. Wilkins, vice president and head of bioinformatics at Proteome Systems in Sydney, Australia, to mean the protein complement encoded by a genome. (The jazzy "-ome" and "-omics" suffixes have proliferated in biology to the point that a Web site now lists dozens of terms carrying the appellations.) The exact definition of proteomics varies depending on whom you ask, but most scientists agree that it can be broken down into three main activities: identifying all the proteins made in a given cell, tissue or organism; determining how those proteins join forces to form networks akin to electrical circuits; and outlining the precise three-dimensional structures of the proteins in an effort to find their Achilles' heels—that is, where drugs might turn their activity off or on.

These tasks sound straightforward, but the title of a 2001 conference on proteomics says it all: "Human Proteome Project: 'Genes Were Easy.'" Some of the hoopla that surrounded the backbreaking, but now essentially completed, Human Genome Project gave the impression

SLIM FILMS [*preceding pages*]

HOW PROTEOMICS CAN HELP DRUG DEVELOPMENT



SLIM FILMS; PROTEIN/DRUG STRUCTURE COURTESY OF DUNCAN McREE *Syrrx*

that knowing the sequence of the roughly three billion code letters, or DNA base pairs, occurring in the human genome—and specifically knowing the sequences in the protein-coding units (the genes)—would lead to an understanding of the proteins themselves.

Unfortunately, the proteome is much more complicated than the genome. The DNA "alphabet" consists of four chemical bases known by their first letters: adenine (A), cytosine (C), guanine (G) and thymine (T). Proteins, in contrast, are constructed from 20 building blocks, called amino acids. Genes specify which amino acids should be strung together to form a given protein. But even when scientists know the amino acid sequence of a protein, they cannot necessarily deduce what the protein does or which other proteins it engages with. Nor can they always forecast its three-dimensional structure with absolute accuracy. Unlike genes, which are linear, proteins fold into shapes that, in some cases, defy prediction.

Moreover, cells usually modify proteins by adding sugars or fats, or both, to them in ways that can be hard to anticipate as well. To produce a protein encoded by a newly discovered gene, scientists cannot merely string together amino acids in the order dictated by the gene; often they must also ensure that the proper fat and sugar modifications are made. And to determine how a protein behaves, researchers must also take into account that some proteins dissolve in water, whereas others act normally only in an oily environment or have regions that are embedded in fat-filled cell membranes.

That's not the end of the complexity. Although most researchers agree that the genome contains roughly 40,000 genes, a typical cell makes hundreds of thousands of distinct proteins. To understand the proteome, scientists have to learn the characteristics of all of those proteins. Simply making use of the data from the Human Genome Project, which finally put to rest the old dogma that one gene encodes one protein, will not do the trick. Clearly, one gene can somehow give rise to many different proteins.

Despite the complexities, proteomics researchers seem optimistic. "Some 30 to 50 percent of human proteins are unknown and of unknown function," admits Alma L. Burlingame of the University of California at San Francisco. But, he adds, "we now have the capacity to identify the protein components of human beings rather rapidly. It's tractable and will occur over the next couple of years."

Proteo-Factories

WHEN SCIENTISTS WANT to find out which proteins are present in selected cells or tissues, they usually turn to two techniques: two-dimensional gel electrophoresis and mass spectrometry. With 2-D gels, scientists add a mixture of proteins to the edge of thin gel that separates proteins in one direction according to their size and in a perpendicular direction according to their electrochemical charge [*see illustration on preceding page*]. Because any given protein has a characteristic size and charge, each one shows up as a discrete dot on the gel. Researchers can cut individual dots from the gels to identify the proteins they contain using other techniques. And they can look for proteins made by one tissue but not another by comparing the dot patterns of gels made from the two tissues.

Mass spectrometry employs magnets or electrical fields to resolve distinct proteins according to the masses of their constituent atoms. The results are displayed as peaks on a graph. Neither the 2-D gel technique nor mass spectrometry is ideal, however. Two-dimensional gels are notoriously difficult to run and can't distinguish very large or very small proteins or those that protrude through membranes, and mass spectrometry is expensive (more than $500,000 per machine) and sometimes fails to detect rare proteins.

Nevertheless, several companies are preparing refined versions of these methods for use in industrial-size operations on the order of the ones that made the Human Genome Project possible. The workhorse of that project was the ABI 3700, a DNA sequencer from Applied Biosystems. (Applied Biosystems is now part of Applera, which also includes Celera Genomics, the company that tied with the government consortium in completing the human sequence in 2000.) In January, Applied Biosystems unveiled its mass-spectrometry-based 4700 Proteomics Analyzer and announced an agreement with PerkinElmer and Millipore to provide an automated system for running and analyzing 2-D gels. Company executives hope the automation will allow scientists to do in days what used to take months or years.

But whether these new systems will be the proteomics standards remains to be seen. "There's not going to be one tool that's going to be dominant to the industry," says Darlene Solomon, who oversees life-sciences research and development for Agilent, an Applera competitor. "There's so much to proteomics."

Meanwhile such companies as Myriad Genetics in Salt Lake City, GeneProt in Geneva, Large Scale Biology in Vacaville, Calif., and MDS Proteomics in Toronto have geared up with custom proteomics plants of their own, some of which employ robotics techniques borrowed from the automotive industry. Last year Myriad announced that it had joined forces with Hitachi and Oracle in a $185-million deal to decipher the entire human proteome in three years, a program that officially began in January of this year. Celera, for its part, has raised almost $1 billion for its proteomics efforts. Celera's founder, J. Craig Venter, stepped down as president in January, however, and the company announced it was looking for a replacement who had more expertise in drug development. The

Unfortunately, the PROTEOME is much MORE COMPLICATED than the genome.

ROBOTIC WORKSTATION in a proteomics facility borrows technology from the assembly lines of the automotive industry. This one is configured to automate repetitive tasks such as pipetting and changing the growth medium—steps involved in growing cell cultures, a prerequisite for proteomics studies. Other such modules industrialize protein isolation and identification to ready samples for further study.

move was widely interpreted as an indication that the company would swing away from a business model based on selling access to its genomics—and proteomics—data to other companies and toward one in which it would devise its own drugs.

Critics of such grand projects have pointed out that there is no single human proteome: the pancreas makes a very different set of proteins than the brain does, for instance, and many variables, such as whether someone has just had a glass of wine, can affect the types of proteins the body produces. "Every state—plus or minus disease, plus or minus drug—is a different proteome," explains Michael F. Moran, chief scientific officer of MDS Proteomics.

In other words, listing human proteins takes you just so far. To understand what proteins do in the body and to develop useful drugs, you need to know how the mix of proteins varies from one cell type to another and within a cell as conditions change. You also need to know how proteins collaborate to carry out a cell's various activities.

Listening In on the Network

MORAN'S COMPANY is focused on this last task—examining how proteins hobnob with one another to form chains of biochemical reactions or make molecular machines such as the spindle that pulls two cells apart during cell division. "Proteins are assembled into networks," he says. "If you had to learn one thing about a protein, it would be what other proteins it interacts with."

In the January 10 issue of *Nature,* scientists from MDS Proteomics and the University of Toronto—and those in an independent group from Cellzome and the European Molecular Biology Laboratory, both in Heidelberg, Germany—reported coming up with a new strategy to find hundreds of such protein interactions in yeast. Their approach involves attaching bits of DNA that encode sticky "tags" to hundreds of selected yeast genes. The researchers can then isolate the proteins made from the modified genes, along with any proteins that have bound to them, by grinding up the yeast and pouring the slurry through a column of microscopic beads that can bind only to the sticky tags. After running the protein complexes through a mass spectrometer and analyzing the results, the scientists found that

MDS PROTEOMICS

A PROTEOMICS ROLODEX

CELERA (an Applera Corporation Business)
www.celera.com
Rockville, Md.
Proteomics efforts focus on comparing normal and diseased tissue to find disease-related proteins that could be targeted with monoclonal antibodies, cellular immunotherapy or small-molecule drugs.

cellzome
www.cellzome.com
Heidelberg, Germany
Founded by scientists at the European Molecular Biology Laboratory. Characterizes cellular protein complexes and is developing maps of protein interactions and pathways under varying experimental conditions.

CuraGen Corporation
www.curagen.com
New Haven, Conn.
Screens libraries of genes to identify interactions among the proteins they encode and to further understand how genes function in disease. Holds a key patent on the yeast two-hybrid method for outlining protein networks.

GeneProt™
U.S. headquarters: North Brunswick, N.J.
www.geneprot.com
Identifies, characterizes and synthesizes select human proteins for use in the discovery and development of new therapeutics. Second industrial-scale proteomics facility to open in 2002 at New Jersey headquarters.

hybrigenics
www.hybrigenics.com
Paris
Has developed industrial-scale technology for identifying, selecting and validating drug targets. Goal is to build a pipeline of disease "biomarkers" and small-molecule and antibody drug products.

LARGE SCALE BIOLOGY
www.lsbc.com
Vacaville, Calif.
Building a linked family of comprehensive databases of the human proteome, including protein markers for use in diagnosing and monitoring disease. Has both in-house and collaborative programs for drug development.

mds proteomics
www.mdsproteomics.com
Toronto
Identifies, selects and validates protein targets for both antibody and small-molecule therapeutics. Focuses on cancer, particularly on receptors and intracellular signaling, the networks of messages within cells.

MYRIAD
www.myriad.com
Salt Lake City
Determines the functions of individual proteins and how proteins form the complexes that constitute enzymatic machines and signaling circuits. Uses yeast two-hybrid and mass-spectrometry techniques.

SGX
www.stromix.com
San Diego
Uses high-throughput technology to determine protein structures of key targets within protein families. Employs bioinformatics techniques to virtually "dock" candidate drugs into the binding sites of drug targets.

syrrx
www.syrrx.com
San Diego
Generates three-dimensional protein structures and uses them to discover new drugs. The Syrrx Protein Structure Factory couples molecular tools with robotics to determine protein structures on an industrial scale.

SOURCE: Company materials

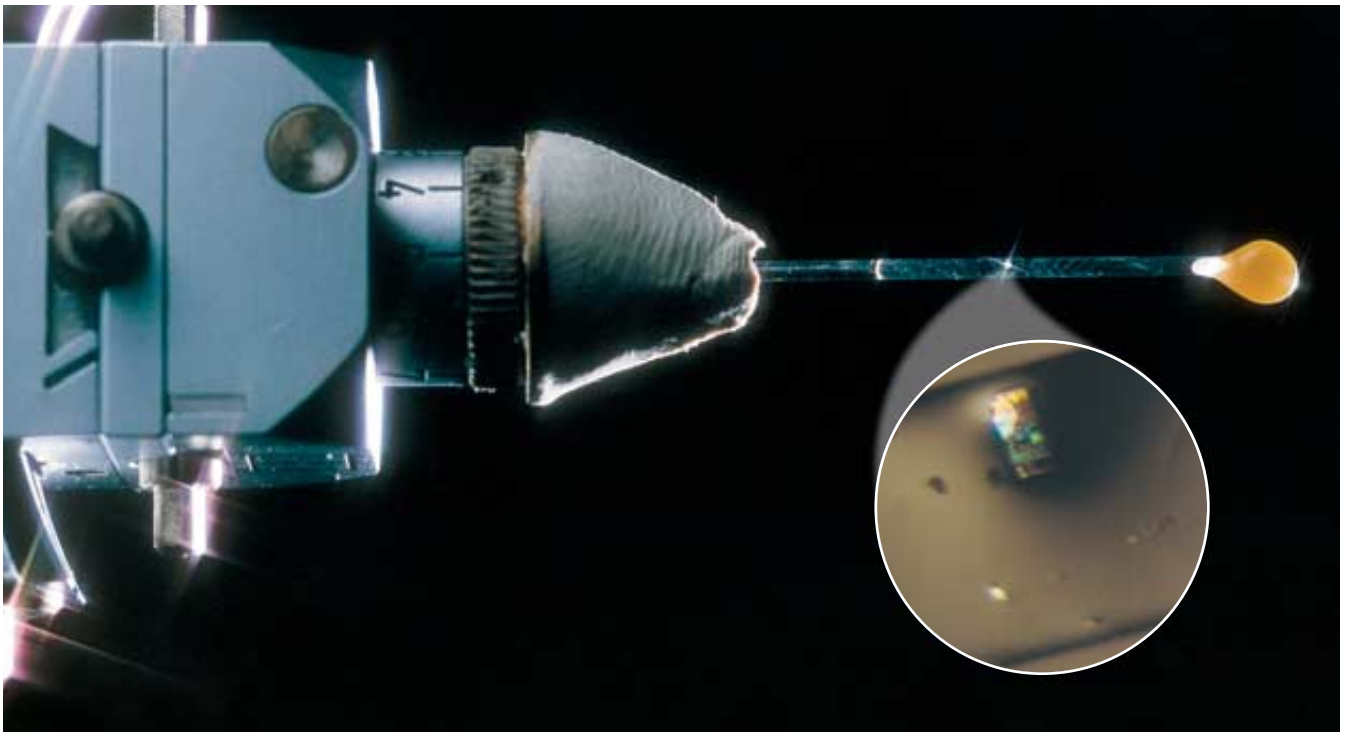
more than 90 percent of the complexes they isolated contained proteins of unknown function. What is more, up to 80 percent of the proteins interacted with at least one other protein, demonstrating the intricacy of the biochemical network within cells.

MDS Proteomics now plans to use the technique on the human proteome. Because the yeast proteome project took only a matter of weeks, company officials predict that they can produce an initial snapshot of the proteome of a human cell within a year. It is not yet clear what type of human cell they will study and under which conditions, however.

The public sector is also gearing up for proteomics. Academic researchers led by Samir M. Hanash of the University of Michigan have established the Human Proteome Organization (HUPO), which aims to link public proteome projects much as the Human Genome Project tied together academic labs deciphering the human genome. One of HUPO's first goals will be to determine the proteins present in blood serum.

The National Cancer Institute (NCI) and the Food and Drug Administration (FDA) have joined in a separate effort to focus on using proteomics to develop more targeted treatments and more reliable diagnostics for cancer. In the program, which was announced in July 2001, researchers will analyze tumor cells from individual patients to come up with a roster of proteins present in cancer cells but not in normal ones. They will also search for protein "markers" that correlate with more aggressive cancers, perhaps leading to better diagnostic tests.

Emanuel Petricoin, co-director of the NCI/FDA program, and his colleagues at the agencies and at Correlogic Systems in Bethesda, Md., recently demonstrated the promise of a proteomics approach to diagnosing cancer. In a paper published February 8 on the Web site of the journal the *Lancet*, the researchers report that they were able to compare the patterns of proteins present in the blood serum of patients with and without ovarian cancer. Through the comparison, they correctly identified all of 50 women who had ovarian cancer. Their test yielded only



X-RAY CRYSTALLOGRAPHY requires growing a pure crystal (*inset*) of the protein under study. Here a crystal of CD4, the protein that serves as a gateway for the AIDS virus to infect immune cells, is held in a tiny tube sealed with a ball of wax. The tube will be bombarded with x-rays to yield a pattern that scientists can interpret to determine the three-dimensional structure of an individual molecule of the protein.

three false positives among the samples of women who did not have the cancer.

Catalogues and maps of protein-protein interactions are only two thirds of proteomics; determining the shapes of proteins is equally important. The classic technique is x-ray crystallography, in which scientists purify proteins, allow them to grow into crystals and then bombard the crystals with x-rays. By analyzing how the x-rays bounce off the individual atoms of a protein, researchers can deduce how the protein is put together and can map its overall three-dimensional shape.

The Shape of Things to Come

X-RAY CRYSTALLOGRAPHY was once something of a cottage industry and required access to the x-ray beam line of a synchrotron. These often enormous rings, which can be miles in diameter, have historically been used by physicists to accelerate atomic particles. The x-rays are produced as part of that process. But advances in x-ray lasers have led to tabletop devices that can be used in labs.

Two companies—Syrrx and Structural GenomiX (SGX), both in San Diego—have now taken x-ray crystallography industrial. "Today everything is done robotically," explains Nathaniel David, cofounder and director of business development at Syrrx. Like the companies that have automated the protein discovery process, Syrrx has borrowed techniques from the automotive industry. Indeed, it brought in consultants from General Motors to automate its 84,000-square-foot facility, where everything from protein purification to crystallization is done on an assembly line. Besides its own x-ray lasers, the company has a dedicated beam line at the Advanced Light Source at Lawrence Berkeley Laboratory. Structural GenomiX has a similar deal with the Advanced Photon Source at Argonne National Laboratory, where it has built a beam line.

Such structural information could be bankable. Oxford GlycoSciences in England is betting that it can tie up the patent rights to a significant portion of the human genome and proteome using proteomics data. Last December the company filed patent applications for 4,000 human proteins, a move that could shake up how intellectual property is defined in biotechnology. In the past, companies sought to patent DNA sequences and the single protein that they predicted would be encoded by them. But because the same gene can make a range of proteins, claims based on the proteins themselves could be more valuable and offer a way to get around patents on the DNA sequences held by competitors. If so, the courts could be one more arena where genes will have to move over in favor of proteins. SA

Carol Ezzell is a staff editor and writer.

MORE TO EXPLORE

High-Speed Biologists Search for Gold in Proteins. Robert F. Service in *Science,* Vol. 294, pages 2074–2077; December 7, 2001.

Separation Anxiety: Why Proteomics Can't Let Go of 2D Gels. Aaron J. Sender in *Genome Technology,* No. 16, pages 34–39; December 2001.

For a glossary of the proliferating biotechnology terms ending in "-ome" and "-omics," visit **www.genomicglossaries.com/content/omes.asp**

KAY CHERNUSH

Augmented Reality: A New Way of Seeing

Computer scientists are developing systems that can enhance and enrich a user's view of the world

By Steven K. Feiner

SEE-THROUGH DISPLAY of a city street is shown in this artist's rendition of an augmented-reality system that could be in use by the end of this decade. The display superimposes graphics and text from wireless networks (for example, a bus schedule and a movie preview) over the appropriate objects in the user's view (the bus stop and the movie theater).

What will COMPUTER USER INTERFACES look like 10 years from now?

If we extrapolate from current systems, it's easy to imagine a proliferation of high-resolution displays, ranging from tiny handheld or wrist-worn devices to large screens built into desks, walls and floors. Such displays will doubtless become commonplace. But I and many other computer scientists believe that a fundamentally different kind of user interface known as augmented reality will have a more profound effect on the way in which we develop and interact with future computers.

Augmented reality (AR) refers to computer displays that add virtual information to a user's sensory perceptions. Most AR research focuses on "see-through" devices, usually worn on the head, that overlay graphics and text on the user's view of his or her surroundings. (Virtual information can also be in other sensory forms, such as sound or touch, but this article will concentrate on visual enhancements.) AR systems track the position and orientation of the user's head so that the overlaid material can be aligned with the user's view of the world. Through this process, known as registration, graphics software can place a three-dimensional image of a teacup, for example, on top of a real saucer and keep the virtual cup fixed in that position as the user moves about the room. AR systems employ some of the same hardware technologies used in virtual-reality research, but there's a crucial difference: whereas virtual reality brashly aims to replace the real world, augmented reality respectfully supplements it.

Consider what AR could make routinely possible. A repairperson viewing a broken piece of equipment could see instructions highlighting the parts that need to be inspected. A surgeon could get the equivalent of x-ray vision by observing live ultrasound scans of internal organs that are overlaid on the patient's body. Firefighters could see the layout of a burning building, allowing them to avoid hazards that would otherwise be invisible. Soldiers could see the positions of enemy snipers who had been spotted by unmanned reconnaissance planes. A tourist could glance down a street and see a review of each restaurant on the block. A computer gamer could battle 10-foot-tall aliens while walking to work.

Getting the right information at the right time and the right place is key in all these applications. Personal digital assistants such as the Palm and the Pocket PC can provide timely information using wireless networking and Global Positioning System (GPS) receivers that constantly track the handheld devices. But what makes augmented reality different is *how* the information is presented: not on a separate display but integrated with the user's perceptions. This kind of interface minimizes the extra mental effort that a user has to expend when switching his or her attention back and forth between real-world tasks and a computer screen. In augmented reality, the user's view of the world and the computer interface literally become one.

Although augmented reality may seem like the stuff of science fiction, researchers have been building prototype systems for more than three decades. The first was developed in the 1960s by computer graphics pioneer Ivan Sutherland and his students at Harvard University and the University of Utah. In the 1970s and 1980s a small number of researchers studied augmented reality at institutions such as the U.S. Air Force's Armstrong Laboratory, the NASA Ames Research Center and the University of North Carolina at Chapel Hill. It wasn't until the early 1990s that the term "augmented reality" was coined by scientists at Boeing who were developing an experimental AR system to help workers assemble wiring harnesses. The past decade has seen a flowering of AR research as hardware costs have fallen enough to make the necessary lab equipment affordable. Scientists have gathered at yearly AR conferences since 1998.

Despite the tremendous changes in information technology since Sutherland's groundbreaking work, the key components needed to build an AR system have remained the same: displays, trackers, and graphics computers and software. The performance of all these components has improved significantly in recent years, making it possible to design experimental systems that may soon be developed into commercial products.

Overview/*Augmented Reality*

- Augmented-reality (AR) systems add computer-generated information to a user's sensory perceptions. Whereas virtual reality aims to replace the real world, augmented reality supplements it.
- Most research focuses on "see-through" devices, usually worn on the head, that overlay graphics and text on the user's view of the world.
- Recent technological improvements may soon lead to the introduction of AR systems for surgeons, repairpeople, soldiers, tourists and computer gamers. Eventually the systems may become commonplace.

Seeing Is Believing

BY DEFINITION, the see-through displays in AR systems must be able to present a combination of virtual and real information. Although the displays can be handheld or stationary, they

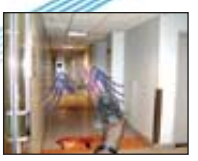
PAT RAWLINGS/SAIC (*preceding pages*)

OPTICAL SEE-THROUGH DISPLAY

OPTICAL SYSTEMS superimpose computer graphics on the user's view of the world. In this current design, the prisms reflect the graphics on a liquid-crystal display into the user's line of sight yet still allow light from the surrounding world to pass through. A system of sensors and targets keeps track of the position and orientation of the user's head, ensuring that the graphics appear in the correct places. But in present-day optical systems, the graphics cannot completely obscure the objects behind them.

1 View of the real world from a computer gamer's perspective

2 Graphics synthesized by the augmented-reality system



3 Image on optical display with superimposed graphics

ILLUSTRATION BY BRYAN CHRISTIE DESIGN, BASED ON A PROTOTYPE DISPLAY BY MIXED REALITY SYSTEMS LABORATORY, INC.

are most often worn on the head. Positioned just in front of the eye, a physically small screen can create a virtually large image. Head-worn displays are typically referred to as head-mounted displays, or HMDs for short. (I've always found it odd, however, that anyone would want to "mount" something on his or her head, so I prefer to call them head-worn displays.)

The devices fall into two categories: optical see-through and video see-through. A simple approach to optical see-through display employs a mirror beam splitter—a half-silvered mirror that both reflects and transmits light. If properly oriented in front of the user's eye, the beam splitter can reflect the image of a computer display into the user's line of sight yet still allow light from the surrounding world to pass through. Such beam splitters, which are called combiners, have long been used in "head-up" displays for fighter-jet pilots (and, more recently, for drivers of luxury cars). Lenses can be placed between the beam splitter and the computer display to focus the image so that it appears at a comfortable viewing distance. If a display and optics are provided for each eye, the view can be in stereo [*see illustration above*].

In contrast, a video see-through display uses video mixing technology, originally developed for television special effects, to combine the image from a head-worn camera with synthesized graphics [*see illustration on next page*]. The merged image is typically presented on an opaque head-worn display. With careful design, the camera can be positioned so that its optical path is close to that of the user's eye; the video image thus approximates what the user would normally see. As with optical see-through displays, a separate system can be provided for each eye to support stereo vision.

In one method for combining images for video see-through displays, the synthesized graphics are set against a reserved background color. One by one, pixels from the video camera image are matched with the corresponding pixels from the synthesized graphics image. A pixel from the camera image appears in the display when the pixel from the graphics image contains the background color; otherwise the pixel from the graphics image is displayed. Consequently, the synthesized graphics obscure the real objects behind them. Alternatively, a separate channel of information stored with each pixel can indicate the fraction of that pixel that should be determined by the virtual information. This technique allows the display of semitransparent graphics. And if the system can determine the distances of real objects from the viewer, computer graphics algorithms can also create the illusion that the real objects are obscuring virtual objects that are farther away. (Optical see-through displays have this capability as well.)

Each of the approaches to see-through display design has its pluses and minuses. Optical see-through systems allow the user to see the real world with full resolution and field of view. But the overlaid graphics in current optical see-through systems are not opaque and therefore cannot completely obscure the physical objects behind them. As a result, the superimposed text may be hard to read against some backgrounds, and the three-

dimensional graphics may not produce a convincing illusion. Furthermore, although a user focuses physical objects depending on their distance, virtual objects are all focused in the plane of the display. This means that a virtual object that is intended to be at the same position as a physical object may have a geometrically correct projection, yet the user may not be able to view both objects in focus at the same time.

In video see-through systems, virtual objects can fully obscure physical ones and can be combined with them using a rich variety of graphical effects. There is also no discrepancy between how the eye focuses virtual and physical objects, because both are viewed on the same plane. The limitations of current video technology, however, mean that the quality of the visual experience of the real world is significantly decreased, essentially to the level of the synthesized graphics, with everything focusing at the same apparent distance. At present, a video camera and display are no match for the human eye.

The earliest see-through displays devised by Sutherland and his students were cumbersome devices containing cathode-ray tubes and bulky optics. Nowadays researchers use small liquid-crystal displays and advanced optical designs to create systems that weigh mere ounces. More improvements are forthcoming: a company called Microvision, for instance, has recently developed a device that uses low-power lasers to scan images directly on the retina [see "Eye Spy," by Phil Scott; News Scan, Scientific American, September 2001]. Some prototype head-worn displays look much like eyeglasses, making them relatively inconspicuous. Another approach involves projecting graphics directly on surfaces in the user's environment.

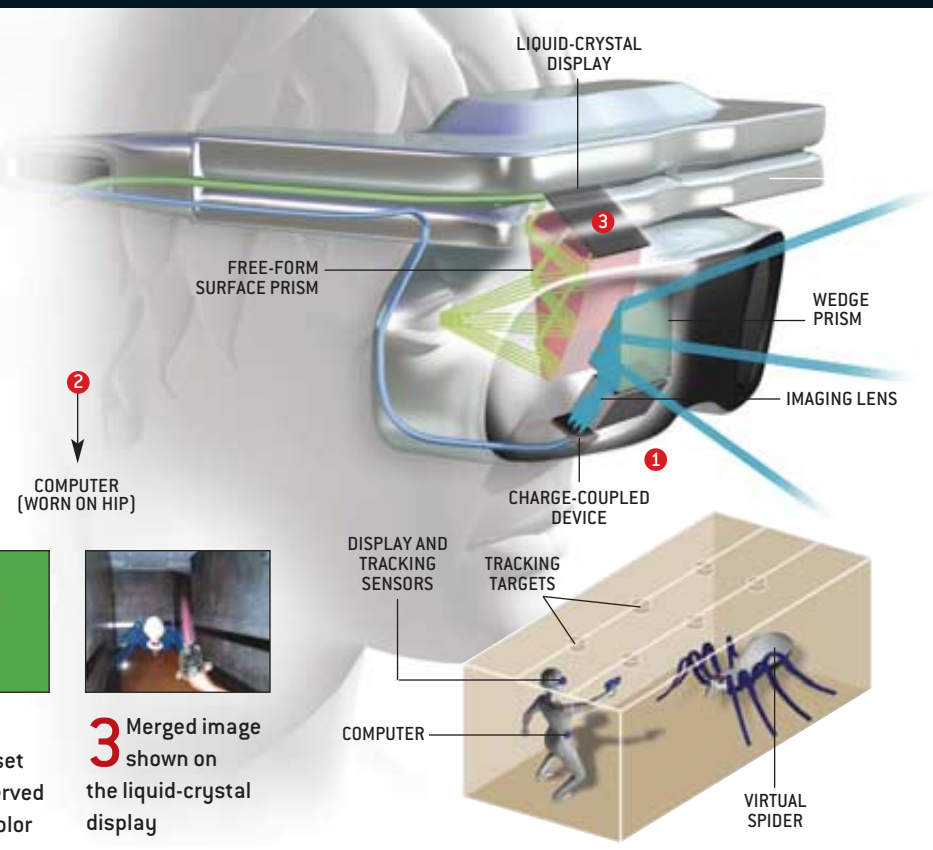
Keeping Track

A CRUCIAL REQUIREMENT of augmented-reality systems is to correctly match the overlaid graphics with the user's view of the surrounding world. To make that spatial relation possible, the AR system must accurately track the position and orientation of the user's head and employ that information when rendering the graphics. Some AR systems may also require certain moving objects to be tracked; for example, a system that provides visual guidance for a mechanic repairing a jet engine may need to track the positions and orientations of the engine's parts during disassembly. Because the tracking devices typically monitor six parameters for each object—three spatial coordinates (x, y and z) and three orientation angles (pitch, yaw and roll)—they are often called six-degree-of-freedom trackers.

In their prototype AR systems, Sutherland and his colleagues experimented with a mechanical head tracker suspended from the ceiling. They also tried ultrasonic trackers that transmitted acoustic signals to determine the user's position. Since then, researchers have developed improved versions of these technologies, as well as electromagnetic, optical and

VIDEO SEE-THROUGH DISPLAY

VIDEO SYSTEMS mix computer graphics with camera images that approximate what the user would normally see. In this design, light from the surrounding world is captured by a wedge prism and focused on a charge-coupled device that converts the light to digital video signals. The system combines the video with computer graphics and presents the merged images on the liquid-crystal display. Video systems can produce opaque graphics but cannot yet match the resolution and range of the human eye.



1 View of the real world captured and converted to a video image

2 Computer graphics set against a reserved background color

3 Merged image shown on the liquid-crystal display

ILLUSTRATION BY BRYAN CHRISTIE DESIGN, BASED ON A PROTOTYPE DISPLAY BY MIXED REALITY SYSTEMS LABORATORY, INC.

The user's VIEW OF THE WORLD and the computer interface LITERALLY BECOME ONE.

video trackers. Trackers typically have two parts: one worn by the tracked person or object and the other built into the surrounding environment, usually within the same room. In optical trackers, the targets—LEDs or reflectors, for instance—can be attached to the tracked person or object, and an array of optical sensors can be embedded in the room's ceiling. Alternatively, the tracked users can wear the sensors, and the targets can be fixed to the ceiling. By calculating the distance to each visible target, the sensors can determine the user's position and orientation.

In everyday life, people rely on several senses—including what they see, cues from their inner ears and gravity's pull on their bodies—to maintain their bearings. In a similar fashion, "hybrid trackers" draw on several sources of sensory information. For example, the wearer of an AR display can be equipped with inertial sensors (gyroscopes and accelerometers) to record changes in head orientation. Combining this information with data from the optical, video or ultrasonic devices greatly improves the accuracy of the tracking.

But what about AR systems designed for outdoor use? How can you track a person when he or she steps outside the room packed with sensors? The outdoor AR system designed by our lab at Columbia University handles orientation and position tracking separately. Head orientation is determined with a commercially available hybrid tracker that combines gyroscopes and accelerometers with a magnetometer that measures the earth's magnetic field. For position tracking, we take advantage of a high-precision version of the increasingly popular Global Positioning System receiver.

A GPS receiver determines its position by monitoring radio signals from navigation satellites. The accuracy of the inexpensive, handheld receivers that are currently available is quite coarse—the positions can be off by many meters. Users can get better results with a technique known as differential GPS. In this method, the mobile GPS receiver also monitors signals from another GPS receiver and a radio transmitter at a fixed location on the earth. This transmitter broadcasts corrections based on the difference between the stationary GPS antenna's known and computed positions. By using these signals to correct the satellite signals, differential GPS can reduce the margin of error to less than one meter. Our system is able to achieve centimeter-level accuracy by employing real-time kinematic GPS, a more sophisticated form of differential GPS that also compares the phases of the signals at the fixed and mobile receivers.

Unfortunately, GPS is not the ultimate answer to position tracking. The satellite signals are relatively weak and easily blocked by buildings or even foliage. This rules out useful tracking indoors or in places like midtown Manhattan, where rows of tall buildings block most of the sky. We found that GPS tracking works well in the central part of Columbia's campus, which has wide open spaces and relatively low buildings. GPS, however, provides far too few updates per second and is too inaccurate to support the precise overlaying of graphics on nearby objects.

Augmented-reality systems place extraordinarily high demands on the accuracy, resolution, repeatability and speed of tracking technologies. Hardware and software delays introduce a lag between the user's movement and the update of the display. As a result, virtual objects will not remain in their proper positions as the user moves about or turns his or her head. One technique for combating such errors is to equip AR systems with software that makes short-term predictions about the user's future motions by extrapolating from previous movements. And in the long run, hybrid trackers that include computer vision technologies may be able to trigger appropriate graphics overlays when the devices recognize certain objects in the user's view.

Managing Reality

THE PERFORMANCE OF GRAPHICS hardware and software has improved spectacularly in the past few years. In the 1990s our lab had to build its own computers for our outdoor AR systems because no commercially available laptop could produce the fast 3-D graphics that we wanted. In 2001, however, we were finally able to switch to a commercial laptop that had sufficiently powerful graphics chips. In our experimental mobile systems, the laptop is mounted on a backpack. The machine has the advantage of a large built-in display, which we leave open to allow bystanders to see what the overlaid graphics look like alone.

THE AUTHOR

STEVEN K. FEINER is professor of computer science at Columbia University, where he directs the Computer Graphics and User Interfaces Lab. He received a Ph.D. in computer science from Brown University in 1987. In addition to performing research on software and user interfaces for augmented reality, Feiner and his colleagues are developing systems that automate the design and layout of interactive graphics and multimedia presentations in domains ranging from medicine to government databases. The research described in this article was supported in part by the Office of Naval Research and the National Science Foundation.

Part of what makes reality *real* is its constant state of flux. AR software must constantly update the overlaid graphics as the user and visible objects move about. I use the term "environment management" to describe the process of coordinating the presentation of a large number of virtual objects on many displays for many users. Working with Simon J. Julier, Larry J. Rosenblum and others at the Naval Research Laboratory, we are developing a software architecture that addresses this problem. Suppose that we wanted to introduce our lab to a visitor by annotating what he or she sees. This would entail selecting the parts of the lab to annotate, determining the form of the annotations (for instance, labels) and calculating each label's position and size. Our lab has developed prototype software that interactively redesigns the geometry of virtual objects to maintain the desired relations among them and the real objects in the user's view. For example, the software can continually recompute a label's size and position to ensure that it is always visible and that it overlaps only the appropriate object.

It is important to note that a number of useful applications of AR require relatively little graphics power: we already see the real world without having to render it. (In contrast, virtual-reality systems must always create a 3-D setting for the user.) In a system designed for equipment repair, just one simple arrow or highlight box may be enough to show the next step in a complicated maintenance procedure. In any case, for mobile AR to become practical, computers and their power supplies must become small enough to be worn comfortably. I used to suggest that they needed to be the size of a Walkman, but a better target might be the even smaller MP3 player.

The Touring Machine and MARS

WHEREAS MANY AR DESIGNS have focused on developing better trackers and displays, our laboratory has concentrated on the design of the user interface and the software infrastructure. After experimenting with indoor AR systems in the early 1990s, we decided to build our first outdoor system in 1996 to find out how it might help a tourist exploring an unfamiliar environment. We called our initial prototype the Touring Machine (with apologies to Alan M. Turing, whose abstract Turing machine defines what computers are capable of computing). Because we wanted to minimize the constraints imposed by current technology, we combined the best components we could find to create a test bed whose capabilities are as close as we can make them to the more powerful machines we expect in the future. We avoided (as much as possible) practical concerns such as cost, size, weight and power consumption, confident that those problems will be overcome by hardware designers in the coming years. Trading off physical comfort for performance and ease of software development, we have built several generations of prototypes using external-frame backpacks. In general, we refer to these as mobile AR systems (or MARS, for short) [*see left illustration below*].

Our current system uses a Velcro-covered board and straps to hold many of the components: the laptop computer (with its

GLIMPSES OF AUGMENTED REALITY

COLUMBIA UNIVERSITY'S Computer Graphics and User Interfaces Lab built an experimental outdoor system designed to help a tourist explore the university's campus. The laptop on the user's backpack supplies the computer graphics that are superimposed on the optical see-through display. GPS receivers track the user's position.

The lab created a historical documentary that shows three-dimensional images of the Bloomingdale Asylum, the prior occupant of Columbia's campus, at its original location.

A user viewing the documentary can get additional information from a handheld display, which provides an interactive timeline of the Bloomingdale Asylum's history.

MEDICAL APPLICATION was built by researchers at the University of Central Florida. The system overlaid a model of a knee joint on the view of a woman's leg. The researchers tracked the leg's position using infrared LEDs. As the woman bent her knee, the graphics showed how the bones would move.

TOBIAS HOLLERER, STEVEN K. FEINER AND JOHN PAVLIK *Computer Graphics and User Interfaces Lab, Columbia University [mobile AR documentaries]*; JANNICK ROLLAND *Optical Diagnostics and Applications Laboratory, School of Optics, University of Central Florida [knee joint]*

The OVERLAID INFORMATION will become part of what we expect to see AT WORK AND AT PLAY.

3-D graphics chip set and IEEE 802.11b wireless network card), trackers (a real-time kinematic GPS receiver, a GPS corrections receiver and the interface box for the hybrid orientation tracker), power (batteries and a regulated power supply), and interface boxes for the head-worn display and interaction devices. The total weight is about 11 kilograms (25 pounds). Antennas for the GPS receiver and the GPS corrections receiver are mounted at the top of the backpack frame, and the user wears the head-worn see-through display and its attached orientation tracker sensor. Our MARS prototypes allow users to interact with the display—to scroll, say, through a menu of choices superimposed on the user's view—by manipulating a wireless trackball or touch pad.

From the very beginning, our system has also included a handheld display (with stylus input) to complement the head-worn see-through display. This hybrid user interface offers the benefits of both kinds of interaction: the user can see 3-D graphics on the see-through display and, at the same time, access additional information on the handheld display.

In collaboration with my colleague John Pavlik and his students in Columbia's Graduate School of Journalism, we have explored how our MARS prototypes can embed "situated documentaries" in the surrounding environment. These documentaries narrate historical events that took place in the user's immediate area by overlaying 3-D graphics and sound on what the user sees and hears. Standing at Columbia's sundial and looking through the head-worn display, the user sees virtual flags planted around the campus, each of which represents several sections of the story linked to that flag's location. When the user selects a flag and then chooses one of the sections, it is presented on both the head-worn and the handheld displays.

One of our situated documentaries tells the story of the student demonstrations at Columbia in 1968. If the user chooses one of the virtual flags, the head-worn display presents a narrated set of still images, while the handheld display shows video snippets and provides in-depth information about specific participants and incidents. In our documentary on the prior occupant of Columbia's current campus, the Bloomingdale Asylum, 3-D models of the asylum's buildings (long since demolished) are overlaid at their original locations on the see-through display. Meanwhile the handheld display presents an interactive annotated timeline of the asylum's history. As the user chooses different dates on the timeline, the images of the buildings that existed at those dates fade in and out on the see-through display.

The Killer App?

AS RESEARCHERS CONTINUE to improve the tracking, display and mobile processing components of AR systems, the seamless integration of virtual and sensory information may become not merely possible but commonplace. Some observers have suggested that one of the many potential applications of augmented reality (computer gaming, equipment maintenance, medical imagery and so on) will emerge as the "killer app"—a use so compelling that it would result in mass adoption of the technology. Although specific applications may well be a driving force when commercial AR systems initially become available, I believe that the systems will ultimately become much like telephones and PCs. These familiar devices have no single driving application but rather a host of everyday uses.

The notion of computers being inextricably and transparently incorporated into our daily lives is what computer scientist Mark Weiser termed "ubiquitous computing" more than a decade ago [see "The Computer for the 21st Century," by Mark Weiser; SCIENTIFIC AMERICAN, September 1991]. In a similar way, I believe the overlaid information of AR systems will become part of what we expect to see at work and at play: labels and directions when we don't want to get lost, reminders when we don't want to forget and, perhaps, a favorite cartoon character popping out from the bushes to tell a joke when we want to be amused. When computer user interfaces are potentially everywhere we look, this pervasive mixture of reality and virtuality may become the primary medium for a new generation of artists, designers and storytellers who will craft the future. SA

MORE TO EXPLORE

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Columbia University's Computer Graphics and User Interfaces Lab is at **www.cs.columbia.edu/graphics/**

A list of relevant publications can be found at **www.cs.columbia.edu/graphics/publications/publications.html**

AR research sites and conferences are listed at **www.augmented-reality.org**

Information on medical applications of augmented reality is at **www.cs.unc.edu/~us/**

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By directing its victims' sex lives, the bacterial parasite ***WOLBACHIA*** may be helping to produce new species

GENDER-BASED GENOCIDE: The bacterium *Wolbachia* eliminates male *Acraea encedon* butterflies because only females can serve as hosts for the parasite and pass its spawn on to the next generation.

Parasitic SEX ppeers

By Laurence D. Hurst and James P. Randerson

Don't bite the hand that feeds you.

The old adage sums up the approach parasites are expected to take with their victims. A freeloader that can spread only when its host reproduces ought not to be overly harmful: too much damage to its unwilling benefactor will affect the parasite's own chances to procreate. This scheme contrasts with the tactics of a pathogen that has a short infectious period, such as the flu virus. In that case, the virus has no long-term interest in the carrier's well-being, so a "get transmitted quick" strategy is favored almost regardless of the cost to the hapless host.

The widely distributed bacterium *Wolbachia* (a close relative of the

FRANCIS M. JIGGINS

gut bacterium *Escherichia coli*) is a boarder with a long-term interest in its invertebrate host. It lives within cells and is transmitted to the next generation by invading its host's eggs. Contrary to the old saying, however, the bacterium engages in various radical manipulations of its hosts, including killing male offspring, turning males into females and rendering some host matings infertile. If *Wolbachia*'s reproduction is so intimately tied up with that of its meal ticket, why does it create so much havoc?

The short answer is that the bacterium is not carried in sperm. This egg-only propagation method means that the parasite's reproductive interests lie firmly with female hosts. Males, as nontransmitters, are akin to evolutionary prison cells for the bacterium.

Over the course of time, however, Darwinian natural selection has been able to sidestep the parasite's custodial sentence in male hosts. Rather than being a dead end, the problem of nontransmission has been turned into an opportunity. *Wolbachia* may have played much more than a walk-on part in this evolutionary drama because its manipulations can have profound long-term effects on its victims. By interfering with host reproduction, *Wolbachia* may be setting the stage for new species to form.

Wolbachia is highly abundant and has rather catholic tastes in choosing its insect and invertebrate carrier species. When John H. Werren and his colleagues at the University of Rochester screened neotropical insects for the presence of *Wolbachia,* they found that 17 percent of 154 species harbored the bacteria.

The true frequency of infection may well be considerably higher, however. Greg Hurst and his co-workers at University College London and the University of Cambridge have found several well-studied species of *Wolbachia* in about a tenth of the individuals in a host population. Sampling only a few individuals from a given species, as the Rochester group did, is therefore likely to miss many incidences of infection. Further, Marjorie Hoy and Jay Jeyaprakash of the University of Florida have determined that the technique employed in the Rochester study often wrongly indicates an absence of parasitization. Using a more robust method, the Florida researchers discovered that more than three quarters of the species they tested were infected with the bacterium.

Nor is the parasite found only in insects; it appears in crustaceans (notably pill bugs and freshwater shrimps), mites and nematode worms as well. So far it has not been detected in a vertebrate animal. We estimate that more than 20 million species may harbor *Wolbachia,* suggesting that scientists have so far studied merely the tip of a huge and important iceberg.

Choosy Males

ONE WAY IN WHICH *Wolbachia* can profoundly influence its victims is by grossly distorting the normally balanced sex ratios of its hosts' populations. For instance, males are extremely rare in some groups of the African butterfly *Acraea encedon* and of the widespread pill bug *Armadillidium vulgare* (also called a wood louse).

COMPULSORY SEX CHANGES and perhaps forced speciation can be traced to the *Wolbachia* bacterium. The tiny parasite transforms would-be male pill bugs (*above*) into females because it can reproduce only through the female's eggs. The split between two *Nasonia* wasp species (*an example is shown at right*) seems to have been caused by *Wolbachia*.

In the butterfly, this phenomenon is caused by the pervasiveness of a male-killing strain of *Wolbachia* (more than 90 percent of *A. encedon* females support the parasite). The bacterium presumably kills off males to benefit its own relatives, which are infecting the slain males' sisters. This act of suicide by the individual makes sense because a *Wolbachia* bacterium in a male host is already a "dead man walking." Sperm do not carry the bacterium, so it has no chance of moving to another host anyway; hence, the parasite has nothing to lose. Moreover, its kin in the dead males' sisters benefit from this behavior because male killing occurs before the hosts have hatched. Consequently, a banquet of unhatched male offspring lies there ready to be devoured when the rest of the brood emerges. Such sibling cannibalism by parasitized females is thought to give them an important advantage over competitors.

Although this adaptive advantage has yet to be definitively demonstrated in *A. encedon* caterpillars, it has been established in *Adalia bipunctata,* commonly called the two-spot ladybug (or ladybird). The period between hatching and finding their first aphid meal is a particularly vulnerable time for the larvae of this ladybug. A free lunch provided by a deceased brother is therefore a great boon to them and consequently to the *Wolbachia* they carry.

In pill bugs, *Wolbachia* converts would-be males into females. By feminizing males, the parasite is changing a non-

THIERRY RIGAUD ET AL. *University of Poitiers*

transmitting host into one that will pass the infection on to its offspring. To return to the prison analogy, this is rather like a convict receiving a hacksaw inside a cake.

In both the butterfly and the pill bug, the bacterium skews the populations' sex ratios massively toward females. Males therefore represent a valuable commodity. This scarcity reverses normal gender roles, because females are in demand in populations with an equal sex ratio. Females make a much larger contribution to the young in the form of large, nutritious eggs, whereas the males' investment of cheap sperm is much smaller. As the chief donors to their young, females are typically much fussier in their choice of mates, accepting only the fittest males.

The selection process is inverted in *Acraea* and *Armadillidium,* however, because males are so hard to come by. Indeed, work by Francis M. Jiggins and his colleagues at the University of Cambridge has revealed that in heavily affected populations of the *A. encedon* butterfly, the entire system of choosing mates has changed. Rather than spreading throughout the habitat, females form dense aggregations on small grassy plots. In one such cluster, 350 butterflies were found packed into a 200-square-meter area. In species with conventional sex roles, such as the sage grouse, these gatherings, known as leks, are where males congregate and females come to shop.

Could the aggregations in *Acraea* represent role-reversed leks to which males come to select a partner? The current evidence is inconclusive. By demonstrating that virgin females are more likely to inhabit the sites than mated females, Jiggins has shown that females are indeed gathering to find mates. The question remains, however, whether the males are doing the choosing.

Jiggins had originally found that mated females are more likely to lack the infection than virgins, implying that males may be selecting uninfected females as partners. Unfortunately, he and one of us (Randerson) have been unable to replicate this result, so the situation continues to be unclear.

In the example of the pill bug, Thierry Rigaud and his collaborators at the University of Poitiers in France have shown that males prefer not to mate with feminized males. Furthermore, if males do mate with transsexual individuals, they deliver relatively few sperm to them.

Our own work using mathematical techniques to model the evolution of choice in these situations has shown that natural selection for such an alteration in mate choice does occur if a host population contains sex-ratio distorters. This result raises the problem, though, of what happens to the parasite when infected females fail to find a mate. The theoretical models show that when males are able to distinguish perfectly between infected and uninfected females, the bacterium will simply be selected out of the population. If, however, the males occasionally make a mistake and mate with parasitized females, then this is enough to keep *Wolbachia* in the population.

Sex Changes in Hosts

MALE MATE CHOICE may well be one response to the spread of a feminizing bacterium. An even more fascinating one may be the evolution of new mechanisms for genetically determining gender. Research by Rigaud and his associates has shown that *Wolbachia* can determine gender in *A. vulgare,* because male pill bugs have all the genes necessary to become females. All that is needed for an individual to become male is a shot of male-inducing hormone from the "male gland" early in development. Thus, if the parasitic bacterium can block development of this gland, its host will be female.

In some infected populations, the responsibility for gender determination has shifted from the pill bug to its parasite. Pill bugs have what is known as a WZ sex-determination system: males have ZZ chromosomes, and females have WZ. (This arrangement contrasts with the more familiar XY system, in which males are XY and females are XX.) Because only the few eggs that do not contain *Wolbachia* become males, infected WZ females give birth mostly to daughters: both WZ females and sex-changed males (ZZ females). These ZZ females in turn almost exclusively produce ZZ females. As a result, infected females of either type beget more daughters than normal females do. Thus, with each succeeding generation, the proportion of individuals with the normal female chromosome W drops and eventually nears zero. At that point, the parasite is left entirely in control of sex because everyone is ZZ—if the pill bug has the parasite, it's female; if not, it's male. In other infected pill bug groups, the hosts seem to have wrestled back control over their sex ratios by setting the proportion of offspring that receive the bacterium in some as yet undetermined manner.

Wolbachia's most common manipulation is to interfere in the success of the host's matings. Known as cytoplasmic incompatibility, this strategy renders all matings between infected males and uninfected females infertile because the bacterium releases toxins into the sperm's protoplasm [*see box on next page*]. Other pairings are left unaffected. Halting the procreation of uninfected females indirectly benefits females carrying the bacterium. As a result, these females contribute a larg-

THE AUTHORS

LAURENCE D. HURST and *JAMES P. RANDERSON* have studied *Wolbachia* parasites at the University of Bath in England. Hurst is professor of evolutionary genetics at Bath. A recent father, he is interested in the evolution of genetic systems and enjoys the late-period works of Beethoven, walking his dog and attempting to cook. In 2001 Randerson completed his doctoral studies at Bath on the wider evolutionary consequences of selfish organelles and symbionts. He next moved to London to join *New Scientist* magazine as a writer. In his spare time, Randerson plays trombone in a soul/funk band.

JOHN H. WERREN

er proportion to the next generation, which allows their freeloading *Wolbachia* to spread more widely.

One consequence of this intervention is that the bacterium restricts gene flow between different groups of its host. This is most pronounced in bidirectional cytoplasmic incompatibility, in which two groups of hosts contain mutually incompatible strains of the bacterium. In that instance, all matings between hosts from the different groups are doomed by internal sabotage.

Barriers to free gene flow between populations are all-important in speciation, the origination of new species. In the classic example, biologists imagine that a physical barrier arises, perhaps the formation of a new mountain range or the creation of an island resulting from a rise in sea level. This obstacle splits a previously homogeneous population into two, preventing interbreeding between the new populations and allowing them to drift apart genetically. Over time the groups diverge to the point that they can no longer interbreed if they are later brought together. Because their parents' genetic systems are now incompatible, hybrid offspring either do not survive or are sterile.

On the Road to Speciation

BIOLOGISTS FAMILIAR with *Wolbachia* began to ask whether the impediments to gene flow created by cytoplasmic incompatibility could be enough to allow a population to bifurcate genetically without the existence of a physical obstruction. Were these bacterial freeloaders the agents of what might be called infectious speciation?

This question is difficult to answer because the process by which one species splits into two takes a long time to complete, much longer than the lifetimes of evolutionary biologists. The for the success of this approach. In the eastern U.S., the so-called Riverside strain of *Wolbachia* that causes cytoplasmic incompatibility is spreading through the territory of its host population (the fruit fly *Drosophila simulans*) along a front traveling about 100 kilometers a year.

In unidirectional cytoplasmic incompatibility, just one strain of *Wolbachia* is involved, so matings in only one direction are sabotaged. Things get more interesting if there is more than one strain that produces cytoplasmic incompatibility, a situation known as bidirectional cytoplasmic incompatibility. For the sake of argument, imagine two bacterial strains, A and B. If the egg-saving antitoxin from strain A is ineffective against the toxin from strain B, and vice versa, then matings in either direction are incompatible. If all individuals in the population are infected with one strain or the other, the only successful matings are those between individuals harboring the same strain. Host matings between strains will always lead to incompatibility. The two *Wolbachia* strains have split the host population into two groups that cannot interbreed. *–L.D.H. and J.P.R.*

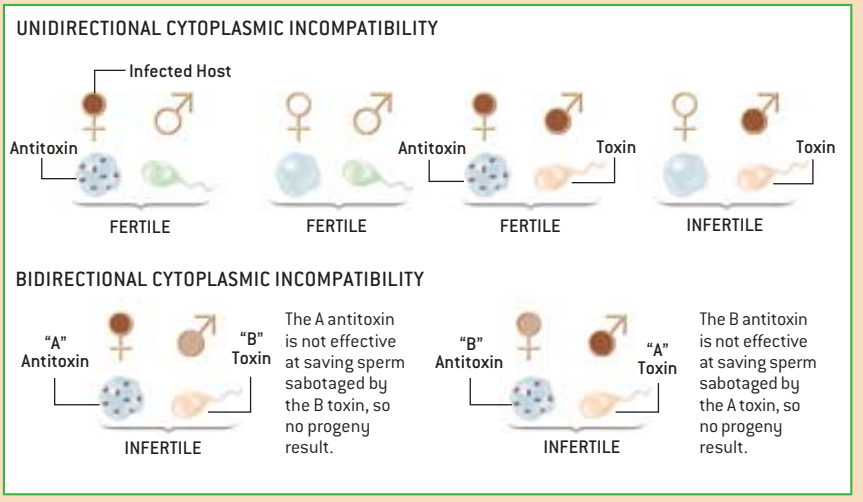
Sexual Sabotage

AN IMPORTANT ADAPTIVE tactic employed by some strains of the *Wolbachia* bacterial parasite is to interfere in the success of host matings by rendering certain pairings barren. By restricting the gene flow among its hosts, *Wolbachia* is thought to be contributing to the development of new species.

Cytoplasmic incompatibility, as the phenomenon is called, occurs when an infected male and an uninfected female attempt to mate. As an evolutionary strategy, it involves indirectly helping hosts that contain one's relatives by harming those that don't.

In males, some strains of *Wolbachia* add a toxin to the host's sperm, which probably alters the proteins that bind to DNA. The poisonous agent causes the male's chromosomes to condense abnormally on fusion with the egg and stops the newly formed zygote from developing. When the male mates with an infected female, however, no such condensation occurs. In this case, *Wolbachia* deploys an antitoxin in the egg that rescues the zygote.

This manipulation of the host by the bacterium has been interpreted as an act of evolutionary spite because it reduces the fertility of unparasitized females with no direct benefit to those bacteria that sabotage the sperm. The strategy is successful, however, because it indirectly benefits infected females and hence their resident *Wolbachia*. These females have no restrictions on their choice of mates and thus have an advantage over parasite-free females. As infected females beget more infected females, this strategy promotes the spread of the bacterium. Michael Turelli of the University of California at Davis and Ary A. Hoffmann of La Trobe University in Australia have uncovered good evidence



NINA FINKEL

UNWANTED HITCHHIKERS: *Wolbachia* bacteria reproduce only through their female hosts, making males superfluous. The parasites are shown here as lighter green spots on an insect egg (*top*) and as specks inside an infected cell (*bottom*).

best that can be done is to look for *Wolbachia* hosts that exhibit cytoplasmic incompatibility and are on the pathway to speciation. By studying such suggestive examples, biologists hope to determine whether the parasite is likely to be a force in the evolution of new species.

Two species of parasitic wasp that appear to be near the end of such a journey are *Nasonia vitripennis* and *N. giraulti,* both of which are found in eastern North America. An investigation of these wasps by Johannes A. J. Breeuwer of the University of Amsterdam and Werren of the University of Rochester revealed that the barriers to successful mating between these species are not determined solely by differences between the wasps themselves—*Wolbachia* is involved. The researchers found that when both species are treated with antibiotics, matings between the two produce fertile young. Without the antibiotics, inviable offspring result because each wasp species contains a different strain of the parasite, leading to bidirectional cytoplasmic incompatibility between the hosts.

Wolbachia is not the only cause of current isolation between these two species of *Nasonia,* though. The second generation of hybrid wasps tends to have severe developmental problems, perhaps indicating that genetic changes in the wasps' own DNA are now sufficient to keep the two species apart. Whether the parasite was involved in promoting this divergence in the past has not been determined.

In the case of the reproductive separation between *N. giraulti* and *N. longicornis,* the story is different. These two parasitic wasps have been taxonomically determined to be different species—for example, they parasitize different host groups. But again, *Wolbachia* plays a key role—in this instance, by causing bidirectional cytoplasmic incompatibility. Werren and his University of Rochester colleagues Seth Bordenstein and Patrick O'Hara have recently shown that in the absence of the bacterium, the hybrids are normal and remain so in subsequent generations. Although genetic divergence of the wasps' DNA has yet to occur, *Wolbachia* appears to be on the cusp of forcing the evolution of new species.

In some cases, *Wolbachia* may contribute to the process of speciation without being the primary cause. A team of researchers, including D. DeWayne Shoemaker of Western Michigan University, Vaishali Katju of Indiana University and John Jaenike of the University of Rochester, has turned up evidence that even the incomplete obstacle to gene flow provided by unidirectional cytoplasmic incompatibility can contribute to reproductive isolation [*see box on opposite page*].

Shoemaker and his coworkers looked at two species of fruit fly, *Drosophila recens* and *D. subquinaria.* The first of these is infected with a *Wolbachia* strain that causes cytoplasmic incompatibility; the second is uninfected. As a result, matings between *D. subquinaria* females and *D. recens* males are infertile. If *Wolbachia* were the only factor at work, then gene flow between the fruit-fly species would still be possible, but it turns out that these matings do not occur successfully. Unlike *D. subquinaria, D. recens* females are quite choosy when selecting mates, hardly ever picking a male of the other species by mistake. Hence, the two barrier mechanisms complement each other. Gene flow in one direction is prevented by *Wolbachia* (even though matings occur), whereas the flow in the reverse direction is prevented by careful mate choice by *D. recens* females.

Despite these and other suggestive examples, the case for infectious speciation has yet to be proved. It is notable, however, that *Wolbachia* infections are especially prevalent in insects and mites, the most species-rich animal groups. Perhaps *Wolbachia* had a hand in nurturing new shoots on these bushy branches of the tree of life.

Who's Running the Show?

FAR FROM BEING a minor freeloader, the *Wolbachia* parasite is widespread in nature and manipulates the reproduction of a variety of host organisms in diverse ways. What is more, attempts by the bacterium's hosts to evade infection have sent their biology and evolution in unexpected directions. As scientists begin to explore more of *Wolbachia*'s still hidden biology, we expect this influential passenger to have other surprises in store. SA

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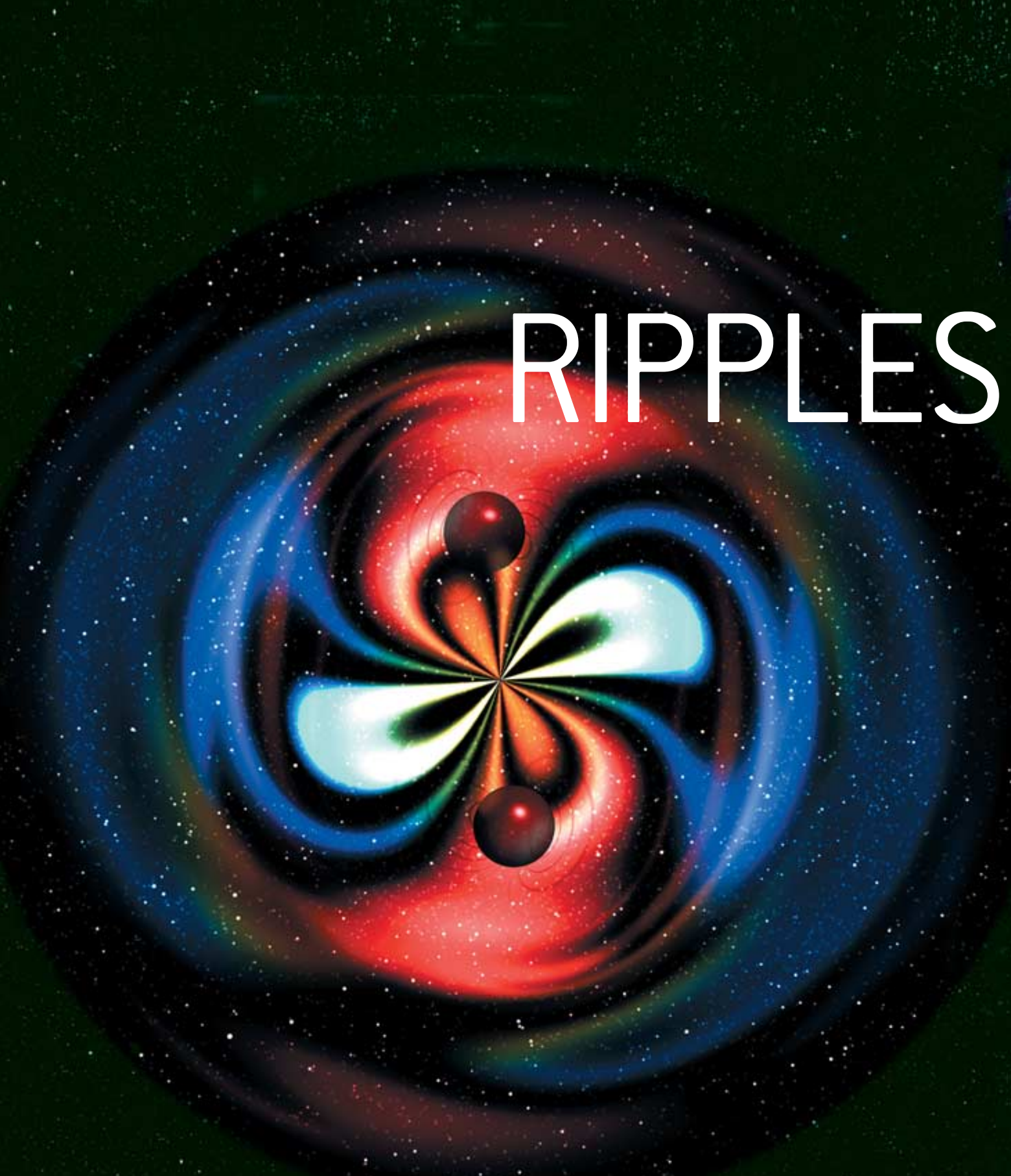
MERIJN SALVERDA AND RICHARD STOUTHAMER (*top*); CLAUDIO BANDI AND LUCIANO SACCHI (*bottom*)

RIPPLES



BIRTH WAILS AND DEATH THROES of celestial titans—such as the black holes (*spheres*) colliding in this supercomputer simulation—rumble through the universe on waves of gravitational energy. This year new instruments of astonishing size and sensitivity will try to tune in those signals for the first time.

IN SPACETIME

PHYSICISTS HAVE SPENT EIGHT YEARS AND $365 MILLION BUILDING A RADICALLY NEW KIND OF OBSERVATORY TO DETECT GRAVITATIONAL WAVES. BUT WILL IT WORK? A TRIAL RUN PUT IT TO THE TEST BY W. WAYT GIBBS

HANFORD, WASH., AND LIVINGSTON, LA.—A chill January wind sends a shiver through Frederick J. Raab as he stands, binoculars to his eyes, on a mound near the center of the LIGO Hanford Observatory. He runs his gaze northward down a ruler-straight concrete tunnel to a building four kilometers to the north: there is one end of the observatory. Pivoting 90 degrees, Raab pans westward across the sagebrush-stubbled desert until he spots an identical tube and another building, also four kilometers distant. "When we talk about locking the laser beam" that shines inside those tubes, Raab says, "we mean holding the light waves steady to better than the width of an atom—over that distance."

Raab oversaw the construction of this giant try square, one of a pair that are the largest, most expensive and—if they fulfill the ambition of their designers—most sensitive detectors yet to join the 40-year hunt for gravitational waves. Part ruler, part clock, these two instruments are spacetime meters that will attempt to record how the

continuum is rattled by the most violent cataclysms in the universe: detonating stars, colliding black holes, perhaps phenomena not yet imagined. As these ripples expand outward at the speed of light, they alternately stretch and squeeze space, causing the distance between free-floating objects to expand and contract. But by the time the vibrations reach the earth, theorists estimate, they are so unsubstantial that they alter distances by less than one part in a trillion billion.

For all the cutting-edge technology crammed into LIGO, it is not yet clear whether it can attain that incredible sensitivity. Reduced to such a tiny murmur, the mightiest cosmic events are easily overpowered by the gentlest mundane disturbance. "The tide deforms the earth's crust as well as the oceans," Raab tells me. It moves the buildings here by a third of a millimeter, 100 billion times the displacement a gravitational wave would cause. Every earthquake in the world over magnitude six, the rumble of every truck on nearby roads, the computer fans in the lab next door—all these things shake the ground by more than an atom's width. "Even engine noise from jets passing overhead can work its way in," Raab says.

Down in the control room, we watch as the instrument struggles to compensate for the thumps and bumps. Fourteen days into an 18-day test run that began on December 28, the noise is winning. Raab stares at a panel of graphs projected onto the far wall. A red line bounces up and down, charting the status of the main detector here as it is thrown out of whack, steadies itself and gets knocked out again a few minutes later. A blue line that represents a smaller quality-control detector has gone flat altogether.

During a teleconference, physicist H. Richard Gustafson troubleshoots glitches with his counterparts at the LIGO Livingston Observatory, which sits in the backwoods of Louisiana. Joining the conversation is the director of the GEO 600, a similar but smaller instrument near Hannover, Germany. "Here at Hanford we had an awful night," Gustafson says, recounting troubles with computer crashes and noisy electronics.

The instrument in Louisiana has been more predictable. During the night it runs smoothly, but at 6:30 A.M. its line on the control screen goes flat as morning traffic picks up on Interstate 12 a few miles from the observatory and as Weyerhaeuser loggers begin felling loblolly pines nearby. GEO, with its shorter, 600-meter arms and less demanding precision, has been a model of reliability, on duty more than 90 percent of the time. But scientists need all three instruments up and running, and over two weeks the best stretch of simultaneous operation lasted just over an hour and a half.

Szabolcs Márka, a 32-year-old Hungarian postdoc at LIGO Livingston, seems content with the progress so far on this test run, the fifth that he has managed and the last before the two instruments begin routine round-the-clock observations in May. "As usual we are in problem-solving mode," Márka says.

Labor Pains, Death Gasps

EVER SINCE THE FOUNDERS of the LIGO project—Kip S. Thorne and Ronald Drever of the California Institute of Technology and Rainer Weiss of the Massachusetts Institute of Technology—first proposed the Laser Interferometer Gravitational Wave Observatory in 1984, no one has doubted that only a Herculean feat of engineering would make it work. That is one reason that "the project faced tremendous opposition from astronomers," says Harry M. Collins, a sociologist at Cardiff University in Wales who has studied the field's halting expansion from a backwater of physics to Big Science.

"The National Science Foundation turned down our first two proposals," Thorne remembers. "And the third, submitted in 1989, went through five years of very extensive review." High-profile astronomers, notably Jeremiah P. Ostriker of Princeton University, objected to the steep price, which by 1993 had risen to $250 million. They feared that smaller and less risky projects would get elbowed out of the budget. A blue-ribbon panel set up to rank U.S. astronomers' priorities for the 1990s excluded LIGO from its wish list. "It was a unanimous decision," recalls John Bahcall, an astrophysicist at the Institute for Advanced Studies in Princeton, N.J., who chaired the committee. Congress passed on the LIGO proposal at first, not approving funding until 1994.

Thorne and other proponents of LIGO argued that gravitational signals could launch a whole new field of astronomy, because they carry information about the universe that scientists can gather in no other way. These ethereal ripples were

DETECTING A QUIVER SO MINUSCULE IS LIKE NOTICING THAT SATURN HAS MOVED CLOSER TO THE SUN BY THE WIDTH OF A HYDROGEN ATOM.

Overview/*Gravitational-Wave Detectors*

- Although astronomers have never detected gravitational waves directly, Einstein's theory of relativity predicts that violent cataclysms such as black-hole collisions will cause the fabric of space itself to vibrate.
- By the time they reach the earth, these ripples are so faint that picking them out of the surrounding noise is comparable to noticing a single grain of sand added to all the beaches of Long Island, N.Y.
- Six ultraprecise interferometers have been built around the world to detect these signals. Three are in the U.S. and are scheduled to start scientific observations next month. But they are still struggling to reach the necessary sensitivity.

PRECEDING PAGES: WERNER BENGER AEI/ZIB (*visualization*); NUMERICAL RELATIVITY GROUP AT AEI (*simulation/science*); LBNL/NERSC (*computing facility*); MAX PLANCK SOCIETY, EU ASTROPHYSICS NETWORK PROJECT, U.S. DEPARTMENT OF ENERGY (*support*)

CONTROL ROOM of the LIGO Livingston Observatory was home away from home for Caltech physicist Szabolcs Márka during the 18-day trial run, which he managed. Despite the challenges, the team was able to collect more than 70 hours of scientific data from all three U.S. interferometers at once.

predicted in 1918 by Albert Einstein, who saw them as an unavoidable consequence of his general theory of relativity. The attractive force we call gravity, Einstein famously postulated, occurs because massive bodies warp the four-dimensional fabric of the universe. If a dense object moves violently, space shudders in response.

When a giant star, for example, exhausts its fuel, it can detonate in a flash as luminous as 10 billion suns—a supernova. Astronomers believe that the star's outer layers are blown into space, while its iron core implodes with enough force to combine all its electrons and protons into neutrons and exotic particles. Within minutes, a solid metal sphere as big as the earth collapses into a neutron star less than 20 kilometers across. It is so dense that a teaspoonful of its surface would weigh nearly a billion tons. Scientists expect that a somewhat lopsided supernova would send out a burst of gravitational energy that would hit the earth several minutes before the flash arrived—time enough to alert conventional astronomers to train their telescopes on it. More important, details about the birth of the neutron star could be extracted from the gravitational signal even though the nascent object itself is tiny and swaddled in a blanket of fiery gas.

LIGO was designed to detect the death of neutron stars as well as their birth. Most stars orbit a mate, and occasionally both stars in a binary pair will go supernova yet remain locked in mutual thrall. With each revolution, the two neutron stars lose a little energy as they induce wrinkles in the surrounding fabric of space. Their orbit thus tightens step by step until they rip apart and merge, sometimes creating a black hole. Near the end of their frenetic tango, the massive bodies whirl around each other hundreds of times a second, flapping the bedsheets of spacetime around them. Radio pulses from such binary systems offer the most convincing, if indirect, evidence so far that gravitational waves actually exist.

But it is still anyone's guess whether the Caltech and M.I.T. groups that operate LIGO for the NSF will be able to detect such waves directly. "The curious thing about LIGO," Collins says, "is that, at least in its first instantiation, it cannot promise success."

Spectral Phenomena

THE PROBLEM IS NOT that gravitational waves are weak. "The energy in gravitational waves is amazingly huge," says Gabriela I. González, a physicist at LIGO Livingston. During the final minute that neutron stars spiral to their death 65 million light-years from the earth, the gravitational pulse would be so energetic

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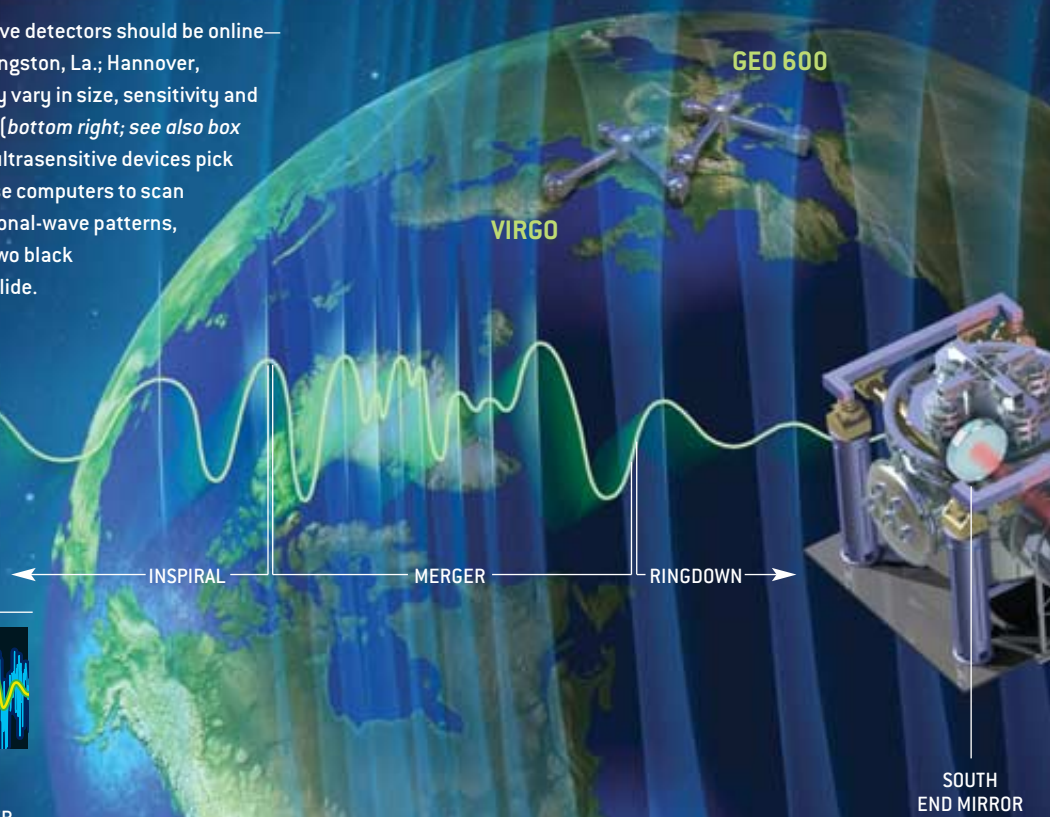
GLOBAL GRAVITY OBSERVATORY

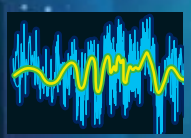
BY THE END OF 2003, six new gravitational-wave detectors should be online—two at Hanford, Wash., and one each near Livingston, La.; Hannover, Germany; Pisa, Italy; and Tokyo. Although they vary in size, sensitivity and details, all work in more or less the same way (*bottom right; see also box on page 68 for more details*). Because these ultrasensitive devices pick up so much terrestrial noise, scientists will use computers to scan the raw output (*below*) for predicted gravitational-wave patterns, such as the chirp, crash and ring emitted by two black holes in the seconds before and after they collide.

PINPOINTING THE SOURCE

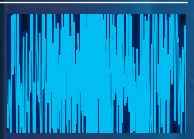
As a gravitational pulse sweeps through the earth, the same waveform (*green*) will hit each detector at a slightly different time, allowing astronomers to pinpoint the source and eliminate other possible causes of the vibration.



LIGO
SPONSOR: U.S.
ARM LENGTH: 4 km at Livingston; 4 km and 2 km at Hanford
PEAK SENSITIVITY: Three parts in 10^{23} at 180 Hz
STATUS: Observations begin May 2002
COST: $530 million through 2007


MATCH WITH TEMPLATE, POSSIBLE MERGER

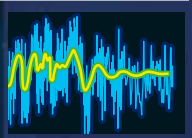
TAMA 300 (NOT SHOWN)
SPONSOR: Japan
ARM LENGTH: 300 m
PEAK SENSITIVITY: Five parts in 10^{21} from 700 to 1,000 Hz
STATUS: Preliminary observations began in 2001
COST: $10 million


OFFLINE BECAUSE OF EARTHQUAKE IN INDONESIA

GEO 600
SPONSORS: U.K., Germany
ARM LENGTH: 600 m
PEAK SENSITIVITY: Eight parts in 10^{23} at 600 Hz
STATUS: Observations to begin in 2002
COST: $10 million


MATCH WITH TEMPLATE, POSSIBLE MERGER

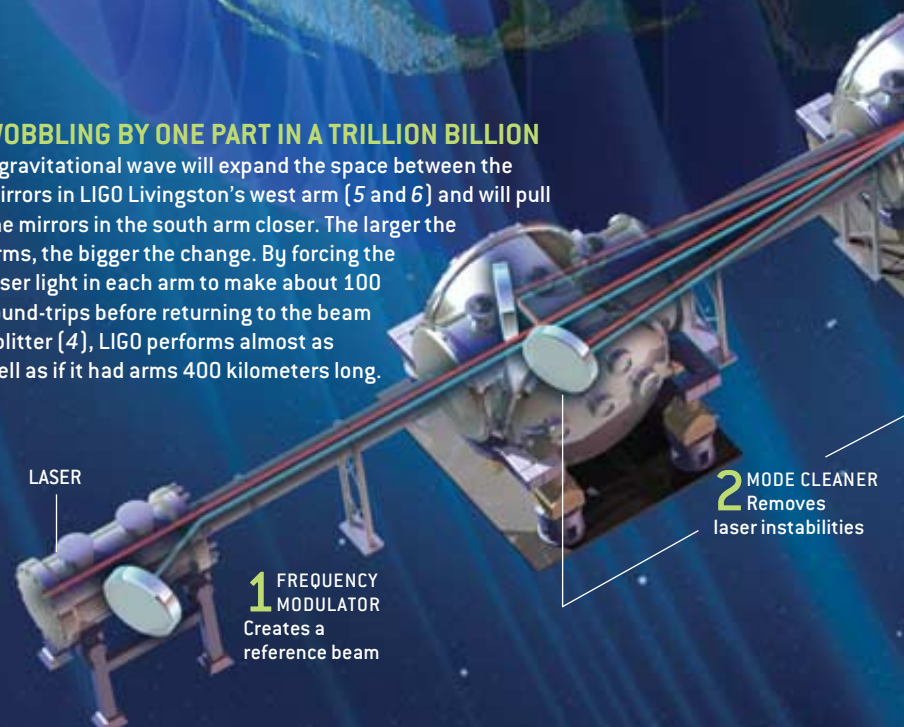
VIRGO
SPONSORS: Italy, France
ARM LENGTH: 3 km
PEAK SENSITIVITY: One part in 10^{22} at 500 Hz
STATUS: Observations to begin in 2003
COST: $66 million


MATCH WITH TEMPLATE, POSSIBLE MERGER

"Peak sensitivity" refers to design goals not yet achieved

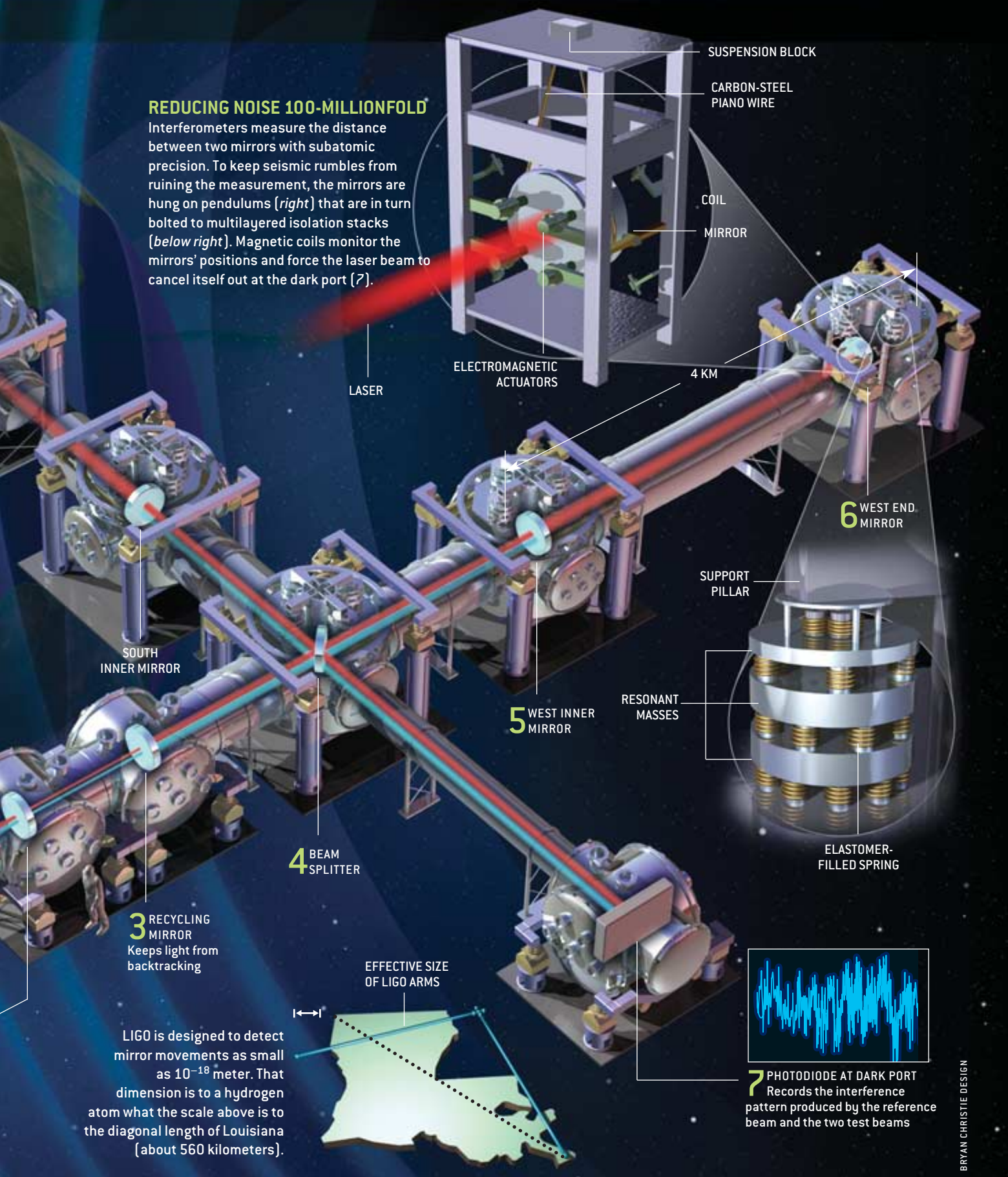
WOBBLING BY ONE PART IN A TRILLION BILLION

A gravitational wave will expand the space between the mirrors in LIGO Livingston's west arm (*5* and *6*) and will pull the mirrors in the south arm closer. The larger the arms, the bigger the change. By forcing the laser light in each arm to make about 100 round-trips before returning to the beam splitter (*4*), LIGO performs almost as well as if it had arms 400 kilometers long.



REDUCING NOISE 100-MILLIONFOLD

Interferometers measure the distance between two mirrors with subatomic precision. To keep seismic rumbles from ruining the measurement, the mirrors are hung on pendulums (*right*) that are in turn bolted to multilayered isolation stacks (*below right*). Magnetic coils monitor the mirrors' positions and force the laser beam to cancel itself out at the dark port (*7*).



LIGO is designed to detect mirror movements as small as 10^{-18} meter. That dimension is to a hydrogen atom what the scale above is to the diagonal length of Louisiana (about 560 kilometers).

BRYAN CHRISTIE DESIGN

that "if it arrived in the form of visible light, it would be brighter than the full moon," González says.

But unlike light, which deposits all its energy when it splats against matter, gravity passes ghostlike through solid objects with only a tingle of interaction. To a gravitational wave, the earth and everything on it are almost perfectly transparent. So even the powerful signal from the merging neutron stars will wiggle the center point of each mirror by just a few attometers (10^{-18} meter), the sensitivity that LIGO was designed to achieve.

As one arm of the observatory swells, the other will shrink. The phase and the frequency of the laser light inside the arms will shift in opposite directions. When the beams from the two arms are superimposed on a reference beam, they will be out of tune, and the wavering beats they generate can be decoded by computers to reveal the changing curvature of spacetime inside the arms. In principle, the technique, known as interferometry, can measure changes in distance much smaller than the wavelength of the infrared laser light—indeed, much smaller than the nucleus of an atom [*see box below*].

Ambitious as LIGO's sensitivity goal is, it leaves astronomers unimpressed. Neutron couplets are relatively rare; their deaths are spectacular but quick. Within 65 million light-years, astronomers estimate, only one such merger occurs every 10,000 years. "So although it is possible that we would see these waves," Thorne says, "it is not highly probable." He thinks it more likely that LIGO would pick up black-hole mergers, which are 100 times more powerful than the neutron-star variety. But theorists are uncertain by a fac-

A Photon's Journey through LIGO

TO UNDERSTAND HOW THE LIGO interferometer works, imagine the adventure of a photon as it passes through the instrument. (We will neglect some details in the interest of clarity.) The photon is created in a suitcase-size laser that is as powerful as 20,000 laser pointers. It is one of trillions of photons marching in lockstep in an infrared beam.

1 Part of the beam takes a detour into a device that converts the light into two reference beams, one of slightly higher frequency than the main beam and one of slightly lower frequency. This frequency modulator thus creates a benchmark against which the test beam can be compared at the end of its journey. After the detour, the beams recombine and pass through a quartz window and into the first vacuum chamber. The builders took every precaution to prevent our photon from scattering out of its intended path. Vacuum pumps hold the air pressure below one trillionth of an atmosphere. The mirrors, as wide as dinner plates and 10 centimeters thick, have been polished to an accuracy of better than 16 atoms. And the thickness of reflective films coating the optics varies by no more than two atoms.

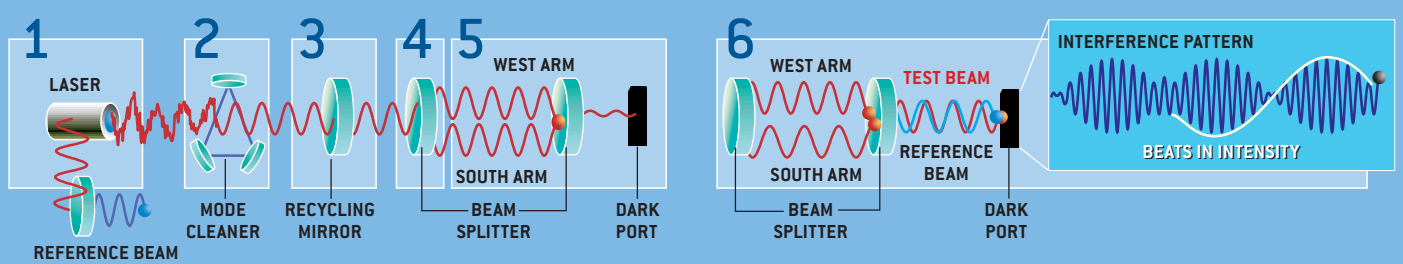
2 The photon enters a loop formed by three mirrors arranged in a narrow triangle. This mode cleaner is a quality checkpoint: the photon can move ahead only if its part of the beam has just the right shape and direction. Any light that is out of place or poorly aimed is tossed out a porthole.

3 The photon hardly notices the one-way mirror it zips through in the next chamber. The mirror blocks any photons that try to head back toward the laser. By trapping photons within the device, this mirror increases the power of the light beam 16-fold.

4 At the beam splitter, the photon divides into identical twins. One stream of photons continues forward into the west arm. The other stream is inverted, its peaks flipped to valleys, as it is reflected into the south arm. The two test beams fly through the inner mirrors and into steel tubes four kilometers long. But the frequency-shifted reference beams are denied entry. They retrace their steps toward the beam splitter and circulate among the central optics until photons from the test beams return.

5 Meanwhile our photon and its inverted twin sail down the long arms to bounce off a mirror at each end. Although the atoms on the mirror surface are vibrating with heat, their motion is random and the beam hits trillions of atoms at once. On average the thermal vibrations cancel out. The twin photons carom between the inner and end mirrors inside their respective arms. They make about 100 round-trips before leaking through the inner mirror and reuniting at the beam splitter, which sends them northward toward the dark port. Normally our photon and its alter ego will be at opposite points in their oscillation. Crest will meet trough, and the two will annihilate each other. The dark port will remain dark.

6 But if during the photons' journey, a gravitational wave sliced through the apparatus, it will have curved space, lengthening one arm and shortening the other. Crest will meet crest, and the dark port will light up. What is more, the reunited photons will also combine with the frequency-modulated reference beams. Like musical notes played slightly out of tune, the light will beat, growing dimmer and brighter with the passage of the gravitational wave. Finally hitting a photodiode, the photon is converted into a perceptible electronic signal, the trace of a trembling spacetime. —*W.W.G.*



tor of 1,000 how frequently these events might occur within LIGO's range. There may be 10 a year or only one a century.

Going out to 300 million light-years would improve the odds, but then a typical event would change the relative length of LIGO's arms by only about one part in 10^{22}. Observers will have to wait for version 2.0 of LIGO to detect such a minuscule quiver, which is comparable to noticing that Saturn has moved closer to the sun by the width of a hydrogen atom.

The Unquiet Earth

AS IF THAT WERE not difficult enough, LIGO engineers must contend with the fact that mirrors wiggle for lots of reasons that have nothing to do with supernovae, neutron stars or black holes. Heat causes molecules in the mirrors and the wires on which they hang to jostle randomly. This thermal noise can drown out gravitational waves whose frequencies lie between 50 and 200 hertz. At higher frequencies, the interferometer is overwhelmed by the quantum effect called shot noise, which occurs because the number of photons hitting its sensors varies from one instant to the next. "You could turn the laser power up to boost the signal over the noise," explains Norna Robertson, one of the designers of the GEO instrument. "But if you put too much light in, it kicks the mirrors around in random ways."

At the moment, though, the biggest challenge for LIGO is at low frequencies, where the earth is constantly in motion. "At 100 hertz, the ground moves up and down by about 10^{-11} meter," Raab says. "We want to see motions of 10^{-19} meter" because that is a 10^{22nd} of the four-kilometer length of LIGO's arms. "So we need to reduce seismic noise 100-millionfold."

We put on goggles and shoe covers and head over to the high bay that contains the laser and most of the detector's sensors. As he opens the door to the cavernous room, Raab lowers his voice to just above a whisper. I try to tread gently.

Raab walks over to a steel vacuum chamber as big as an upended van. To get from the ground to the mirror inside, a seismic rumble must pass through a stack of devices designed to sap its energy: a one-meter slab of reinforced concrete, scissor jacks, air bearings, four layers of thick custom-made springs, four heavy steel plates (each resonating at a different frequency) and, finally, a pendulum of steel piano wire. "We reduce seismic noise by a factor of 100 in the pendulum suspension and by another factor of a million with the isolation stacks," Raab notes. Some ground movements, such as lunar tides, still must be fought with more active devices, such as computer-controlled electromagnets that push and pull on tiny magnets glued to the mirrors.

Yet sometimes dampening external noise 100-millionfold isn't enough. "Just recently there was a magnitude-seven earthquake in Sumatra; that knocked us offline," Raab says. Strong winds have pulled the Hanford interferometer out of lock as well.

Not all seismic noise is natural. Robert Schofield, a postdoc at the University of Oregon, has become the designated noise detective for LIGO. One evening he is sitting at a control station frowning at a chart of the latest signals picked up by the detector. "Look at this peak," he says. "Right here at 2.3 hertz. I hadn't noticed it before because it is so narrow, but it accounts for 20 percent of the noise getting into the interferometer." Scanning over readouts from a battery of seismometers that surround the observatory, he concludes that the noise is coming from near

MARK COLES, director of LIGO's Louisiana facility, is trying to deal with logging, traffic and other sources of noise that thwart his engineers' efforts. "It may be that in the first few years we won't be able to get all the way to full design sensitivity," he says. "But it's still a great project to work on."

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the 200 East section of the Hanford Nuclear Reservation, the 1,400-square-kilometer radioactive waste depository that surrounds the LIGO Hanford site.

Schofield marches down the hall, grabs a seismometer and an oscilloscope and hauls them into a van. He drives several miles farther into the reservation, then pulls over and sets up his equipment. We can see the bright lights of some night operation in 200 East several miles away. But we can't get any closer because the area contains tanks of plutonium-laced waste, and it is protected by security forces with submachine guns. Schofield sets the seismometer to listen for almost five minutes. But it reveals no trace of the 2.3-hertz noise. "I think it must be a large piece of rotating machinery doing some fiendish thing out there," he tells co-workers later.

Fortunately, noise near two hertz isn't an immediate problem. LIGO, like the other giant gravitational-wave observatories nearing completion—GEO in Germany, TAMA in Tokyo and VIRGO near Pisa, Italy—is tuned to listen for gravitational waves from only 40 to about 3,000 hertz, coincidentally right in the range of human hearing. In the control room, LIGO operators have connected a speaker to sensors on the interferometer; it plays what the device "hears." A nearby supernova might come through as a burst of static. The wail of dying neutron stars would start low and sweep higher in an almost musical chirp.

Noise usually hisses and pops, but occasionally some recognizable sound leaks in. "There is a periscope on the laser table that raises the beam up to the right height," Schofield explains. Various noises can shake the periscope, introducing subtle Doppler shifts in the frequency of light passing through it. "If someone is talking near that periscope," he says, "you can hear their voice on that speaker."

"THEORISTS HAVE A VERY POOR TRACK RECORD FOR PREDICTING WHAT WE WILL SEE WHEN A NEW WINDOW IS OPENED ON THE UNIVERSE."

Speed Bumps

SO IN ADDITION to the seismographs, LIGO engineers have studded the facility with microphones and magnetometers, as well as sensors that monitor temperature, pressure and wind. A stream of data from about 5,000 sensor channels gets recorded simultaneously. The first thing that scientists would do if they thought they saw a gravitational wave is look for glitches or noise that had leaked into the system.

On the last day of the test run, Gonzalez hands the director, Mark Coles, a plot of the interferometer output from

Next-Generation Detectors

IF LIGO ACHIEVES the sensitivity for which it was designed, it will still have only a middling chance of detecting gravitational waves. "But our strategy from the beginning has been to do this in two steps," says Caltech physicist Kip S. Thorne: first get the machines working and gain confidence in their reliability, then upgrade to advanced components that will virtually guarantee regular signal detections.

Although the project's leaders have not yet made a formal proposal, they know roughly what they want. "It'll cost on the order of $100 million, begin around 2006 and take about two years to complete," says LIGO director Barry Barish. The laser will be boosted from 10 to 180 watts. Instead of single loops of steel wire, the optics will hang on silica ribbons attached to a three-stage pendulum now being tested in the GEO 600 detector in Germany. And the 11-kilogram silica glass mirrors will be replaced with 30-kilogram sapphire crystals.

The changes will boost sensitivity by a factor of 20, Barish estimates. That will put the instrument, Thorne says, "into the domain where, for the first time in history, humans will be seeing human-size objects behaving quantum-mechanically." Researchers have devised so-called quantum nondemolition techniques that can make measurements twice as precise as normally allowed by the Heisenberg indeterminacy principle. If it all works, "it will increase by 8,000 times the volume of space we can search," Barish says.

The Japanese have also designed a successor to their TAMA 300-meter interferometer, although project manager Yoshihide Kozai says, "I am afraid it will be a few years before we obtain the funds" to start construction. The Large-Scale Cryogenic Gravitational Wave Telescope would have three-kilometer arms built deep underground in the Kamioka mine. Supercooled sapphire mirrors of 51 kilograms each would help it match the sensitivity of LIGO II at frequencies below 40 hertz.

NASA and the European Space Agency are designing an even more ambitious gravitational-wave observatory called LISA. A trio of laser-toting satellites to be launched in 2011 would form an interferometer with arms five million kilometers long—better than 10 times the distance from the earth to the moon. As they orbited the sun, the trio would hold their position relative to one another with one-micron precision. LISA would be no more sensitive than LIGO II, but it could sense gravitational waves of much lower frequency than any detector built on the quaking earth.

"The most likely thing LISA would see is the motion of extremely massive black holes—from a million to billions of times the mass of the sun—orbiting each other in the center of very distant galaxies," Thorne says. "The astronomers are all over themselves about LISA," reports M.I.T.'s Rainer Weiss. "They know for sure they will see events." But because its cost will probably exceed half a billion dollars, Weiss predicts that "it will be much tougher to get LISA through Congress even than it was to get LIGO approved." —*W.W.G.*

that morning. It contains a bounce that looks like a real signal. It isn't. "We just invented a speedometer for the cattle guard on the entrance road," she says with a laugh. As each axle of a passing truck hits the horizontal rails, a rumble appears in the gravitational-wave channel.

Spurious signals can also be rejected by comparing data from two or more observatories, Márka explains. "If both LIGO sites see the same shape signal within a few milliseconds of each other and so does GEO, which sits on a different continental plate and is connected to a different electrical grid, then it is very, very unlikely to be a fake signal from some common source of noise."

Yet there is only so much they can do to overcome human-generated noise. The problem is especially bad at the Livingston site. "We can see the trains that go by three times a day," Coles says. "We can see the workers hauling trees. We can see when traffic picks up at lunchtime." During this test run, the Livingston instrument was online just 62 percent of the time, not including short blips. All three LIGO interferometers were up simultaneously for only 18 percent of the run.

"We know we have a problem with ground noise at Livingston," acknowledges Rainer Weiss, spokesperson for the LIGO Scientific Collaboration. "And it will get worse still. Society creeps in on us." Barry Barish, head of the project, says new active isolation stacks are being developed and will be installed next year. "I wish we didn't have to do it," Weiss says. "That was an engineering enhancement we had planned to add during the upgrade to LIGO II in 2006." The upgrade will add at least $750,000 to the $365 million that NSF has spent so far on the project and to the $165 million that it has just allotted for the next five years.

Yet even when the systems are locked and working, Weiss says, "we're still miles away—a factor of 1,000 away—from our design sensitivity. We're hoping to get at least 10 times better by June. But beyond that I don't know."

The uncertainty still troubles LIGO's old critic, Ostriker: "I have always believed that detecting gravitational waves will provide us insights obtainable in no other way. That said, I think that the LIGO program has been an egregious waste of funds—funds that could have been used for more productive science."

But Thorne sees things differently. "Theorists have a very poor track record for predicting what we will see when a new window is opened on the universe," he says. "Early radio telescopes discovered that the signals were much stronger than theorists expected. That happened again when the x-ray window opened in the 1960s. And when we started looking for neutrinos arriving from the sun, we were surprised by how few there were. In some sense, opening the gravitational window will give us a more radically different view on the universe than those previous advances did." Ripples in spacetime may shake up science yet. SA

W. Wayt Gibbs is senior writer.

STRAIGHTER THAN THE SURFACE OF THE EARTH, the concrete tunnel that houses the west arm of the LIGO Livingston Observatory rises several meters off the ground on its four-kilometer run as the planet curves beneath it. The tunnel houses an airtight steel pipe. Inside the pipe is a vacuum, and through the vacuum shines a beam of infrared light with the power of 20 million laser pointers.

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MORE TO EXPLORE

Einstein's Unfinished Symphony. Marcia Bartusiak. Joseph Henry Press, 2000.

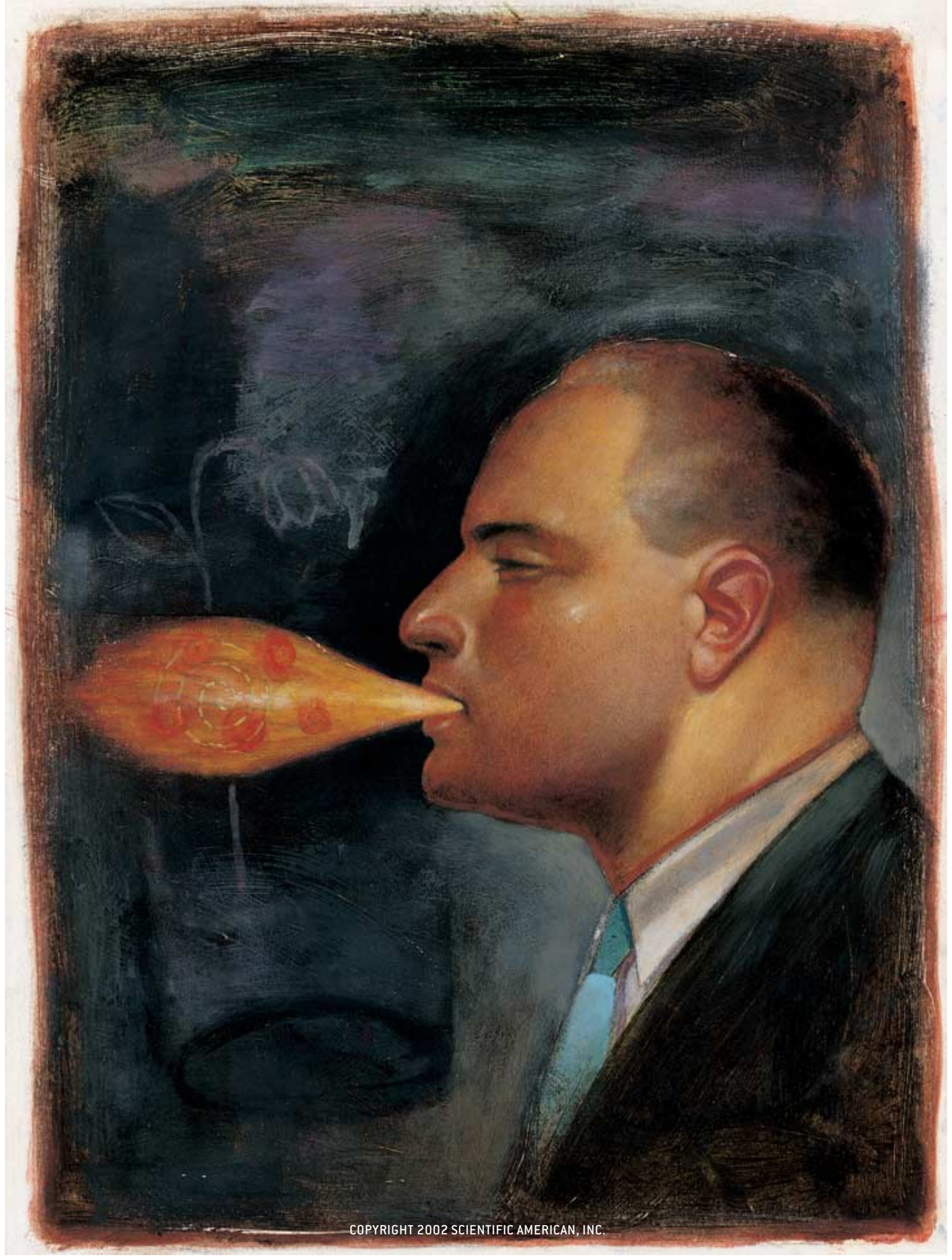
Laser Interferometric Gravitational Wave Detectors. Norna A. Robertson in *Classical and Quantum Gravity,* Vol. 17, No. 15, pages R19–R40; August 7, 2000. Available at **www.iop.org/Journals/CQG**

New Physics and Astronomy with the New Gravitational-Wave Observatories. Scott A. Hughes et al. in *Proceedings of the 2001 Snowmass Meeting.* Available at **www.ligo.caltech.edu/docs/P/P010029-00.pdf**

The Science of Bad Breath

The age-old condition of bad breath is coming under new scientific scrutiny, leading to insights into diagnostic approaches and possible solutions

BY MEL ROSENBERG • ILLUSTRATIONS BY JOSEPH DANIEL FIEDLER



Consider the case of Dr. John Floss.

A dedicated dentist, Dr. Floss works long hours, often so focused on his patients that he neglects to eat or drink. His own teeth and gums are, of course, exemplary. Nevertheless, Dr. Floss is unaware of a problem emanating from his mouth. His patients know, as does his hygienist. But they are too embarrassed to inform Dr. Floss: he has exceedingly bad breath.

In this bad-breath scenario, as in many, the foul odor is the result of the metabolic activity of oral bacteria that are happily feeding on a small pool of postnasal drip that regularly collects on the back of the dentist's tongue. The bacteria leave behind a collection of rank compounds. Gargling with an effective mouthwash and cleaning the tongue would most likely alleviate the problem. Even chewing a few bites of food would help. For now, though, the dentist's patients are protected only by his surgical mask.

Obviously, people have always been aware of the phenomenon of bad breath, or halitosis (from the Latin *halitus,* breath, and the Greek *–osis,* meaning abnormal condition). But halitosis is now emerging as a fascinating scientific subject, involving an intimate human condition of widespread concern and traversing a wide range of scientific fields, including bacteriology, chemistry, physiology and psychology.

Millions have bad breath and, like Dr. Floss, probably don't know it, which makes it difficult to generate accurate statistics about the frequency of halitosis. One recent study, a survey of Brazilian college students by Paulo Nadanovsky of the Institute of Social Medicine at the University of the State of Rio de Janeiro, revealed that 31 percent of the students had at least one family member with habitual bad breath, with serious implications: 24 percent reported that they had trouble enjoying the company of the family member with halitosis, and 62 percent said that they were affected in some way by their relative's breath problem.

My own interest in this area began almost 20 years ago, when my group embarked on the development of a two-phase mouthwash designed to trap oral bacteria and debris on the surface of small oil droplets. At that time, only a handful of academic researchers, led by the late Joseph Tonzetich of the University of British Columbia, were investigating halitosis. Now hundreds of scientists in universities and industry study the problem. Last July the fledgling International Society for Breath Odor Research (ISBOR) drew about 350 attendees to its fifth international meeting in Tokyo.

The growth in the science reflects a general public concern (or in some cases obsession) with sweet-smelling breath. According to a market research firm's findings, Americans spent $1.8 billion on toothpaste in 2000, around $715 million on oral-care gum, almost $740 million on mouthwash and other dental rinses, and almost $950 million on toothbrushes and dental floss. Although many of those products are primarily for maintenance of oral health, people are certainly buying them to ensure that their breath is pleasant as well. And the $625 million spent on breath fresheners other than gum and mouthwash—for example, breath mints—is directly for that purpose.

Overview/*Halitosis*

- Halitosis, or bad breath, is a common condition that affects personal relationships. In addition to cases of actual halitosis, a pervasive fear of bad breath, known as halitophobia, severely interferes with some people's quality of life.
- Researchers have recently begun to analyze halitosis qualitatively and quantitatively, leading to new insights concerning the causes and possible treatments of the condition. Entire new species of oral bacteria have been discovered in the process, and the fact that the vast majority of halitosis cases originate in the mouth has been confirmed.
- Breath freshening and oral hygiene are big business, with billions of dollars spent annually in the U.S. on toothpaste, toothbrushes, floss, mouthwashes, mints and other breath fresheners.

The Source of the Smell

THE BASIC CAUSES of most cases of halitosis are now fairly well understood. According to research conducted by ISBOR co-founder Daniel van Steenberghe and his co-workers at Catholic University–Leuven in Belgium and our group at Tel Aviv University in Israel, about 85 to 90 percent of cases originate in the mouth. As with other odors emanating from the moist microbial jungles of the body—such as underarms and shod feet—bad breath is primarily the result of microbial metabolism.

The mouth is home to hundreds of bacterial species with various nutritional preferences. These tiny organisms particularly enjoy proteins, and the chemical compounds that result from the digestion of these proteins include some truly fetid substances. At any given time, oral bacteria, usually anaerobic, may be producing hydrogen sulfide, with its distinctive rotten-egg smell; methyl mercaptan and skatole, also present in feces; indole, used in small amounts in perfume but foul in large quantities; cadaverine, associated with rotting corpses; putrescine, found in decaying meat; and isovaleric acid, which smells like sweaty feet. No wonder human breath can at times be so offensive.

The University of Michigan's Walter J. Loesche, a past president of ISBOR, recently discovered that the microbiota on the tongue differ from those species living in plaque on teeth. Loesche, who received a grant from the National Institutes of Health to study halitosis, has uncovered previously undescribed bacterial species making their home in our mouths. He is currently cataloguing the microbiota in people with and without halitosis, work that should be completed this summer.

Oral bacteria may be producing hydrogen sulfide, with its ROTTEN-EGG smell, as well as the aptly named CADAVERINE and PUTRESCINE.

In otherwise healthy people, the very back of the tongue, rather than teeth or gums, is the main source of bad breath. This region is poorly cleansed by saliva and contains numerous tiny invaginations in which bacteria can hide. These bacteria have a field day putrefying postnasal drip—common in perhaps one quarter of the urbanites studied—and other oral debris that can collect there.

Additional oral sources of bad breath include poor oral hygiene (especially if it leaves proteinaceous particles between teeth), gum inflammation, faulty dental work, unclean dentures, and abscesses. Because a steady flow of saliva washes away bacteria and their smelly chemical products, anything that promotes dryness—mouth breathing, fasting, prolonged talking, stress and hundreds of medications—can exacerbate the situation. Tobacco smoking is a notable enemy of fresh breath. Although smoke may reduce bacterial activity, this potentially positive effect is drowned out by negatives: smoke dries out the mouth, worsens gum conditions and postnasal drip, and leaves a residue whose aroma mixes with the preexisting oral bouquet.

Some bad breath seems to be associated with actual periodontal disease, the destruction of the gums, and is therefore useful as a clue to physicians and dentists. Hydrogen sulfide and methyl mercaptan are toxic as well as malodorous; they can damage cells and thus may be a factor in gum disease. In addition, some bacterial species implicated in gum disease work up quite a stink when grown anaerobically on amino acids in the laboratory, according to research by Israel Kleinberg of the State University of New York at Stony Brook. The presence of several of these key bacteria—such as *Treponema denticola*,

THE AUTHOR

MEL ROSENBERG grew up in Canada and moved to Israel in 1969. He is professor of microbiology at the Maurice and Gabriela Goldschleger School of Dental Medicine at Tel Aviv University. He has received several awards for his research as well as honorary academic appointments in the U.S., the U.K. and Canada. In 1996, together with Karl Laden and university support, he founded InnoScent, a company that develops products for fighting body odors. He has published a children's book on bacteria and enjoys expelling air through his saxophone.

OLFACTORY OBSESSIONS

RUBY (a composite of patients) dresses impeccably and is particularly well groomed. She runs a successful small business and seems to have everything under control. There is only one problem. A schoolmate told her once, 30 years ago, that she had bad breath. Since that time, she has lived in constant fear that people can smell her breath. She addresses customers at a distance and chews gum incessantly. Ruby visits her dentist regularly and brushes her teeth four or five times a day; she cleans her tongue, flosses, and gargles with antiseptic mouthwash. She avoids kissing her husband on the mouth and refrains from being physically close to people at parties. Outside, Ruby tries to stand downwind when talking to people. She was so embarrassed about her bad breath that she had never before talked to anyone about it.

When Ruby finally came to our clinic, she broke down in tears. "I feel that I have succeeded in my life despite this debilitating problem," she confided. But when we smelled her breath, we detected no odor at all. Subsequent visits did not turn up any telltale odors either. Ruby's breath was pristine.

Ruby and millions of others suffer from halitophobia, the exaggerated fear of having halitosis. In 1997 Murray B. Stein, a social-phobia expert now at the University of California at San Diego, found in a study of 1,206 people in Alberta, Canada, that 15.8 percent worried "a lot" about how their breath smelled, 2.8 percent had seen a professional about their breath, and 2.7 percent said that breath concerns interfered with their lives a moderate or severe amount. One percent revealed that they had avoided going to a party because they were worried about their breath. Clearly, halitophobics may shun social activities and live in a state of self-enforced solitude.

Halitophobics I have interviewed include lawyers, teachers, judges, performers, a physician, a high-ranking politician and even someone who became a dentist, hoping that his studies would help him deal with his "problem." Halitophobics conceal their concern. A colleague of mine once tried to persuade me that halitophobics are practically nonexistent. "What are you talking about?" his wife of more than 30 years suddenly blurted out, "I'm one myself!"

Halitophobics usually think that they have logical reasons for believing that their breath smells. They may interpret bad taste as a sign of bad breath, although taste and breath are not necessarily connected. A family member who has bad breath may lead some to conclude that they have inherited the problem. And some halitophobics are sure that they have foul breath because they misinterpret others' behavior—for example, opening a window or simply rubbing their noses—as a reaction to the halitophobic's breath. The few halitophobics who are ready to entertain the possibility that their fears have a psychological basis can often be helped by psychotherapy. Indeed, in collaboration with Ilana Eli of Tel Aviv University in Israel, we noted that halitophobics have tendencies toward hypersensitivity in interpersonal interactions and toward obsession-compulsion, according to psychological profiles [see "Patient, Smell Thyself," by Steve Mirsky; Anti Gravity, SCIENTIFIC AMERICAN, August 1996]. Most halitophobics, however, continue to search for the cure to a problem that doesn't exist. *—M.R.*

Porphyromonas gingivalis and *Bacteroides forsythus*—in plaque or the tongue coating can be determined in minutes in the dental clinic using a color assay, the BANA test (for benzoyl-DL-arginine-naphthylamide), devised by Loesche. These bacteria produce an enzyme that degrades BANA, forming a new, colored compound. Not surprisingly, positive BANA tests are statistically associated with halitosis.

The various oral bacteria that prefer feeding on sugars instead of on proteins have traditionally been considered irrelevant to bad breath. Research by Nir Sterer in my laboratory, however, suggests otherwise. Much of the available protein in the mouth is actually in the form of glycoproteins, in which sugar residues are linked to the protein core. The sugar-feeding organisms can clip the residues from the glycoproteins, leaving naked proteins to be digested by bacteria that favor them. Sterer and his co-workers have recently shown, using a simple color test, that the amount of enzymatic sugar cleavage in saliva correlates with bad breath levels. In the future, scientists may be able to attack bad breath by preventing the initial sugar cleavage.

One might be tempted to conclude that the eradication of all microorganisms on the tongue would be a potential treatment for halitosis. These bacteria, however, also play a protective role. Ordinarily our tongues harbor the yeastlike *Candida* fungus in small numbers, the population kept in check by the presence of bacteria. When tongue bacteria are wiped out by antibiotics, *Candida* can run rampant. And candidal diseases are more severe and difficult to control than halitosis. The idea, then, is to keep bacterial populations present but under control.

More Halitosis Diagnosis

THE MOST COMMON SOURCE of bad breath, after the mouth, is the nose and nasal passages. In these 5 to 10 percent of cases, the odor comes mainly out of the nose, not the mouth, and has a very different quality, which once again can be a diagnostic tool to the physician or dentist. Nasal odor may result from sinusitis or conditions that impede or block mucus flow. In one odd case, an uncharacteristic breath odor in a 28-year-old woman led us to discover an embedded bead that she had apparently stuck up her nostril as a young child. Indeed, children are notorious for sticking objects up their nose, sometimes generating a foul nasal discharge that they may smear all over themselves; a foreign body in a nasal passage is something to check for when a child suddenly develops an overall offensive odor.

Putrid tonsils may cause about 3 percent of halitosis cases. Hundreds of other diseases and conditions together cause less than 1 percent of the halitosis generally encountered. One interesting but rare instance is so-called fish-odor syndrome. Subjects with this condition sense that their saliva and sweat sometimes have a fishy quality, although others may have trouble verifying the smell. A physician unaware of this condition may even refer these patients for psychotherapy. In fact, fish-odor syndrome, or trimethylaminuria, results from an insufficiency of an enzyme that normally breaks down trimethylamine, a fishy-smelling molecule.

Many people believe—and some businesses through advertising have attempted to foster that belief—that bad breath comes from the stomach rather than from the mouth. The infrequency of the stomach's being such a source was central to a recent court case in which I participated as an expert witness [*see box on page 79*]. Bad breath originating outside the mouth or nasal passages is, in fact, quite uncommon. The esophagus is a closed tube, and continuous flow (as opposed to a simple

Most Unwanted List

Compounds commonly produced by mouth bacteria and their odors

Hydrogen sulfide	Rotten eggs
Methyl mercaptan	Feces
Skatole	Feces
Cadaverine	Corpses
Putrescine	Decaying meat
Isovaleric acid	Sweaty feet

BILLIONS OF DOLLARS of breath-freshening products may be bought by individuals who only fear they have A PROBLEM.

SMALL STONES called tonsilloliths grow in the crypts of the tonsils and consist of partially calcified bacteria and debris. Tonsilloliths smell foul themselves but don't always cause bad breath. They are relatively uncommon (perhaps 2 to 3 percent of the adolescent and adult population have or have had them). Because they do not usually cause any medical problems, many physicians and dentists have never heard of them. The samples at the left were collected from a single individual.

RELLU SAMUEL *Tel Aviv University*

TIPS FOR GOOD BREATH

- Gently clean the very back of your tongue with a plastic tongue cleaner. Take care not to damage your tongue; just sweep the mucus layer away. Practice helps to overcome the gag reflex.
- Eat a good breakfast; it cleanses the mouth and gets the saliva flowing.
- Prevent your mouth from drying out. Chewing gum for just a few minutes can reduce bad breath. Drink sufficient quantities of liquids.
- Use a mouthwash. The most effective method is to rinse and gargle just before sleep. This prevents the buildup of microorganisms and odor during the night.
- Clean your mouth after eating odorous foods or drinks such as garlic, onions, curry and coffee. Make sure to clean between your teeth, especially after eating food or beverages rich in proteins.
- Brush and floss (or otherwise clean between your teeth) according to your dentist's instructions.
- Ask an adult family member or close friend about your breath. This is the most reliable (and cheapest) way to find out if you have halitosis.

burp) of gas or putrid matter from the stomach indicates a health problem, such as a fistula between the stomach and intestine or reflux serious enough to be bringing up stomach contents. Even after garlic is eaten, it is the mouth that retains a substantial part of the sharp odor.

A lingering mystery is why people tend to be exquisitely sensitive to the breath quality of their fellows and notoriously bad at smelling their own. One previous theory, that we become somehow inured to our own bad breath, seems lacking. Research conducted with Ilana Eli, Ronit Bar-Ness Greenstein and others in our laboratory revealed that people such as the blithely unaware Dr. Floss are able to assess samples of their own oral malodors more objectively when the source is removed from the mouth—for example, when they smell debris sampled from between their teeth with a toothpick.

The answer may be simply that because we expel air from our mouths horizontally and only subsequently breathe in vertically through our nose, the chance of getting a representative whiff is low. Whatever the reason, it is difficult for someone to know if he or she has bad breath without being told. And given the embarrassment involved, being told is unlikely. Ironically, the billions of dollars that buy breath-freshening products annually may be spent in large part by individuals who do not in fact have a problem but merely fear they do. An extreme version of this common belief is the phenomenon of halitophobia—a conviction, usually unsupported by objective analysis, that one has bad breath [*see box on page 76*].

A Fresh Approach

THOUGH BY NO MEANS the only factors in halitosis, the volatile sulfur compounds produced by bacterial metabolism are a prime suspect. In the late 1980s, with Jacob H. Gabbay of the Israeli Ministry of the Environment and later with Christopher A. G. McCulloch of the University of Toronto, our research group determined that the sulfides that contribute to bad breath could be assessed using a portable sulfide monitor. The monitor's manufacturer, Manny Shaw of Interscan in Chatsworth, Calif., was initially skeptical that there would be a market for Halimeters, but he has since sold his device to thousands of dentists and researchers. In 1999 Alfredo Sanz-Medel, a chemist at the University of Oviedo in Spain, reported a different technique, one that indirectly quantifies sulfide concentration by optically measuring the fluorescence induced by the reaction of sulfides with a mercury compound.

Such technologies might someday lead to the development of an effective, pocket-size sulfide meter. Existing Halimeter scores do correlate statistically with more complex chromatographic analyses and with the gradings of human odor judges, who personally smell the breath of study subjects and rate it for research purposes.

Once the presence of halitosis is established, the affected individual ordinarily wishes to be rid of the condition. Of course, basic oral hygiene—regular flossing and brushing—cannot be underestimated as a preventive. The gingivitis medication chlorhexidine, an antimicrobial agent sold by prescription in

the U.S., is quite effective against halitosis. Unfortunately, it can also discolor teeth, impair taste and generate oral ulcerations. These effects, though reversible, preclude the use of chlorhexidine for more than a few days at a time.

Other cures date back thousands of years. Tongue cleaning is an ancient oral hygiene practice from the Far East that is still popular there and that is catching on in the West. One early antidote mentioned in the Babylonian Talmud is gum mastic, which may be the same ladanum referred to in Genesis. Gum mastic is the resin of the *Pistacia lentiscus* shrub, which is still cultivated for this purpose on the Mediterranean island of Chios, although modern synthetic chewing gums have largely supplanted mastic. Interestingly, this resin was once used extensively for treating wounds and is now known to have potent antibacterial properties. Chewing the gum, therefore, might both increase saliva flow and kill some bad-breath microbes.

Other natural products chewed around the world for breath freshening include guava peels (Thailand), anise seeds (Far East), parsley (Italy), clove (Iraq) and cinnamon (Brazil). Some of the molecules responsible for the flavor in these plants have antibacterial properties that give scientific credibility to these folk practices. Many popular mouthwashes contain flavor oils, including menthol, eucalyptol and methyl salicylate (wintergreen oil).

The American Dental Association currently has guidelines whereby a product can get ADA approval as being efficacious against plaque, gingivitis or cavities. The ADA is now reviewing guidelines that would allow products to receive similar approval for their breath-freshening powers. Seemingly paradoxically, some companies that manufacture breath fresheners are against the ADA effort. A closer look reveals that the approval would require the companies to create better products: most available breath products work only briefly, on the order of 20 to 120 minutes, and the ADA will most likely demand a significantly longer effect for official recognition. For example, mint is widely accepted as a primary example of a good ingredient in a breath treatment. But mint is actually relatively weak and its effect short-lived compared with other essential oils.

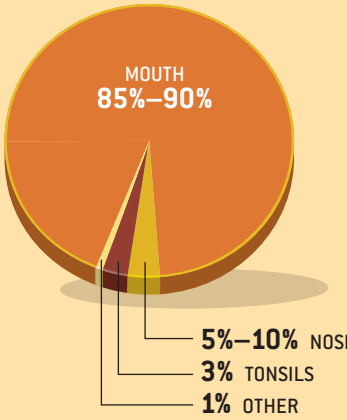
Over the past 15 years I have had the opportunity to smell the mouths of thousands of individuals in clinics and in research studies, not to mention the hundreds I have smelled surreptitiously in supermarkets, in airplanes and in synagogue during the fast day of Yom Kippur. Just as Camembert cheese smells quite different than Edam does, bad breath is not one odor but a constellation of them, depending on the microorganisms involved, where they come from and what they have been up to. Whereas researchers continue to argue about the best ways to quantify offensive breath, future electronic noses [see "Plenty to Sniff At," by Mia Schmiedeskamp; News and Analysis, Scientific American, March 2001] may provide not only halitosis levels but also an indication of the types of odors detected, which would give clues about their origins.

The ability to identify the probable origin is of considerable importance in halitosis research and in counseling individuals, and it requires extensive "nose-on" experience. There remains much that we do not know. For example, we must match individual bacterial species to the odors with which they are associated. The details of the contributions of the nasal passages and the tonsils to bad breath are still incompletely understood. And few psychologists actively study halitophobics. Although the recognition and treatment of halitosis may seem insignificant in the pantheon of medical conditions, it can have a profound effect on a person's life and relationships. SA

Odor in the Court

IN 1999 I was an expert witness for Warner-Lambert (it has since merged with Pfizer), which made Listerine, Certs and other breath products, in its suit against BreathAsure. The latter company marketed BreathAsure capsules, which allegedly combated bad breath internally. Warner-Lambert claimed that the trade names of BreathAsure's products "constituted false and misleading claims that the products alleviated bad breath and gave the defendant an unfair advantage over the plaintiff." In part because BreathAsure's claims of an internal source for halitosis were not supported by credible scientific evidence, the U.S. Court of Appeals for the Third Circuit eventually found for Warner-Lambert. —*M.R.*

SITES OF ORIGIN OF BAD BREATH



ORAL MALODOR is indeed an oral phenomenon for the most part. Research suggests that the vast majority of cases of bad breath start in the mouth, with almost no cases originating below the tonsils.

MORE TO EXPLORE

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What to Do about Halitosis. C. Scully, S. P. Porter and J. Greenman in *British Medical Journal,* Vol. 308, pages 217–218; January 22, 1994.

Clinical Assessment of Bad Breath: Current Concepts. M. Rosenberg in *Journal of the American Dental Association,* Vol. 127, pages 475–482; April 1996.

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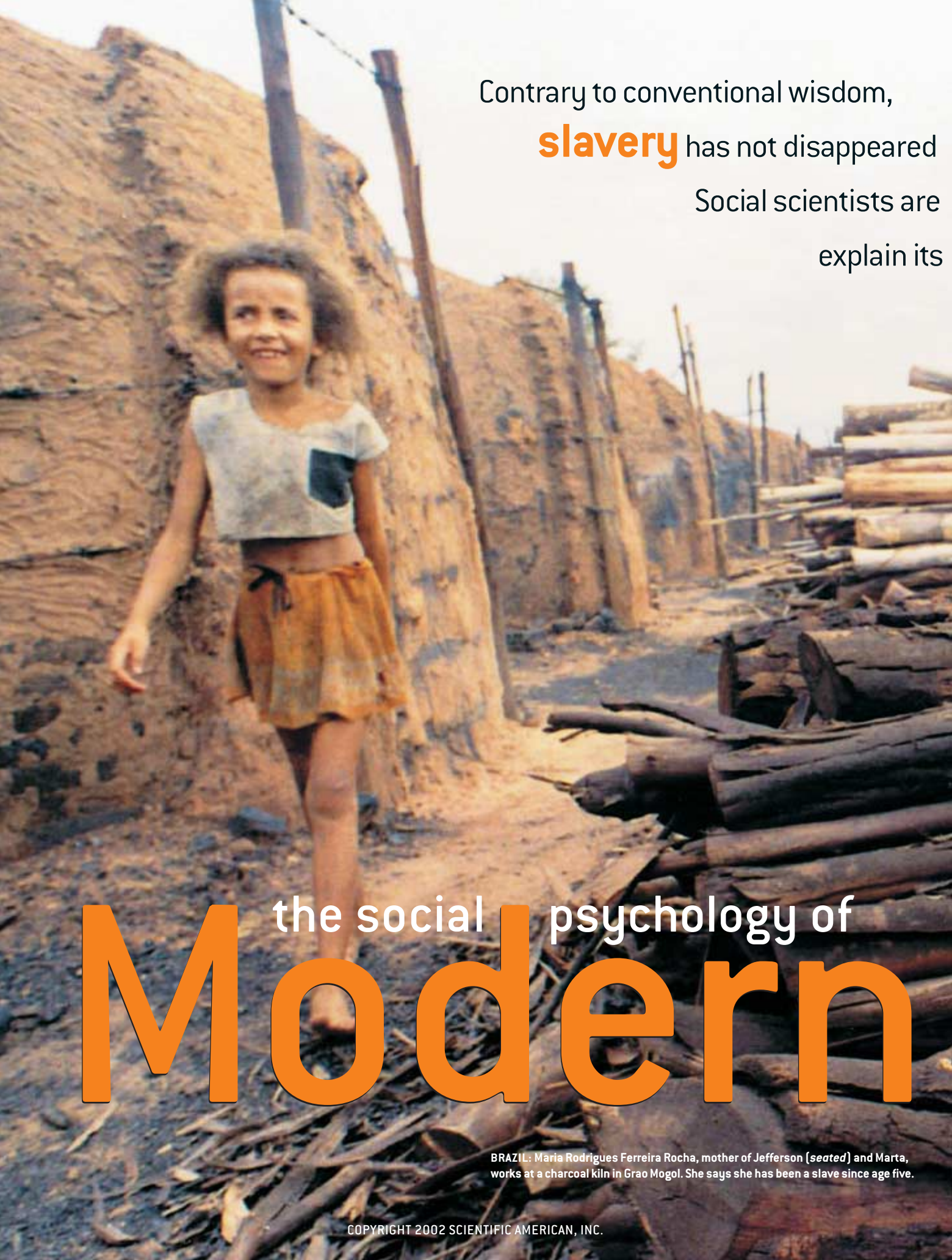
Tel Aviv University's Web site on bad breath: **www.tau.ac.il/~melros/**

Possible causes of halitosis: **www.tau.ac.il/~melros/bda/index.html**

Bacterial species that inhabit the mouth: **www.tau.ac.il/~melros/faq/5.html**

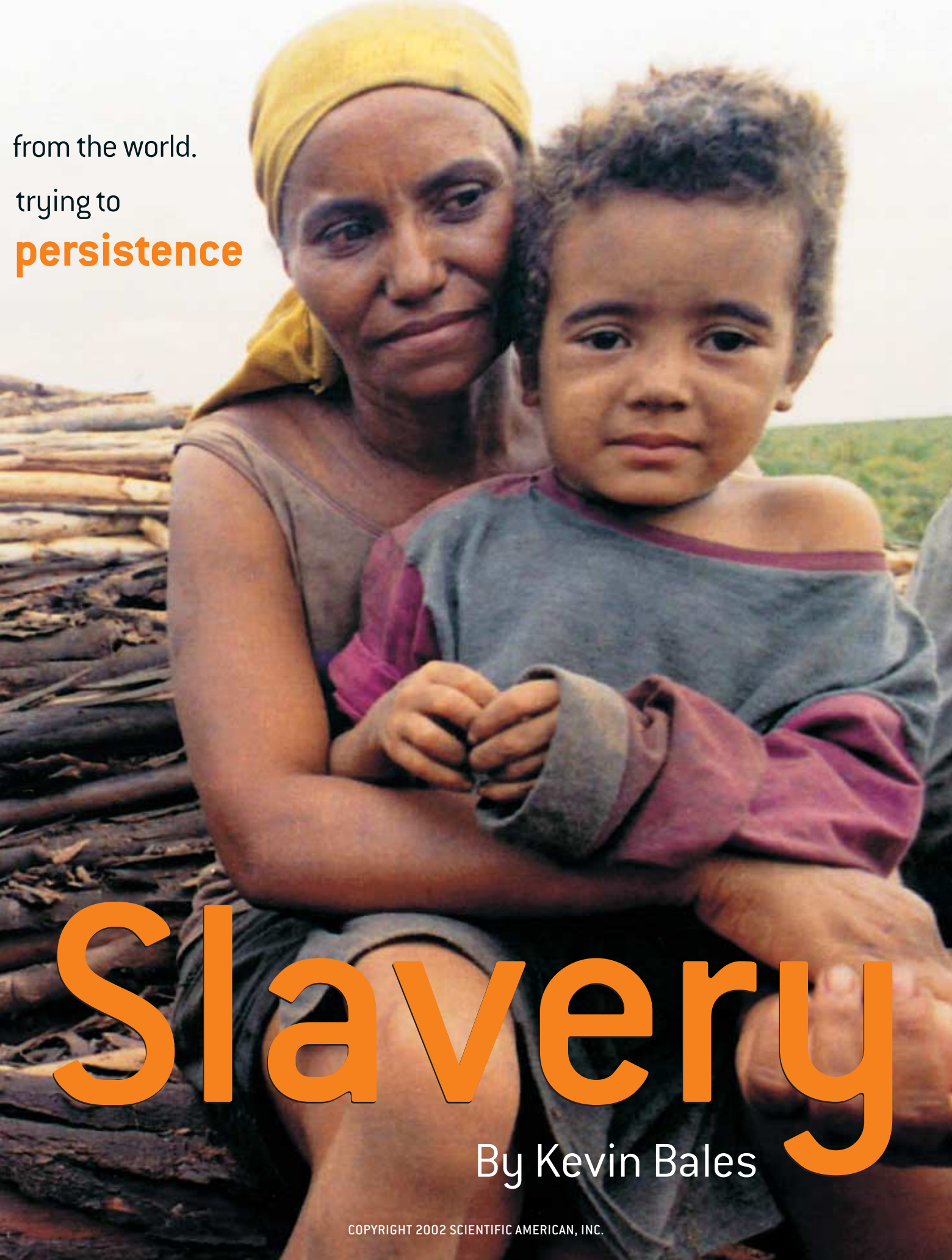
NINA FINKEL



Contrary to conventional wisdom, **slavery** has not disappeared. Social scientists are explain its

the social psychology of Modern

BRAZIL: Maria Rodrigues Ferreira Rocha, mother of Jefferson (*seated*) and Marta, works at a charcoal kiln in Grao Mogol. She says she has been a slave since age five.



from the world.

trying to

persistence

Slavery

By Kevin Bales

For Meera, the revolution began with a single rupee.

When a social worker came across Meera's unmapped village in the hills of Uttar Pradesh in India three years ago, he found that the entire population was in hereditary debt bondage. It could have been in the time of their grandfathers or great-grandfathers—few in the village could remember—but at some point in their past, the families had pledged themselves to unpaid labor in return for loans of money. The debt passed down through the generations. Children as young as five years old worked in quarry pits, making sand by crushing stones with hammers. Dust, flying rock chips and heavy loads had left many villagers with silicosis and injured eyes or backs.

Calling together some of the women, the social worker proposed a radical plan. If groups of 10 women agreed to set aside a single rupee a week from the tiny sums the moneylenders gave them to buy rice, he would provide seed money and keep the funds safe. Meera and nine others formed the first group. The rupees slowly mounted up. After three months, the group had enough to pay off the loan against which Meera was bonded. She began earning money for her work, which greatly increased the amount she could contribute to the group. In another two months, another woman was freed; the following month, a third came out of bondage.

At that point, the other members, seeing that freedom was possible, simply renounced their debts and declared themselves free. The moneylenders quickly moved against them, threatening them and driving them from the quarries. But the women were able to find jobs in other quarries. New groups followed their example. The social worker has taken me to the village twice, and on my second visit, all its inhabitants were free and all their children in school.

Less than 100 kilometers away, the land turns flat and fertile. Debt bondage is common there, too. When I met Baldev in 1997, he was plowing. His master called him "my *halvaha*," meaning "my bonded plowman." Two years later I met Baldev again and learned that because of a windfall from a relative, he had freed himself from debt. But he had not freed himself from bondage. He told me:

MACEDONIA: Tanja, age 24, sits in a refugee center in Skopje. She escaped from prostitution after ethnic Albanian guerrillas raided the bar where, she says, she was enslaved. She is waiting to return to her native Moldova.

CRAIG CHIVERS *AP Photo [preceding pages]*; ALEXANDER NEMENOV *AFP Photo*

SUDAN: Akuac Malong (*left*), age 13, walks home to her village, Madhol, in southern Sudan. She says she was kidnapped and held for seven years as a domestic slave in northern Sudan.

JEAN-MARC BOUJU *AP Photo*

> After my wife received this money, we paid off our debt and were free to do whatever we wanted. But I was worried all the time—what if one of the children got sick? What if our crop failed? What if the government wanted some money? Since we no longer belonged to the landlord, we didn't get food every day as before. Finally, I went to the landlord and asked him to take me back. I didn't have to borrow any money, but he agreed to let me be his *halvaha* again. Now I don't worry so much; I know what to do.

Lacking any preparation for freedom, Baldev reenrolled in slavery. Without financial or emotional support, his accidental emancipation didn't last. Although he may not bequeath any debt to his children, his family is visibly worse off than unbonded villagers in the same region.

To many people, it comes as a surprise that debt bondage and other forms of slavery persist into the 21st century. Every country, after all, has made it illegal to own and exercise total control over another human being. And yet there are people like Baldev who remain enslaved—by my estimate, which is based on a compilation of reports from governments and nongovernmental organizations, perhaps 27 million of them around the world. If slaveholders no longer own slaves in a legal sense, how can they still exercise so much control that freed slaves sometimes deliver themselves back into bondage? This is just one of the puzzles that make slavery the greatest challenge faced by the social sciences today.

Despite being among the oldest and most persistent forms of human relationships, found in most societies at one time or another, slavery is little understood. Although historians have built up a sizable literature on antebellum American slavery, other types have barely been studied. It is as if our understanding of all arachnids were based on clues left by a single species of extinct spider. In our present state of ignorance, we have little hope of truly eradicating slavery, of making sure that Meera, rather than Baldev, becomes the model.

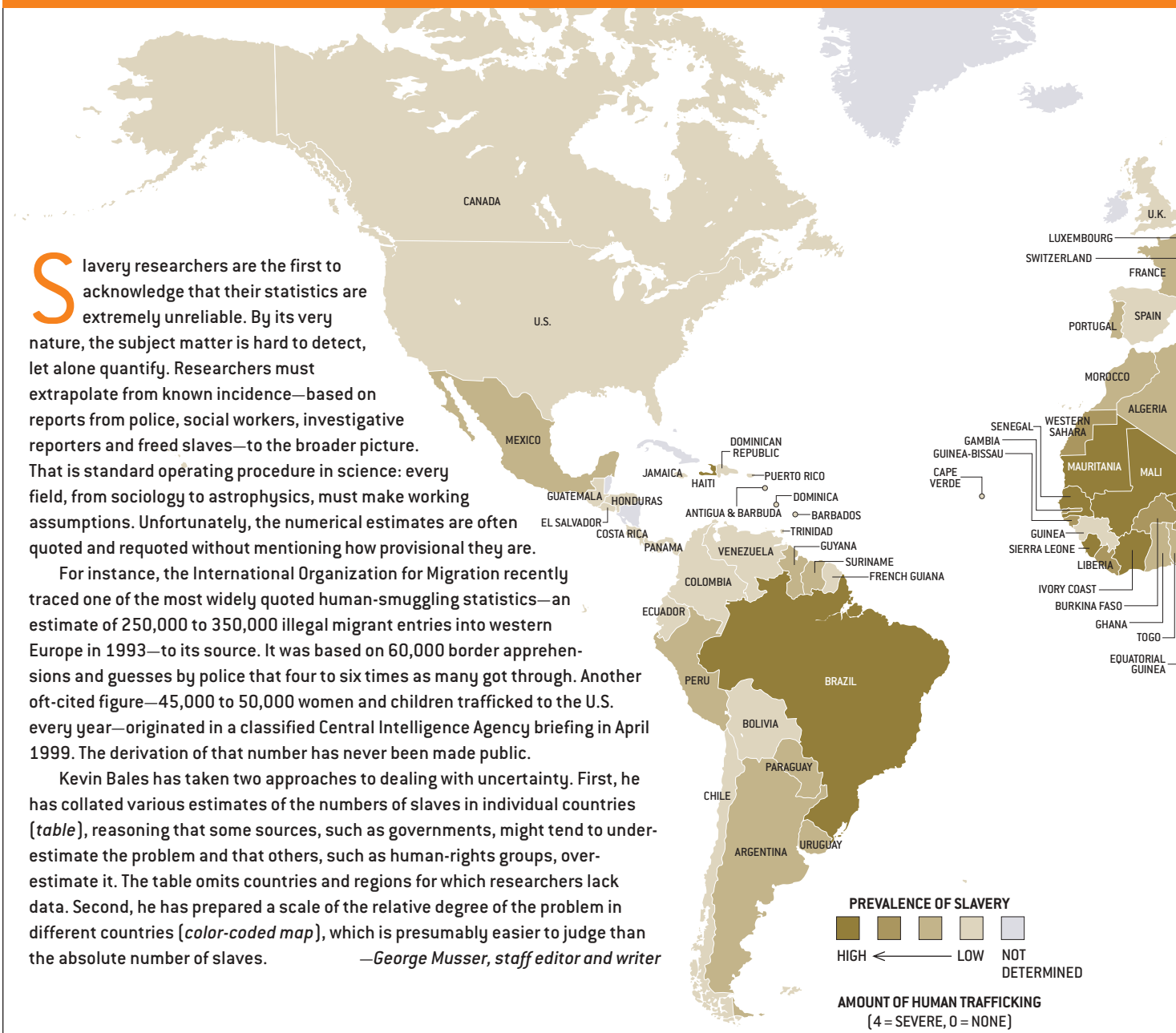
The New Slavery

RESEARCHERS DO KNOW that slavery is both evolving and increasing in raw numbers. Like spiders, it permeates our world, typically hidden in the dark spaces of the economy. Over the past few years, journalists and activists have documented numerous examples. Human trafficking—the involuntary smuggling of people between countries, often by organized crime—has become a huge concern, especially in Europe and Southeast Asia. Many people, lured by economic opportunities, pay smugglers to slip them across borders but then find themselves sold to sweatshops, brothels or domestic service to pay for their passage; others are kidnapped and smuggled against their will. In certain areas, notably Brazil and West Africa, laborers have been enticed into signing contracts and then taken to remote plantations and prevented from leaving. In parts of South Asia and North Africa, slavery is a millennia-old tradition that has never truly ended.

The plight of these people has drawn the attention of governments and organizations as diverse as the Vatican, the United Nations, the International Organization for Migration, and Amnesty International. Two years ago the U.S. government established a central coordinating office to deal with human trafficking. Academic researchers are beginning to conduct intensive studies. The anecdotal and journalistic approach is slowly transforming into the more rigorous inquiry of social science. For example, Urs Peter Ruf of the University of Bielefeld in Germany has documented the evolution of master-slave relations in

THE AUTHOR

KEVIN BALES is a professor of sociology at the University of Surrey Roehampton in London. He is a trustee of Anti-Slavery International and a consultant to the United Nations Global Program on Trafficking of Human Beings, to the Economic Community of West African States, and to the U.S., British, Irish, Norwegian and Nepali governments. Bales began studying slavery in the early 1990s, when few Westerners realized it still existed. Unable to secure funding for his research, he took on a commercial research project and devoted the profits to travel. The outcome—his book *Disposable People*—was nominated for the Pulitzer Prize in 2000. His work won the Premio Viareggio for services to humanity in 2000, and a television documentary based on it (shown on HBO and on Britain's Channel 4) won a Peabody Award in 2000.



Slavery researchers are the first to acknowledge that their statistics are extremely unreliable. By its very nature, the subject matter is hard to detect, let alone quantify. Researchers must extrapolate from known incidence—based on reports from police, social workers, investigative reporters and freed slaves—to the broader picture. That is standard operating procedure in science: every field, from sociology to astrophysics, must make working assumptions. Unfortunately, the numerical estimates are often quoted and requoted without mentioning how provisional they are.

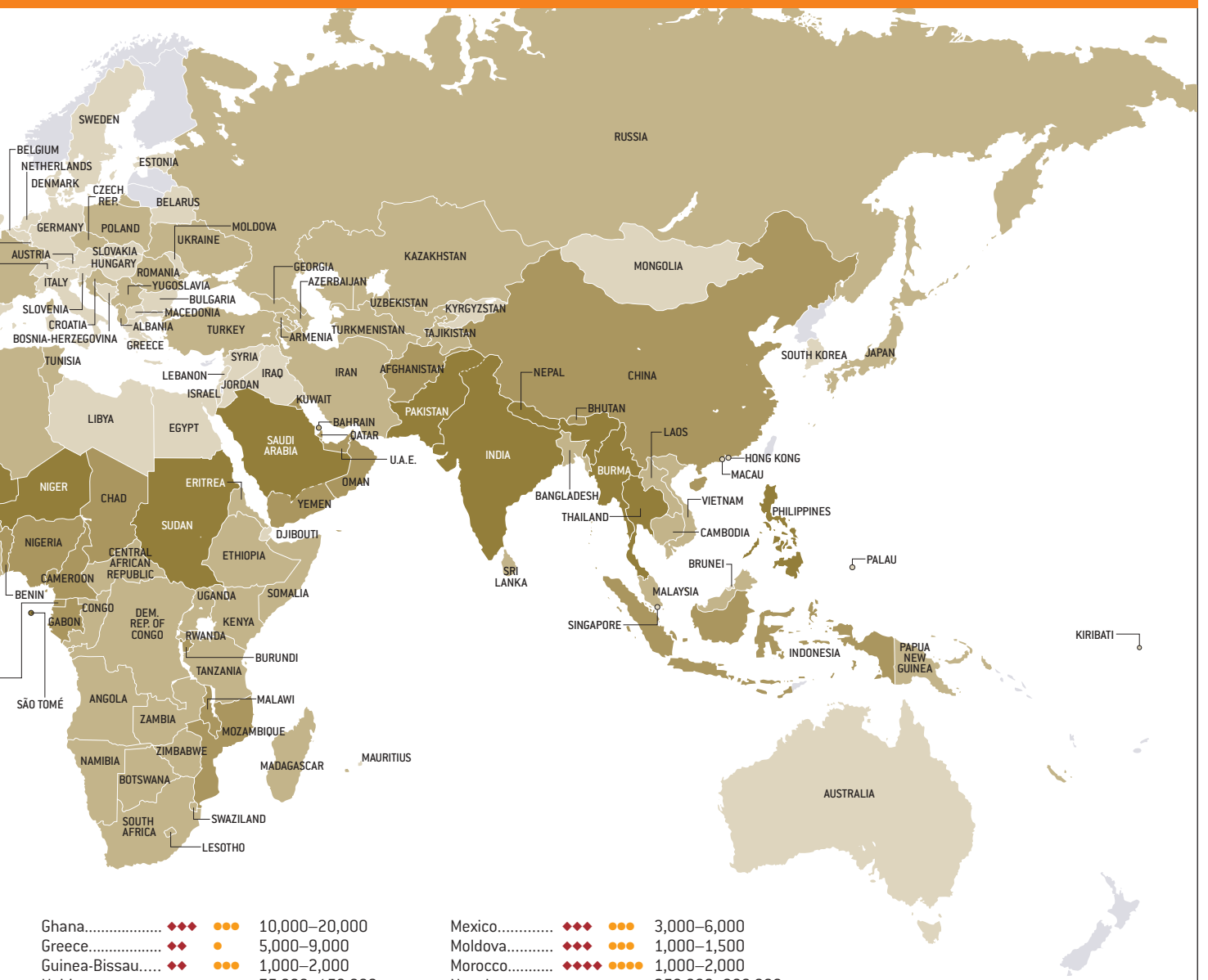
For instance, the International Organization for Migration recently traced one of the most widely quoted human-smuggling statistics—an estimate of 250,000 to 350,000 illegal migrant entries into western Europe in 1993—to its source. It was based on 60,000 border apprehensions and guesses by police that four to six times as many got through. Another oft-cited figure—45,000 to 50,000 women and children trafficked to the U.S. every year—originated in a classified Central Intelligence Agency briefing in April 1999. The derivation of that number has never been made public.

Kevin Bales has taken two approaches to dealing with uncertainty. First, he has collated various estimates of the numbers of slaves in individual countries (*table*), reasoning that some sources, such as governments, might tend to underestimate the problem and that others, such as human-rights groups, overestimate it. The table omits countries and regions for which researchers lack data. Second, he has prepared a scale of the relative degree of the problem in different countries (*color-coded map*), which is presumably easier to judge than the absolute number of slaves.

—George Musser, staff editor and writer

COUNTRY OR REGION	TRAFFICKING IN	TRAFFICKING OUT	ESTIMATED NUMBER OF SLAVES
Afghanistan	◆◆	●●●	20,000–50,000
Albania	◆	●●●	5,000–10,000
Algeria	◆◆	●●	1,000–2,000
Argentina	◆◆	●●	1,000–1,000
Armenia	◆	●●	2,000–4,000
Australia	◆◆◆	●	4,000–6,000
Austria	◆◆		1,000–2,000
Azerbaijan	◆	●●	1,000–2,000
Bahrain	◆◆	●●	1,000–2,000
Bangladesh	◆	●●●●	10,000–10,000
Barbados	◆	●	0–100
Belarus	◆	●●●	2,000–3,000
Belgium	◆◆	●	5,000–7,000
Benin	◆◆◆◆	●●●●	20,000–40,000
Bosnia-Herzegovina	◆◆	●●	3,000–4,000
Brazil	◆◆◆◆	●●●●	300,000–500,000
Bulgaria	◆◆	●●●●	2,000–4,000
Burkina Faso	◆◆◆	●●●	2,000–4,000
Burma	◆	●●●●	50,000–100,000
Cambodia	◆◆	●●●	3,000–6,000
Cameroon	◆◆◆	●●●	6,000–12,000
Canada	◆◆	●	10,000–20,000
China	◆◆◆	●●●	250,000–500,000
Colombia	◆◆	●●●	5,000–10,000
Congo (Kinshasa)	◆◆◆	●●●	1,000–1,500
Costa Rica	◆	●●	0–100
Croatia	◆◆	●●●	1,000–2,000
Czech Republic	◆◆◆◆	●●●●	2,000–5,000
Denmark	◆	●	1,000–2,000
Dominica	◆	●	0–100
Dominican Republic	◆	●●	5,000–6,000
Egypt	◆◆	●●	1,000–2,000
Equatorial Guinea	◆◆◆	●●●●	1,000–2,000
Estonia	◆◆	●●	1,000–2,000
France	◆◆◆	●	10,000–20,000
Gabon	◆◆	●●●	5,000–10,000
Gambia	◆◆◆◆	●●●●	3,000–6,000
Georgia	◆◆	●●●●	1,000–2,000
Germany	◆◆◆	●	5,000–9,000

OF SLAVERY



Ghana	◆◆◆	●●●	10,000–20,000
Greece	◆◆	●	5,000–9,000
Guinea-Bissau	◆◆	●●●	1,000–2,000
Haiti	◆◆	●●●●	75,000–150,000
Hong Kong	◆◆◆	●●	1,000–2,000
Hungary	◆◆◆	●●●	1,000–2,000
India	◆◆◆	●●●●	18,000,000–22,000,000
Indonesia	◆◆	●●●	4,000–8,000
Israel	◆◆◆◆	●	4,000–6,000
Italy	◆◆◆◆	●●	30,000–40,000
Ivory Coast	◆◆◆◆	●●●●	30,000–80,000
Jamaica	◆◆	●●	0–500
Japan	◆◆◆◆	●●	5,000–10,000
Kazakhstan	◆	●●	1,000–2,000
Kenya	◆	●●	3,000–5,000
South Korea	◆◆	●●	10,000–15,000
Kuwait	◆◆	●	1,000–2,000
Kyrgyzstan	◆	●	1,000–1,500
Laos	◆	●●●	5,000–10,000
Lebanon	◆◆	●●	1,000–1,500
Liberia	◆◆	●●	3,000–6,000
Luxembourg	◆◆	●	2,000–3,000
Macedonia	◆◆	●●●	1,000–1,500
Malaysia	◆◆◆	●●●	3,000–6,000
Mali	◆◆◆◆	●●●●	10,000–20,000
Mauritania	◆◆	●●●	250,000–300,000
Mexico	◆◆◆	●●●	3,000–6,000
Moldova	◆◆◆	●●●	1,000–1,500
Morocco	◆◆◆◆	●●●●	1,000–2,000
Nepal	◆◆	●●●●	250,000–300,000
Netherlands	◆◆◆	●	3,000–5,000
Niger	◆◆◆◆	●●●●	3,000–5,000
Nigeria	◆◆	●●●●	20,000–40,000
Oman	◆◆◆	●●	1,000–2,000
Pakistan	◆◆◆	●●●●	2,500,000–3,500,000
Panama	◆	●	0–100
Peru	◆◆	●●	3,000–5,000
Philippines	◆◆	●●●●	3,000–10,000
Poland	◆◆◆◆	●●●●	2,000–4,000
Portugal	◆◆◆	●●	5,000–6,000
Puerto Rico	◆	●	0–100
Qatar	◆◆◆	●●	1,000–2,000
Romania	◆◆◆	●●●●	5,000–6,000
Russia	◆◆◆◆	●●●●	8,000–10,000
São Tomé	◆◆◆◆	●●●●	1,000–2,000
Saudi Arabia	◆◆◆◆	●●●●	2,000–5,000
Senegal	◆◆◆◆	●●●●	6,000–12,000
Sierra Leone	◆◆◆◆	●●●●	3,000–6,000
Singapore	◆◆◆	●●●	1,000–1,500
Slovakia	◆◆◆	●●●	2,000–3,000
South Africa	◆◆◆	●●●	5,000–6,000
Spain	◆◆	●●	10,000–15,000
Sri Lanka	◆◆	●●●●	5,000–10,000
Sudan	◆◆◆◆	●●●●	20,000–50,000
Sweden	◆		2,000–3,000
Switzerland	◆	●	1,000–1,500
Tajikistan	◆◆	●●	2,000–4,000
Tanzania	◆◆	●●	2,000–4,000
Thailand	◆◆◆◆	●●●●	30,000–60,000
Togo	◆◆	●●●	6,000–8,000
Trinidad	◆	●	0–100
Turkey	◆◆◆◆	●●●●	20,000–30,000
Turkmenistan	◆◆◆	●●●	1,000–2,000
Uganda	◆◆	●●●	5,000–8,000
Ukraine	◆◆	●●●●	3,000–5,000
U.A.E.	◆◆◆◆	●●	1,000–2,000
U.K.	◆	●	4,000–5,000
U.S.	◆	●	100,000–150,000
Uzbekistan	◆◆	●●	1,000–2,000
Vietnam	◆◆	●●●	5,000–7,000
Yemen	◆◆◆	●●	1,000–2,000
Yugoslavia	◆◆◆	●●●●	8,000–10,000

SARA CHEN

modern Mauritania. Louise Brown of the University of Birmingham in England has studied women forced into prostitution in Asia. David Kyle of the University of California at Davis and Rey Koslowski of Rutgers University have explored human smuggling. I have posited a theory of global slavery and tested it through case studies in five countries.

A common question is why these practices should be called slavery rather than just another form of superexploitation. The answer is simple. Throughout history, slavery has meant a loss of free will and choice backed up by violence, sometimes exercised by the slaveholder, sometimes by elements of the state. That is exactly what other researchers and I have observed. Granted, workers at the bottom of the economic ladder have few options to begin with, but at some point on the continuum of exploitation, even those options are lost. These workers are unable to walk away.

Human suffering comes in various guises, yet slavery has a distinctive horror that is evident to those of us who have seen it in the flesh. Even when it does not involve beating or other physical torture, it brings about a psychological degradation that often renders victims unable to function in the outside world. "I've worked in prisons and with cases of domestic violence," says Sydney Lytton, an American psychiatrist who has counseled freed slaves. "This is worse."

Although each of the manifestations of slavery has unique local characteristics, one of the aims of social scientists is to understand their universal features, so that therapies developed in one place can be applied elsewhere. Foremost among these commonalities is the basic economic equation. In 1850 an agricultural slave cost $1,500 in Alabama (around $30,000 in today's dollars). The equivalent laborer can be had for around $100 today. That payment might be made as part of a "loan" or as a "fee" to a trafficker. A young woman in Southeast Asia or eastern Europe might be sold several times, through a series of brokers and pimps, before she ends up in a brothel.

One should not read too much into these specific dollar amounts, because what the slaveholder purchases is somewhat different in each case. The basic point is that forced labor represents a much smaller percentage of business expenses than it used to. It took 20 years of labor for an antebellum American slave to repay his or her purchase price and maintenance costs; today it takes two years for a bonded laborer in South Asia to do the same. This fall in price has altered not only the profitability of slavery but also the relationship between slave and master. The expensive slave of the past was a protected investment; today's slave is a cheap and disposable input to low-level production. The slaveholder has little incentive to provide health care or to take care of slaves who are past their prime.

Several trends could account for this shift. The world's population has tripled since World War II, producing a glut of potential slaves. Meanwhile the economic transformation of the developing world has, whatever its benefits, included the loss of community and social safety nets, matched by the erection of vast shantytowns. But the vulnerability of large numbers of people does not make them slaves; for that, you need violence. The key factor in the persistence of slavery is the weak rule of law in many regions. Widespread corruption of government and police allows violence to be used with impunity even when slavery is nominally illegal.

Free Your Mind Instead

A SECOND COMMONALITY among different forms of slavery is the psychological manipulation they all involve. The widely held conception of a slave is someone in chains who would escape if given half a chance or who simply does not know better. But Meera's and Baldev's stories, among numerous others, suggest that this view is naive. In my experience, slaves often know that their enslavement is illegal. Force, violence and psychological coercion have convinced them to accept it. When slaves begin to accept their role and identify with their master, constant physical bondage becomes unnecessary. They come to perceive their situation not as a deliberate action taken to harm them in particular but as part of the normal, if regrettable, scheme of things.

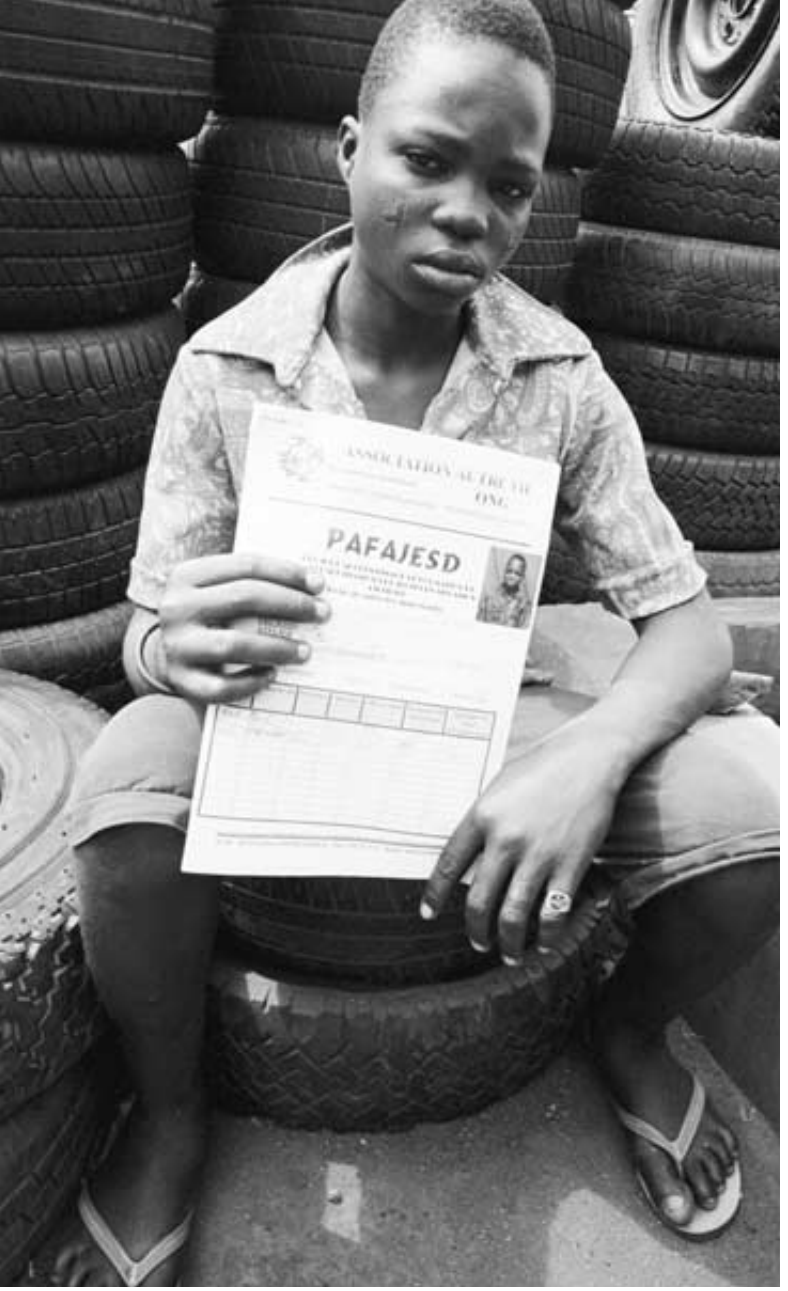
Throughout HISTORY, slavery has meant a loss of free will and choice backed up by VIOLENCE, sometimes exercised by the slaveholder, sometimes by elements of the state.

One young woman I met in northeastern Thailand, Siri, has a typical story. A woman approached her parents, offered to find their 14-year-old daughter a job, and advanced them 50,000 baht (at the time, about $2,000) against her future income. The broker transferred Siri to a low-end brothel for twice that sum. When she tried to escape, her debt was doubled again. She was told to repay it, as well as a monthly rent of 30,000 baht, from her earnings of 100 baht per customer.

Siri had little idea what it meant to be a prostitute. Her initiation took the form of assault and rape. Shattered, the teenager had to find a way to carry on with life. In the world in which she lived, there were only those with total power and those with no power. Reward and punishment came from a single source, the pimp. Young women in Siri's position often find building a relationship with the pimp to be a good survival strategy. Although pimps are thugs, they do not rely solely on violence. They are adept at fostering insecurity and dependence.

Cultural norms have prepared these young women for control and compliance. A girl will be told how her parents will suffer if she does not cooperate and work hard, how the debt is on

MICHAEL ST. MAUR SHEIL *Black Star*



BENIN: Constant Ayitcheou, age 13, says he was trafficked at eight years old by a friend of his father. Promised education and money, he was instead taken to become a domestic servant in Nigeria. "PAFAJESD" is the French acronym of the aid organization that helped to free him.

her shoulders and must be repaid. Thai sex roles are clearly defined, and women are expected to be retiring, nonassertive and obedient—as the women are repeatedly reminded. The pimps also cite religion. The young women are encouraged to believe that they must have committed terrible sins in a past life to deserve their enslavement and abuse. They are urged to accept this karmic debt, to come to terms with it and to reconcile themselves to their fate.

To live in slavery, the young women often redefine their bondage as a duty or a job or a form of penance. To accept their role and the pimp's, they must try to diminish their view of themselves as victims who have been wronged. They must begin to see their enslavement from the point of view of the slaveholder. At the time of my visit, the women in Siri's brothel were at various stages in this process of submission. Some were even allowed to visit their families during holidays, for they always came back.

A similar psychology operates in a different form of slavery, one that involves domestic servants that African and Asian diplomats and business executives have brought with them to Europe and North America. As an employee of the Committee against Modern Slavery, Cristina Talens worked for several years to free and rehabilitate domestic slaves who had been brought to Paris. She told me that liberating the body was much easier than freeing the mind:

> In spite of the violence, and the living and working conditions, people in slavery have their own mental integrity and their own mechanisms for surviving. Some may actually like different aspects of their life, perhaps the security or their understanding of the order of things. When you disrupt this order, suddenly everything is confused. Some of the women who were freed have attempted suicide. It is easy to assume that this happened because of the abuse they had lived through. But for some of these women, slavery had been the major psychological building block in their lives. When that was destroyed, the meaning of their life was like a bit of paper crushed up and thrown away. They were told: "No, this is not the way it is supposed to be. Start all over again." It was as though their life had no meaning.

Plausible Deniability

THE PSYCHOLOGY OF THE SLAVE is mirrored by that of the slaveholder. Slavery is not a simple matter of one person holding another by force; it is an insidious mutual dependence that is remarkably difficult for slaveholder as well as slave to break out of. Branding the slaveholder as pure evil may in some way comfort us, but maintaining that definition becomes difficult when one meets actual slave masters.

Almost all the slaveholders I have met and interviewed in Pakistan, India, Brazil and Mauritania were family men who thought of themselves simply as businessmen. Pillars of the local community, they were well rewarded financially, well integrated socially, and well connected legally and politically. Their slaveholding was not seen as a social handicap except, possibly, by "outsiders" who, they felt, misunderstood the local customs of business and labor.

How is it that such nice men do such bad things? A government official in Baldev's district who held bonded workers was frank about his slaveholding:

> Of course I have bonded laborers: I'm a landlord. I keep them and their families, and they work for me. When they aren't in the fields, I have them doing the household work washing clothes, cooking, cleaning, making repairs, everything. After all, they are from the Kohl caste; that's what they do, work for Vaisyas like me. I give them food and a little land to work. They've also borrowed money, so I have to make sure that they stay on my land till it is paid back. They will work on my farm till it is all paid back. I don't care how old they get; you can't just give money away!

After all, there is nothing wrong in keeping bonded labor. They benefit from the system, and so do I. Even if agriculture is completely mechanized, I'll still keep my bonded laborers. You see, the way we do it, I am like a father to these workers. It is a father-son relationship; I protect them and guide them. Of course, sometimes I have to discipline them as well, just as a father would.

Other slaveholders also have told me that their slaves are like their children, that they need close control and care. They make the argument of tradition: because the practice has been going on for so long, it must be the natural order of things. For others, it is a simple question of priorities: they say that enslaving people is unfortunate but that their own family's welfare depends on it. Often slaveholders have interposed many layers of management between themselves and the slaves. They purposely deny themselves the knowledge of what they are doing and thus the responsibility for it.

SLAVERY is not a simple matter of one person holding another by force; it is an insidious MUTUAL DEPENDENCE that is remarkably difficult to break out of.

Forty Acres and a Mule

ALL THIS POINTS to the need for a highly developed system of rehabilitation for freed slaves and slaveholders alike. Physical freedom is not enough. When slaves were emancipated in the U.S. in 1865, the government enacted no such rehabilitation. General William Tecumseh Sherman's promise to give each former slave "forty acres and a mule" never materialized. The result was four million people dumped into a shattered economy without resources and with few legal protections. It can be argued that America is still suffering from this liberation without rehabilitation.

Human-rights worker Vivek Pandit of the Vidhayak Sansad organization in India has been liberating bonded laborers for more than 20 years. He is adamant that real liberation takes place in the mind, that physical freedom isn't enough—as was the case with Baldev. Conversely, mental freedom can bring about physical freedom—as it did for Meera.

Pandit's organization has devised a program of education that prepares former bonded laborers for a life of freedom. They are taught basic science to promote their curiosity and attention to detail; role-playing to stimulate problem solving; and games to develop strategic thinking and teamwork. This training comes after a challenging public dialogue in which the laborer recounts and renounces his or her bondage. The renunciation is recorded and read out in the village. "When the ex-slave has fixed his thumbprint to this public document," Pandit says, "they can't go back."

Several models of liberation and rehabilitation are currently being field-tested. [*Editors' note: Visit www.sciam.com/explorations/2002/031102gabon for a case study of a program in Gabon.*] The experience of these programs suggests that a combination of economic support, counseling and education can lead to stable, sustainable freedom. This kind of work is still in its early stages, though. No systematic evaluations of these programs have been carried out. No social scientist has explored a master-slave relationship in depth.

Slave economics are another puzzle. How can would-be liberators crack the dark economy and trace the slave-made products to our homes? Why are such large numbers of people being trafficked across continents, how many of these people really are enslaved, and why are these flows apparently increasing? What is the impact of this workforce on national economies? What are the links among the traffic in people, drugs and guns?

Studying bondage can be socially and politically controversial. Researchers in the field face numerous ethical dilemmas, and clarity and objectivity are all the more difficult to achieve when individuals and governments seek to conceal what they are doing. If there is good news, it is the growing recognition of the problem. The plight of enslaved child workers has drawn significantly increased funding, and new partnerships between antislavery organizations and industries that use slave-made commodities provide an innovative model for abolition. But if our figures are correct, only a small fraction of slaves are reached and freed every year. Our ignorance of their hidden world is vast. SA

MORE TO EXPLORE

The Small Hands of Slavery: Bonded Child Labor in India. Human Rights Watch, 1996. Available at **hrw.org/reports/1996/India3.htm**

Crime and Servitude: An Exposé of the Traffic in Women for Prostitution from the Newly Independent States. Gillian Caldwell, Steven Galster and Nadia Steinzor. Global Survival Network, November 1997. Available at **www.globalsurvival.net/femaletrade/9711russia.html**

Disposable People: New Slavery in the Global Economy. Kevin Bales. University of California Press, 1999.

International Trafficking in Women to the United States: A Contemporary Manifestation of Slavery and Organized Crime. Amy O'Neill Richard. Center for the Study of Intelligence, Central Intelligence Agency, November 1999. Available at **usinfo.state.gov/topical/global/traffic/report/homepage.htm**

Sex Slaves: The Trafficking of Women in Asia. Louise Brown. Virago, 2000.

Ending Slavery: Hierarchy, Dependency and Gender in Central Mauritania. Urs Peter Ruf. Transcript Verlag, 2001.

Global Human Smuggling: Comparative Perspectives. Edited by David Kyle and Rey Koslowski. Johns Hopkins University Press, 2001.

Antislavery Web sites:

www.freetheslaves.net

www.antislavery.org

"The World Is Broad and Wide"

A MODERN MATHEMATICIAN ANNOTATES A CLASSIC AND GIVES IT YET ANOTHER DIMENSION **BY PETER RENZ**

THE ANNOTATED FLATLAND: A ROMANCE OF MANY DIMENSIONS
By Edwin A. Abbott
Introduction and notes by Ian Stewart
Perseus Publishing, 2002 ($30)

Why is *The Annotated Flatland* piled in heaps at the front of the Harvard Coop? Partly because of the strengths of *Flatland* itself and partly because of Ian Stewart's annotations.

Edwin A. Abbott published *Flatland* in 1884. More than 12 editions are available today, a measure of the book's appeal. It is a social satire that carries readers beyond conventional ideas and surface appearances to an appreciation of new worlds—those of higher-dimensional space.

Many satirists have used voyages to fantastic lands as a means to develop social commentary; Swift's *Gulliver's Travels* is a classic example. The science in such works is often itself a parody, like that which Gulliver sees on his voyage to Laputa. In contrast, Abbott gets the science right. Included in this edition is the introduction written by William Garnett in 1926 that recommends the book as a guide to the geometry of spacetime and relativity. Indeed, *Flatland* has introduced countless readers to the geometry of higher dimensions, having been "read by every self-respecting physicist, mathematician and science-fiction writer, inspiring sequels, elaborations and imitations," as Edward Rothstein observed last year in the *New York Times*.

As headmaster of the City of London School, Abbott worked to extend the benefits of education to Victorian England's women and lower classes. He was also a sought-after preacher, and in *Flatland* he satirizes abuses of power and position and urges greater open-mindedness in that role. As Stewart says of Abbott's hero and narrator, "A twenty-first-century reader can identify with poor A. Square, and with his lonely battle against mindless orthodoxy and social hypocrisy, as easily as a nineteenth-century one."

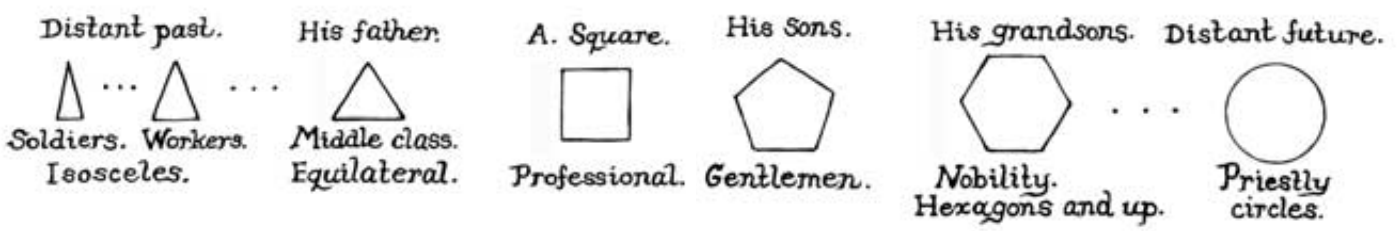
Ian Stewart is a perfect annotator for *Flatland*, being the author of a sequel, *Flatterland*. He is familiar to readers of this magazine from his Mathematical Recreations column. More broadly, he is the author of some 60 books bringing mathematics and science to general readers. Geometry is his specialty, and his enthusiasm shines through in his notes.

In *Flatland*, Abbott draws on an idea of 19th-century mathematician C. H. Hinton, who imagined intelligent creatures confined to a plane. Abbott's characters are segments, triangles, squares and polygons. The closer a figure is to a circle, the higher its status, and the Chief Circle is supreme. His hero is a professional man and gentleman, whose name, A. Square, is a play on "Edwin Abbott Abbott."

Geometric irregularity leads to criminal or deviant behavior. If reform fails, the deviants are "induced to enter State Hospitals, where they are kept in honourable confinement for life; one or two alone of the more obstinate, foolish, and hopelessly irregular are led to execution."

Lowest are triangles; the duller the wit, the sharper the apex. Women are line segments and in low esteem, though somewhat aside from the male hierarchy. Nei-

A. SQUARE'S FOREFATHERS are pointier-headed as we go back in time. His father is an equilateral triangle, and his sons, pentagons. His grandsons are nobility, hexagons. Down the generations the side number will increase. His heirs will move into the circular priesthood. But their fertility will decrease, and his line will then die out. This creates room at the top in Flatland.



DRAWING BY PATRICIA J. WYNNE, IN THE STYLE OF A. SQUARE, FROM AN IDEA SUPPLIED BY PETER RENZ

ther women nor the lower classes are to be trifled with. They are deadly fighters, using their sharpness to impale and destroy.

Progress from generation to generation is the norm [*see illustration on preceding page*], so all live with hope—but also with fear of the power of the state. The social hierarchy, educational system, machinations of the state and cleverness of the Chief Circle allow for the satirical twists of Part I.

In Part II, A. Square is visited by the Sphere from Spaceland. The Sphere brings the Gospel of Three Dimensions. By explorations of Spaceland and Pointland our hero learns the geometry of other dimensions, which he ably explains to the reader. He fails to convince the priestly circles, is declared a heretic and imprisoned, and writes this account from his cell.

So ends Abbott's book, but there is much more to Stewart's story. For example, Stewart quotes Hinton on the possible role of a fourth dimension in our reality: "… our proportions [of the fourth dimension] must be infinitely minute, or we should be conscious of them. If such be the case, it would probably be in the ultimate particles of matter, that we should discover the fourth dimension."

This, Stewart points out, anticipates ideas of today's string theory, one approach to fundamental particles. In addition to our three regular space dimensions plus time, this theory postulates at least six more space dimensions curled so small as to be undetectable by current means. Our universe may be sitting in a space of 10 or more dimensions—somewhat as Flatland sits in Spaceland. As Stewart warns us in his closing words: "Creatures from the fourth dimension? Arrant nonsense. It's creatures from the *tenth* dimension we need to worry about." SA

Peter Renz has taught mathematics at Reed, Wellesley, and Bard colleges and served as associate director of the Mathematical Association of America.

THE EDITORS **RECOMMEND**

HOW TO BUILD A TIME MACHINE

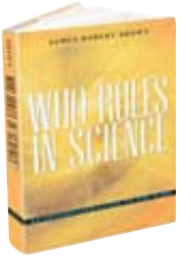
by Paul Davies. Viking (Penguin Putnam), New York, 2002 ($19.95)

Is time travel possible? Yes, says Davies, who recently retired (in his early 50s) as professor of mathematical physics at the University of Adelaide in Australia to concentrate on his writing. But "a moment's thought uncovers some tricky questions." Whereupon he discusses lucidly and engagingly both the concepts of physics that establish the possibility of time travel and the tricky questions. You could reach the future "by simply moving very fast." For visiting the past, the most popular proposal is a wormhole, "a sculpture in the structure of space that provides a shortcut between two widely separated spaces." There may be "cosmic taboos," though, that make time travel forever elusive.

WHO RULES IN SCIENCE? AN OPINIONATED GUIDE TO THE WARS

by James Robert Brown. Harvard University Press, Cambridge, Mass., 2001 ($26)

Meaty and challenging are the words to describe Brown's treatment of the arguments that go on over the nature and social impact of science. "The battleground in the current round of the science wars," he writes, "is epistemology (What is evidence? Objectivity? Rationality? Could any belief be justified?)…. The stakes are political, however; social issues are constantly lurking in the background. How we structure and organize our society is the consequence. Whoever wins the science wars will have an unprecedented influence on how we are governed." Brown, professor of philosophy at the University of Toronto, gives a rich and closely reasoned discussion of the issues in the science wars.



All the books reviewed are available for purchase through www.sciam.com

FURTHER ADVENTURES IN **FLATLAND**

C. H. Hinton's *An Episode of Flatland: Or, How a Plane Folk Discovered the Third Dimension* (1907) confines his two-dimensional creatures to the surface of a circular planet, Astria.

Dionys Burger's *Sphereland* (written in Dutch in 1957 and translated in 1965) is narrated by A. Square's grandson, A. Hexagon.

A. K. Dewdney's *The Planiverse* (1984) details the physics and biology of a two-dimensional universe.

Jeffrey R. Weeks's *The Shape of Space* (1985) combines tales of Flatland with a mathematics text on the topology of surfaces and three-dimensional spaces.

Rudy Rucker's *The Fourth Dimension* (1985) extends Flatland in several directions. His short story "Message Found in a Copy of *Flatland*" (in ***The 57th Franz Kafka,*** 1983) offers a fanciful explanation of how a staid clergyman came to write this book.

Ian Stewart's *Flatterland* (2001) traces the adventures of A. Square's great-great-granddaughter, Victoria Line, through higher-dimensional geometry and quantum physics.

A Fairy Tale

BY DENNIS E. SHASHA

In a mythical land, fairies visit children at night and leave them pearls. But each fairy is attracted only to a particular color. Suppose, for example, that a fairy named Liane is attracted to the color aqua. While making her nightly visitations, she will leave a pearl on a child's bedside table for each aqua star she sees above the child's head. If a fairy named Ariana, who is attracted to crimson, flies with Liane and sees a child with a crimson star, she will leave a pearl on the child's table. So a child having both crimson and aqua stars would receive two pearls. Your task is to find out which fairy is attracted to which color.

Here is what you know:

- The fairies' names are Juliana, Katiana, Oliviana, Anya and Heather.
- The colors are silver, sage, gold, rose, turquoise, ivory, violet, emerald and earth.
- At least one fairy likes turquoise and one likes earth.
- The children are Augustine, Jonathan and Theo.
- Augustine has rose, turquoise and violet stars above his head. Jonathan has sage, violet and ivory. Theo has sage, violet and emerald.

Here is what happens:

- The first night Anya, Heather and Juliana fly in and leave one pearl for Augustine, one for Jonathan and two for Theo.
- The second night Anya, Heather and Oliviana fly in and leave no pearls for Augustine, but two for Jonathan and two for Theo.
- The third night Anya, Heather and Katiana fly in and leave no pearls for Augustine, but one for Jonathan and two for Theo.
- The fourth night Juliana, Katiana and Oliviana fly in and leave one pearl for Augustine, one for Jonathan and none for Theo.
- The fifth and last night Anya, Juliana and Oliviana fly in and leave one pearl for Augustine, two for Jonathan and one for Theo. SA

SARA CHEN

Answer to Last Month's Puzzle

Alice can win the game no matter how Bob arranges the cards bearing numbers greater than four. Let *x* stand for each of Bob's cards. Alice arranges the remaining cards at the bottom of the deck to create the order *x, x, x, x, x, x,* 4, 4, 3, 3, 2, 2, 1, 1, in which the final 1 represents the ace of spades. Alice will win any game using this order.

Alice can also force a win if Bob arranges seven of the cards in the order 5, 1, 2, 6, 7, 3, 3. She simply inserts the remaining cards (indicated by brackets) to create the order [7], [6], [4], [2], 5, 1, 2, 6, [5], [4], 7, 3, 3, [1]. But I know of no proof showing that Alice can win in general, no matter how Bob orders seven cards.

Web Solution

For a peek at the answer to this month's problem, visit www.sciam.com

LAB TESTS

Grow, Then Kill

You've had a fever for two days and have been coughing up phlegm, so you visit your doctor. He examines you, asks a few questions, suspects a bacterial infection and says, "I'm going to do a lab test." While you open your mouth and say, "Aaah," he rubs a long swab against the back of your throat to grab some infected cells. He then sends the swab to a lab at a local hospital or health department. If he had suspected other pathogens, he would have taken a sputum, blood, urine or stool sample and sent that, too. You go home, miserable, and wait for the results.

At the lab a technologist unpacks the sample at a bench beneath a hood that draws air away into a filter system. That way, pathogens don't become airborne in the room. From there, the specimen can undergo a variety of tests done in series, each step narrowing its possible identity until one specific pathogen is determined. The most common sequence in dealing with a bacterium is to grow more of it in a lab dish and then test it with carbohydrates and antibiotics to assess what it is and which drugs might kill it most effectively [*see illustration at right*]. Two days after your visit to the doctor, you get your test results.

Viruses are too small to observe through common microscopes and must be grown in biological cells known as cell lines. A technologist can then test the cells in various ways. In one common test, the technologist places drops of your serum—the clear component of your blood containing antibodies—into small wells on various plastic panels. Antigens for different viruses are in the wells. The technologist can tell which virus you have by observing which antigen your antibodies react with.

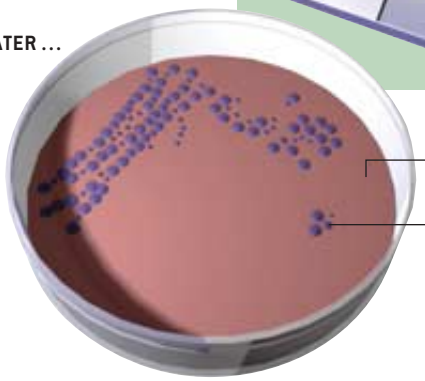
Lab tests can be complex and costly and can take time. And none is 100 percent accurate. Faster tests would help health officials stem the spread of infectious diseases. "For years, there was no money going into better lab tests," says Phyllis Della-Latta, director of the clinical microbiology lab at Columbia-Presbyterian Medical Center in New York City. But since the anthrax attacks, millions of dollars are suddenly being earmarked. It's a good thing, Della-Latta says: "We're behind the eight ball. Maybe now we can catch up."

—Mark Fischetti

1 GROWTH

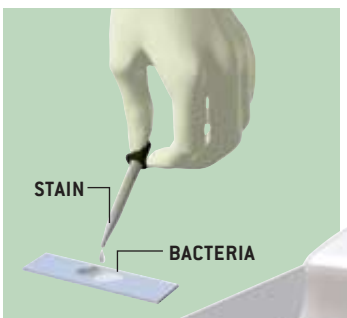
A lab technologist streaks a patient's infected cells across a film of hard, waxy agar in a petri dish. The agar, made from seaweed, is impregnated with sheep's blood to nurture the bacteria. She closes the lid and incubates the dish at 37 degrees Celsius (body temperature) for 24 hours so the bacteria will grow, providing more specimens for further tests.

24 HOURS LATER ...



2 STAIN

The technologist smears grown bacteria on a glass slide. She heats it over a flame to "fix" the bacteria onto the slide and render it safe to handle. Next she squeezes a few drops of stain onto the slide. Some organisms, such as strep or staph, will absorb blue stain; others, like *Salmonella* or *Escherichia coli,* will absorb red stain. The technologist examines the slide under a microscope to see if the bacteria are round or rod-shaped and if they are linked in clusters or chains. All these clues narrow the search for the germ's identity.



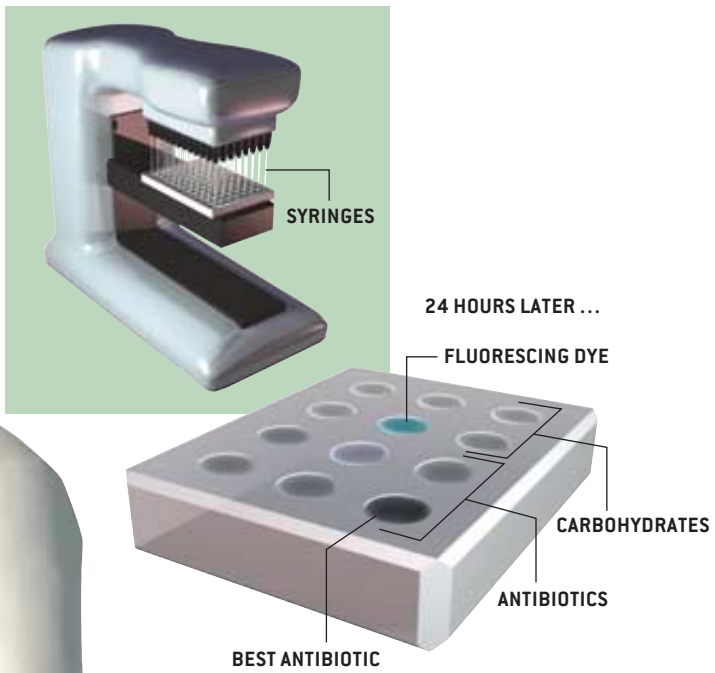
BRYAN CHRISTIE DESIGN

DID YOU KNOW . . .

➤ ANTHRAX Certain pathogens, such as anthrax, do not show up well in standard lab tests and must be examined with highly specific techniques that only state or federal labs can afford. Samples from suspicious envelopes found during the U.S. anthrax attacks last autumn were sent to the Centers for Disease Control and Prevention. Pathogens such as Ebola are so contagious they can be handled only in a "biosafety level 4" lab, where technologists wear full-body suits and breathe through hooded respirators.

➤ TUBERCULOSIS *Mycobacterium tuberculosis* can take three to eight weeks to grow in a lab dish. If a patient is contagious, he can infect many others in the interim. The Columbia-Presbyterian Medical Center is one of the first hospitals to try a new "rapid test" of the germ's nucleic acids; it can indicate TB in four hours. The quick turnaround would help doctors keep a suspect patient in hospital quarantine during testing or would at least get the patient back in quarantine sooner, reducing contagion.

➤ VERSATILE AGAR Agar is a gel extracted from a red-algae variety of seaweed that thrives off eastern Asia and along the U.S. Pacific coast. It forms the substrate in lab dishes in which bacteria are grown. It is also used in laxatives, as a thickening agent for processed foods, as a gelatin in Chinese cooking and sweet potato pie, and as the base for certain Japanese sweets.



3 TYPE AND SENSITIVITY

The technologist places bits of bacteria into 12 adjacent wells in a plastic panel. She slides the panel underneath a matrix of syringes. Six syringes each release a drop of dye and a different carbohydrate—sucrose, lactose, glucose—into corresponding wells. The six other syringes dispense different antibiotics. The technologist incubates the panel for 24 hours. Different bacteria ferment different carbohydrates, producing acid that causes the dye to fluoresce. The well that glows identifies the bacterium type. Antibiotic wells that appear clear, gray or black indicate which drug has had no effect, has had a mild effect or has thoroughly killed the bacteria, respectively.

Have a topic for a future column? Send it to workingknowledge@sciam.com

Bringing the Net to the Bedroom

EVEN AN AMATEUR CAN CREATE A CUSTOM-DESIGNED INTERNET APPLIANCE **BY W. WAYT GIBBS**

SAN FRANCISCO—When I first set out to build a better wake-up machine 18 months ago, it did not once occur to me to connect the mini blinds on our bedroom window to the Internet. I want to be very clear about this: I'm not one of those wacko Webcam exhibitionists. My wife and I like our privacy, and those thin pecan strips are all that shield us from the cars and electric buses that creep past the other side of that window day and night. It's just that somewhere along the tortuous path of invention, putting the blinds online seemed the most feasible and elegant way to solve my problem. And now it wouldn't surprise me if one day the drapes in your house—along with the security system and the heat pump and various other appliances—are plugged into the Net, too. You might be surprised at how little technical expertise is needed to create the connecting electronics and software.

For me, the whole thing started with a simple motivation: hate. I hate alarm clocks. My theory is that over millions of years, evolution has hardwired the human nervous system to rouse in two ways. There is the gradual stirring in response to the warming pink glow of sunlight on the eyelids. And there is the startled jolt of adrenaline in response to the roar of a leopard—or the wail of an alarm. That may not be scientific fact, but that is how it feels to me. Besides, researchers in Siberia reported recently that the circadian hormone cycles of experimental subjects who awoke in darkened rooms tended to shift a little later each day. But subjects rising to a simulated dawn held comfortably to a 24-hour cycle.

Of course, the easiest solution would be to leave the blinds open all night; come morning, sunbeams would inch down the wall onto my face. But to sleep with the blinds open, I'd have to buy a rifle and shoot out the confounded sodium vapor streetlight that, but for those blessed pecan strips, throws a 9,500-lumen glare over the room. Not that I haven't thought about it.

My first real plan was more socially acceptable: I would get a lamp-clock that could be programmed to turn itself on in the morning and brighten gradually over 30 to 60 minutes. I'd seen such a product in the SkyMall catalogue that clutters up the back pocket of airplane seats, but the device was ugly and overpriced. I resolved to build one myself.

Never mind that never in my life had I constructed any electronic machine more complicated than a doorbell. At the time, I was doing a fellowship at the Massachusetts Institute of Technology. I had been auditing a course on custom microchip design, and the spirit of invention was infectious. These 20-year-olds were creating digital video cameras. Why couldn't I simply program a chip to keep track of the time and activate power transistors to control the lamp?

I had just about finished a working design for the microprocessor when the fellowship ended and with it my access to the oscilloscopes, logic analyzers, chip programmers and other expensive equipment I needed to complete the device. After returning to San Francisco, I realized the lamp might be a bad idea anyway; the bedroom was already full of furniture, and a novice like me probably shouldn't be working with 120 volts of alternating current.

Months later I stumbled on the Web site of NetMedia, a company in Tucson, Ariz., that makes what it claims is the world's smallest Ethernet Web server. This $30 "Web co-processor," which can hold 48 kilobytes of Web pages and graphics, is the size of a large postage stamp. Even attached to a development board that adds three buttons, two LEDs, and jacks for Ethernet, serial and

SAMUEL VELASCO

power connections, the thing is only half the size of my Palm Pilot. In a white paper on the NetMedia site, CEO Jack Schoof explained how the SitePlayer (as it is called) could read data from a temperature sensor and run a fan to make a Web-enabled thermostat. A quick search turned up other tinkerers. One had used it to make an online weather station; another, to check on the door, lights and heater in his basement.

The beauty of the SitePlayer is that it can transform a simple appliance into a marionette capable of complicated behavior. Attached by virtual strings to a puppeteer program running on a real computer somewhere on the Internet, the device gains a sense of time, an ability to make logical decisions, and a way to communicate, via Web browser, with its owner. A new plan began to gel. I would connect the mini blinds to a motor, connect the motor to the SitePlayer, connect the SitePlayer to my Web server, add a bit of programming and voilà! Like magic, the shades would open quietly every morning precisely at sunup—or at whatever time I had entered into the Web page.

The more I thought about the design, the more obsessed I became with the project. I sketched out the details from a chaise longue overlooking the Coral Sea while vacationing in Australia. My appliance would use a photoresistor attached to the window frame to sense the rosy fingers of dawn. I'd glue a small magnet to the top blind slat and use a Hall effect sensor attached to the frame to determine when the blinds were fully open or closed. A stepper motor, which can be turned a degree at a time, would twist the wand back and forth as needed. Push buttons would let us control the blinds manually, and LEDs would confirm that the wake-up machine was programmed and working properly.

Once I started construction, I quickly realized that the SitePlayer alone could not handle all the sensors, lights

SAMUEL VELASCO

On the Web

WWW.SCIENTIFICAMERICAN.COM

FEATURED STORY

Breaking the Bonds of Child Slavery

Slavery still flourishes underground, as Kevin Bales's article beginning on page 80 shows. He has studied the social psychology of human bondage all over the world. An examination of a unique regional form of child slavery and traffic in children appears this month on the *Scientific American* Web site.

This case study presents the perspectives of West African social scientists, diplomats, activists and escaped slaves in Gabon. Though distinctively local in character, slavery there follows patterns that will be familiar to readers of Bales's article. Of particular interest is the Gabonese effort to rehabilitate and repatriate those children who have the luck and courage to escape their bonds.

www.sciam.com/explorations/2002/031102gabon/

ASK THE EXPERTS

What happens when an airplane breaks the sound barrier?

Tobias Rossmann, research engineer at Advanced Projects Research, Inc., and visiting researcher at the California Institute of Technology, explains.

JOHN GAY

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TECHNICALITIES

and buttons in addition to the motor. I needed some more chips: the Hall sensor, an analog-to-digital converter, a motor controller, and a simple microprocessor to coordinate them all and talk to the SitePlayer. This could add up to real money. Fortunately, I discovered that chip manufacturers are happy to give out one or two free samples of almost any integrated circuit they make. Dissecting a deceased laser printer that I'd rescued from the trash pile, I found three compact LEDs and a stepper motor of just the right size. I did end up spending $50 on a "BASIC Stamp" microprocessor from an electronics surplus store. And I became a familiar face at the neighborhood Radio Shack as I dropped in nearly every Saturday for resistors and other components.

In dribs and drabs, parts of the appliance came together. By summer the microprocessor could convert light and magnetism into precise digital numbers. By autumn I had a program on my PC turning the motor shaft anywhere I wanted it. And as the first snow fell in the Sierras, I let out a whoop: there in Internet Explorer was my creation. Click here, and the green light goes on. Click there, and the motor spins. Refresh the page and see the latest sensor readings. I had put a tiny slice of the real world online. Even more satisfying, I had harnessed the computer and made it do actual, physical work.

I expect it will be well into spring before the appliance is complete. There are still mechanical linkages to build, control programs to debug. But someday soon the sun will rise, a computer miles away will obey my wishes, and with a noise no louder than the thrum of a hummingbird, a warm pink glow will wake me the way that nature intended. SA

W. Wayt Gibbs is senior writer at Scientific American. *An enhanced version of this column with details on the design of the wake-up appliance is available at www.sciam.com*

Copy That

TECHNOLOGY IS MAKING IT HARDER FOR WORD THIEVES TO EARN OUTRAGEOUS FORTUNES **BY STEVE MIRSKY**

It was the best of times, it was the worst of times,[1] it was the *New York Times*. Specifically, it was a *Times* article that discussed computer programs and other techniques designed to root out plagiarism.[2] The article revealed that there is now software that can look for a lengthy passage, like a string of pearls,[3] in a new document that is identical to a passage in a previously published work. In another method, every fifth word from sample passages is removed, and the author has to fill in the blanks[4] to reveal his or her familiarity with the work. These high-tech ways to spot literary theft will surely rob copycats of the sleep that knits up the raveled sleave of care.[5]

When I first read the *Times* article, I remember thinking, it's a good thing[6] and attention must be paid.[7] After all, as a writer, I find plagiarism to be a constant concern. (Although from time to time, I have to admit, I shall consider it.[8]) Of course, it can be hard to define. When you steal from one author, it's plagiarism; if you steal from many, it's research.[9] One might say that a writer should neither a borrower nor a lender be.[10] On the other hand, imitation is the sincerest form of flattery.[11]

I shall never believe that God plays dice with the world.[12] Therefore, the plagiarized passages that programs pinpoint are probably purposeful and potentially punishable.[13] There is grandeur in this view of life.[14] I think.[15]

Plagiarism is a central issue of science[16] as well. Relying on the work of others is the lifeblood of scientific research. Indeed, if I (who had the chance to learn physics that Newton never dreamed of) have seen further it is by standing on the shoulders of giants.[17] One might even say that I have always depended on the kindness of strangers[18] in this regard.

But employing the findings of other researchers is one thing; claiming such findings as one's own is intellectual murder most foul.[19] So when in the course of human events,[20] a case of plagiarism is revealed, it represents a clear and present danger[21] to intellectual liberty. And naturally, eternal vigilance is the price of liberty.[22] It is thus incumbent on all researchers to say, "Let me make this perfectly clear:[23] I am not a crook.[24]" SA

1. Dickens, Charles. *A Tale of Two Cities,* opening lines.
2. See Eakin, Emily. "Stop, Historians! Don't Copy That Passage! Computers Are Watching!" in the *New York Times,* January 26, 2002.
3. Miller, Glenn. Song title.
4. Rayburn, Gene. *The Match Game,* television program (1962–1969, 1973–1984).
5. Shakespeare, William. *Macbeth,* Act 2, Scene 2.
6. Stewart, Martha.
7. Miller, Arthur. *Death of a Salesman*, end of Act 1.
8. Spock, Mr. (with beard), to Captain Kirk on the transporter pad. *Star Trek,* episode 39, "Mirror, Mirror."
9. Mizner, Wilson (1876–1933).
10. Shakespeare, William. *Hamlet,* Act 1, Scene 3.
11. Colton, Charles Caleb (1780–1832).
12. Einstein, Albert, according to *Bartlett's Familiar Quotations.*
13. See Piper, Peter.
14. Darwin, Charles. *On the Origin of Species*, closing paragraph.
15. Descartes, René. "*Cogito ergo sum.*"
16. "Science" refers to the enterprise by which human beings attempt to discover basic truths about the universe. It is, however, also the name of a journal published by the American Association for the Advancement of Science.
17. Attributed to Isaac Newton but probably existed in some form earlier.
18. Williams, Tennessee. *A Streetcar Named Desire,* Scene 11.
19. Shakespeare, William. *Hamlet,* Act 1, Scene 5.
20. Declaration of Independence, opening paragraph.
21. Holmes, Oliver Wendell, Supreme Court justice. *Schenck v. United States*, 1919.
22. Phillips, Wendell (1811–1884). 1852 speech to the Massachusetts Antislavery Society, paraphrasing John Philpot Curran, who in 1790 said, "The condition upon which God hath given liberty to man is eternal vigilance."
23. Nixon, Richard M., 37th president of the United States. On numerous occasions.
24. Ibid., about the Watergate scandal.

FRANK VERONSKY

ASK THE EXPERTS

Q What is antimatter?

—R. Bingham, Lakewood, Colo.

R. Michael Barnett of Lawrence Berkeley National Laboratory and Helen R. Quinn of the Stanford Linear Accelerator Center offer this answer, parts of which are paraphrased from their book, *The Charm of Strange Quarks:*

In 1930 Paul Dirac formulated a quantum theory for the motion of electrons in electric and magnetic fields, the first theory that correctly included Einstein's theory of special relativity in this context. This theory led to a surprising prediction—the equations that described the electron also described, and in fact required, the existence of another type of particle with exactly the same mass as the electron but with a positive instead of a negative electric charge. This particle, which is called a positron, is the antiparticle of the electron, and it was the first example of antimatter.

Its discovery in experiments soon confirmed the remarkable prediction of antimatter in Dirac's theory. A cloud chamber picture taken by Carl D. Anderson in 1931 showed a particle entering a lead plate from below and passing through it. The direction of the curvature of the path, caused by a magnetic field, indicated that the particle was a positively charged one but with the same mass and other characteristics as an electron.

Dirac's prediction applies not only to the electron but to all the fundamental constituents of matter (particles). Each type of particle must have a corresponding antiparticle type. The mass of any antiparticle is identical to that of the particle. All the rest of its properties are also closely related but with the signs of all charges reversed. For example, a proton has a positive electric charge, but an antiproton has a negative electric charge.

There is no intrinsic difference between particles and antiparticles; they appear on essentially the same footing in all particle theories. But there certainly is a dramatic difference in the numbers of these objects we find in the world around us. All the world is made of matter, but any antimatter we produce in the laboratory soon disappears because it meets up with and is annihilated by matter particles.

Modern theories of particle physics and of the evolution of the universe suggest, or even require, that antimatter and matter were once equally common during the universe's earliest stages. Scientists are now attempting to explain why antimatter is so uncommon today.

SARA CHEN

Q Why does your stomach growl when you are hungry?

—A. Gillespie, Lancaster, Calif.

Mark A. W. Andrews, associate professor of physiology and associate director of the Independent Study program at the Lake Erie College of Osteopathic Medicine, provides this explanation:

The physiological origin of this "growling" involves muscular activity in the stomach and small intestines. Although such growling is commonly associated with hunger—when the stomach and intestines are empty of contents that would otherwise muffle the noise—such sounds can occur at any time.

In general, the gastrointestinal tract is a hollow tube that runs from mouth to anus with walls primarily composed of layers of smooth muscle. This muscle is nearly always active to some extent. When these walls squeeze to mix and propel food, gas and fluids, rumbling noises may be heard. Such squeezing, called peristalsis, involves a ring of contraction moving toward the anus, a few inches at a time.

A rhythmic fluctuation of electrical potential in the smooth muscle cells, known as the basic electrical rhythm (BER), generates the waves of peristalsis. BER is the result of the inherent activity of the enteric nervous system found in the walls of the gut. The autonomic nervous system and hormonal factors also modulate this rhythm.

After the stomach and small intestines have been empty for about two hours, there is a reflex generation of waves of electrical activity (migrating myoelectric complexes, or MMCs) in the enteric nervous system. These trigger hunger contractions, which can be heard as they clear out any stomach contents and keep them from accumulating at any one site. SA

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert

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Voyage to galaxy many, many light years away	$50,000,000,000,000,000,000,000,000