SPECIAL ISSUE on the Most Powerful Idea in Science

SCIENTIFIC AMERICAN

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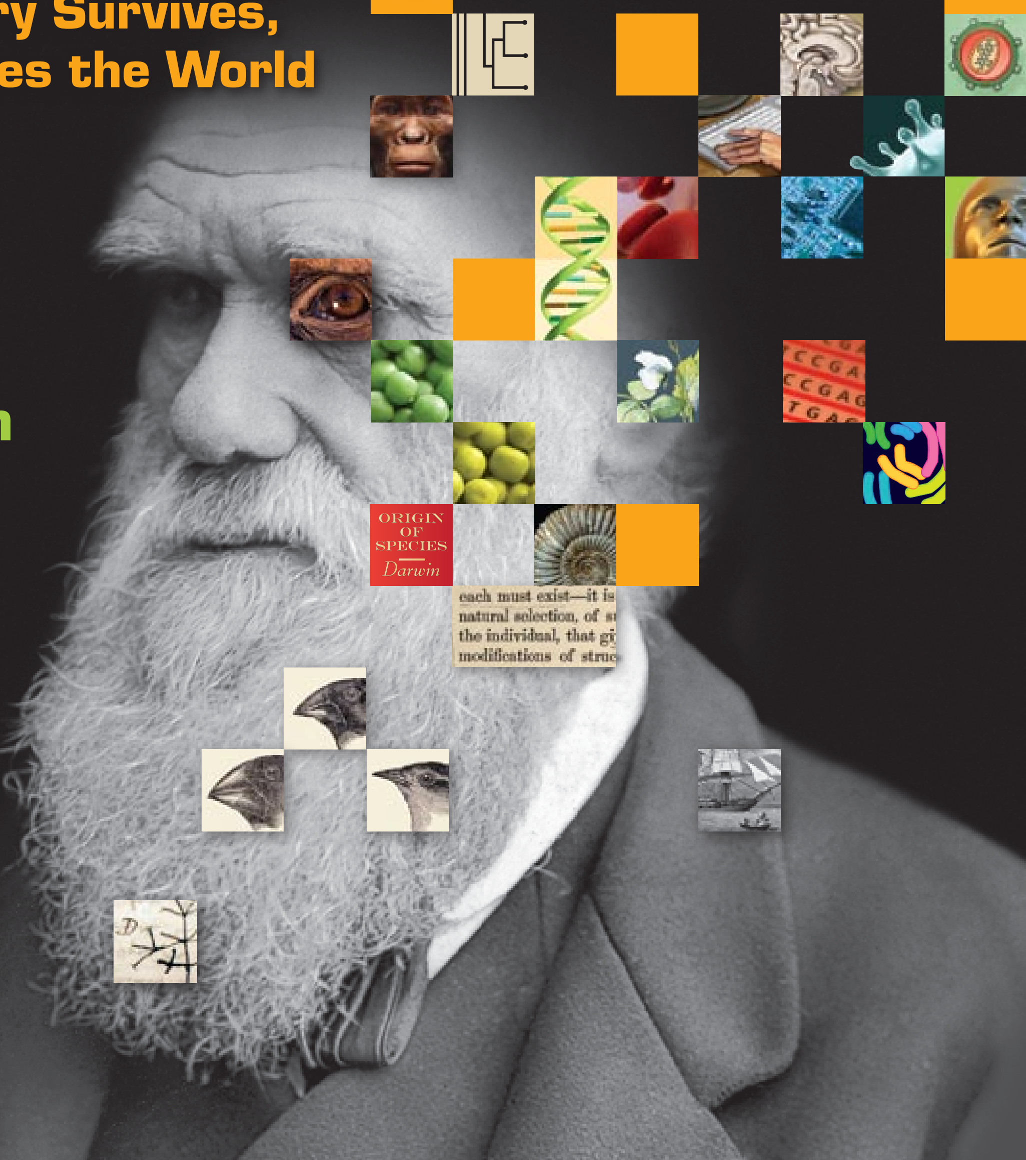
EVOLUTION AT WORK
How Doctors, Police and Others Use It on the Job

The Evolution of EVOLUTION

How Darwin's Theory Survives, Thrives and Reshapes the World



The Future of **Human Evolution**

Molecular Proof of **Natural Selection**

How Life Invents **Complex Traits**

Creationists' **Latest Tricks**

IN THE NEW ENERGY FUTURE IF IT DOESN'T EXIST WE'LL NEED TO INVENT IT.

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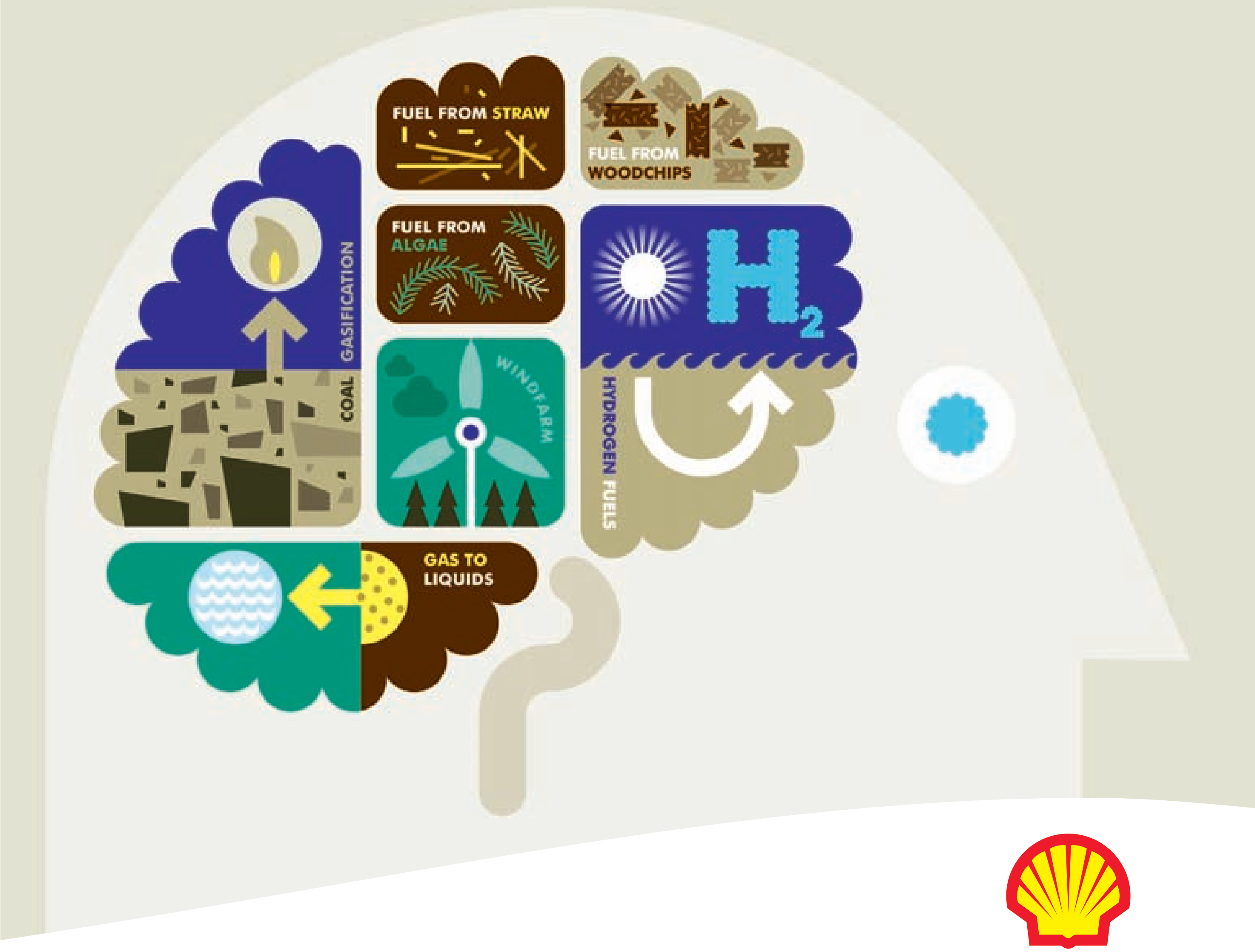
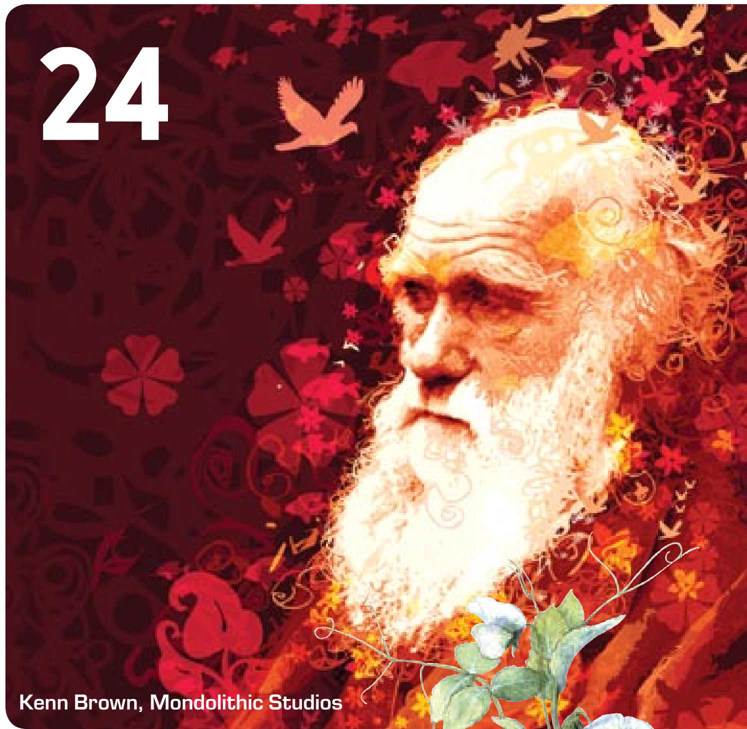


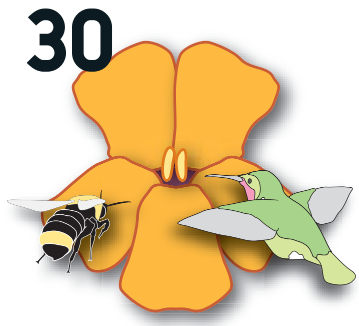
SCIENTIFIC AMERICAN January 2009 ▪ Volume 300 Number 1

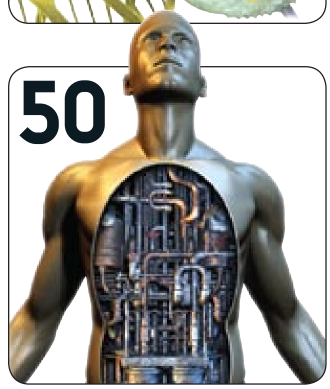
SPECIAL ISSUE

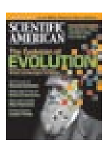
the evolution of Evolution



Kenn Brown, Mondolithic Studios







ON THE COVER

From finch beaks to genes to the future of humanity, Charles Darwin's profound insights about evolution have shaped our view of life. Cover concept by Jen Christiansen.

COVER IMAGES: TIME LIFE PICTURES/GETTY IMAGES (*Charles Darwin*); KENN BROWN *Mondolithic Studios* (*robot woman*); TAMI TOLPA (*HIV particles*); TAYLOR S. KENNEDY *National Geographic* (*computer chips*); © MEDICALRF.COM/CORBIS (*blood cells* and *blue cell surface*); ALBERT J. COPLEY (*ammonite*); KEN EWARD (*DNA*); © DLILLC/CORBIS (*chimpanzee eye*); ROBIN MACDOUGALL (*peas*); SCIENCE SOURCE (*finches*)

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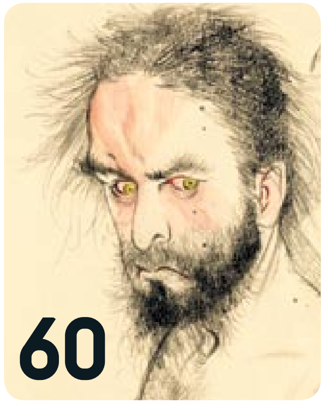

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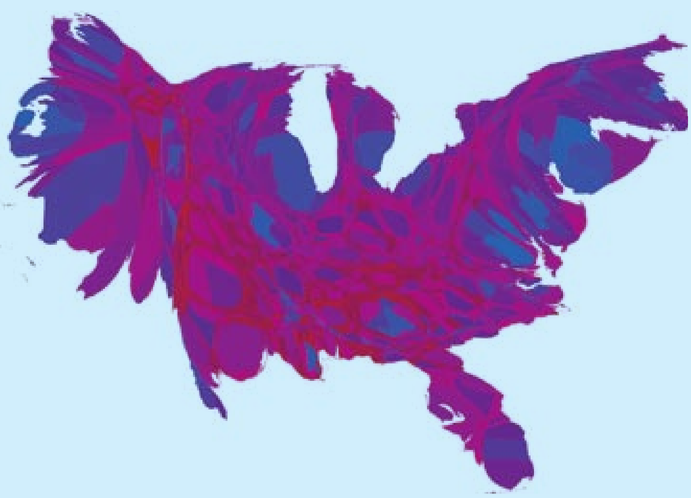
IN-DEPTH REPORT: 2008 IN REVIEW ▼

A look back at the people, discoveries and events (or, in the case of the Large Hadron Collider, the nonevents) that shaped the past year—and where they will take us in 2009.
More at **www.SciAm.com/jan2009**



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"CARTOGRAM" reshapes the U.S. to reflect 2008 presidential election results.

News
Raising a Glass to Your Health? Not with These Wines
Potentially dangerous heavy metals have been found in more than 100 types of wine from a dozen nations.

Science Talk
Science in the Obama Administration
Stanford University biologist Sharon Long, a science adviser to the Barack Obama campaign, talks about the role science will play after Inauguration Day.

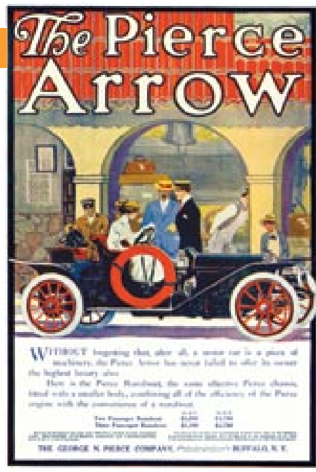
Feature
Are You Evil? Profiling the Truly Wicked
A cognitive scientist employs malevolent logic to define the dark side of the human psyche.

60-Second Psych Podcast
More Sex for Women?
Surveys suggest that women, young couples and the over-60 crowd are closing the infidelity gap.

Slide Show
A "Narcotic Farm" That Tried to Grow Recovery
A federal prison in Kentucky was a temporary home for thousands, including Sonny Rollins, Peter Lorre and William S. Burroughs, as well as a lab for testing the effects of such substances as LSD.

DEPARTMENTS

7



ETHAN HILL

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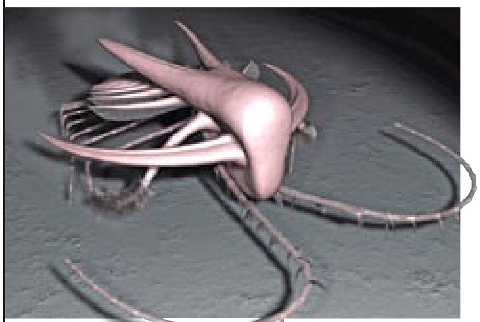
Dynamic Darwinism

The naturalist would approve of how evolutionary science continues to improve

A billion and a half years ago, life on earth was staggeringly dull. The ocean, once a steaming primordial soup, had become a cold, thin, dreary broth of look-alike organisms. Eukaryotic cells with internal structures had appeared, but multicellular creatures were scarcely a blip in the census. Life lazed through those doldrums for a million millennia.

Then something happened: some unidentified combination of environmental circumstance and genetic novelty triggered crazy diversification in the variety and complexity of animal life over tens of millions of years, climaxing in the so-called Cambrian explosion. By 530 million years ago the seas held all the bizarre creatures fossilized in the Burgess Shale (and popularized two decades ago by Stephen Jay Gould in his book *Wonderful Life*). Many of those animals were evolutionary dead ends, but a few were the progenitors of every animal alive today.



CAMBRIAN ARTHROPOD: ***Marrella splendens.***

When Charles Darwin published *On the Origin of Species* in 1859, he touched off a Cambrian explosion in evolutionary thought. Naturalists had theorized about evolution for centuries before him, but their ideas were generally unfruitful, untestable or wrong. Darwin's breakthrough insight was not that a simple mechanism—natural selection—made evolution possible. Rather it was that in organisms whose environment changed nonrandomly and whose reproductive success in that environment depended on inherited traits, evolution became *inevitable*.

In the decades that followed, Darwin's ideas connected up with the nascent field of genetics and then, at an ever quickening pace, with molecular biology, ecology and embryology. The explanatory power of his concepts proved irresistible. Today, 200 years after his birth and 150 years after *Origin of Species*, Darwin's legacy is a larger, richer, more diverse set of theories than he could have imagined.

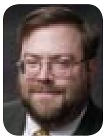
Consider the notion of selection itself. What Darwin called natural selection was the competition for ecological resources often abbreviated as "survival of the fittest." As H. Allen Orr describes, beginning on page 30, natural selection demonstrably drives much of evolution and speciation. Yet modern biologists have also elaborated greatly on Darwin's ideas about sexual selection, in which members of a species compete for opportunities to breed. Kin selection and other forms of group selection are active areas of study, too, with theorists debating roles for selection at the level of single genes, individual organisms, whole species—or all of the above.

Meanwhile the sources of heritable variation go far beyond point mutations in genes, as David M. Kingsley explains, starting on page 38. Such changes might facilitate the rapid evolution of complex traits.

Just as most of the weird Cambrian monsters eventually went extinct, many current hypotheses in evolution will also wither over time. Those that survive, however, will be inestimably powerful for explaining the natural world. We humans can also continue to use those ideas to make technologies more adaptable and robust. Why shouldn't we learn from billions of years of nature's experiments? ■

JOHN RENNIE
editor in chief

Among Our Contributors



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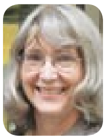

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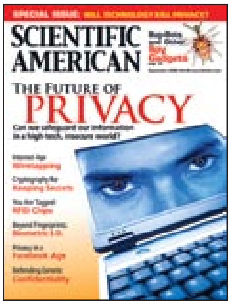
PETER WARD
led the University of Washington node of the NASA Astrobiology Institute until 2006. He is especially known as an expert on mass extinctions.

FLYNN LARSEN (*Rennie*); SIMON TERREY *Photo Researchers, Inc.* (*computer artwork*)

Privacy ▪ Animal Testing ▪ RFID Tags ▪ Tidal Bulge



SEPTEMBER 2008

"People seem to often confuse privacy with anonymity, which we invented only a few generations ago."
—*Sheri S. Tepper* SANTA FE, N.M.

▪ Neighborhood Watched?

Each time I read about our "loss of privacy," such as in Daniel J. Solove's examination of effects of social-networking sites ["The End of Privacy?"], it makes me laugh. People seem often to confuse privacy with anonymity, which we invented only a few generations ago. Earlier, most Americans lived in small towns or villages, which provide limited privacy and no anonymity.

The rise of big cities gave us anonymity, which lets some of us do things we would probably not have done in the villages, where there wasn't much crime because no one was unknown. That social control was just waiting to be replaced, so now our villagers are electronic.

Sheri S. Tepper
Santa Fe, N.M.

SOLOVE REPLIES: *There is a key difference between the small towns of yesteryear, where everybody knew your name, and the sprawling "global village" of today. In small towns, people knew one another well; they could judge one another in context. Today, in our more anonymous life, we often judge people based on information fragments without context. This is a much more impoverished way to understand and judge others, and the information we have about them is far more dubious. The idyllic image of the small village cannot be re-created through modern electronic technology. Moreover, a brief dip into 19th-century history and literature shows a world rife with oppressive norms, nosy neighbors and communities ready to condemn, often unfairly. Although social control can be good, not all of it is, and sometimes it can be downright unfair, stifling, misguided and cruel.*

▪ Animal Ethics

"Primate Motions," by Lizzie Buchen [News Scan], reports on a Swiss ruling denying two neuroscientists' applications to experiment on macaques on the basis that their proposals did not have sufficient expected benefits to society. In criticizing strict regulation on primate research, these scientists and others interviewed seem only interested in research, with no sense of moral duty. As people of science, we must be absolutely certain that the animals we use are treated as compassionately as possible, and we must be thankful to them for the knowledge they afford us.

Bassam Salim
Boston

▪ Tagging Trouble?

The article "RFID Tag—You're It," by Katherine Albrecht, continued an important discussion around privacy and radio-frequency identification (RFID) that EPCglobal has been addressing for some time. But it is important to remind readers that the majority of RFID tags do not store or collect personal information. Just like ubiquitous barcodes, the electronic product code (EPC) carried by a tag is a string of numbers that identifies only a thing—typically the tag itself—not a person. The author's claim that anyone with an RFID reader can skim tags is therefore pointless—skimming would provide neither personal information nor access to it.

This emerging technology is a powerful tool with the potential to improve the safety, security, and availability of food, medicine and other products, providing tremendous societal benefits. To learn more about RFID and EPC and to see our full privacy guidelines, readers can visit http://aboutepc.org

Elizabeth Board
EPCglobal Public Policy Steering Committee

CONTRIBUTING TO the growing ubiquity of radio-frequency ID tags, retailers are exploring uses for the technology beyond inventory tracking.

COURTESY OF AVERY DENNISON AND THEBIGSPACE

Albrecht paints a broad picture of RF technologies and their privacy risks. RFID tags based on the EPCglobal standard EPC Gen 2 are different from chips that comply with international ID card standards ISO/IEC 7816 and ISO/IEC 14443. The Smart Card Alliance has long stated that EPC Gen 2 RFID tags can pose significant risks to privacy and are not appropriate for identity applications.

EPC Gen 2 RFID tags were designed to *enable* tracking, have minimal or no security, and are readable from up to 10 meters away. RF-enabled smart cards contain a fully functioning microprocessor and can deliver security such as public-key cryptography, mutual authentication and encrypted communications. They operate over a 10-centimeter range to *prevent* tracking or eavesdropping.

Randy Vanderhoof
Smart Card Alliance

Basis of the Bulge

In "A Solar Big Gulp" [News Scan], David Appell refers to an analysis concluding that in billions of years, as the sun loses mass and expands, its rotation rate will slow down, creating a tidal bulge on its surface whose gravity will pull Earth inward. A tidal bulge, however, is not caused by rotation but by differential gravitation from an external body.

David C. Halley
via e-mail

APPELL REPLIES: *Halley is right: an external body, not rotation, causes a tidal bulge. But only when the sun's rotation is very small or nonexistent does its tidal bulge lag behind Earth in orbital motion, pulling Earth back in its orbit, taking energy out of Earth's orbital motion and causing the planet to spiral inward. Otherwise, with rapid rotation, the bulge is ahead of Earth, which would be pulled forward and spiral outward (as happens to the moon in the Earth-moon system).*

ERRATUM The box "The Supersize Radio Telescope" in "The New Radio Sky," by Mark Wolverton [News Scan], gives the wrong name for the head of the Square Kilometer Array's Technology Development Project. The correct name is Jim M. Cordes.

CLARIFICATIONS The box "How the Metrics Measure Up" in "Beyond Fingerprinting," by Anil K. Jain and Sharath Pankanti, states that iris-recognition security systems have a lower false accept rate than fingerprint-recognition systems, but the accompanying table gives both the same false accept rate. The table's rate values are based on National Institute of Standards and Technology tests. Other tests have given iris recognition a lower false accept rate.

"RFID Tag—You're It," by Katherine Albrecht, refers to a law passed by Washington State designating unauthorized reading of an RFID tag for criminal purposes as a class C felony. Another law also makes it a class C felony to read the state's RFID-enhanced driver's licenses without consent for any purpose, excepting border-crossing facilitation, security-related research and inadvertent scanning.

Letters to the Editor

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Join the discussion of any article at
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Compiled by Daniel C. Schlenoff

JANUARY 1959

A VOICE FROM THE SCOPES TRIAL—"'This is Clarence Darrow,' said the voice at the other end of the wire, 'I suppose you have been reading the papers, so you know Bryan and his outfit are prosecuting that young fellow Scopes. Well, Malone, Colby and I have put ourselves in a mess by offering to defend. We don't know much about evolution. We don't know whom to call as witnesses. But we do know we are fighting your battle for academic freedom. We need the help of you fellows at the University, so I am asking three of you to come to my office to help lay plans.'

That afternoon in Darrow's office three of us from the University of Chicago—Horatio Hackett Newman, professor of biology; Shailer Mathews, dean of the Divinity School; and I—met to outline the strategy for what turned out to be one of the most publicized trials of the century. —Fay-Cooper Cole"

[NOTE: In 1925 Cole was an anthropologist at Chicago. The 1959 article is available at **www.SciAm.com/jan2009**]

THE ATOMIC NUCLEUS—"In fact the trouble in the recent past has been a surfeit of different models [of the nucleus], each of them successful in explaining the behavior of nuclei in some situations, and each in apparent contradiction with other successful models or with our ideas about nuclear forces. In the past few years great progress has been made in bringing some order into this confusion and in understanding the justification for each of the models in the domain to which it is properly applied. A picture thus emerges in which the various, apparently contradictory, models of the nucleus are seen as consistent parts of a whole, each appropriate for answering certain questions about the behavior of nuclei. —R. E. Peierls"

JANUARY 1909

WHY EARTHQUAKES?—"In all probability, an earthquake is one of the necessary consequences of the gradual cooling of the earth. As terrestrial heat is gradually declining through its radiation out into space, it follows that the bulk of the earth must be gradually shrinking. Accordingly the crust of the earth has from time to time to accommodate itself to the fact that the whole globe is slowly but surely getting smaller. Even a slight displacement of one extensive surface over another would be accompanied by violence greatly exceeding that which we might expect from so small a displacement, resulting in the wholesale destruction of houses, villages, and even large cities, and infrequently great sacrifice of human life."

WOOD FOR THE IRON HORSE—"So serious is becoming the question of supplying ties for our railroads, that the Santa Fe system recently sent its manager of the timber and tie department on a tour to the Orient and Europe, to make a study of conditions. It was learned, among other things, that three hundred years ago the Japanese government began to conserve its forests; and that, as a result of its foresight, Japan is now selling ties to railroads in this country and Mexico. That we should be paying a twenty per cent import duty on ties is one among many constantly accumulating evidences of the thoughtless extravagance with which our magnificent timber supply has been ruthlessly swept away."

FROM THE AUTOMOBILE ISSUE, January 16, 1909: the back page had this stylish and colorful full-page advertisement for Pierce Arrow motor cars. The company, well known for its luxury cars, ceased manufacturing in 1938.

SCIENTIFIC AMERICAN, VOL. C, NO. 3; JANUARY 16, 1909

JANUARY 1859

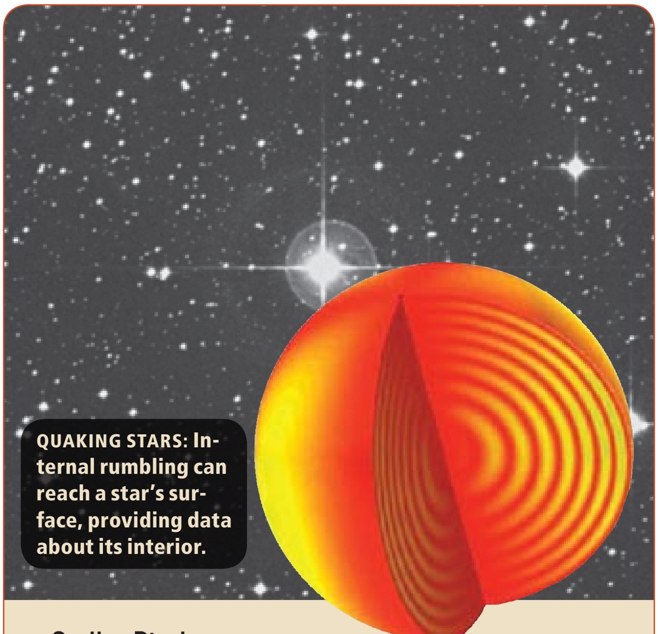
WHAT USE ARE COMETS?—"The question of the utility of comets has always held a conspicuous place. S. W. Fullom, well known as the author of some pleasant books, suggests a use for comets in his 'Marvels of Science': Descartes, Euler, and many others believed that there is a subtle media pervading all space, which they called 'ether,' and which forms the ocean in which the planets and fixed stars swim. In this media the comets act as scavengers, preventing any accumulations of ether, and keeping it in such a proper and equable state of tenuity that the forces of nature, as gravity, electricity, and light, always act with regularity and precision."

Die-off from Germs ▪ Star Vibes ▪ Rodent Resurrection ▪ Stinky Relaxation

Edited by Philip Yam

Extinction by Disease

Theories for what killed off the woolly mammoth and other North American megafauna some 11,000 years ago have long focused on climate change and human hunting pressure. But in 1997 another possible culprit was proposed: hyperlethal disease introduced to the immunologically naive behemoths by dogs or vermin that accompanied humans when they arrived in the New World [see "Mammoth Kill"; SciAm, February 2001]. Now Alex D. Greenwood of Old Dominion University and his colleagues have produced the first evidence of disease-induced extinction among mammals. The team's genetic analyses indicate that two species of rat endemic to Christmas Island in the Indian Ocean went extinct because they contracted a deadly pathogen from black rats, which arrived via the SS *Hindustan* in 1899. Less than a decade after the black rats landed, the endemic rats were gone. The findings appear in the November 5 *PloS ONE*. *—Kate Wong*



QUAKING STARS: Internal rumbling can reach a star's surface, providing data about its interior.

Stellar Ripples

The COROT space telescope, an international effort led by France, looks for planets around other stars as well as ripples on stellar surfaces [see "Dangling a COROT"; SciAm, September 2007]. It is not disappointing researchers, who last fall announced that COROT discovered an exoplanet 20 times Jupiter's mass, raising the question of whether the object is an enormous planet or a failed star. The telescope also observed vibrations and granulation on the surfaces of three stars—features previously studied only on the sun. Similar to seismology data on Earth, these "star quakes" reveal much about stellar interiors. In the case of the three stars, described in the October 24 *Science*, the oscillations were 75 percent as strong as models had predicted.

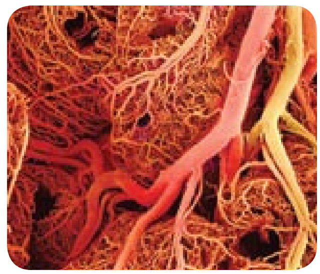
Cloning Mice on Ice

Too bad Christmas Island is not near the North Pole. Rats that went extinct on that island might then have left frozen remains for cloning—an idea advanced to save species [see "Cloning Noah's Ark"; SciAm, November 2000]. In a new study scientists in Japan created healthy clones from mice preserved for 16 years at –20 degrees Celsius without chemical protection from ice. They took nuclei primarily from thawed brain cells and put them into host cells, which led to a line of embryonic stem cells from which the researchers ultimately bred 13 mice. Freezing and thawing ruptures cells and damages DNA, but the work, reported online November 3 in the *Proceedings of the National Academy of Sciences USA*, reveals that significant genomic information survives. Whether the success can help resurrect woolly mammoths is unclear, but it offers hope at least for smaller extinct species.

RESURRECTED: The dark fur–bearing critter is a clone of a mouse kept frozen for 16 years.

Relaxing with Hydrogen Sulfide

In the 1980s scientists discovered that nitric oxide relaxes blood vessels and is crucial in circulatory health [see "Biological Roles of Nitric Oxide"; SciAm, May 1992, and "Insights into Shock"; SciAm, February 2004]. Another simple, inorganic gas also acts as a vasodilator: hydrogen sulfide, the source of the smell of rotten eggs. Mice genetically engineered not to produce an enzyme called CSE, which makes hydrogen sulfide, lacked the gas ordinarily present in their tissues. The mice developed hypertension and did not respond well to compounds that relax vessels. Human blood vessels probably also make the gas, so the study, in the October 24 *Science*, could lead to novel hypertension treatments.



BLOOD VESSELS dilate under the influence of hydrogen sulfide, a gas better known for its odor.

COURTESY OF 1993–1995 ANGLO-AUSTRALIAN OBSERVATORY BOARD (*stars*); COURTESY OF S. FRANDSEN *Aarhus University* (*stellar global oscillation*); SUSUMU NISHINAGA *Photo Researchers, Inc.* (*blood vessels*); COURTESY OF TERUHIKO WAKAYAMA *Riken Center for Developmental Biology* (*mice*)

BIODIVERSITY

Environmental Payoff

Furor over a conservation group taking fees from developers BY WENDEE HOLTCAMP

TURBULENT WATERS AHEAD: After mating, some olive ridley sea turtles will nest on a beach in northeastern India. That site might be damaged by a nearby port, the construction of which, some say, has the paid approval of the famous conservation group IUCN.

COURTESY OF SUMER VERMA/GREENPEACE

Every winter and spring, tens of thousands of endangered olive ridley sea turtles clamber onto the shores of Gahirmatha Marine Sanctuary, along India's northeastern coast, to lay eggs in one of the world's most spectacular phenomena—the arribada, or mass nesting, which occurs only in India, Costa Rica and Mexico. This past season, however, the arribada did not happen at Gahirmatha.

Although turtles have occasionally failed to mass-nest in previous years, conservationists fear this time the cause is dredging for a new seaport. Indian scientists and conservation groups place some blame on the International Union for Conservation of Nature (IUCN), among the world's most respected conservation organizations. The union has taken corporate money to consult on the port, effectively giving it a green stamp of approval even though it may spell the end for this nesting site.

Formed in 1948 under the aegis of the United Nations, the IUCN consists of 1,100 member nonprofits and governments plus nearly 11,000 volunteer scientists around the globe. Headquartered near Geneva, the union pushes for sustainable development and conservation solutions, especially in developing nations. Most famously, it manages the Red List of Threatened Species, which keeps track of the plant and animal species left on the planet. In 2004 the IUCN passed two resolutions to engage more closely with the private sector, which ultimately led to the controversy surrounding India's sea turtles and the IUCN's involvement with the port.

The idea of the seaport began in the 1990s, when the Indian state of Orissa began discussing its construction at the mouth of the Dhamra River, part of a broader desire to increase coastal development. But scientists and conservation groups have consistently opposed it, arguing that even at 15 kilometers from Gahirmatha, one of the world's largest rookeries for olive ridleys, the port and its traffic might prove disastrous. In 2004 a committee on the Indian supreme court concluded that the proposed port site "will seriously impact Gahirmatha's nesting turtles and could lead to the beach being abandoned by the marine creatures. It is therefore necessary that an alternative site is located for this port." Renowned Indian scientist and IUCN member B. C. Choudhury, who started radio-telemetry studies on the turtles, says that the Gahirmatha nesting beaches "are eroding at a much faster rate than before and will probably be not even fit for turtles to nest in the future."

Despite the threat, the port project gained momentum in 2006, when the Indian conglomerate Tata helped to create the Dhamra Port Company Limited. The firm hired Nicholas Pilcher, a co-chair of the IUCN's marine turtle specialist group who is based in Malaysia, as a consultant. After a visit to the site, Pilcher wrote to the IUCN presiding species survival commission chair, Holly Dublin, that "this port WILL impact marine turtles, of that there can be no doubt." But by helping the company develop the best environmental management plan possible, he believed the IUCN could mitigate any effects.

Today he is of a different mind-set. "Realistically, the impacts on turtles will be so minimal as to not be noticed," he says. "I just can't see the hoo-ha people are making over this, particularly as there is not one single scientific piece of literature that suggests the port will be a catastrophe." Such data could emerge from a new comprehensive environmental impact study, but Tata has steadfastly refused to update its 10-year-old analysis, which critics consider woefully inadequate. (The company said it would relocate the port if it affected the turtles, according to Pilcher's letter to Dublin.) Tata did agree to turtle-safe dredging techniques and a lighting plan that would avoid serious disturbance of nighttime nesting.

Pilcher claims all opposition has "come out of ignorance and being misled by Greenpeace and others rather than being against the IUCN's involvement." But Indian scientists and conservationists remain united in opposition both to the port and to the IUCN's role. In 2008 several of Pilcher's India-based colleagues and other IUCN member groups wrote to IUCN director general Julia Marton-Lefèvre, arguing that the union's involvement casts "aspersions on the credibility and neutrality" of the IUCN. The letter stated that the port company "is using this purported support of the IUCN to claim that environmental impacts have been adequately addressed and mitigated." The regional chair of the marine turtle specialty group, Kartik Shanker, has resigned over the situation. "Almost unanimously," he says, all the specialty group members in India "have opposed the involvement of the IUCN in this project."

The Dhamra port is just one of the IUCN's corporate controversies. Another arose in 2007, when Marton-Lefèvre signed a partnership agreement with Royal Dutch Shell "to enhance the biodiversity conservation performance by Shell" and "to strengthen IUCN's capacity for leadership in business and biodiversity," as the agreement puts it. That deal has led to internal dissension, with one of the IUCN's commission chairs, M. Taghi Farvar, insisting that it should not partner with industries causing wide-scale environmental damage, particularly in light of the IUCN's mandate for reversing global warming. The controversy led to a motion at the World Conservation Congress last October to cancel the contract. That motion narrowly failed, after Marton-Lefèvre argued that legal action by Shell was possible.

The IUCN's dealings with the business world is not likely to slow down, but if the union wants to soothe internal strife, conflicts of interest must be eliminated, and transparency is key, Farvar insists. Tata and Shell can exert undue pressure on the IUCN, because what are financial peanuts to megacorporations are substantial funds to nonprofits. Other groups have managed the balancing act to some degree, such as scientists conducting clinical trials on behalf of pharmaceutical companies. While members continue to debate how the IUCN should navigate these rocky waters, all hope that endangered species and biodiversity will not pay the price.

Wendee Holtcamp, based near Houston, Tex., writes frequently about wildlife and conservation issues.

POLICY

Space Sticker Shock

The laws of physics are easy; it's economics that vexes NASA BY GEORGE MUSSER

In October, NASA announced that the $1.5-billion Mars Science Laboratory (MSL), a car-size rover planned for launch this fall, had become the $2-billion Mars Science Laboratory. When first conceived, it was the $650-million Mars Science Laboratory. Even more egregious is the $1-billion-make-that-$4.5-billion James Webb Space Telescope, successor to Hubble. Complex projects of any kind—not only in the space program—always cost more than anticipated. But experts say the agency could—and needs to—do better.

"We have to accept the fact that there will be some cost overruns, but I think a lot of it could be mitigated if we managed things differently," insists Sushil K. Atreya of the University of Michigan, a member of the MSL team and of a National Research Council (NRC) panel that evaluated NASA's planetary exploration program last year.

The panel's prognosis was bad. Between ballooning costs and shrinking budgets, NASA has had to delay or cancel many projects. Some worry that Congress may never trust it with ambitious future projects, such as bringing samples of Mars back to Earth for analysis, which scientists feel is ultimately the only way to tell whether the Red Planet was once inhabited. "As a result of the disregard for cost control, I'm now pessimistic that Mars sample return can ever happen," says Alan Stern, who was NASA associate administrator for science until resigning last March in protest at the agency's handling of MSL overruns.

It is not as if agency officials are unaware of the problem. Every project goes through independent evaluations and sets aside about a third of its budget as "reserves" for contingencies. But this is never quite enough to hold the line. "In an organization run almost exclusively by engineers and scientists, the technical will always supersede the financial," says Humbolt Mandell of the University of Texas at Austin, a former high-level manager for the space shuttle and space station. The competition among project proposals reinforces this inclination; to get funded, projects have to promise the moon (sometimes literally).

Many experts argue that NASA should invest more in technology development. The agency used to have a stand-alone program to invent rockets, power supplies and communications systems that science missions could then pull off the shelf—making it easier to price them out. That program is now gone, and some scientists argue that MSL is one victim. "I think the cost of everything was severely underestimated because they didn't have enough good information, because not enough investment had been made in the technology," concludes Wesley Huntress of the Carnegie Institution of Washington, co-chair of the NRC panel.

Longer lead times could also mitigate overruns. Right now designing a spacecraft takes about a year and a half and 15 to 20 percent of the mission's total budget. "It's rather short," Atreya says. An extra year or more would give engineers more time to nip problems in the bud.

To plug gaps, NASA headquarters should also maintain its own reserves, amounting to maybe 5 percent of the agency's science budget, says the University of Michigan's Lennard Fisk, until recently chair of the NRC Space Studies Board. Otherwise, when a project comes up short, NASA either cancels it (which can be expensive, if a new effort has to start from scratch) or raids another project for the money (which disrupts it, so it will probably end up overrunning, too).

Stern, though, argues that none of the above would have saved MSL. He says that the initial cost guesstimate was unrealistic and that managers failed to scale back the project once they realized it was going to break the bank. "No one ever made any compromises to try to keep it on cost," he maintains. In extreme cases, NASA should hit the abort button, Mandell says: "Putting the absolute kill levels on a program ahead of time and sticking with them will force people to be less optimistic and to build in more reserves."

Some finances, though, are beyond NASA's control. Five years ago President George W. Bush ordered NASA to replace the shuttle but failed to pay the transition costs, forcing NASA to make internal cuts, such as eliminating technology development and delaying projects that were ready to go, which ultimately raised costs. If those who foot the bill expect NASA to make the best use of their money, then it would help if they, too, set expectations in line with resources.

COURTESY OF NASA/JPL

PRICEY PROBLEMS: Mars Science Laboratory rover has had troubles with actuator motors for its wheels and other systems. Fixing them is one reason project costs have skyrocketed.

NANOTECH

Big Little Problem

Trying to figure out where each atom belongs in a nanostructure BY MARK WOLVERTON

In nanotechnology, the position of a single atom can make all the difference—whether a material functions as a semiconductor or an insulator, whether it triggers a vital chemical process or stops it cold. The ability to define every atom in a nanoparticle precisely would permit full control of the properties and behavior of a nanomaterial. But deep-down atomic imaging techniques, such as electron microscopy and scanning tunneling microscopy, are not enough for nanoengineering, because they do not provide the precise mathematical coordinates of every atom that nanotechnologists need.

"Beautiful pictures of nanostructures capture the imagination, but if a picture is worth 1,000 words, then a table, filled with accurate atomic coordinates, is worth 1,000 pictures," says Simon Billinge, who studies what he has dubbed the nanostructure problem at Columbia University and Brookhaven National Laboratory. Billinge and his like-minded colleagues instead are looking to combine methods and use conventional techniques in novel ways.

Defining the exact atomic structure of everyday solids, as opposed to those of nanostructured ones, is relatively easy, because they feature what physicists call long-range, or crystalline, order: a regular, repeating structure that does not change much over atomic or molecular scales.

Scientists have traditionally examined such materials by crystallography, which relies on scattering techniques: a beam of x-rays or neutrons shines on a sample of material, and the atoms scatter and reflect the beam, forming patterns called Bragg diffraction peaks (after Sir William Henry Bragg and his son, who discovered the phenomenon in 1903). The Bragg peaks, which are related to the spacing between atomic layers, provide details from which the ordered atomic structure of the substance can be mathematically determined. This powerful method has revealed how the atoms of many substances—from cosmic dust to our own DNA—are put together.

But crystallography does not provide the resolution needed for the nanoscale, where structural differences occur over much shorter distances. When a nanomaterial is examined with traditional crystallography, "the Bragg peaks essentially broaden out and completely overlap, and you can no longer differentiate them from each other," Billinge explains. "The algorithms that were developed for crystallography fail," he adds, and investigators cannot tell where each atom lies. Without precise structural data, nanotechnology fabrication remains a game of approximations and best guesses.

Because a simple, one-size-fits-all solution is not anywhere on the horizon, researchers are using a combination of various imaging techniques and mathematical methods to tame the nanostructure problem. Such a multifaceted strategy builds accurate and useful models from different sets of data, in what is called complex modeling.

Billinge has combined crystallography with an approach that has long been used to examine noncrystalline substances, such as glasses and liquids. It makes use of the so-called pair distribution function (PDF), which describes the probability of finding one atom at a certain distance from another and provides statistical data from which structure can be computed. "The PDF technique is the realization of the fact that there's all this information in between the Bragg peaks," says Stephen Streiffer, acting director of the Center for Nanoscale Materials at Argonne National Laboratory.

In 2006 Billinge and his colleagues proved the PDF strategy by computing from first principles the soccer-ball structure of the carbon 60, or buckyball, molecule. Since then, they have developed more algorithms to reconstruct other nanoscale structures.

Although ingenious algorithms are indispensable, Streiffer says that imaging techniques must also continue to improve. "The holy grail of x-ray microscopy right now," he observes, "is to be able to put a single nano-object into an x-ray beam and know not only the nanoscopic shape but the position and chemical identity of every atom that makes up that nanoscopic structure." Matthias Bode, also at Argonne's center, notes that spectroscopic methods—the study of materials based on the light they absorb or emit—will be another weapon in the imaging arsenal. "Usually what you want to do in nanoscience is correlate structure with some kind of property that acts on the nanoscale," he explains, adding that spectroscopy would enable investigators "to correlate, say, the size or shape of the particle to specific electronic or magnetic properties."

Taming the nanostructure problem will be the key to achieving the ultimate goal of nanotechnology: custom-designing nanomaterials for specific functions. "We're obviously very far away from that," Billinge admits. Still, he insists, "it's a rich and exciting problem, and I'm kind of glad it's not solved. It gives me something exciting to do."

Mark Wolverton, based in Bryn Mawr, Pa., described upgrades to radio telescopes in the November 2008 issue.

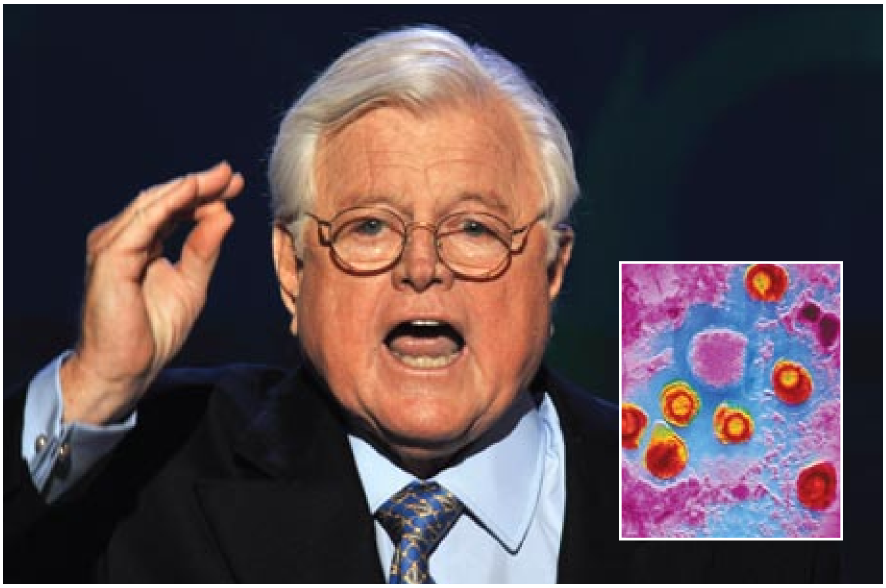
CANCER

Virus in the Brain

Does a herpesvirus cause the deadly brain cancer glioblastoma? BY MELINDA WENNER

More and more in recent years, cancer biologists are pointing their fingers at viruses. Human papillomavirus, they found, causes cervical cancer; hepatitis B induces liver cancer; and Epstein-Barr virus has been implicated in lymphoma. Most recently, scientists discovered that malignant brain tumors called glioblastoma multiforme, the late-stage version of the cancer that has afflicted Senator Edward Kennedy of Massachusetts, are almost always teeming with cytomegalovirus (CMV), a common, typically harmless herpesvirus. Although the nature of the association is still a mystery, researchers are already taking advantage of the link to find new cancer treatments.

The saga began in the late 1990s, when Charles Cobbs, a neurosurgeon then at the University of California, San Francisco, started pondering the link between inflammation and brain cancer. Malignant tumors are often associated with abnormal immune activity, and he wanted to know why. "Is it just something that happens out of the blue, or is it possible that there's something maybe driving that inflam-



VIRAL POLITICAL CONNECTION: **The malignant brain tumor called glioblastoma multiforme, the late-stage version of the cancer that has afflicted Senator Edward Kennedy of Massachusetts, often teems with cytomegalovirus particles (*red-yellow spots in inset*). Some researchers suspect that the pathogen, a herpesvirus, causes the tumor to develop.**

PAUL J. RICHARDS *Getty Images* (Kennedy); CNRI *Photo Researchers, Inc.* (*cytomegalovirus*)

matory cascade?" he recalls wondering.

Because they elicit immune responses, infections immediately sprang to mind as possible candidates. Cobbs and his colleagues analyzed glioblastoma samples from 22 patients and found that all harbored CMV. Four out of five people have this virus, which remains in the body for life. Usually a person's immune system keeps CMV in a latent state in which it does not replicate, but Cobbs found the virus actively reproducing in these tumor cells—and not in healthy cells nearby. "It was stunningly obvious that these tumors were infected," says Cobbs, whose findings, published in *Cancer Research* in 2002, were confirmed in 2007 by Duke University neuro-oncologist Duane Mitchell.

What was not obvious was why, exactly, the infection was there. Did CMV cause the cancer, or did it simply proliferate in tumor cells? "It's a chicken-and-egg question: What came first, the virus or the tumor?" Mitchell points out. Glioblastoma patients have compromised immune systems, which might enable a latent CMV infection to reactivate, Mitchell says. And CMV might be frequently found in brain tumor cells because these cells are easy to infiltrate. A 2008 study Cobbs published in *Nature* revealed that a cell-surface receptor responsible for letting CMV inside is more frequently found on brain tumor cells than other cell types.

Cobbs, now at San Francisco's California Pacific Medical Center Research Institute, believes that CMV plays a more active role in generating tumors. He points to a study published in May in *Science* showing that CMV makes proteins that "turn off" human genes important for preventing unwanted cell growth, a prerequisite to tumor development. It is as if CMV is "clipping the brake line," remarks study co-author Robert Kalejta, a molecular virologist at the University of Wisconsin–Madison. Other studies have shown that CMV can interrupt a cell's ability to commit suicide when the cell growth has gone awry. Still, no one has shown that CMV can turn healthy cells into cancer cells, Kalejta notes. So although the virus has some of the tools necessary to cause cancer, there is no proof that it does.

The good news is that when it comes to formulating cancer treatments, understanding the details of CMV's link to brain cancer is less important than the link itself. "For our purposes, it doesn't really matter," says Mitchell, whose lab focuses on new cancer treatments. "We see the presence of the virus as a unique opportunity to go after it as a target in tumor cells." His lab has "trained" immune system cells to recognize CMV proteins and has used those cells to identify and kill CMV-infected tumor cells.

Mitchell and his colleagues are currently testing their vaccine—and a second version using a different immune cell—in clinical trials, and although they have not yet published their results, he says that outcomes look promising. Cobbs, for one, is hopeful. "I'm holding my breath," he remarks. "It looks like this may be a radically new way to consider treating these tumors."

Melinda Wenner, based in New York City, often writes on biomedical issues.

When Cleanliness Is Next to Malignancy

Cytomegalovirus (CMV) infects about 80 percent of the population. So if CMV causes glioblastoma multiforme, as Charles Cobbs of San Francisco's California Pacific Medical Center Research Institute hypothesizes, why do only a small number of people develop brain tumors? Cobbs argues that the same question could be asked for known cancer-causing pathogens such as human papillomavirus: "That's actually the dogma—that you have widespread infection and in only a small percentage of cases there is cancer." In glioblastoma, he has noticed that the majority of patients are affluent, and he speculates that people infected with latent CMV might be more likely to get tumors if they grow up in hygienic environments.

The idea stems from the "hygiene hypothesis," used to explain the rising incidence of allergies in developed countries. It posits that childhood exposure to pathogens primes the immune system to respond appropriately; however, when people grow up in "superclean" environments, their immune system does not mature properly. When infected with CMV, these patients might then be at a heightened risk for developing glioblastoma, Cobbs says—but he admits his idea is based on little more than a hunch.

ASTROPHYSICS

Neighborhood Darkness

Does dark matter encircle Earth and heat up the gas giants? BY CHARLES Q. CHOI

Dark matter is five times as abundant as normal matter in the universe. But it continues to be an enigma because it is invisible and nearly always passes right through normal matter. Astronomers only found out about dark matter by inferring its presence from the gravity it exerts—notably, it keeps spinning galaxies from flying apart. Rather than peering at distant galaxies to study it, though, astronomers might want to look closer to home: dark matter could be exerting measurable effects in our own solar system.

Specifically, investigators should target Earth and the moon, insists theoretical physicist Stephen Adler of the Institute for Advanced Study in Princeton, N.J. If the mass of Earth and the moon when measured together seems greater than their masses separately, he explains, the difference could be attributed to a halo of dark matter in between.

Adler reaches this conclusion in part after examining studies that measured the mass of the moon with lunar orbiters and that of Earth with the LAGEOS geodetic survey satellites—laser-beam-reflecting spheres that have been in orbit for many years now. Lasers fired at the satellites reveal the radius of each satellite's orbit and how long each takes to complete that orbit. From such measurements, scientists can calculate the gravitational pull on the satellites and, hence, the amount of mass exerting that pull.

Next Adler examined research that gauged the distance from Earth to the moon with lasers reflecting off lunar mirrors planted by the Apollo missions. If Earth exerts an unusually stronger pull on the moon, which lies roughly 384,000 kilometers out, than on the LAGEOS satellites, about 12,300 kilometers away, the added pull could be attributed to a dark matter halo between the moon and the artificial satellites. Based on current data, Adler estimates in the October 17 *Journal of Physics A* that at most some 24 trillion metric tons of dark matter lies between Earth and the moon. Such a dark matter halo might explain the anomalies seen in the orbits of the Pioneer, Galileo, Cassini, Rosetta and NEAR mission spacecraft, he adds.

Adler also speculates that dark matter could exert dramatic effects on the four gas giants in our solar system—Jupiter, Saturn, Uranus and Neptune. If these massive worlds have gravitationally captured dark matter, then dark matter particles could smash into them—rare events but enough to heat up the gas giants and account for why the insides of these planets (and even Earth) seem hotter than known mechanisms can explain. It might also account for why Uranus seems anomalously cold—the planet is bizarrely tilted, perhaps because of a colossal impact, and Adler surmises that this collision might have knocked away most of the dark matter cloud that might typically have heated Uranus.

The possible planetary heating by dark matter may also hold clues to the substance's unknown properties—how often it collides with normal matter, say, or whether dark matter clumps around stars and planets as opposed to spreading evenly across the galaxy, remarks theoretical astrophysicist Ethan Siegel of the University of Portland. For example, if dark matter particles are their own antiparticles, as some researchers theorize, the energy released when they annihilate themselves would heat up the planets far more than mere collisions with atoms. Such a scenario would imply that dark matter cannot clump much in our solar system, or else the solar system would be much hotter.

Astrophysicist Annika Peter of the California Institute of Technology is skeptical that dark matter is altering the heat of the planets, saying that it would take "a seriously unrealistic amount of dark matter." And astronomer Andrew Gould of Ohio State University doubts that much dark matter clumps in the solar system—he argues that gravitational interactions with the planets should mostly eject it, just as they cleared out much of the solar system's original nor-

DARKNESS AT JUPITER? **A theory suggests that particles of the mysterious dark matter of the universe may be the cause of unexplained internal heating of the solar system's gas-giant planets.**

COURTESY OF NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE/GODDARD SPACE FLIGHT CENTER mal matter. Still, Siegel thinks, as the solar system plows through the galaxy, it could be accreting additional dark matter.

As of now, the existence of any dark matter in the solar system remains as mysterious as its presence everywhere else. "It would be fascinating if there were a halo of dark matter around Earth, just as there are the Van Allen belts, or rings around Saturn," Adler says—because then researchers might have an easier time demystifying what is so common and yet so elusive.

Charles Q. Choi is a frequent contributor based in New York City.

Paparazzi Physics

Physicists are so eager for any new data about dark matter that some will literally snap at anything. Earlier this year rumors abounded that the latest results from the PAMELA satellite mission, launched in 2006, revealed dark matter interactions with normal matter. But the researchers in charge of the mission did not share their findings beyond flashes of slides at conferences.

Still, those glimpses were enough for Marco Cirelli of the Institute for Theoretical Physics in Gif-sur-Yvette, France, among other researchers. They snapped photographs of an August 20 PAMELA presentation in Stockholm. (Cirelli notes he did so with permission from the speaker there.)

So far Cirelli and others have released more than half a dozen online papers referencing the slides. Some scientists condemned the paparazzi physics, fearing it might jeopardize journal publication of the data; some defended it because the data was obtained thanks to public funding.

PALEOGENETICS

Decoding the Mammoth

Scientists sequence half the woolly mammoth's genome BY KATE WONG

Thousands of years after the last woolly mammoth lumbered across the tundra, scientists have sequenced a whopping 50 percent of the beast's nuclear genome. Earlier attempts to sequence the DNA of these icons of the Ice Age produced only tiny quantities of code. The new work marks the first time that so much of the genetic material of an extinct creature has been retrieved. Not only has the feat provided insight into the evolutionary history of mammoths, but it is a step toward realizing the science-fiction dream of being able to resurrect a long-gone animal.

WOOLLY MAMMOTH and many other large mammals went extinct 10,000 years ago, for reasons that remain uncertain.

JONATHAN BLAIR *Corbis*

Researchers led by Webb Miller and Stephan C. Schuster of Pennsylvania State University extracted the DNA from hair belonging to two Siberian woolly mammoths and ran it through a machine that conducts so-called high-throughput sequencing. Previously, the largest amount of DNA from an extinct species comprised around 13 million base pairs—not even 1 percent of the genome. Now, writing in the November 20 issue of *Nature*, the team reports having obtained more than three billion base pairs. "It's a technical breakthrough," says ancient-DNA expert Hendrik N. Poinar of McMaster University in Ontario.

Interpretation of the sequence is still nascent, but the results have already helped overturn a long-held assumption about the proboscidean past. Received wisdom holds that the woolly mammoth was the last of a line of species in which each one begat the next, with only one species existing at any given time. The nuclear DNA reveals that the two mammoths that yielded the DNA were quite different from each other, and they seem to belong to populations that diverged 1.5 million to two million years ago. This finding confirms the results of a recent study of the relatively short piece of DNA that resides in the cell's energy-producing organelles—called mitochondrial DNA—which suggested that multiple species of woolly mammoth coexisted. "It looks like there was speciation that we were previously unable to detect" using fossils alone, Ross D. E. MacPhee of the American Museum of Natural History in New York City observes.

Thus far the mammoth genome exists only in bits and pieces: it has not yet been assembled. The researchers are awaiting completion of the genome of the African savanna elephant, a cousin of the woolly mammoth, which will serve as a road map for how to reconstruct the extinct animal's genome.

Armed with complete genomes for the mammoth and its closest living relative, the Asian elephant, scientists may one day be able to bring the mammoth back from the beyond. "A year ago I would have said this was science fiction," Schuster remarks. But as a result of this sequencing achievement, he now believes one could theoretically modify the DNA in the egg of an elephant to match that of its furry cousin by artificially introducing the appropriate substitutions to the genetic code. Based on initial comparisons of mammoth and elephant DNA, he estimates that around 400,000 changes would produce an animal that looks a lot like a mammoth; an exact replica would require several million.

(The recent cloning of frozen mice is not applicable to woolly mammoths, Schuster believes, because whereas mice are small and therefore freeze quickly, a mammoth carcass would take many days to ice over—a delay that would likely cause too much DNA degradation for cloning.)

In the nearer term, biologists are hoping to glean insights into such mysteries as how woolly mammoths were adapted to their frigid world and what factors led to their demise. Miller notes that by studying the genomes of multiple mammoths from different time periods, researchers will be able to chart the decrease in genetic diversity as the species died out. The downfall of the mammoths and other species may contain lessons for modern fauna in danger of disappearing, he says.

Indeed, the team is now sequencing DNA they have obtained from a thylacine, an Australian marsupial that went extinct in 1936, possibly as a result of infection. They want to compare its DNA with that of the closely related Tasmanian devil, which is currently under threat from a devastating facial cancer.

"We're hoping to learn why one species went extinct and the other didn't and then use that [knowledge] in conservation efforts," Miller says. If the research turns up genes associated with survival, scientists can use that information to develop a breeding program for the Tasmanian devil that maximizes the genetic diversity of the population—and increases the frequency of genes that confer immunity. Perhaps the greatest promise of ancient DNA is not raising the dead but preserving the living.

MATERIALS

Chasing Rainbows

From infrared to ultraviolet, a new photovoltaic material responds to the full spectrum of sunlight BY JESSE EMSPAK

Overcast days are the enemy of solar energy. Most photovoltaic cells respond to only a relatively narrow part of the sun's spectrum—and it just happens to be the one that clouds tend to block out. Manufacturers deal with the problem by layering different materials in the cell, but that approach makes them more expensive.

Led by chemist Malcolm Chisholm, a team at Ohio State University took a different tack. They doped a polymer commonly used for semiconductor applications, called oligothiophene, with atoms of the metals molybdenum and tungsten. The result was a substance that generates power in response to light of wavelengths from 300 (ultraviolet) to 1,000 nanometers (the near infrared). In contrast, traditional, silicon-based cells function best starting from 600 (orange) to 900 nanometers (deep red). The polymer can work at such a wide range because it both fluoresces and phosphoresces.

Most solar cell materials just fluoresce: sunlight striking them excites electrons into a higher energy state, and then they drop back down to their ground state and emit light. (Generally, the fluorescence is not noticeable—the wavelength of the emitted light is in the infrared spectrum, or else the light is too feeble to see in the sun; a few solar cell designs reuse the light to boost efficiency.) Some of those electrons become excited enough to break free from the atoms they surround; these electrons can serve as the basis for the electric current.

But the electrons do not stay free for long—only trillionths of a second. They may drop back to the ground state before serving any useful purpose. This is one reason solar cells do not operate with 100 percent efficiency.

The polymer Chisholm and his team developed also phosphoresces like glow-in-the-dark toys. Electrons hold on to their energy longer in phosphorescence than in fluorescence and thus stay free longer, on a scale of microseconds. Although based on their calculations the team expected the material to fluoresce, they only saw the phosphorescence after they tested it.

The doping makes the difference. Both tungsten and molybdenum are metal atoms that have more electrons that are available for conduction than those of the polymer alone. Moreover, the electron configurations of the metals allow for longer-lived free electrons.

The team, which described its results in the October 7 *Proceedings of the National Academy of Sciences USA*, has laid the polymer down as a thin film, similar to what would be used in a solar cell. But the researchers are still years away from an actual device. Chisholm hopes that even if these polymer solar cells are less efficient than silicon, they will ultimately be cheaper to produce.

Jesse Emspak is a freelance writer based in New York City.

ENVIRONMENT

Climate Control of Dynasties

In the late ninth century a disastrous harvest precipitated by drought brought famine to China, ultimately ending the three-century rule of the Tang Dynasty. Climate change may have been a cause, according to a stalagmite from northwestern China. Composed of calcium carbonate leached from dripping water, the stalagmite preserves a record of rainfall in this region. It shows that the vital rains of the Asian monsoon weakened at the time of the downfalls of the Tang, Yuan and Ming dynasties over the past 1,810 years. These times of strong and weak rains, when compared with Chinese historical records, coincide with periods of imperial turmoil or prosperity, as in the case of the expansion of the Northern Song Dynasty, when harvests were abundant. In the past 50 years, however, industrial soot and greenhouse gases are causing the rains to weaken. Perhaps that is why today's rulers of China are eager to act on climate change. The stalagmite analysis appears in the November 7 *Science*. —*David Biello*

WARRIOR STATUE from the Tang Dynasty was found at a remote Silk Road outpost. Climate change may have undone the far-flung dynasty (A.D. 618–907).

NANOTECH

Sounds like Thunder

Conventional loudspeakers produce sound by vibrating back and forth, but new speakers made from sheets of carbon nanotubes create music the way lightning generates thunder. When an audio-frequency electric current was applied to stretchable, flexible transparent films of 10-nanometer-thick carbon nanotubes, physicists at the Tsinghua-Foxconn Nanotechnology Research Center in Beijing unexpectedly discovered they could make sounds as loud as commercial speakers. The scientists reason that the electrified nanotubes heat and expand the air near them, producing sound waves. These loudspeaker membranes can be stretched up to twice their original length without breaking and with little change to sound intensity. These sheets could be placed over paintings, windows, video screens—even in clothing, the researchers say, as a means to keep a person warm. They even put their handiwork—described online October 29 in *Nano Letters*—on a waving flag. —*Charles Q. Choi*

PERCEPTION

Seeing on Faith

Religion might literally influence how you view the world. Scientists in the Netherlands compared Dutch Calvinists with Dutch atheists, looking for any effects potentially imposed on thinking by the neo-Calvinist concept of sphere sovereignty, which emphasizes that each sector of society has its own responsibilities and authorities. The researchers hypothesize that Calvinists might therefore not be as good as atheists at seeing the big picture. Participants were shown images of large rectangles or squares that each consisted of smaller rectangles or squares. In some tests, volunteers had to quickly identify the shapes of the smaller parts; in others, the larger wholes. The Calvinists scored slightly but significantly lower than atheists did in correctly identifying whole images. The investigators plan to study other religions for similar influences. See more in the November 12 *PLoS ONE*. —*Charles Q. Choi*

Data Points

Take Two Pills and Don't Call Me in the Morning

Up to 58 percent of physicians in the U.S. regularly prescribe placebos, according to a survey of 679 rheumatologists and general internists conducted by Jon C. Tilburt of the National Institutes of Health and his colleagues. Even though placebos may contain no active ingredients, many ailments still respond positively to them [see "The Placebo Effect," by Walter A. Brown; SCIENTIFIC AMERICAN, January 1998].

Percent of physicians who believe prescribing placebos is ethical:	62
Percent who have prescribed placebos that were:	
Over-the-counter painkillers:	41
Vitamins:	38
Antibiotics:	13
Sedatives:	13
Saline:	3
Sugar pills:	2
Percent who told patients that the treatment is:	
Potentially beneficial but not typically used for their condition:	68
Medicine:	18
A placebo:	5

SOURCE: British Medical Journal, *online October 23, 2008*

WERNER FORMAN *Corbis* (*statue*); ILLUSTRATION BY MATT COLLINS

In Brief

X-RAYS FROM TAPE

Peeling adhesive tape can create nanosecond bursts of x-rays. The effect occurs when electrons from the stuck surface leap to the sticky side of the tape. They travel so fast that on impact with the adhesive side, they give off radiation. The x-rays appear only in near-vacuum conditions, however—air molecules slow down the electrons enough so that they produce just a faint glow. The discovery, which came to light in the October 23 *Nature,* could lead to inexpensive x-ray machines that do not require electricity. —*Susannah F. Locke*

PLAYING CHICKEN

The world's 40 billion commercial chickens are susceptible to crippling disease outbreaks because they are genetically uniform. On average, farmed chickens lack 50 percent of the genes in the chicken genome. To avert mass deaths and preserve a reservoir of potentially useful genes, farmers could breed commercial varieties with other types of chicken—possibly at the expense of traits such as enhanced egg-laying, however. The study appears in the November 11 *Proceedings of the National Academy of Sciences USA.* —*David Biello*

FIELD EFFECT ON THE BRAIN

Strong magnetic fields might make the brain run slow. Scientists at Louis Pasteur University in Strasbourg, France, had repeatedly seen delayed response times during functional magnetic resonance imaging (fMRI) experiments, which generate a two-tesla magnetic field (30,000 times stronger than the earth's field at its magnetic poles). To investigate this phenomenon, the researchers had subjects press buttons when they saw a particular cue on a monitor, such as an "X" in a flow of consonants. As the scientists reported online October 29 in *Nature Precedings,* fMRI slowed response times up to 30 percent. Magnetic fields might be dampening the excitability of brain cells. —*Charles Q. Choi*

EPIDEMICS

Fungal Clue in Mystery Bat Deaths

A novel fungus may be devastating bats in the northeastern U.S. In the past two years several species have displayed unusual behavior such as flying during the winter when they should be hibernating. Census counts in Connecticut, Massachusetts, New York and Vermont have revealed that populations have thinned by at least 75 percent.

A clue has been a white, powdery organism on the muzzles, ears and wings of the dead and dying bats, creating what is called white nose syndrome. In a report published online October 30 in *Science,* microbiologist David S. Blehert of the U.S. Geological Survey and his colleagues identify the white stuff as a type of *Geomyces* fungus, one of a group of ubiquitous organisms that reproduce at refrigerator temperatures of four degrees Celsius—and a typical bat-cave reading.

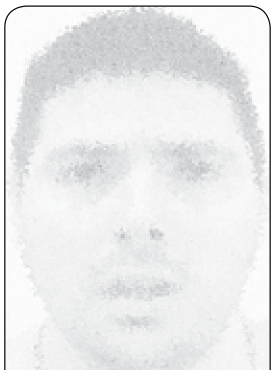
WHITE NOSE SYNDROME is affecting bats.

Researchers remain unaware of the source of the fungus or even its exact role in the deaths. The pathogen may attack torpid bats and keep them awake, so that the mammals burn too much of their stored fat—most victims have been rail-thin, and some have been found outside their caves, perhaps after a futile attempt to catch insects to eat in winter. Or the fungus may simply be an opportunistic infection following a more profound sickness sweeping the animals. The researchers plan to study the effect of this fungus on healthy bats in the lab this winter. —*Larry Greenemeier*

BEHAVIOR

Politics of Blank Looks

How we react to faces could be linked to our political affiliations. Psychologist Jacob M. Vigil of the University of North Florida had 740 college students look at 12 photographs of faces digitally blurred to not display any clear emotion. The volunteers were then asked if these faces expressed sadness, joy, disgust, surprise, fear or anger. The students who identified themselves as Republicans were more likely than those who identified themselves as Democrats to interpret these vague faces as more threatening, as measured by anger or disgust, and less submissive, as conveyed by fear or surprise. These findings, which appeared online October 21 in *Nature Precedings,* are consistent with research linking conservative political views on military spending and capital punishment with heightened reactions to disturbing images and sounds. Vigil conjectures that the political ideologies we advocate could be linked with the way that we respond to ambiguous details. —*Charles Q. Choi*



ANGRY OR SURPRISED? **Your view may depend on your political leaning.**

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COURTESY OF NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION (*bat*); DAVID SILVERMAN *Getty Images* (*eggs and chickens*); COURTESY OF JACOB M. VIGIL (*face*)

Czech Technical University in Prague

Czech Biomedical Engineering Research

Prague: ©ČTK (photo)

www.cvut.cz

Nobel prize winner Professor Horst Störmer visited CTU in 2006.

After the changes in the Czech Republic in 1989, parents were quick to seek opportunities to send their children to study abroad, normally for a year or less, and the dream destination was the United States. Programs in support of such study abroad sprung up in the 1990s and plenty of young Czechs lived with host families and attended school in the US.

By the mid 1990s, some US universities were responding positively to the Czech Technical University in Prague's invitation to set up student exchange programs. Kansas State University (KSU) and Union College, in Schenectady, NY agreed to establish exchanges that have now been sustained for more than a decade. What was of particular importance at first was that these universities accepted a non-standard exchange agreement, under which the outgoing students covered the cost not only of tuition but also of board and lodging at their home institution. This meant that the Czech students, who pay no tuition and have access to subsidized dorms, canteens and public transportation, could afford to study at a US university, live in a dorm and eat in the refectory. This was crucial at a time when salaries in the Czech Republic were several times lower than in the US, and the rate of exchange made life in the US very expensive for Czechs. The generosity of Union College and KSU was repaid by hosting outstanding Czech students, who remember their time as students in the US with considerable gratitude for the remarkable opportunity.

The Czech Technical University in Prague itself is no poor cousin, though it may have appeared that way a decade ago. Currently, more than 24,000 students, both undergraduate and graduate, are enrolled at seven faculties and three institutes. Many programs are taught in English, including some joint-degree and double-degree programs with foreign universities. International students form a significant and growing part of the academic community. The University's International Student Club was awarded the Erasmus Student Network's Section of the Year Prize as the best student club in Europe in 2003. Today, the Czech Technical University in Prague is a large and very highly rated technical university, ranked among the top 500 world universities in the 2008 QS World Universities ranking. It is located in one of the most attractive cities in Europe and offers several study programs and many courses taught in English. American students from Union College, KSU and other partner universities are able to have a wonderful academic and personality-building experience and, at the end of it, to transfer credits to their home university. We invite other US universities to join our exchange program.

CTU Department of Biomechanics
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In the CTU, the Department of Biomechanics (www.biomechanics.cz), the Faculty of Mechanical Engineering, utilizes the engineering tradition of the CTU in the field of biosciences. Research activities include all stages of bioimplant development in cooperation with manufacturers and medical clinics. The main strength of the department is in the field of mathematical modelling, e.g. FEA or CFD, and experimental testing of biomaterials and structures. The department utilizes a unique 8-DOF mechanical testing system, a spine simulator and contact or noncontact deformation measurement systems, e.g. 3D Digital Image Correlation.

Areas of Expertise

Musculoskeletal System Replacements
Modular systems of total hip and knee replacements have been developed in cooperation with Medin Orthopaedics Inc. Further outcomes of the research are spine implants, patented intervertebral disc and cages, custom made implants, and the future development of tissue engineering replacements.

Cardiovascular Biomechanics
A unique physical model of human cardiovascular circulation simulates a pulsatile flow through a blood vessel.

Modelling in Nanomechanics
Mathematical modelling of phospholipide assemblies is used to predict stable shapes of non-lamellar biomembrane structures.

New Biomaterials
Advanced biocomposites based on biocompatible and/or bioactive matrix with different types of reinforcement can potentially be used in orthopedics in the form of substitutive/filling or connective elements.

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CTU Department of Circuit Theory

In the CTU Department of Circuit Theory, the Faculty of Electrical Engineering conducts frontier research in the fields of biological signal analysis and measurement. We have improved the method of the statistical evaluation of the coherence function, surface Laplacion, and we constantly optimize methods for the forward and inverse tasks in EEG. In the field of applied research, we are devising new algorithms for EEG classification with applications in Brain Computer Interface systems.

We develop algorithms for the analysis of disordered speech, supporting the diagnosis of speech dysphasia. The Cochlear Implant (CI) group programs the implants for pediatric CI patients and organizes training of CI specialists from Central and Eastern Europe. We are inventors of new circuitry and system designs that allow for more comfortable measurement of biological signals.

CTU Department of Electromagnetic Field

Medical applications of microwaves (i.e. using microwave technique and technology for therapeutic and diagnostic purposes) are being developed at the CTU Department of Electromagnetic Field since 1981. Microwave thermotherapy can be used for cancer treatment and for treatment of some other diseases (various applications in cardiology, urology, physiotherapy etc.).

During the last few years our research focused on local external applicators working at 434 MHz and 2450 MHz. These applicators were used for the treatment of more then 1,000 patients suffering from superficial or subcutaneous tumors (up to the depth cca 4 – 6 cm). Successful treatment has been indicated in the case of 84% of patients.

We continue our research toward the development of deep local and regional applicators to treat tumors deep in the body.

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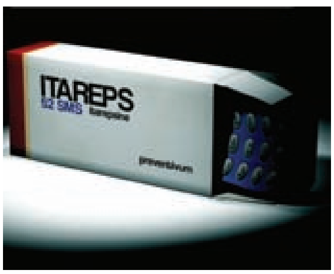
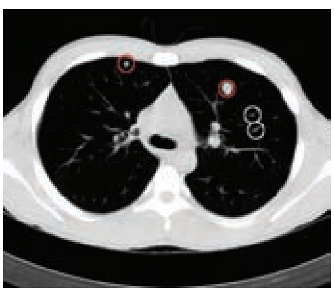
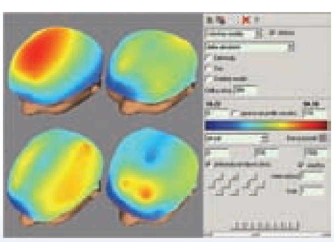






The department combines skills in statistical data analysis, signal processing and data mining with approaches based on artificial intelligence, such as evolutionary and agent-based computation or machine learning. With this background, we conduct research into biomedical informatics, serving three kinds of end-users: the patient, the physician and the scientist. As detailed below, we yield a spectrum of tangible results ranging from information technology support for daily **clinical practice,** over high-throughput medical data analysis aimed at **automated diagnosis,** to supporting scientific **knowledge discovery** tasks in genomics research.

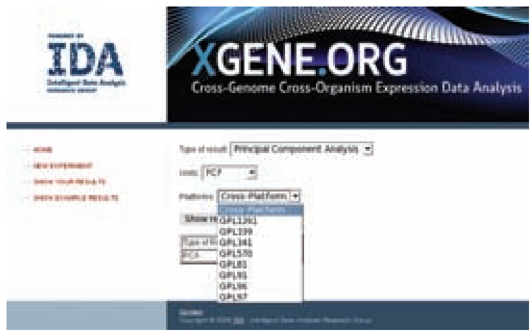
For target groups, such as diabetes or schizophrenia patients, the elderly or physically impaired, we design **interactive assistive tools** that noninvasively monitor physiological signals or behavior, issue early alarms, provide guidance or mediate communication. Our award-winning technology I4Control enables computer control through gaze interaction using an eyeball-movement tracker. Our ontology-based system MedAT deployed in two Prague hospitals supports interactive semantic annotation of textual medical records and thus enables search for patterns in patient data.

We apply image processing techniques to 2D and 3D medical data originating from ultrasound, X-ray, MRI, CT, EG, MEG and other modalities. One of our key topics is elastic image registration, that is, finding corresponding points between images taken at different times or by different modalities to quantify changes in between them. Our other successful projects involve **detection of lung nodules,** localization of surgical tools in ultrasound, segmentation of bones from CT and MRI and imaging of elastic properties of tissues using ultrasound elastography.

Beyond traditional computational approaches, we employ scalable artificial intelligence methods based on nature-inspired approaches, such as evolutionary computation, to tackle high-complexity tasks pertaining to filtration and segmentation of nonstationary bio-medical signals such as EEG, signal analysis in time and frequency domains or feature extraction from very large signal repositories.

These methods are integrated in our **signal analysis software tools** ECGframework and EEGLab as well as the data-transformation tool SumatraTT.

We support scientific knowledge discovery in biology research. Integrating gene expression data with biological pathway structures, gene ontology and gene interaction information, our machine learning algorithms construct



understandable models explaining why specific genes are active in specific situations. Our current focus is on the development of the **web-based tool XGENE.ORG** for integrated analysis of gene expression profiles collected from genomes of diverse organisms measured through heterogeneous gene expression chips.

We address the above topics through European research projects (K4Care, OLDES) and networks (WARTHE, COGAIN, DfA@eInclusion) as well as numerous national research grants. Aside from project consortia, we participate in several bilateral endeavors, either pursuing joint research (e.g. with INSA Lyon, France or the University of Minnesota, USA) or acting as a technology provider (e.g. for STI Medical, Hawaii, USA or INTA, Spain). Selected results of the department are transferred to clinical practice through spin-off companies www.certicon.cz, www.neovision.cz and www.eyedea.cz. Students' research is supported by the foundation www.cvutmedialab.cz.

Further details and web links for the above topics and tools are provided at http://cyber.felk.cvut.cz/biomed.

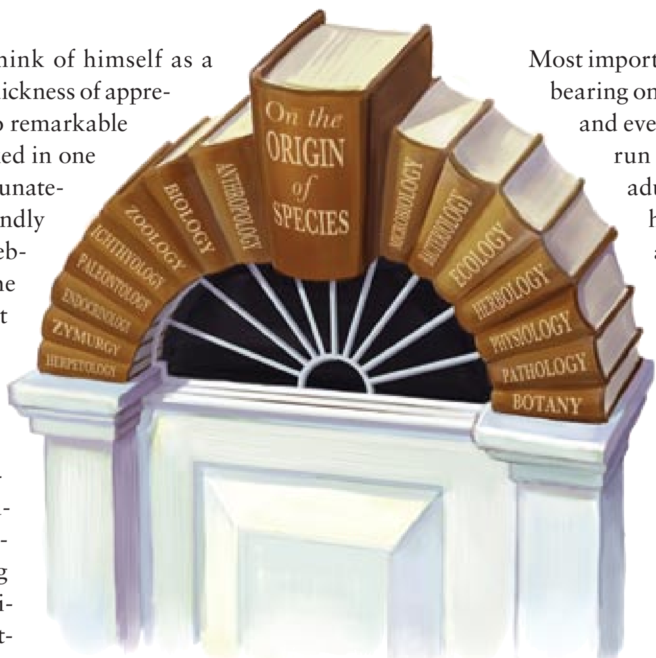
SciAm Perspectives

A Theory for Everyman

Evolution should be taught as a practical tool for understanding drug resistance and the price of fish

BY THE EDITORS

Charles Darwin did not think of himself as a genius. "I have no great quickness of apprehension or wit which is so remarkable in some clever men ..." he remarked in one passage of his autobiography. Fortunately for the rest of us, he was profoundly wrong in his assessment. So on February 12 the world will mark the bicentennial birthday of a scientist who holds a rightful place alongside Galileo, Copernicus, Newton and Einstein.



MATT COLLINS

Darwin's genius—and, yes, genius is the right word—is manifest in the way his theory of evolution can tie together disparate biological facts into a single unifying framework. Evolutionary geneticist Theodosius Dobzhansky's oft-cited quotation bears repeating here: "Nothing in biology makes sense, except in the light of evolution."

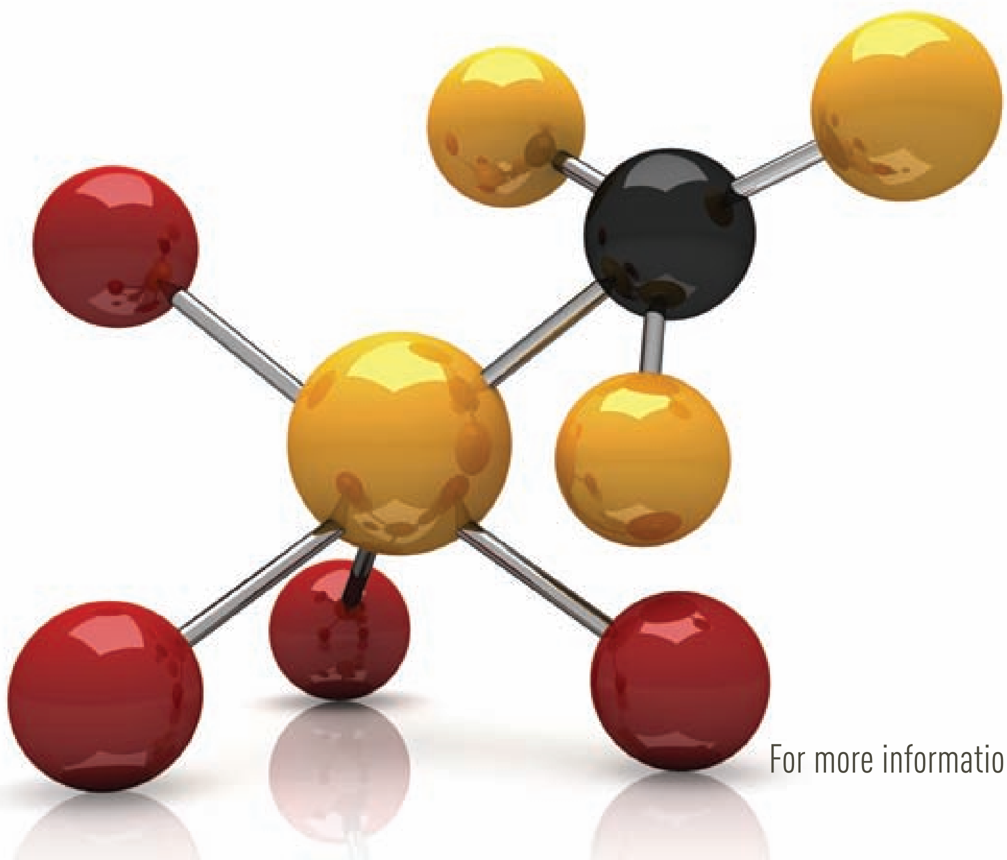
Yet it is also worth noting during this anniversary year that Darwin deserves a lot better than he gets. When the popular press needs an iconic image of a brilliant scientist, it invariably recycles the famous photograph of Albert Einstein having a bad hair day. (Einstein accompanies John Lennon and Andy Warhol on *Forbes*'s list of top-earning deceased celebrities.) Darwin's failure to achieve icon status is the legacy of creationists and neocreationists and of the distortion of his ideas by the eugenics movement a century ago.

But Darwin is so much more than just a quaint, Victorian historical figure whose bust in the pantheon deserves a place among those of other scientific greats. Theory needs to explain past, present and future—and Darwin's does all three in a form that requires no simplifying translation. His theory is readily accessible to any literate person who allots a pleasurable interlude for *On the Origin of Species*, its prose sometimes bordering on the poetic: "... from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

Most important, Darwin's legacy has a direct bearing on how society makes public policy and even, at times, on how we choose to run our lives. Overfishing of mature adults selects for smaller fish (and higher prices at the supermarket), and excessive use of antibiotics leads, by natural selection, to drug resistance, all considerations for regulators and legislators. Many modern diseases—obesity, diabetes and autoimmune disorders—come about, in part, because of the mismatch between our genes and an environment that changes more quickly than human genomes can evolve. Understanding this disparity may help convince a patient to make a change in diet to better conform to the demands of a genetic heritage that leaves us unable to accommodate excess, refined carbohydrates and saturated fats from a steady intake of linguine alfredo and the like.

Biologist David Sloan Wilson initiated a program in evolutionary studies called EvoS at Binghamton University that extends beyond just the life sciences to encompass the humanities and the social sciences: the program is now being adopted at other schools. Students learn the basics, that evolution is both theory and fact and, crucially, that it serves as a way of looking at the world that provides deep predictive and explanatory power. They then proceed to use this analytical framework to explore subjects as diverse as cancer, pregnancy, mate choice, literature and religion.

One way to celebrate Darwin's birthday is to contemplate how evolutionary studies can achieve broader adoption in secondary and higher education. Natural selection and the complementary idea of how genes, individuals and species change over time should be as much a part of developing critical thinking skills as deductive reasoning and the study of ethics. ■



Sustainable Developments

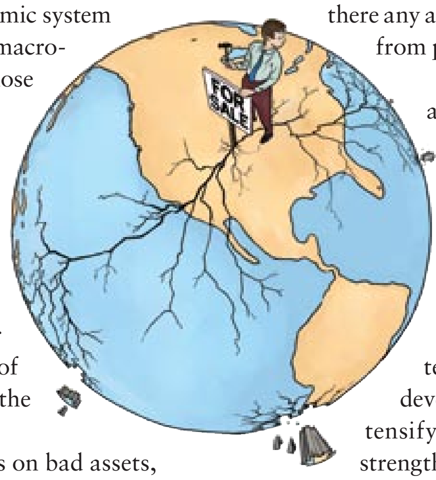
Blackouts and Cascading Failures

Feedbacks in the economic network can turn local crises into global ones

BY JEFFREY D. SACHS

The global economic crisis is akin to a power black-out. A single downed power line or transient overload causes power to be shunted to another part of the grid, which in turn leads to new overloads, more shunting and ultimately to a cascade of failures that pushes a region into darkness. Similarly, a U.S. banking emergency caused by worsening national market conditions has sent shock waves through the world's financial system, causing a global banking crisis that now threatens to become a severe global economic downturn.

Cascading failures are emergent phenomena of a network, rather than independent and coincidental failures of its individual components. Although many banks in the U.S. and Europe simultaneously overinvested in mortgage-backed securities (MBSs) to their peril, positive feedbacks in the global economic system amplified those errors. Bank regulators and macroeconomic policymakers have not yet given those feedbacks proper regard.



The first key feedback is the "debt-deflation spiral." When default rates on mortgages started to rise in 2007, the banks suffered capital losses on their holdings of MBSs. To repay their creditors (such as the money-market funds that had lent them short-term money), the banks sold their MBSs en masse, driving the market prices of those securities even lower and amplifying the banking sector's losses.

Second, when banks suffer capital losses on bad assets, they cut back on lending by a multiple of their capital losses. That cutback further depresses housing and other prices, reducing the value of the banks' assets and amplifying the downturn.

Third, as one or more banks fail, panic ensues. Banks borrow short term to invest in longer-term assets, which they can liquidate quickly only at large losses. When a bank's short-term creditors suddenly believe that *other* short-term creditors are withdrawing their loans, each creditor rationally tries to withdraw its own loan ahead of the others. The result is a self-fulfilling stampede to the exits, as was triggered worldwide last September by the failure of Lehman Brothers. Such "rational panics" can finish off otherwise solvent banks.

Fourth, as banks cut back on lending, consumer spending and business investment plummet, unemployment soars and banks suffer further capital losses as more of their loans go sour. The economy goes into a tailspin. Only aggressively expansionary fiscal and monetary policies in China, Japan, Germany and other nations with international surpluses can avert that outcome in the current situation. The U.S. recession can no longer be avoided, but its effects can still be moderated in the U.S. and largely averted in east Asia, assuming corrective actions are taken.

The possibility of such amplifying feedbacks has been understood since the Great Depression, and some partial protections were put in place. The main ones include capital adequacy standards that cushion individual banks against capital losses, emergency loans from the central bank, deposit insurance and countercyclical macroeconomic policies. In practice, these policies have been applied haphazardly, without regard for cross-border spillovers, and have generally been too little, too late. Nor was there any attention to building "firewalls" to stop shocks from percolating quickly among countries.

As policymakers now begin to revamp global financial and economic systems, they would be wise to consult the classic analysis of the Great Depression in *A Monetary History of the United States, 1867–1960,* by Milton Friedman and Anna Jacobson Schwartz. "Economic collapse," they wrote, "often has the character of a cumulative process. Let it go beyond a certain point, and it will tend for a time to gain strength from its own development as its effects spread and return to intensify the process of collapse. Because no great strength would be required to hold back the rock that starts a landslide, it does not follow that the landslide will not be of major proportions."

Our risks go far beyond finance. Our reckless gambles on the recent financial bubble are dwarfed by the long-term gambles we have taken through failure to address the interconnected crises of water, energy, poverty, food and climate change. The financial crisis should open our eyes to these much more grave systemic threats and the global cooperation needed to redress them. ■

Jeffrey D. Sachs is director of the Earth Institute at Columbia University (www.earth.columbia.edu).

SCI AM An extended version of this essay is available at **www.SciAm.com/jan2009**

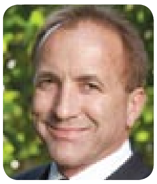
PHOTOGRAPH BY BRUCE GILBERT/EARTH INSTITUTE; ILLUSTRATION BY MATT COLLINS

Skeptic

Telephone to the Dead

Talking to the dead is easy. Getting the dead to talk back is hard. Why not phone them?

BY MICHAEL SHERMER



"Is Matthew there?" asked Cheyenne, directing her voice toward the box on the table in hopes that her brother would come through from the other side. "Yes," the reply came. With the connection "validated," Cheyenne shakily continued: "Was the suicide a mistake?" The speaker crackled, "My death was a mistake." With tears cascading down her cheeks, Cheyenne asked to speak with her mother, and when the connection was made she sputtered out, "Do you see my children, your beautiful grandchildren?" Mom replied, "Yes. I see the children."

Cheyenne's life-affirming messages were coming out of Thomas Edison's "Telephone to the Dead"—or at least a facsimile of a rumored machine that the great inventor never built. It was just one of many readings that day (at $90 a pop) conducted by Christopher Moon, senior editor and president of *Haunted Times* magazine, and part of the spectacle that is Univ-Con, a paranormal conference organized by Ryan Buell, the telegenic host of A&E's television unreality series *Paranormal State*. I was invited to provide some scientific sensibility.

I couldn't hear Cheyenne's brother, mother or any other incorporeal spirits, until Moon interpreted the random noises emanating from the machine that, he explained to me, was created by a Colorado man named Frank Sumption. "Frank's Box," according to its inventor, "consists of a random voltage generator, which is used to tune an AM receiver module rapidly. The audio from the tuner ("raw audio") is amplified and fed to an echo chamber, where the spirits manipulate it to form their voices." Apparently doing so is difficult for the spirits, so Moon employs the help of "Tyler," a spirit "technician," whom he calls on to corral wayward spirits to within earshot of the receiver. What it sounded like was the rapid twirling of a radio dial so that only noises and word fragments were audible.

"Are the dead in that little box?" I asked Moon. "I don't know where the dead are. Another dimension probably," Moon conjectured. "Well, since we know how easy it is for our brains to find meaningful patterns in meaningless noise," I continued, "how can you tell the difference between a dead person's real words and the random noises that just sound like words?" Moon agreed, "You have to be very careful. We record the sessions and get consistency in what people hear." I persisted: "Consistency, as in what, 95 percent, 51 percent?" "A lot," Moon rejoined. The Q&A ended there, because the next session was about to start, and I didn't want to miss the lecture on "Quantum Mechanics: Is It Proving the Existence of the Paranormal?" by another paranormal speculator with the uni-name of Konstantinos.

That evening in my keynote address I explained how "priming" the brain to see or hear something increases the likelihood that the percepts will obey the concepts. I played a part of Led Zeppelin's *Stairway to Heaven* backwards, in which one can hear an occasional "Satan," and then played it again after priming their brains with the alleged lyrics on the screen. The auditory data jumped off the visual cues (the funniest being "there was a little toolshed where he made us suffer, sad Satan"—see it in my lecture "Skepticism 101" at www.skeptic.com). I also played a number of auditory illusions produced by psychologist Diana Deutsch of the University of California, San Diego (http://deutsch.ucsd.edu/), in which a repetitive tape loop of a two-syllable word educes different words and phrases in different people's minds.

These are examples of patternicity, the tendency to find meaningful patterns in meaningless noise (a concept I introduced in my December 2008 column), and the next day I put it to the test when Moon gave me a personal demo. With the Telephone to the Dead squawking away, I tried to connect to my deceased father and mother, asking for any "validation" of a connection—name, cause of death … anything. I coaxed and cajoled. Nothing. Moon asked Tyler to intervene. Nothing. Moon said he heard something, but when I pressed him he came up with nothing. I willingly suspended my disbelief in hopes of talking to my parents, whom I miss dearly. Nothing. I searched for any pattern I might find. Nothing.

And that, I'm afraid, is my assessment of the paranormal. Nothing. ■

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* Why People Believe Weird Things.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

Anti Gravity

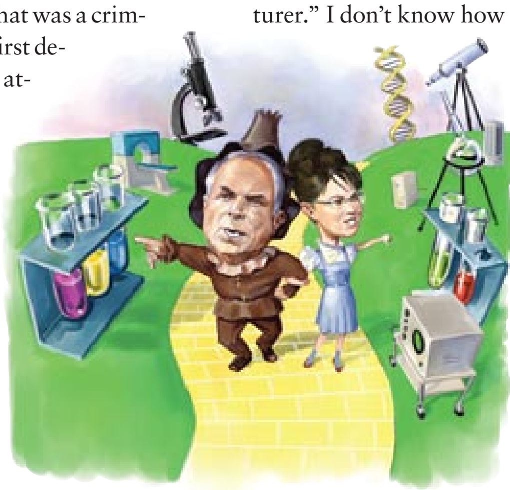
Flies and Projectors and Bears, Oh My

Chastising cherry-picking chumps on the stumps

BY STEVE MIRSKY

You're not supposed to kick a guy when he's down. Of course, in reality, when he's down is the perfect time to kick him. He's closer to your feet, for one thing. But the particular kicking I have in mind should be thought of as tough love. These kicks at the freshly defeated McCain-Palin ticket, as I write in early November, are an attempt to knock some sense back into the group of my fellow Americans who seem determined to ignore or even denigrate valuable scientific research because it's something outside the realm of Joe the Plumber's daily activities.

So let's review. During the presidential campaign, Senator John McCain repeatedly attacked a specific bit of federal funding to study bear DNA. "You know, we spent $3 million to study the DNA of bears in Montana. I don't know if that was a criminal issue or a paternal issue," he said in his first debate with Senator Barack Obama. (That attempt at humor went over like an iridium balloon, which is denser than a lead balloon.) As an article published in February on the *Scientific American* Web site showed, the money (actually closer to $5 million since 2003) is paying for an accurate population count of grizzlies living on the eight million acres of the Northern Continental Divide Ecosystem.



Says biologist Richard Mace of Montana Fish, Wildlife & Parks, "We have a federal law called the Endangered Species Act, and [under this law] the federal government is supposed to help identify and conserve threatened species." The first step to protect endangered grizzlies is to know how many there are. A reliable—and safe—way to do that is to set up barbed wire stations that grab fur as a grizzly wanders by. The researchers retrieve the fur and analyze the DNA to count individuals. Some bear haters, such as comic commentator Stephen Colbert, may question the need to save the grizzlies in the first place. But unless the Endangered Species Act is changed, federal law requires this expenditure. Strike one.

In the second debate McCain attacked Obama for voting for funding that included what the Arizona senator called "$3 million for an overhead projector at a planetarium in Chicago, Illinois. My friends, do we need to spend that kind of money?" Well, yes. (Three Chicago-area Republican members of the House of Representatives thought so, too.)

It's possible that the last time McCain attended a science talk the lecturer put transparencies on an overhead projector, state-of-the-art multimedia equipment half a century ago. But this projector, meant for the world-renowned Adler Planetarium, is somewhat different. It's a star projection system, of course. The planetarium issued a statement after that debate: "To clarify, the Adler Planetarium requested federal support—which was not funded—to replace the projector in its historic Sky Theater, the first planetarium theater in the Western Hemisphere. The Adler's Zeiss Mark VI projector—not an overhead projector—is the instrument that re-creates the night sky in a dome theater, the quintessential planetarium experience. The Adler's projector is nearly 40 years old and is no longer supported with parts or service by the manufacturer." I don't know how many kids started a life-long interest in science at a sky show at a planetarium, but I bet we hear from some of you out there. Swing and a miss, strike two.

Then came the coup de graceless. On October 24 vice presidential candidate Governor Sarah Palin took on what looked through her designer eyeglasses like silly pork-barrel spending by the U.S.: "Some of these pet projects, they really don't make a whole lot of sense, and sometimes, these dollars, they go to projects having little or nothing to do with the public good. Things like fruit-fly research in Paris, France. I kid you not." Never mind that fruit-fly research has brought us modern genetics and molecular biology. The particular earmark in question was some $211,000 to a laboratory in Montpelier, France, with long experience studying ways to protect olive trees from fruit flies. And the little pests are threatening California's olive crop—with a retail value estimated in 2005 at $85 million. So this money might be looked at by anybody with business savvy as an investment. I kid you not. Oh, and strike three.

Science and technology are probably going to be the driving forces that lift us out of the economic hole we're in. The Obama campaign had an entire science advisory team that included two Nobel laureates, Harold Varmus and Peter Agre. The McCain campaign did not have a dedicated science adviser. Future Republican presidential candidates: come to the clean energy–powered, low-wattage, high-lumen light. It beats cursing the darkness. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS

Darwin's Living Legacy

A Victorian amateur undertook a lifetime pursuit of slow, meticulous observation and thought about the natural world, producing a theory 150 years ago that still drives the contemporary scientific agenda • • • BY GARY STIX

When the 26-year-old Charles Darwin sailed into the Galápagos Islands in 1835 onboard the HMS *Beagle,* he took little notice of a collection of birds that are now intimately associated with his name. The naturalist, in fact, misclassified as grosbeaks some of the birds that are now known as Darwin's finches. After Darwin returned to England, ornithologist and artist John Gould began to make illustrations of a group of preserved bird specimens brought back in the *Beagle*'s hold, and the artist recognized them all to be different species of finches.

From Gould's work, Darwin, the self-taught naturalist, came to understand how the finches' beak size must have changed over the generations to accommodate differences in the size of seeds or insects consumed on the various islands. "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends," he noted in *The Voyage of The Beagle,* published after his return in 1839.

Twenty years later Darwin would translate his understanding of finch adaptation to conditions on different islands into a fully formed theory of evolution, one emphasizing the power of natural selection to ensure that more favorable traits endure in successive generations. Darwin's theory, core features of which have withstood critical scrutiny from scientific and religious critics, constituted only the starting point for an endlessly rich set of research questions that continue to inspire present-day scientists. Biologists are still seeking experimental results that address how natural selection proceeds at the molecular level—and how it affects the development of new species.

Darwin's famed finches play a continuing role in providing answers. The scientist had assumed that evolution proceeded slowly, over "the lapse of ages," a pace imperceptible to the short lifetime of human observers. Instead the finches have turned into ideal research subjects for studying evolution in real time because they breed relatively rapidly, are isolated on different islands and rarely migrate.

Since the 1970s evolutionary biologists Peter R. Grant and B. Rosemary Grant of Princeton University have used the Galápagos as a giant laboratory to observe more than 20,000 finches and have shown conclusively how average beak and body size changes in a new generation as El Niños come and go, shifting climate from wet to arid. They have also been able to chronicle possible examples of new species that are starting to emerge.

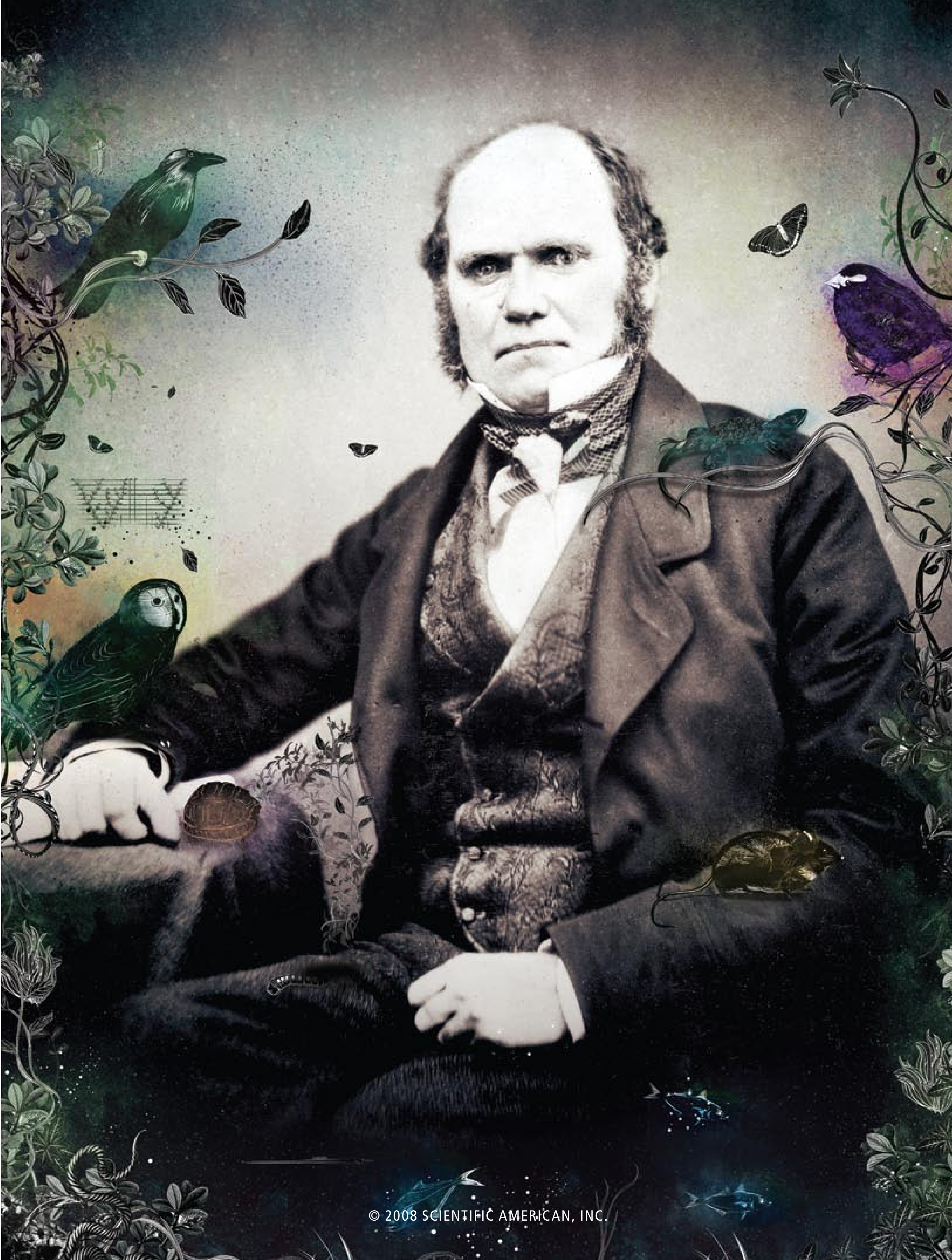
The Grants are just one among many groups that have embarked on missions to witness evo-

KEY CONCEPTS

- Charles Darwin's insights about evolution have withstood 150 years of scrutiny.
- But evolutionary theory has broadened and changed as his ideas have been melded with genetics.
- Evolutionary biology still must contend with some of the same questions that preoccupied Darwin: What, for one, is a species?

—The Editors

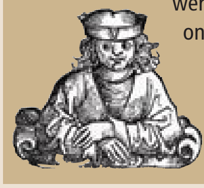
DOUG ALVES (*illustration*); GRANGER COLLECTION (*Darwin*)



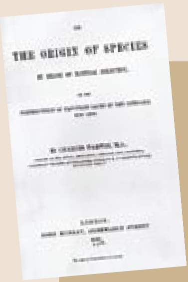
Evolution before and after Darwin

The concept of evolution stretches back to ancient times. Here are some key events in a history that has been marked by continual change.

610–546 B.C.: Greek philosopher Anaximander suggests that all life-forms evolved from fish in the seas and went through a process of modification once they were established on land.



1735: Carl Linnaeus publishes the first volume of *Systema Naturae,* which laid the foundations for taxonomy. Later he suggested that plants descend from a common ancestor.

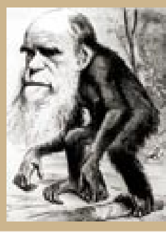


1838: Charles Darwin formulates the theory of natural selection, which is not published for more than 20 years.

1859: *On the Origin of Species* sells out as soon as it is published.

1865: Czech monk Gregor Mendel publishes his research on inheritance, but the importance of his work is not recognized for 35 more years.

1871: In *The Descent of Man*, Darwin ties the human lineage to primate ancestors, provoking outrage in some quarters and the caricaturing of his image.



1882: Darwin dies.

1925: The Scopes Monkey trial in Tennessee tries a teacher based on a law that made it illegal to teach any theory that denies divine creation.

APPROACHABLE GENIUS

Darwin's writings were remarkably accessible to any literate person, as is evident in this description of natural selection from the introduction to *Origin of Species:*

"As many more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form."

lution in action, exemplars of how evolution can at times move in frenzied bursts measured in years, not eons, contradicting Darwin's characterization of a slow-and-steady progression. These studies focus on the cichlid fish of the African Great Lakes, Alaskan sticklebacks, and the *Eleutherodactylus* frogs of Central and South America and the Caribbean, among others.

Ruminations on evolution—often musings on how only the fittest prevail—carry an ancient pedigree, predating even Socrates. The 18th and 19th centuries produced fertile speculations about how life had evolved, including ideas forwarded by Darwin's grandfather, Erasmus Darwin, who lived between 1731 and 1802.

Darwinian evolution was the first capable of withstanding rigorous tests of scientific scrutiny in both the 19th century and beyond. Today investigators, equipped with sophisticated cameras, computers and DNA-sampling tools thoroughly alien to the cargo hold of the *Beagle,* demonstrate the continued vitality of Darwin's work. The naturalist's relevance to basic science and practical pursuits—from biotechnology to forensic science—is the reason for this year's worldwide celebration of the bicentennial of his birth and the sesquicentennial of the publication of his masterwork, *On the Origin of Species by Means of Natural Selection, or the Preservation of Favored Races in the Struggle for Life.*

Darwin's theory represents a foundational pillar of modern science that stands alongside relativity, quantum mechanics and other vital support structures. Just as Copernicus cast the earth out from the center of the universe, the Darwinian universe displaced humans as the epicenter of the natural world. Natural selection accounts for what evolutionary biologist Francisco J. Ayala of the University of California, Irvine, has called "design without a designer," a term that parries the still vigorous efforts by some theologians to slight the theory of evolution. "Darwin completed the Copernican Revolution by drawing out for biology the notion of nature as a lawful system of matter in motion that human reason can explain without recourse to supernatural agencies," Ayala wrote in 2007.

In this anniversary year, Darwin's greatest bequest can be found in the enormous body of research and theorizing that extends directly from his writings. It also serves to underline how evolution itself has undergone radical alteration in the past 150 years, a merger of the original theory with the science of the gene, which Darwin had as little understanding of as the ancients did.

This special issue of *Scientific American* highlights major questions that are still being addressed: How common is natural selection? To what extent does natural selection actually occur at the molecular level of the gene? What is

GETTY IMAGES (*Anaximander*); GRANGER COLLECTION (*Charles and Catherine Darwin*); ROSANNE OLSON *Getty Images* (*Grand Canyon*); BETTMANN *Corbis* (*HMS* Beagle); BETTMANN *Corbis* (*On the Origin of Species*); BETTMANN *Corbis* (*Mendel*); GALLERY COLLECTION *Corbis* (*Darwin caricature*); GRANGER COLLECTION (*Scopes trial cartoon*); A. BARRINGTON BROWN *Photo Researchers, Inc.* (*Watson and Crick*); COURTESY OF CÀTEDRA DE DIVULGACIÓ DE LA CIÈNCIA UNIVERSITAT DE VALÈNCIA (*Darwin drawing*)

1809: Darwin (*shown opposite his younger sister*) is born in Shrewsbury, England, into the comfort of a wealthy family.

1830: Charles Lyell publishes *Principles of Geology*, a formative influence on Darwin's thinking about the gradualism of natural processes as can be witnessed in the Grand Canyon (*right*).

1831: Darwin leaves on a five-year around-the-world journey on the HMS *Beagle*.

1936–1947: The modern synthesis combines Darwin's evolutionary theory with Mendelian genetics.

1953: James D. Watson and Francis Crick discover the structure of DNA, making it possible to study the molecular biology of evolution.

Mid-2000s: Genetic analyses have shown evidence of relatively recent human evolution—dating back several thousand years.

2009: Darwin Day marks the naturalist's birthday on February 12 and will be observed with dozens of events in at least 10 countries. Stay abreast of what's happening at www.darwinday.org

the origin of the genetic variation on which natural selection operates? Does it work by administering a fitness test to individual genes, whole organisms, or even entire groups of animals, plants or microbes? Does it apply to humans if they are able to exercise a rigid control over their environment and even their biology?

A Naturalist by Nature

Like Albert Einstein and others gifted with genius, Darwin marched to his own drumbeat. He showed no signs of academic precociousness. Born into a well-to-do family in the English countryside, the young Darwin was a decidedly mediocre student who hated the regimentation of a curriculum centered on the classics. (Einstein was a rebellious youth and an erratic university student.) Following his father's desire, Darwin entered medical school but was repulsed by cutting open a human cadaver and never finished his studies. Paradoxically, he had little problem killing birds and small animals when hunting, just one of the tasks he set for himself on forays to watch wildlife and collect specimens.

Despairing that Charles would ever amount to anything, Robert Darwin ordered his second son to apply to the University of Cambridge to obtain a degree that would allow him to join the clergy. The man whose ideas are viewed by some clerics as a fundamental insult to religious faith graduated (barely) with a degree in theology.

Although his father tried to dissuade him, Darwin jumped at the offer to become a naturalist onboard a survey ship named the *Beagle*, an experience he would later characterize as "the first real training or education of my mind." The five-year, around-the-globe journey provided exposure to the natural world—and ample time for contemplation—that shaped his later thinking.

Milestones along the way included experiencing the great diversity of species in tropical Brazil and discovery of fossils, including a giant sloth 400 miles south of Buenos Aires, which caused him to ponder how these creatures became extinct. Accounts by gauchos on the Argentine pampas of their killing of indigenous peoples taught him about the primal, territorial impulses of the human animal. And of course, there was the relatively brief, five-week stay in the "frying hot" Galápagos, where he was able to contemplate how closely related species of turtles and mockingbirds inhabited neighboring islands, implying a common ancestry for both groups.

At sea, Darwin also read avidly two volumes of Charles Lyell's *Principles of Geology* that embraced the idea of "uniformitarianism" in which the processes of erosion, sedimentation and volcanic activity occurred in the past at about the same rates as they do now. Lyell rejected the then prevailing catastrophism, which holds that sudden, violent events driven by supernatural forces had driven the shaping of the landscape.

THE QUOTABLE MR. DARWIN

Darwin's wit extended from the natural sciences to his own work habits. Here is a sampling:

"Man still bears in his bodily frame the indelible stamp of his lowly origin."

"It is a cursed evil to any man to become as absorbed in any subject as I am in mine."

"My mind seems to have become a kind of machine for grinding laws out of large collections of facts."

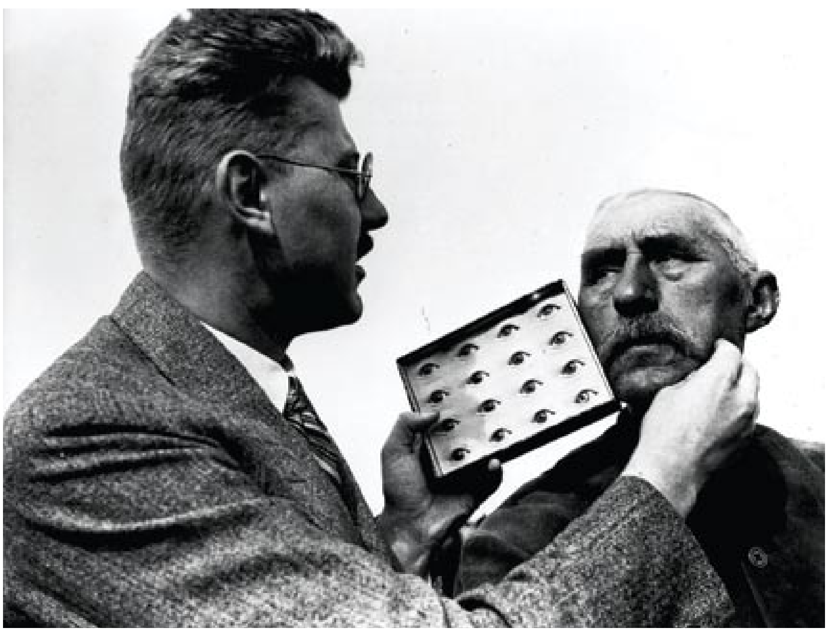
"To kill an error is as good a service as, and sometimes even better than, the establishing of a new truth or fact."

A trek inland in the Andes, where the explorers found an ancient marine deposit uplifted to 7,000 feet, helped to bring Lyell's ideas vividly to life.

Darwin had no awareness that he had embarked on a trip that would forever transform the biological sciences. The 57-month journey produced no moment of sudden realization, nothing equivalent to Einstein's "*annus mirabilis*" of 1905 in which he published papers about special relativity, Brownian motion and other themes. The treasure trove of the journey was what today could be called an immense database: a collection of 368 pages of zoology notes, 1,383 pages of geology notes, a 770-page diary, in addition to 1,529 species in bottles of alcohol and 3,907 dried specimens, not to mention live tortoises caught in the Galápagos.

By the time the *Beagle* returned to England in October of 1836, Darwin's letters, along with some specimens, had circulated among British scientists, cementing his reputation as a peer. This recognition assured that his father's aspirations for his son's place in the clergy were cast aside. Within a few years Darwin married a first cousin, Emma Wedgwood, and then moved to a country estate whose gardens and greenhouses would provide a living laboratory for his work until his death, an existence made possible by the family's substantial wealth. Unexplained illness, with symptoms ranging from headaches to heart flutters to muscle spasms, plagued Darwin after the expedition until he died in 1882, quashing any thoughts of further expeditions.

SOCIAL DARWINISM and the eugenics movement that flourished in the late 19th and early 20th centuries were pseudoscientific attempts, now discredited, to apply Darwin's ideas to social planning. Below, a German anthropologist attempts to ascertain ethnic characteristics from the eye.



GRANGER COLLECTION

Origins of a Theory

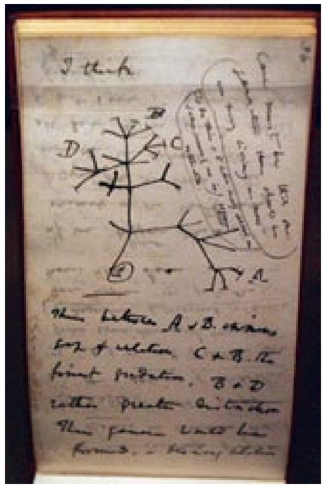
Darwin had begun to formulate his theories by the late 1830s, but he waited for two decades to publish (and then only under pressure from a competitor, Alfred Russel Wallace) because he wanted to ensure that his facts and arguments were beyond reproach.

The process of theory building crept along at an almost glacial tempo. From his readings of Lyell, Darwin took the idea of gradual change in the geological landscape and reasoned that it must also apply to biological organisms: one species must beget another. The recognition of biology's mutability was shared by some other evolutionary thinkers of the day. But it was conceived as a *scala naturae*—an ascending ladder in which each lineage of plant or animal arose by spontaneous generation from inanimate matter and then progressed inexorably toward greater complexity and perfection.

Darwin rejected this straight-line progression in favor of what is now called branching evolution, in which some species diverge from a common ancestor along separate pathways, contradicting the prevailing view that there are fixed limits on how far a new species can diverge from an ancestral one. Darwin recalled that three species of mockingbird he observed in the Galápagos could be traced to a single colonization of a related species he had observed in Latin America. His sketch of a branching "tree of life" is the only illustration in *Origin of Species*.

The concept of a tree of life still begged a "how" for evolution, a gap that led to Darwin's most revolutionary idea, the theory of natural selection. From reading the work of Thomas Malthus, Darwin recognized that populations tend to grow quickly, thereby overwhelming limited resources. He also had an obsession with animal and plant breeding. He would visit agricultural markets and collected plant catalogues.

In 1838 he came to the realization (shared at first with only a few friends) that the natural world, instead of deliberately choosing favorable traits as if it were a cattle breeder, has its own way of addressing a bulging demographic that threatens to exhaust an ecological niche. From the vast hereditary diversity within a given species, natural selection blindly weeds out those individuals with less favorable traits: in essence, Ayala's concise "design without a designer." Moreover, if two populations of the same species remain isolated—one in a desert, the other in the mountains—they may over long periods develop into wholly separate species, no longer able to breed.



TREE OF LIFE, originally sketched by Darwin in 1837 (*below*), still exists as a highly intricate, multidimensional computer model (*left*) that shows how evolution proceeds in branching descent but also through lateral transfer of genes among microorganisms (*red lines*).

COURTESY OF EUROPEAN MOLECULAR BIOLOGY LABORATORY (*computer model of tree of life*); WILLIAM PERLMAN *Corbis* (*sketch of tree of life*)

Origin of Species was rushed to publication in 1859 because Wallace had a manuscript that came to virtually identical conclusions. The first 1,250 copies of the 155,000-word "abstract" immediately sold out. The clarity and accessibility of Darwin's argument stood out. No quips came forth, as they did for Einstein's theories, about how only three people on the rest of the planet could understand his work.

Darwin spent the rest of his life continuing to explore natural selection firsthand with orchids and other plants at his country estate in Downe, 16 miles south of London. He left it to others to defend his work. The publication provoked controversy that continues to this day in the form of creationist debates that still dog public school boards. An article that appeared in *Scientific American* on August 11, 1860, described a meeting of the British Academy of Sciences at which a "Sir B. Brodie" rejected Darwin's hypothesis, saying: "Man had a power of self-consciousness—a principle differing from anything found in the material world, and he did not see how this could originate in lower organisms. This power of man was identical with the divine intelligence." But even then, Darwin had many defenders among leading scientists. At the same conference, the periodical reported, the renowned Joseph Hooker told the bishop of Oxford, another critic in attendance, that the cleric simply lacked any understanding of Darwin's writings.

Darwin had avoided discussion of human evolution in *Origin of Species,* but his *The Descent of Man, and Selection in Relation to Sex* attributed human beginnings to Old World monkeys, an assertion that also offended many and made its way into cartoonish newspaper caricatures of the scientist as half-man, half-ape. Even in the 1860s Darwin's cousin, Francis Galton, and others had begun to complain that modern society protects its "unfit" members from natural selection. The distortion and misunderstanding of Darwinism, from Nazi ideologues to neoliberal economists to popular culture, have yet to cease. American novelist Kurt Vonnegut once remarked that Darwin "taught that those who die are meant to die, that corpses are improvements."

The concept of evolution as a form of branching descent from a common ancestor achieved a relatively rapid acceptance, but accommodation for natural selection came much more slowly, even within the scientific community. The hesitation was understandable. In his work, Darwin had not described a mechanism for inheritance, attributing it to minuscule, hypothetical "gemmules" that ejected from each tissue and traveled to the sex organs, where copies were made and passed to subsequent generations. It took until the decades of the 1930s and 1940s for natural selection to gain broad acceptance.

It was then that the modern synthesis emerged as an expansive framework that reconciled Darwin's natural selection with the genetics pioneered by Gregor Mendel. In 1959, the centennial of the publication of *Origin of Species,* the place of natural selection seemed assured.

But in the ensuing years, the scope of evolutionary biology has had to broaden still further to consider such questions as whether the pace of evolution proceeds in fits and starts—a paroxysm of change followed by long periods of stasis. Do random mutations frequently get passed on or disappear without enhancing or diminishing fitness, a process called genetic drift? Is every biological trait an evolutionary adaptation, or are some characteristics just a random by-product of a physical characteristic that provides a survival advantage?

The field has also had to take another look at the notion that altruistic traits could be explained by natural selection taking place across whole groups. And as far as the origin of species, what role does genetic drift play? Moreover, does the fact that single-celled organisms often trade whole sets of genes with one another undermine the very concept of species, defined as the inability of groups of organisms to reproduce with one another? The continued intensity of these debates represents a measure of the vigor of evolutionary biology—as well as a testament to Darwin's living legacy. ■

MORE TO EXPLORE

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The Cambridge Companion to Darwin. Edited by Jonathan Hodge and Gregory Radick. Cambridge University Press, 2003.

On the Origin of Species: The Illustrated Edition. Charles Darwin. Edited by David Quammen. Sterling, 2008.

The Complete Works of Charles Darwin Online can be accessed at **http://darwin-online.org.uk**

Testing Natural Selection

Biologists working with the most sophisticated genetic tools are demonstrating that natural selection plays a greater role in the evolution of genes than even most evolutionists had thought • • • BY H. ALLEN ORR

Some ideas are discovered late in the history of a scientific discipline because they are subtle, complex or otherwise difficult. Natural selection was not one of these. Although compared with other revolutionary scientific ideas it was discovered fairly recently—Charles Darwin and Alfred Russel Wallace wrote on the subject in 1858, and Darwin's *On the Origin of Species* appeared in 1859—the idea of natural selection is simplicity itself. Some kinds of organisms survive better in certain conditions than others do; such organisms leave more progeny and so become more common with time. The environment thus "selects" those organisms best adapted to present conditions. If environmental conditions change, organisms that happen to possess the most adaptive characteristics for those new conditions will come to predominate. Darwinism was revolutionary not because it made arcane claims about biology but because it suggested that nature's underlying logic might be surprisingly simple.

In spite of this simplicity, the theory of natural selection has suffered a long and tortuous history. Darwin's claim that species evolve was rapidly accepted by biologists, but his separate claim that natural selection drives most of the change was not. Indeed, natural selection was not accepted as a key evolutionary force until well into the 20th century.

The status of natural selection is now secure, reflecting decades of detailed empirical work. But the study of natural selection is by no means complete. Rather—partly because new experimental techniques have been developed and partly because the genetic mechanisms underlying natural selection are now the subject of meticulous empirical analysis—the study of natural selection is a more active area of biology than it was even two decades ago. Much of the recent experimental work on natural selection has focused on three goals: determining how common it is, identifying the precise genetic changes that give rise to the adaptations produced by natural selection, and assessing just how big a role natural selection plays in a key problem of evolutionary biology—the origin of new species.

KEY CONCEPTS

- Charles Darwin's theory that evolution is driven by natural selection—by inherited changes that enhance survival—struggled against competing theories for the acceptance it has within biology today.
- Random genetic mutations having neither positive nor negative effects were once thought to drive most changes at the molecular level. But recent experiments show that natural selection of beneficial genetic mutations is quite common.
- Studies in plant genetics show that changes in a single gene sometimes have a large effect on adaptive differences between species.

—The Editors

Natural Selection: The Idea

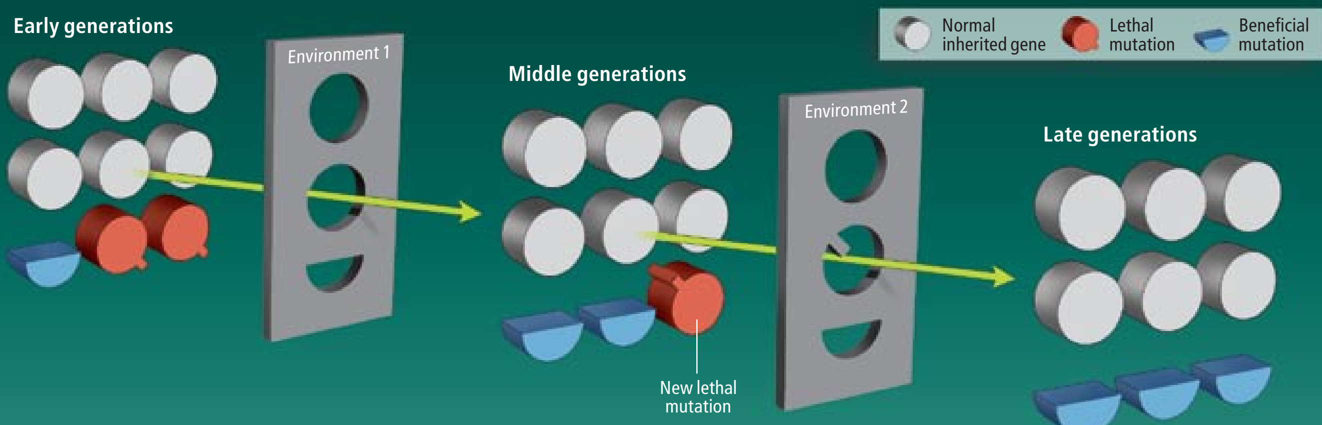
The best way to appreciate evolution by natural selection is to consider organisms whose life cycle is short enough that many generations can be observed. Some bacteria can reproduce themselves every half an hour, so imagine a population of bacteria made up of two genetic types that are initially present in equal numbers. Assume, moreover, that both types breed true: type 1 bacteria produce only type 1 offspring, and type 2 bacteria produce only type 2s. Now suppose the environment suddenly changes: an antibiotic is introduced to which type 1s are resistant but to which type 2s are not. In the new environment,

ART OF the taxidermist and expertise of the scientist-curator combine to suggest the variety of life-forms to which evolution has given rise in the animal kingdom alone. The exhibit was photographed in the Hall of Biodiversity at the American Museum of Natural History in New York City.

GRANT DELIN

Mutation and Natural Selection

Evolution by natural selection is a two-step process: first, random genetic mutations appear in a population; then the environment screens the organisms that carry them.



Some random mutations are lethal (*red*): organisms that carry them do not survive to pass their genes along to their progeny. In effect, the environment screens out lethal changes to the genome.

When a mutation is beneficial (*blue*), organisms that carry it are more likely than organisms without it to pass it along to future generations. The beneficial mutation thus begins to displace the earlier inherited version of the gene in the population. Meanwhile new lethal mutations continue to appear at random.

As the environment changes, beneficial mutations can become increasingly frequent in the population.

type 1s are fitter—that is, better adapted—than type 2s: they survive and so reproduce more often than type 2s do. The result is that type 1s produce more offspring than type 2s do.

"Fitness," as used in evolutionary biology, is a technical term for this idea: it is the probability of surviving or reproducing in a given environment. The outcome of this selection process, repeated numberless times in different contexts, is what we all see in nature: plants and animals (and bacteria) that fit their environments in intricate ways.

Evolutionary geneticists can flesh out the preceding argument in much richer biological detail. We know, for instance, that genetic types originate in mutations of DNA—random changes in the sequence of nucleotides (or string made up of the letters A, G, C and T) that constitutes the "language" of the genome. We also know a good deal about the rate at which a common kind of mutation—the change of one letter of DNA to another—appears: each nucleotide in each gamete in each generation has about one chance in a billion of mutating to another nucleotide. Most important, we know something about the effects of mutations on fitness. The overwhelming majority of random mutations are harmful—that is, they reduce fitness; only a tiny minority are beneficial, increasing fitness. Most mutations are bad for the same reason that most typos in computer code are bad: in finely tuned systems, random tweaks are far more likely to disrupt function than to improve it.

Adaptive evolution is therefore a two-step process, with a strict division of labor between mutation and selection. In each generation, mutation brings new genetic variants into populations. Natural selection then screens them: the rigors of the environment reduce the frequency of "bad" (relatively unfit) variants and increase the frequency of "good" (relatively fit) ones. (It is worth noting that a population can store many genetic variants at once, and those variants can help it to meet changing conditions as they arise. The gene that protected the type 1 bacteria from the antibiotic may have been useless or even slightly harmful in the earlier, antibiotic-free environment, but its presence enabled the type 1s to survive when conditions changed.)

Population geneticists have also provided insight into natural selection by describing it mathematically. For example, geneticists have shown that the fitter a given type is within a population, the more rapidly it will increase in frequency; indeed, one can calculate just how quickly the increase will occur. Population geneticists have also discovered the surprising fact that natural selection has unimaginably keen "eyes," which can detect astonishingly small differences in fitness among genetic types. In a population of a

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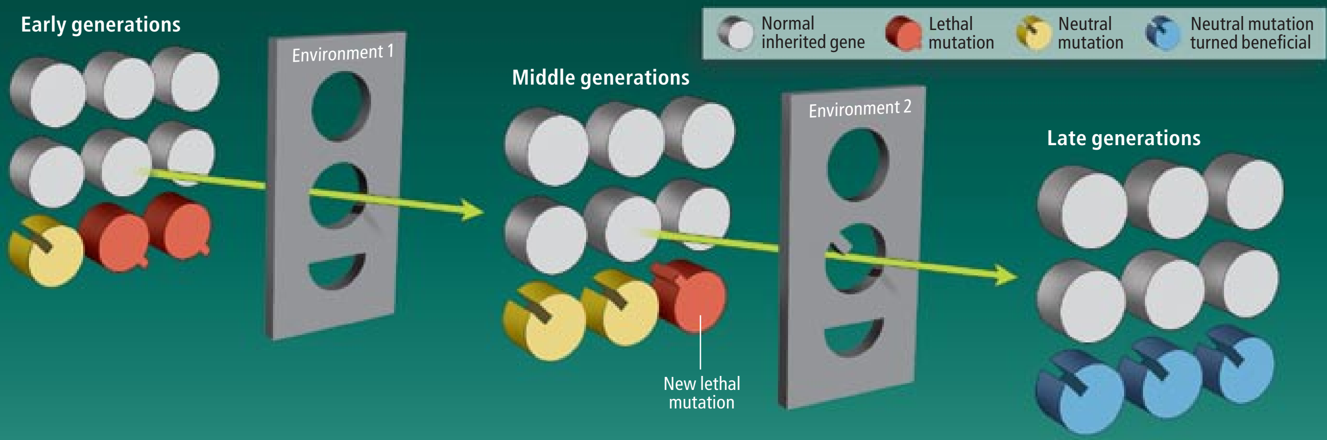
H. Allen Orr is University Professor and Shirley Cox Kearns Chair of Biology at the University of Rochester and author (with Jerry A. Coyne) of *Speciation*. His research focuses on the genetic basis of speciation and adaptation. Orr has been the recipient of a Darwin-Wallace Medal from the Linnean Society of London, a Guggenheim Fellowship, a David and Lucile Packard Fellowship, and the Dobzhansky Prize from the Society for the Study of Evolution. He has published many book reviews and essays in the *New Yorker* and the *New York Review of Books*.

“Neutral” Evolution and Genetic Drift

Until recently, biologists believed that many of the changes in DNA that persist in a population for multiple generations were neutral (*yellow*), having no effect on survival or reproduction. The mix of such changes within a population can fluctuate randomly from generation to generation, a process known as genetic drift. The presumed abundance of neutral mutations led some geneticists to think that genetic drift, not natural selection, was the chief force driving change of DNA in populations. New experimental findings show that natural selection is also an important factor in such change.



Neutral mutations pass through environmental screening just as the old inherited genes do; lethal mutations are screened out.

Random fluctuations in the frequencies of the neutral variants of a gene in a population can sometimes lead to large departures from the usual frequencies, particularly in small populations.

If the environment changes, some neutral variants can prove beneficial (*blue*) and even essential for survival. Natural selection will then act to increase their frequency.

million individuals, natural selection can operate on fitness differences as small as one part in a million.

One remarkable feature of the argument for natural selection is that its logic seems valid for any level of biological entity—from gene to species. Biologists since Darwin, of course, have considered differences in fitness between individual organisms, but in principle natural selection could act on differences in survival or reproduction between other entities. For example, one might reason that species with broad geographic ranges will survive—as species—longer than species whose geographic ranges are narrow. After all, broad-ranging species can tolerate the extinctions of a few local populations more readily than species with restricted ranges can. The logic of natural selection might predict, then, that the proportion of broad-ranging species should increase with time.

Yet though this argument is formally sound—and evolutionists do suspect higher-level selection does take place now and then [see “What’s Good for the Group,” on page 37]—most biologists agree that natural selection typically occurs at the level of individual organisms or genetic types. One reason is that the lifetimes of organisms are much shorter than the lifetimes of species. Thus, the natural selection of organisms typically overwhelms the natural selection of species.

How Common Is Natural Selection?

One of the simplest questions biologists can ask about natural selection has, surprisingly, been one of the hardest to answer: To what degree is it responsible for changes in the overall genetic makeup of a population? No one seriously doubts that natural selection drives the evolution of most physical traits in living creatures—there is no other plausible way to explain such large-scale features as beaks, biceps and brains. But there has been serious doubt about the extent of the role of natural selection in guiding change at the molecular level. Just what proportion of all evolutionary change in DNA is driven, over millions of years, by natural selection—as opposed to some other process?

Until the 1960s biologists had assumed that the answer was “almost all,” but a group of population geneticists led by Japanese investigator Motoo Kimura sharply challenged that view. Kimura argued that molecular evolution is not usually driven by “positive” natural selection—in which the environment increases the frequency of a beneficial type that is initially rare. Rather, he said, nearly all the genetic mutations that persist or reach high frequencies in populations are selectively neutral—they have no appreciable effect on fitness one way or the other. (Of course, harmful mutations continue to appear at a high

TOMMY MOORMAN (*illustrations*)

rate, but they can never reach high frequencies in a population and thus are evolutionary dead ends.) Since neutral mutations are essentially invisible in the present environment, such changes can slip silently through a population, substantially altering its genetic composition over time. The process is called random genetic drift; it is the heart of the neutral theory of molecular evolution.

By the 1980s many evolutionary geneticists had accepted the neutral theory. But the data bearing on it were mostly indirect; more direct, critical tests were lacking. Two developments have helped fix that problem. First, population geneticists have devised simple statistical tests for distinguishing neutral changes in the genome from adaptive ones. Second, new technology has enabled entire genomes from many species to be sequenced, providing voluminous data on which these statistical tests can be applied. The new data suggest that the neutral theory underestimated the importance of natural selection.

In one study a team led by David J. Begun and Charles H. Langley, both at the University of California, Davis, compared the DNA sequences of two species of fruit fly in the genus *Drosophila*. They analyzed roughly 6,000 genes in each species, noting which genes had diverged since the two species had split off from a common ancestor. By applying a statistical test, they estimated that they could rule out neutral evolution in at least 19 percent of the 6,000 genes; in other words, natural selection drove the evolutionary divergence of a fifth of all genes studied. (Because the statistical test they employed was conservative, the actual proportion could be much larger.) The result does not suggest that neutral evolution is unimportant—after all, some of the remaining 81 percent of genes may have diverged by genetic drift. But it does prove that natural selection plays a bigger role in the divergence of species than most neutral theorists would have guessed. Similar studies have led most evolutionary geneticists to conclude that natural selection is a common driver of evolutionary change even in the sequences of nucleotides in DNA.

The Genetics of Natural Selection

Even when biologists turn to ordinary physical traits ("beaks, biceps and brains") and are confident that natural selection drove evolutionary change, they are often in the dark about just how it happened. Until recently, for instance, little was known about the genetic changes that underlie adaptive evolution. But with the new developments in genetics, biologists have been able to attack this problem head-on, and they are now attempting to answer several fundamental questions about selection. When organisms adapt by natural selection to a new environment, do they do so because of changes in a few genes or many? Can those genes be identified? And are the same genes involved in independent cases of adaptation to the same environment?

Answering those questions is not easy. The main difficulty is that the increase in fitness arising from a beneficial mutation can be very small, making evolutionary change quite slow. One way evolutionary biologists have coped with this problem is to place populations of rapidly reproducing organisms in artificial environments where fitness differences are larger and evolution is, therefore, faster. It also helps if the populations of the organisms are large enough to provide a steady stream of mutations. In microbial experimental evolution, a population of genetically identical microorganisms is typically placed in a novel environment to which they must adapt. Since all the individuals begin by sharing the same DNA sequence, natural selection must operate only on new mutations that arise during the experiment. The experimenter can then plot how the fitness of the population changes with time by measuring the rate of reproduction in the new environment.

Some of the most intriguing research in experimental evolution has been performed with bacteriophages, viruses so small that they infect bacteria. Bacteriophages have commensurately tiny genomes, and so it is practical for biologists to sequence their entire genomes at the beginning and end of experiments as well as at any time in between. That makes it possible to track every genetic change that natural selection "grabs" and then perpetuates over time.

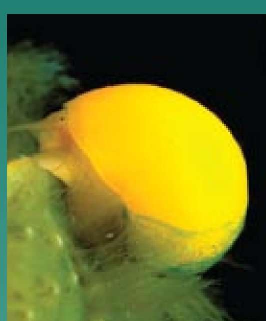
K. Kichler Holder and James J. Bull, both at the University of Texas at Austin, performed such an experiment with two closely related species of bacteriophages: ΦX174 and G4. Both viruses infect the common gut bacterium *Escherichia coli*. The experimenters subjected the bacteriophages to an unusually high temperature and allowed them to adapt to the new, warm environment. In both species, fitness in the new environment increased dramatically during the experiment. Moreover, in both cases the experimenters saw the same pattern: fitness improved rapidly near the start of the experiment and then leveled off with time. Remarkably, Holder and

EVOLUTION IN ACTION

In some animals, adaptive changes have unfolded fast enough to be observed:

Wild rabbit (Australia)
Animals brought from Europe changed in body size, weight and ear size as they adapted to the hot, dry Australian climate.

Scarlet honeycreeper (Hawaii)
As its favorite source of nectar began disappearing, the bird sought nectar elsewhere, and its bill became shorter.



Marine snail (New England)
Likely in response to being hunted by crabs, the snail's shell changed shape and became thicker.

ERIC WANDERS *Minden Pictures* (*European rabbit*); CHUCK BABBITT (*scarlet honeycreeper*); CHRISTOPHE COURTEAU *NPL* (*marine snail*)

Bull were able to identify the exact DNA mutations underlying the increased fitness.

Natural Selection "in the Wild"

Although research in experimental evolution provides an unprecedented view of natural selection in action, the approach remains limited to simple organisms for which repeated sequencing of entire genomes is feasible. Some workers have also cautioned that experimental evolution might involve unnaturally harsh selective pressures—perhaps much harsher than the ones encountered in the wild. We would like, then, to study selection in higher organisms under more natural conditions—and so we must find another way to investigate the glacial pace of much evolutionary change.

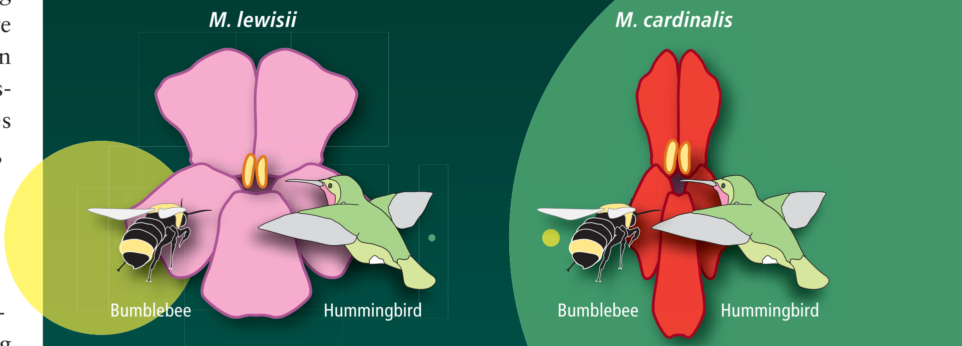
To do so, evolutionists typically turn to populations or species that have been separated long enough that the adaptive differences between them that were crafted by natural selection are readily found. Biologists can then study those differences genetically. For example, Douglas W. Schemske of Michigan State University and H. D. Bradshaw, Jr., of the University of Washington analyzed natural selection in two species of monkeyflower. Though closely related, *Mimulus lewisii* is pollinated primarily by bumblebees, whereas *M. cardinalis* is pollinated primarily by hummingbirds. Data from other species show that bird pollination in the genus *Mimulus* evolved from bee pollination.

Flower color alone—*M. lewisii* has pink flowers, and *M. cardinalis* has red [*see box at right*]—explains much of these differences in pollinator preference. When Schemske and Bradshaw crossed the two species, they showed that this color difference is controlled to a considerable extent by what appears to be a single gene called *Yellow Upper,* or *YUP*. On the basis of that finding, they created two kinds of hybrids. In the first kind, the *YUP* gene came from *M. cardinalis,* but the rest of the hybrid's genome derived from *M. lewisii*. The resulting flowers were orange. The second kind of hybrid was a "mirror image" of the first: the *YUP* gene came from *M. lewisii,* but the rest of the genome derived from *M. cardinalis*. The resulting flowers were pink.

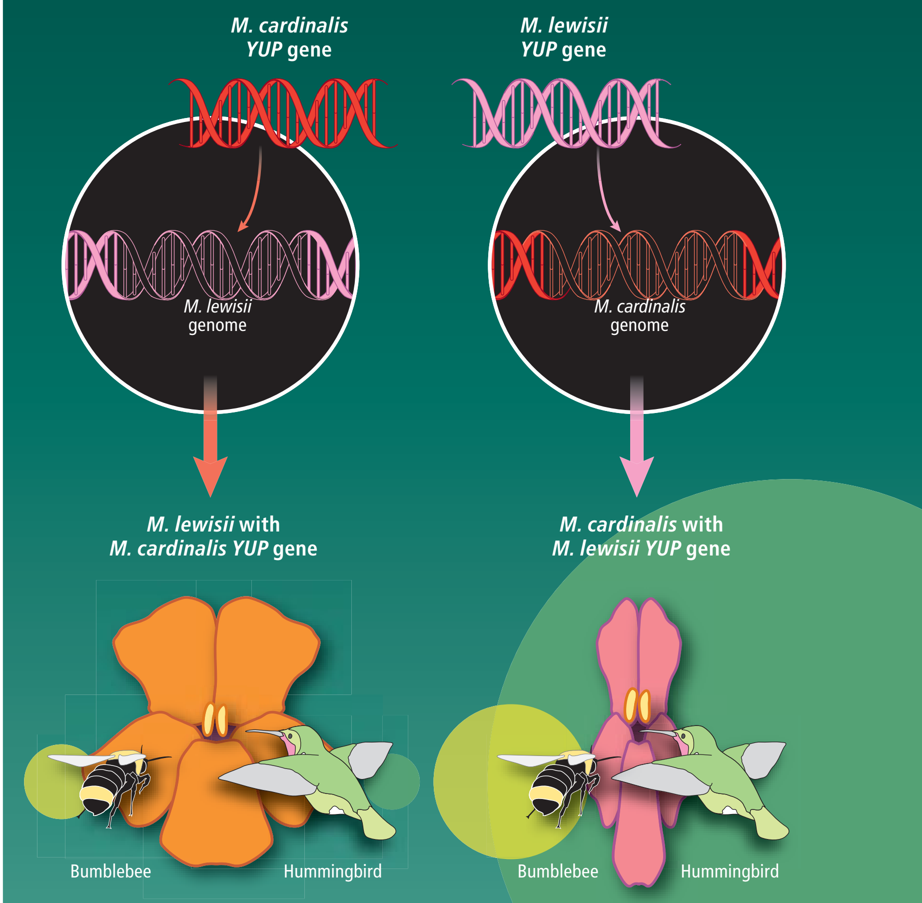
When the hybrids were transplanted into the wild, the investigators noted that *YUP* had an enormous effect on pollinator visitation: *M. lewisii* plants, for instance, that carried *YUP* from *M. cardinalis* were visited by hummingbirds about 68 times more often than were pure

Speciation and the Single Gene

Two species of monkeyflower that rarely interbreed in the wild owe much of their reproductive isolation to a difference in pollinators: bumblebees almost always pollinate *Mimulus lewisii;* birds almost never do (*below left*). Those patterns are reversed for *M. cardinalis* (*below right*). Flower color largely explains the differences, and a good deal of the color difference is almost certainly controlled by one gene: *Yellow Upper,* or *YUP*. The areas of the yellow and green circles in the diagrams reflect the frequencies of the pollinators' visits.



Research on monkeyflowers shows that mutations in what appears to be just one gene can contribute to the divergence of new species. Investigators created two kinds of hybrids by moving a small chromosome region known to contain the *YUP* gene, as shown below, and found that hummingbirds visited *M. lewisii* hybrids 68 times more often than they did pure *M. lewisii* plants. Similarly, bumblebees visited *M. cardinalis* hybrids 74 times more often than they did pure *M. cardinalis* plants.



TOMMY MOORMAN

M. lewisii plants; in the reciprocal experiment (*M. cardinalis* plants with *YUP* from *M. lewisii*), the effect was a 74-fold increase in bumblebee visits. There can be no doubt, then, that *YUP* played a major role in the evolution of bird pollination in *M. cardinalis*. Schemske and Bradshaw's work shows that natural selection sometimes builds adaptations from what appear to be fairly simple genetic changes.

The Origin of Species

One of Darwin's boldest claims for natural selection was that it explains how new species arise. (After all, the title of his masterpiece is *On the Origin of Species*.) But does it? What role does natural selection play in speciation, the splitting of a single lineage into two? To this day, these questions represent an important topic of research in evolutionary biology.

To understand the answers to those questions, one must be clear about what evolutionists mean by "species." Unlike Darwin, modern biologists generally adhere to the so-called biological species concept. The key idea is that species are reproductively isolated from one another—that is, they have genetically based traits preventing them from exchanging genes. Different species, in other words, have separate gene pools.

It is thought that two populations must be geographically isolated before reproductive isolation can evolve. The finches that inhabit various islands in the Galápagos Archipelago, which Darwin famously describes in *Origin of Species*, obviously diverged into the distinct species observed today after they became geographically isolated.

Once reproductive isolation does evolve, it can take several forms. For example, during courtship females of one species might refuse to mate with males of another (if the two species ever do come into geographic contact). Females of the butterfly species *Pieris occidentalis*, for instance, will not mate with males of the related species *P. protodice*, probably because the males of the two species have different wing patterns. And even if two species do court and mate, the inviability or sterility of any resulting hybrids can represent another form of reproductive isolation: genes cannot move from one species to another if all hybrids between them are dead or sterile. To contemporary biologists, then, the question of whether natural selection drives the origin of species reduces to the question of whether natural selection drives the origin of reproductive isolation.

For much of the 20th century, many evolutionists thought the answer was no. Instead they believed that genetic drift was the critical factor in speciation. One of the most intriguing findings from recent research on the origin of species is that the genetic drift hypothesis about the origin of species is probably wrong. Rather natural selection plays a major role in speciation.

A good example is the evolutionary history of the two monkeyflower species mentioned earlier. Because their pollinators seldom visit the "wrong" species of monkeyflower, the two species are almost completely isolated reproductively. Even though both species sometimes occur in the same locations in North America, a bumblebee that visits *M. lewisii* almost never visits *M. cardinalis*, and a hummingbird that visits *M. cardinalis* almost never visits *M. lewisii*. Thus, pollen is rarely transferred between the two species. In fact, Schemske and his colleagues showed that pollinator differences alone account for 98 percent of the total blockage in gene flow between the two species. In this case, then, there can be no doubt that natural selection shaped the plants' adaptations to distinct pollinators and gave rise to strong reproductive isolation.

Other evidence for the role of natural selection in speciation has come from an unexpected quarter. In the past decade or so several evolutionary geneticists (including me) have identified half a dozen genes that cause hybrid sterility or inviability. The genes in question—studied mostly in species of *Drosophila* fruit flies—play various normal roles within the species: some encode enzymes, others encode structural proteins, and yet others encode proteins that bind to DNA.

These genes exhibit two striking patterns. First, among the genes that cause problems in hybrid offspring, it turns out that many have diverged extremely rapidly. Second, population genetics tests show that their rapid evolution was driven by natural selection.

The studies of the monkeyflower and of hybrid sterility in fruit flies only begin to scratch the surface of a large and growing literature that reveals the hand of natural selection in speciation. Indeed, most biologists now agree that natural selection is the key evolutionary force that drives not only evolutionary change within species but also the origin of new species. Although some laypeople continue to question the cogency or adequacy of natural selection, its status among evolutionary biologists in the past few decades has, perhaps ironically, only grown more secure. ■

MORE TO EXPLORE

Pollinator Preference and the Evolution of Floral Traits in Monkeyflowers (*Mimulus*). Douglas W. Schemske and H. D. Bradshaw, Jr., in *Proceedings of the National Academy of Sciences USA,* Vol. 96, No. 21, pages 11910–11915; October 12, 1999.

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What's Good for the Group

Does natural selection drive evolution at levels higher than selfish genes and fertile individuals? **BY STEVE MIRSKY**

Want to start a brawl at an evolution conference? Just bring up the concept of group selection: the idea that one mixed bag of individuals can be "selected" as a group over other heterogeneous groups from the same species. Biologists who would not hesitate to form a group themselves to combat creationism or intelligent design might suddenly start a pie fight to defend the principle that "it's every man for himself."

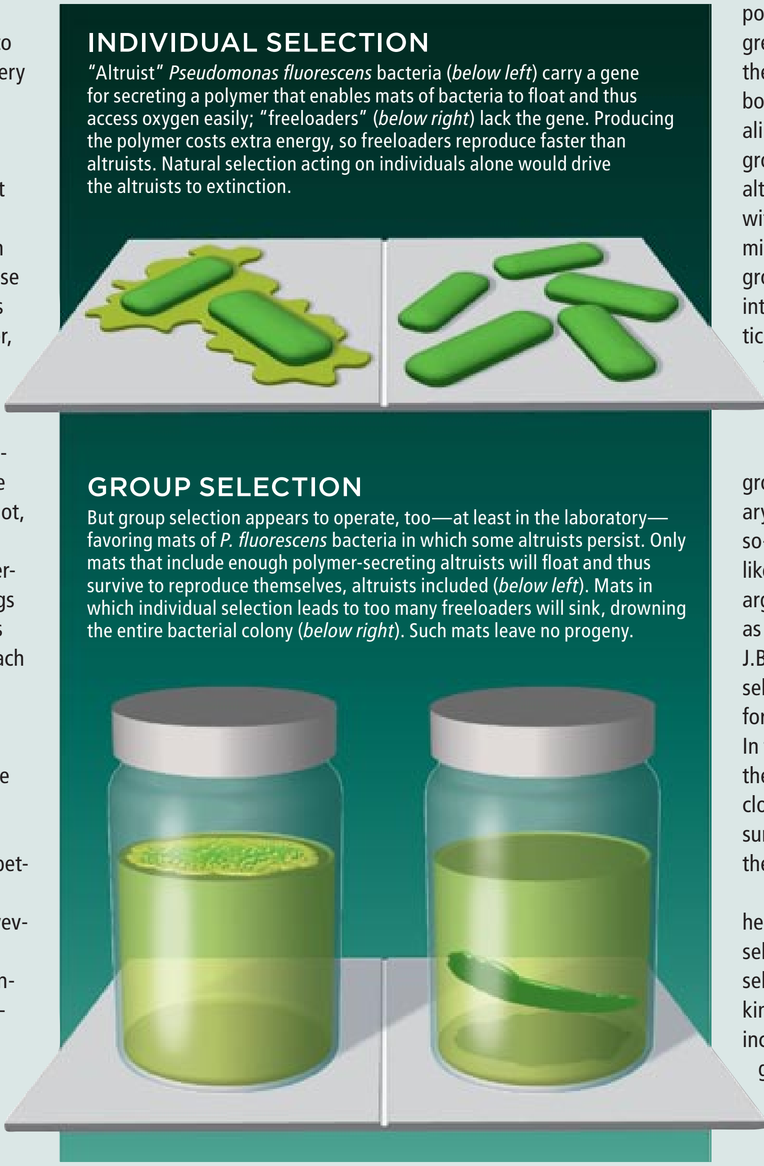
Yet Charles Darwin himself argued for group selection. He postulated that moral men might not do any better than immoral men but that tribes of moral men would certainly "have an immense advantage" over fractious bands of pirates. By the 1960s, however, selection at the group level was on the outs. Influential theorist George Williams acknowledged that although group selection might be possible, in real life "group-related adaptations do not, in fact, exist."

Richard Dawkins of the University of Cambridge, whose writings have reached millions, maintains that selection might not even reach such a high level of biological organization as the individual organism. Instead, he claims, selection operates on genes—the individual is the embodiment of the selection of thousands of selfish genes, each trying to perpetuate itself.

In the past few decades, however, group selection has made a quiet comeback among evolutionary theorists. E. O. Wilson of Harvard University and David Sloan Wilson (no relation) of Binghamton University are trying to give group selection full-fledged respectability. They are rebranding it as multilevel selection theory: selection constantly takes place on multiple levels simultaneously. And how do you figure the sum of those selections in any real-world circumstance? "We simply have to examine situations on a case-by-case basis," Sloan Wilson says.

But the Wilsons did offer some guidelines in the December 2007 issue of *Quarterly Review of Biology.* "Adaptation at any level," they write, "requires a process of natural selection at the same level, and tends to be undermined by natural selection at lower levels."

Experiments with actual groups illustrate the point. *Pseudomonas fluorescens* bacteria quickly suck all the dissolved oxygen out of a liquid habitat, leaving a thin habitable layer near the surface. But some bacteria spontaneously develop a beneficial mutation. These group-saving individuals secrete a polymer that enables bunches of individuals to form floating mats. As a mat, all the bacteria survive, even though most of them expend no metabolic energy producing the polymer. But if the freeloaders get greedy and reproduce too many of their kind, the mat sinks and everybody dies, altruists and freeloaders alike. Among these bacteria, then, groups that maintain enough altruists to float outcompete groups with fewer altruists than that minimum number. The former groups survive, grow and split up into daughter groups. Thus, altruistic individuals can prosper, despite the disadvantage of expending precious resources to produce the polymer.



INDIVIDUAL SELECTION

"Altruist" *Pseudomonas fluorescens* bacteria (*below left*) carry a gene for secreting a polymer that enables mats of bacteria to float and thus access oxygen easily; "freeloaders" (*below right*) lack the gene. Producing the polymer costs extra energy, so freeloaders reproduce faster than altruists. Natural selection acting on individuals alone would drive the altruists to extinction.

GROUP SELECTION

But group selection appears to operate, too—at least in the laboratory—favoring mats of *P. fluorescens* bacteria in which some altruists persist. Only mats that include enough polymer-secreting altruists will float and thus survive to reproduce themselves, altruists included (*below left*). Mats in which individual selection leads to too many freeloaders will sink, drowning the entire bacterial colony (*below right*). Such mats leave no progeny.

TOMMY MOORMAN

Perhaps the biggest change that group selection brings to evolutionary theory is its implication for so-called kin selection. What looks like group selection, some theorists argue, can actually be understood as genetic relatedness. Evolutionist J.B.S. Haldane pithily explained kin selection: "I would lay down my life for two brothers or eight cousins." In this view, altruistic bacteria in the *Pseudomonas* mats are saving close relatives, thereby ensuring the survival of most of the genes they themselves also carry.

Turning that argument on its head, the Wilsons assert that kin selection is a special case of group selection. "The importance of kinship," they note, "is that it increases genetic variation among groups." The individuals within any one group are much more like one another and much less like the individuals in any other group. And that diversity between groups presents clearer choices for group selection. Kinship thus accentuates the importance of selection at the group level as compared with individual selection within the group.

The Wilsons think evolutionists must embrace multilevel selection to do fruitful research in sociobiology—"the study of social behavior from a biological perspective." When doing so, other investigators can keep in mind the Wilsons' handy rule of thumb: "Selfishness beats altruism within groups. Altruistic groups beat selfish groups."

Steve Mirsky is a member of the board of editors at *Scientific American.*

From Atoms to Traits

Charles Darwin saw that random variations in organisms provide fodder for evolution. Modern scientists are revealing how that diversity arises from changes to DNA and can add up to complex creatures or even cultures

BY DAVID M. KINGSLEY

On a shelf in a library in Texas sits a small green volume, originally published 150 years ago and now generally recognized as one of the most important scientific books ever written. Its future success was not at all apparent when this first-edition copy of *On the Origin of Species* was printed, however. As Charles Darwin finished the proofs of his new work, he drew up a short list of important colleagues who should receive advance copies. He then anxiously awaited the verdicts of the leading thinkers of his time.

England's most famous living scientist in 1859 scribbled his reactions in notes found throughout that little green volume preserved at the University of Texas at Austin. Marked "from the author" on its frontispiece, it is the advance copy that Darwin sent to Sir John Herschel, one of his scientific heroes, whose own treatise on natural philosophy had first inspired Darwin to become a scientist. In the 1830s Herschel had memorably described the origin of species as a "mystery of mysteries" that might occur by natural processes. Darwin quoted Herschel's words in the very first paragraph of the book, which laid out the ingenious solution to the "mystery of mysteries" that Darwin was offering to both Herschel and the world.

Darwin's theory was at once sweeping and simple. He proposed that all living things on earth are descended from one or a few original forms. He did not presume to know how life itself first arose. Once life began, though, Darwin argued, organisms would slowly begin to change and diversify through a completely natural process: all living things vary; the differences are inherited. Those individuals with trait variants that are favorable in the environment they inhabit will thrive and produce more offspring than individuals with unfavorable variants. Advantageous traits will therefore accumulate over time by an inevitable process of "natural selection." To convince readers of the cumulative power of spontaneous variation and differential reproduction, Darwin pointed to the huge changes in size and form that had occurred in domesticated plants, pigeons and dogs after only a few centuries of selective breeding by humans.

Some of his scientific colleagues instantly saw the power of Darwin's argument. "How stupid of me not to have thought of that!" exclaimed Thomas Henry Huxley, after reading his own advance copy of Darwin's book. Unfortunately, the reaction of the man whose opinion Darwin said he valued "more than that of almost any other human being" was far less favorable. Herschel did not believe that useful new traits and species could arise from simple random variation, an idea he dismissed as the "law of higgletly-pigglety." In his personal copy of *Origin of Species,* Herschel zeroed in on the fact that "favorable variations must 'occur' if anything is to be 'effected.'" Darwin actually knew nothing about

KEY CONCEPTS

- The idea that nature "selects" favorable variations in organisms was at the heart of Charles Darwin's theory of evolution, but how those variations arise was a mystery in Darwin's time.
- Random changes in DNA can give rise to changes in an organism's traits, providing a constant source of variation.
- Certain kinds of DNA changes can produce major differences in form and function, providing raw material for the evolution of new species and even new human cultures. —*The Editors*

the origin of the variant traits themselves, and Herschel felt that if Darwin could not explain the source of variation, he did not really have a theory sufficient to explain the origin of species.

In the 150 years since the debut of Darwin's theory, key questions about how traits are passed down to subsequent generations and how they undergo evolutionary change have been resolved by remarkable progress in the study of genes and genomes. Darwin's scientific descendants studying evolutionary biology today understand at least the basic molecular underpinnings of the beautiful diversity of plants and animals around us. Like Darwin's theory itself, the causes of variation are often simple, yet their effects are profound. And fittingly, these insights have come in a series of steps, many of them just in time for the successive 50-year anniversaries of Darwin's book.

Variation Revealed

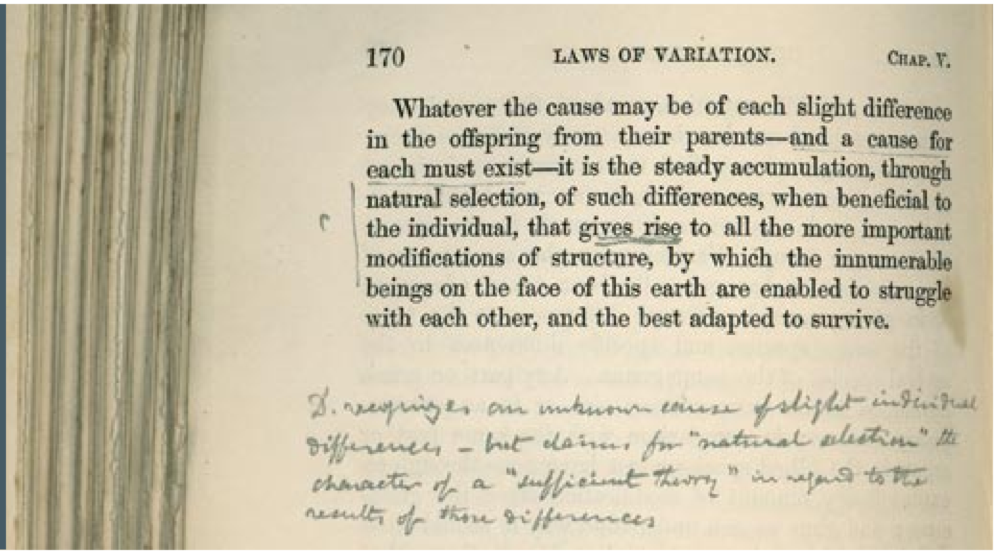
Darwin was not only unable to say where variants came from, he did not explain how those new traits could spread in subsequent generations. He believed in blending inheritance, the idea that offspring take on characteristics intermediate between their parents. But even Darwin recognized that the theory was problematic because if traits truly blended, then any rare new variant would be progressively diluted by generations of breeding with the great mass of individuals that did not share the trait.

Confusion about blending inheritance was swept away in 1900 by the rediscovery of Gregor

AMADEO BACHAR

VARIATION in a pea plant, and in all life, stems from DNA.

SIR JOHN HERSCHEL, a prominent scientist of Charles Darwin's era, doubted the theory laid out in *On the Origin of Species.* Because Darwin could not explain the cause of trait variations, the idea that nature selected the advantageous variants seemed incomplete. In his personal copy of the book, Herschel wrote, "D. recognizes an unknown cause of slight individual differences—but claims for 'natural selection' the character of a 'sufficient theory' in regard to the results of those differences."



170 LAWS OF VARIATION. CHAP. V.

Whatever the cause may be of each slight difference in the offspring from their parents—and a cause for each must exist—it is the steady accumulation, through natural selection, of such differences, when beneficial to the individual, that gives rise to all the more important modifications of structure, by which the innumerable beings on the face of this earth are enabled to struggle with each other, and the best adapted to survive.

D. recognizes an unknown cause of slight individual differences – but claims for "natural selection" the character of a "sufficient theory" in regard to the results of those differences

Mendel's famous breeding experiments with peas, conducted in the 1850s and 1860s. Different pea plants in the Austrian monk's garden showed obvious morphological differences, such as tall versus short stems, wrinkled versus smooth seeds, and so forth. When true-breeding pea plants of contrasting types were crossed, the offspring usually resembled one of the two parents. With further crosses, both forms of a trait could reappear in undiluted form in future generations, however, demonstrating that the genetic information for alternative forms had not blended away. Mendel's experiments changed the general perception of heritable variants from ephemeral and blendable to discreet entities passed from parents to offspring, present even though they are not always visible.

Soon the inheritance patterns of Mendel's "genetic factors" were, intriguingly, found to be mirrored by the behavior of chromosomes in the cell nucleus. At the 50-year anniversary of *Origin of Species,* the origin of variants was still unknown, but genetic information was becoming a physical entity, and it was finally visible as threads inside the nucleus. By the 100th anniversary of the book's publication, hereditary information in chromosomes had already been traced to a large acidic polymer called deoxyribonucleic acid (DNA). James D. Watson and Francis Crick had proposed a structure for the DNA molecule in 1953, with stunning implications for our physical understanding of heredity and variation.

DNA is a long, two-stranded helix, with a backbone made of repetitive chains of sugar and phosphate. The two strands of the polymer are held together by the complementary pairing between four possible chemical bases: adenine, cytosine, guanine and thymine (A, C, G, T), which also form the foundation of a simple genetic language. Just like the 26 letters in the English alphabet, the four chemical letters in the DNA alphabet can occur in any sequence along one strand of the helix, spelling out different instructions that are passed from parent to offspring.

The double-stranded helix provides a clear mechanism for copying genetic information as well. Cs always pair with Gs, and As pair with Ts across the middle of the DNA molecule, with these affinities determined by the complementary size, shape and bonding properties of the corresponding chemical groups. When the two strands of the DNA helix are separated, the sequence of letters in each strand can therefore be used as a template to rebuild the other strand.

Watson and Crick's DNA structure immediately suggested a possible physical basis for spontaneous variation. Physical damage or mistakes made in copying the DNA molecule prior to cell division might alter its normal sequence of letters. Mutations could take many different forms: substitution of a single letter for another at a particular position in the polymer, deletion of a block of letters, duplication or insertion of new letters, or inversion and translocation of the letters already present. Such changes were still theoretical at the time the structure was proposed. But as the 150th anniversary of Darwin's famous publication approaches, large-scale sequencing methods have made it possible to read entire genomes and to study genetic variation—the raw material for his proposed evolutionary process—with unprecedented detail.

By sequencing various organisms and their offspring, then looking for any spontaneous

THE AUTHOR

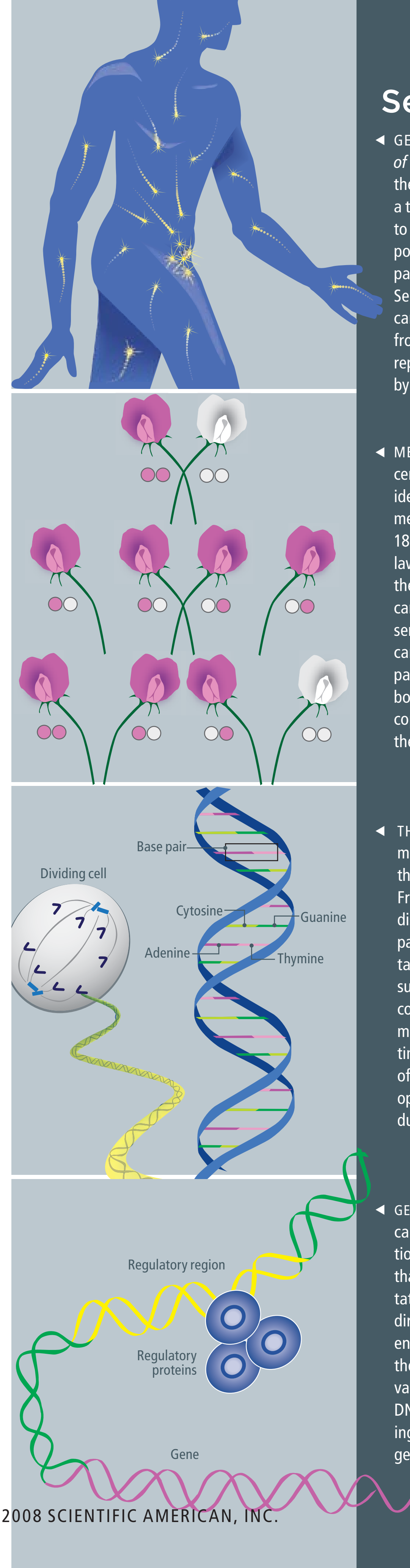
David M. Kingsley is professor of developmental biology at the Stanford University School of Medicine and a Howard Hughes Medical Institute investigator. His studies of how genes control the development and maintenance of skeletons and joints shed light on modern health problems as well as on the evolution of new animal forms over the course of millennia. Kingsley has shown how several basic genetic mechanisms work in diverse organisms to create new traits in natural populations.

COURTESY OF DAVIS T. KINGSLEY (*author*); COURTESY OF THE HARRY RANSOM CENTER, UNIVERSITY OF TEXAS AT AUSTIN (*book*) changes in the long chain of DNA letters passed from generation to generation, scientists have clearly shown that such mutations do occur fairly regularly. (Of course, only mutations that occur in germ cells would be passed to offspring and therefore detectable in this manner.) Absolute rates of mutation differ in different species but typically average 10^{-8} per nucleotide per generation for single base-pair substitutions. That frequency may sound low, but many plants and animals have very large genomes. In a multicellular animal with 100 million or even 10 billion base pairs in its genome, some spontaneous single base-pair changes are likely to occur every time hereditary information is passed down.

Particular types of substitutions are more likely than others, based on the chemical stability and structural properties of the DNA bases. In addition, some types of larger sequence changes occur much more frequently than the overall average rate of single base-pair substitutions. Stretches of DNA with eight or more identical letters in a row, known as homopolymers, are very prone to copying errors during the process of DNA replication, for example. So are regions known as microsatellites that consist of sequences of two, three or more nucleotides repeated over and over.

All these spontaneous changes within genomes add up to a lot of diversity, even within a single species, including our own. In a historic milestone, a reference sequence for the entire three-billion-base-pair human genome was completed in 2003, and four years later the nearly complete personal genome of Watson was published, making it possible to compare the two human sequences to each other and to that of Celera founder Craig Venter, whose genome sequence has also been made public. A side-by-side comparison of the three sequences offers several interesting revelations.

First, each individual's genome differs from the reference sequence by roughly 3.3 million single base-pair changes, which corresponds to variation in one of every 1,000 bases on average. Although deletions and insertions of larger DNA stretches and whole genes are not as frequent as single base-pair changes (a few hundred thousand instead of a few million events per genome), these events account for the majority of total bases that differ between genomes, with up to 15 million base pairs affected. Many entire genome *regions* have also recently been found to exist in different copy numbers between individuals, which reflects an unappreciated level of genome



MELISSA THOMAS

Seeking Variation

◀ GEMMULES: Nine years after *Origin of Species,* Darwin put forth his theory that a new variant version of a trait might be passed from parent to offspring, and thus into the larger population, by "infinitely minute" particles that he called gemmules. Secreted by cells, the particles would carry the essence of the body parts from which they derived to the reproductive organs, to be absorbed by the germ cells.

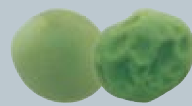
◀ MENDEL'S FACTORS: Early 20th-century scientists rediscovered the ideas of Gregor Mendel, who experimented with pea plants during the 1850s and 1860s to derive detailed laws of inheritance. Mendel posited the existence of discrete factors carrying trait information and observed that each individual would carry two copies—one from each parent—of a given factor. Although both were present, only one of the copies would dominate and produce the visible trait.

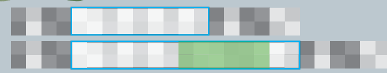
◀ THE DOUBLE HELIX: The DNA molecule was already recognized as the vehicle for trait information when Francis Crick and James D. Watson discovered its structure in 1953. The paired strands joined by complementary chemical bases immediately suggested both an alphabet to convey the genetic message and a mechanism for it to change. Each time a cell divides, it makes a copy of its chromosomes, providing an opportunity for "typos" to be introduced into the sequence of bases.

◀ GENE REGULATION; Mendel 's factors came to be known as genes, traditionally defined as stretches of DNA that encode a protein. Typos, or mutations, can alter or disable genes directly, but in the past decade scientists have also come to appreciate the importance of another source of variation: mutations that alter a DNA region responsible for regulating when and where in the body a gene is activated.

○○○ The Origin of Variation

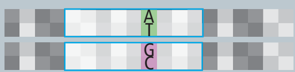
Random changes to an organism's DNA can produce trait variations that are subtle or dramatic. The nature of the DNA mutation can also range from a simple substitution of one base pair for another to the duplication of entire genes or chromosomal regions. Examples below illustrate many of the ways spontaneous DNA alterations can give rise to diversity.





Insertion

In pea plants, an 800-base-pair sequence inserted into a gene produces peas that are wrinkled rather than smooth. The intruding DNA element disables a gene necessary for starch synthesis, altering the peas' sugar and water content. Such mobile elements are seen in the genomes of most multicellular organisms, including humans.



Point Mutation

In whippet dogs, a single base-pair change makes the difference between a slender silhouette and the hulking animal at the right. The mutation inactivates the gene for a signaling molecule that regulates muscle growth. In animals with both copies of the gene mutated, muscle growth is uncontrolled for lack of a "stop" signal. (When only one copy of the gene is disabled, the dogs are moderately more muscular and prized as racers.)

Gene Copy Number

Entire genes can be duplicated by copying errors during cell division, leading to differences between species and to variation among members of the same species. The genome of chimpanzees, which eat mostly green plants, normally contains just a single gene for the starch-digesting enzyme salivary amylase, whereas humans can carry up to 10 copies of the gene.

structural variation whose implications scientists are only beginning to explore. Finally, the sequence changes seen when comparing complete human genomes alter either the protein-encoding or regulatory information or the copy number of a substantial proportion of all 23,000 human genes, providing an abundant source of possible variation underlying many traits that differ between people.

The Molecular Basis of Traits

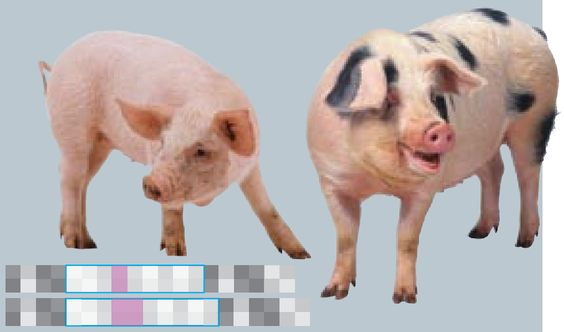
Herschel wanted an answer for how and why variants arose before he could accept Darwin's theory that natural selection acts on those traits, generating new living forms by completely natural processes. Today scientists know that spontaneous changes in DNA are the simple "why" of variation, but the answer to "how" those mutations translate into trait differences is more complex and makes for an active field of research with implications far beyond evolution studies.

Biologists can now often connect the dots all the way from classic morphological and physiological traits in plants and animals to specific changes in the atoms of the DNA double helix. They know, for example, that Mendel's tall and short pea plants differ by a single G to A substitution in a gene for the enzyme gibberellin oxidase. The so-called short variant of the gene changes a single amino acid in the enzyme, which reduces enzyme activity and causes a 95 percent drop in the production of a growth-stimulating hormone in the stems of the pea plants.

In contrast, Mendel's wrinkled seed trait results from the insertion of an 800-base-pair sequence in a gene for a starch-related enzyme. That inserted sequence interferes with the enzyme's production, reducing starch synthesis and producing changes in sugar and water content that lead to sweeter but wrinkly seeds. The inserted sequence also appears at multiple other locations in the pea genome, and it has all the hallmarks of a transposable element—a block of DNA code that can move from one place in the genome to another. Such "jumping" elements within genomes may be yet another common source of new genetic variants—either by inactivating genes or by creating new regulatory sequences that change gene activity patterns.

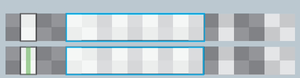
One of the few generalizations evolutionary

WALLY EBERHART (*peas*); ZUMA LIVE/NEWSCOM (*mutated whippet*); TRACY MORGAN (*whippet*); FRANS LANTING *Corbis* (*chimp*); ALTRENDO IMAGES (*boy*)



Duplication

Sequences containing the same base pair repeated eight or more times, known as homopolymers, are highly prone to copying errors. In pigs, the gain of two additional C-G pairs in such a sequence inactivates a gene for a signal receptor in pigment cells, producing light-colored coats. Copying mistakes within individual cells can also cause the duplicated sequence to lose bases, restoring the gene's function and producing dark patches on the body.



Regulatory Changes

Mutations in the DNA that controls when and where genes are activated can produce profound trait changes by altering the formation of entire body parts during the organism's development. Changes in the regulatory regions of a single gene that controls patterns of cell division during stem development account for much of the shape difference between the bushy teosinte plant (*top*) and its descendant, the tall modern cornstalk.

biologists can make about the nature of variation is that one usually cannot tell just by looking what the underlying genetic source of a trait variant is going to be. Darwin wrote extensively about dramatic morphological differences present in pigeons, dogs and other domesticated animals, for example. Today we know that the interesting traits in domesticated animals are based on many different types of DNA sequence change.

The difference between black and yellow color in Labrador retrievers stems, for instance, from a single base change that inactivates a signal receptor in the pigment cells of yellow dogs. Increased muscle size and improved racing performance in whippet dogs have also been traced to a single base-pair change, which inactivates a signal that normally suppresses muscle growth. In contrast, the special dorsal stripe of hair in Rhodesian ridgeback dogs comes from the duplication of a 133,000-base-pair region containing three genes that encode a growth factor for fibroblast cells, which amps up production of the growth factor.

Modern-day critics of Darwin and evolutionary theory have often suggested that small differences such as these between individuals might arise by natural processes, but bigger structural differences between species could not have done so. Many small changes can add up to big ones, however. In addition, certain genes have powerful effects on cell proliferation and cell differentiation during embryonic development, and changes in those control genes can produce dramatic changes in the size, shape and number of body parts. A subspecialty within evolutionary biology that has come to be known as evo-devo concentrates on studying the effects of changes in important developmental genes and the role they play in evolution.

The potent influence of such genes is illustrated by the modern maize plant, which looks completely different from a wild, weedy ancestor called teosinte in Central America. Many of the major structural differences between maize and teosinte map to a few key chromosome regions. Mutations in a regulatory area of a single gene that controls patterns of cell division during plant stem development account for much of the difference between an overall bush shape and a single, central stalk. Changes in a second gene that is active during seed development help to transform the stony, mineral-encased seeds of teosinte into the softer, more exposed kernels of maize. Ancient Mesoamerican farmers developed maize from teosinte without any direct knowledge of DNA, genetics or development, of course. But by mating plants with desirable properties, they unwittingly selected spontaneous variants in key developmental control genes and thereby converted a bushy weed into a completely different looking plant that is useful for human agriculture in relatively few steps.

Similar principles underlie the evolution of new body forms in completely wild populations of stickleback fish. When the last Ice Age ended 10,000 years ago, migratory populations of ocean fish colonized countless newly formed lakes and streams in North America, Europe and Asia. These populations have since had approximately 10,000 generations to adapt to the new food sources, new predators, and new water colors, temperatures and salt concentrations found in the freshwater environments. Today many freshwater stickleback species show structural differences that are greater than those seen between different genera of fish, including 30-fold changes in the number or size of their bony plates, the presence or absence of entire fins, and major changes in jaw and body shape, tooth structures, defensive spines and body color.

STICKLEBACKS ADAPT

In just 10,000 generations, three-spined stickleback fish have evolved myriad forms to suit diverse environments. Mutations affecting the activity of three developmental-control genes have produced striking anatomical changes, including the complete loss of pelvic hind fins, large differences in bony armor and much lighter skin color. In each fish pair shown below, a typical marine ancestor is on top and an evolved freshwater stickleback is underneath.

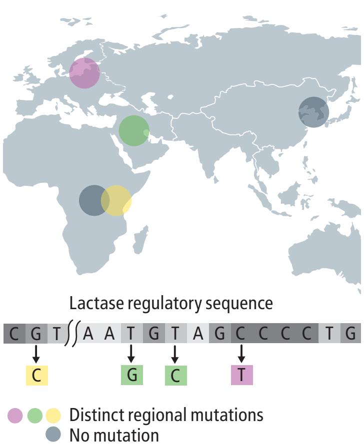
BILL LING (*pig*); PETER ANDERSON (*spotted pig*); JERRY FRIEDMAN *Creative Commons Attribution-Share Alike 3.0 Unported (teosinte)*; PAUL DAMIEN *National Geographic (cornstalks)*; MICHAEL SHAPIRO, PAMELA COLOSIMO, FRANK CHAN, CRAIG MILLER AND DAVID M. KINGSLEY *Stanford University (sticklebacks)*

Mutations Meet Culture

Humans need only look at our own genomes to find striking examples of relatively recent variations that have produced novel traits, ranging from disease resistance to skin color. In the case of some dietary adaptations, the changes enabled entire populations to take up new ways of life, such as herding and agriculture. An example of such a trait, the ability to digest milk into adulthood, is found to have arisen independently in groups on different continents, attesting to the great nutritional advantage the variant provides and to the possibility of directly connecting simple DNA sequence changes to human cultural evolution.

Lactose Tolerance

An enzyme called lactase, produced in the intestines, allows infants and children to digest the complex milk sugar lactose. Only a minority of people continue to produce lactase as adults, and in 2002 that ability was traced in Europeans to a mutation in regulatory DNA that controls the lactase gene. More recently, different mutations affecting the same gene were found to predominate in East African and Saudi Arabian populations (*below*) who traditionally herd milk-producing animals. The differing DNA changes indicate that the trait of lactose tolerance has arisen independently many times in the past 9,000 years. Its retention in milk-dependent societies also illustrates how culture can reinforce the forces of evolution.



DISTINCT MUTATIONS in the same regulatory region of DNA that controls the lactase gene predominate in different regions of the world.

Just as with maize, recent genetic studies show that some of the large morphological changes can be mapped to a few important chromosome regions. And the key genes within these regions turn out to encode central regulators of development. They include a signaling molecule that controls the formation of many different surface structures, another molecule that turns on batteries of other genes involved in limb development, and a secreted stem cell factor that controls the migration and proliferation of precursor cells during embryonic development.

The overall evolution of diverse new stickleback forms clearly involves multiple genes, but some of the same variants in particular developmental regulators have been seen repeatedly in independent populations. The adaptation of these fish to their respective environments thus demonstrates nicely how random variations can give rise to major differences among organisms, and if those changes confer an advantage, natural selection will preserve them, again and again.

The Casual Concourse of Atoms

Humans can also look in the mirror and see further examples of relatively recent variation preserved by natural selection. We come in a variety of colors in different environments around the world, and the lighter skin shades found in populations at northern latitudes have recently been traced to the combined effects of several genetic changes, including single-base mutations in the genes for a signal receptor and a transporter protein active in pigment cells. Additional changes in DNA that regulate the migration, proliferation and survival of nascent pigment cells are also suspected.

A relative lack of variation in the DNA regions flanking two of these pigment genes suggests the light-skin variants were initially rare and probably originated with a small number of people. The variants would have then rapidly increased in frequency as ancient humans migrated into new environments with colder temperatures and higher latitudes, where light skin more

STEFAN BECKER (*herder with cows*); MELISSA THOMAS (*map*)

Skin Color
Changes to at least three genes have been linked to the trait of light-colored skin, which is believed to have arisen in northern Europe. Light skin more easily absorbs ultraviolet rays needed to produce vitamin D, an advantage where sunlight is limited.

Starch Digestion
People vary widely in the number of copies they carry of a gene for the starch-digesting enzyme salivary amylase. Members of cultures with starch-rich diets tend to have higher numbers of the amylase gene and high levels of the enzyme in their saliva.

PATRIK GIARDINO *Corbis* (*women*); TRAVEL INK (*man with rice pot*)

readily makes vitamin D from limited sunlight.

Similarly, strong molecular "signatures of selection" have been found around a gene that controls the ability to digest lactose, the predominant sugar in milk. Humans are mammals, nurse their young and produce an intestinal enzyme that breaks lactose into the simpler sugars glucose and galactose. Humans are also unique among mammals in continuing to use the milk of other animals as a significant source of nutrition well beyond childhood. This cultural innovation has occurred independently in groups in Europe, Africa and the Middle East, using milk derived from cattle, goats and camels.

An ability to digest milk in adulthood depends on a mutant form of the intestinal lactase gene, which in most mammals and most human groups, is active only during the infant nursing period. In humans from populations with a long history of dairy herding, however, a mutant form of the lactase gene continues to be active in adulthood. This genetic innovation has been linked to single base-pair changes in the regulatory DNA regions that control the gene, but different lactose-tolerant populations have different mutations in the key region—a striking example of the repeated evolution of a similar trait by independent changes affecting one gene.

Another example of a recent nutrition-related adaptation in humans involves the multiplication of a complete gene. Whereas chimpanzees have only one copy of the gene for salivary amylase, an enzyme that digests starch in food, humans show marked variation in the number of amylase gene copies they carry. In some individuals, duplications of the gene have produced as many as 10 copies along a single chromosome. People from cultures that eat diets rich in starch, such as rice, have higher average amylase gene copy numbers and higher amylase enzyme levels in their saliva than do people from cultures that rely on hunting and fishing.

Dairy herding and agriculture both arose in the past 10,000 years. Although that only corresponds to just 400 or so human generations, major new sources of nutrition are clearly already leading to the accumulation of novel genetic variants in populations that exploit those food sources.

Herschel's most persistent objection to Darwin's theory was his feeling that useful new traits could never appear from simple random variation. In published comments and letters, he argued that such characteristics would always require "mind, plan, design, to the plain and obvious exclusion of the haphazard view of the subject and the casual concourse of atoms." Herschel was correct to point out that the origin of variation was still a mystery in 1859. After 150 years of additional research, however, we can now catalogue a variety of spontaneous DNA sequence variants that occur every time a complex genome is passed from parents to offspring.

Only a tiny fraction of these changes are likely to improve, rather than degrade, the original hereditary information and the trait that derives from it. Nevertheless, sweeter peas, bigger muscles, faster running ability or improved ability to digest new foods have all arisen from simple new arrangements of atoms in the DNA sequence of peas, dogs and humans. Thus, the "casual concourse of atoms" clearly can generate interesting new traits. And the intrinsic variability of living organisms continues to provide the raw material by which, in Darwin's famous words at the end of his small green book, "endless forms most beautiful and most wonderful, have been, and are being evolved." ■

MORE TO EXPLORE

***cis*-Regulatory Changes in *Kit Ligand* Expression and Parallel Evolution of Pigmentation in Sticklebacks and Humans.** Craig T. Miller et al. in *Cell*, Vol. 131, No. 6, pages 1179–1189; December 14, 2007.

Independent Introduction of Two Lactase-Persistence Alleles into Human Populations Reflects Different History of Adaptation to Milk Culture. Nabil S. Enattah et al. in *American Journal of Human Genetics*, Vol. 82, No. 1, pages 57–72; 2008.

Evolution: Constant Change and Common Threads. HHMI 2005 Holiday Lectures on Science. Sean B. Carroll and David M. Kingsley. Webcast or DVD available at **www.hhmi.org/biointeractive/evolution**

THE HUMAN PEDIGREE

Some 180 years after unearthing the first human fossil, paleontologists have amassed a formidable record of our forebears

• • • BY KATE WONG
• • • Illustrations by Viktor Deak

When Charles Darwin wrote *On the Origin of Species*, he pondered the evolution of organisms ranging from orchids to whales. Conspicuously missing from his magnum opus, however, was any substantive discussion of how humans might have arisen. He wrote only "light will be thrown on the origin of man and his history." Scholars attribute Darwin's relative silence on this matter to reluctance on his part to further nettle the Victorian establishment (and his pious wife), for whom the origin of all living things—especially humans—was God's work.

Thomas Henry Huxley, the biologist otherwise known as "Darwin's bulldog," had no such reservations. In 1863 Huxley penned *Evidence as to Man's Place in Nature*, in which he explicitly applied Darwin's theory of evolution to humans, arguing that we had descended from apes. Eight years later Darwin himself, possibly encouraged by Huxley's effort, wrote *The Descent of Man*. In it he declared the chimpanzee and gorilla our closest living relatives based on anatomical similarities and predicted that the earliest ancestors of humans would turn up in Africa, where our ape kin live today. At the time, only a handful of human fossils were known—all of them Neandertals from sites in western Europe.

Since then, abundant evidence from fossils and genetic analyses has validated Darwin's claims. We now know that our closest living relative is the chimpanzee and that humans arose in Africa between five million and seven million years ago, after our lineage diverged from that of the chimp. We have also learned that for much of human prehistory, our predecessors shared the planet with one or more other hominid species. Indeed, far from being a linear succession of increasingly upright creatures, the human family tree contains many dead branches.

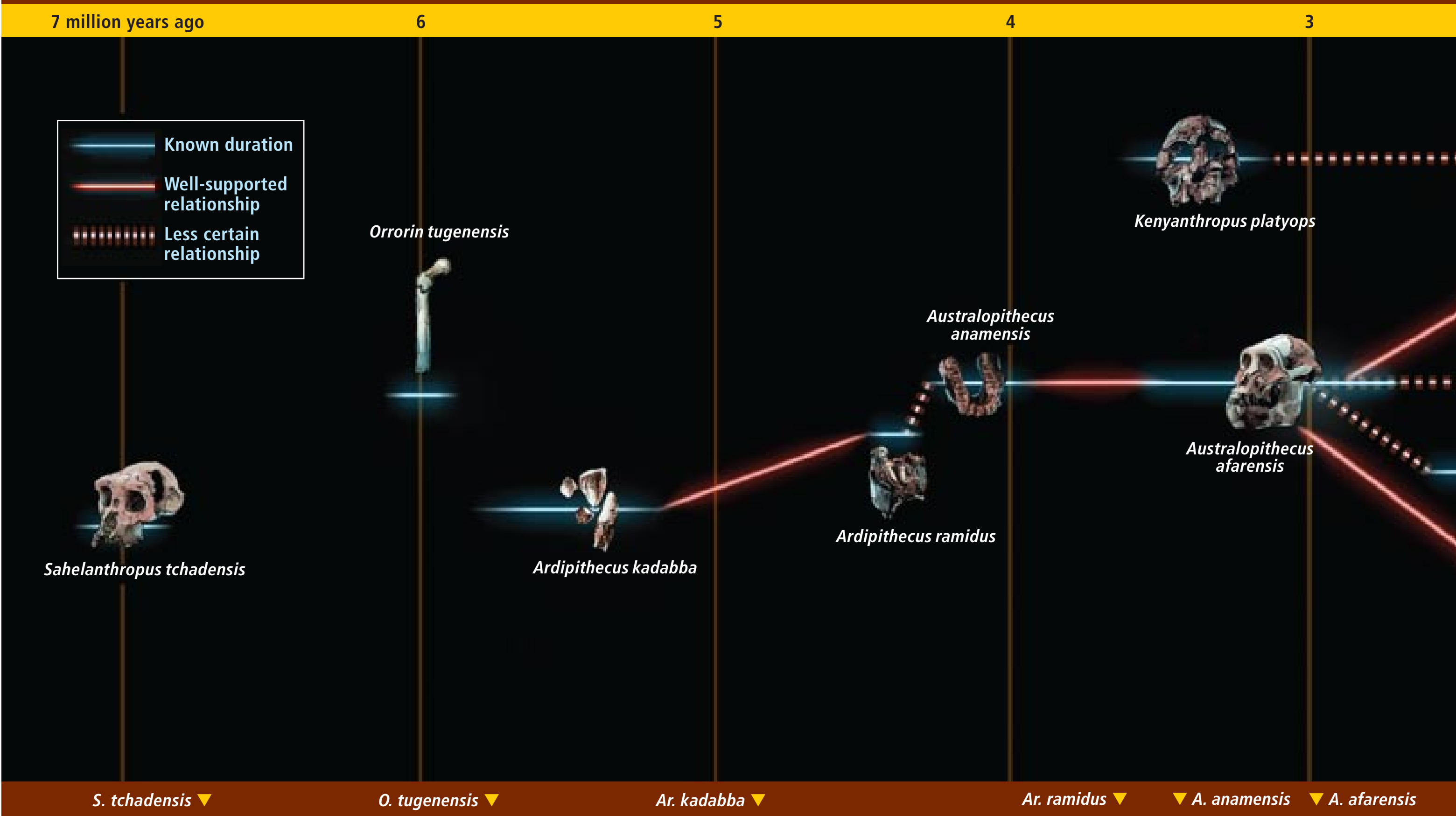
The story of our origins is far from complete. Paleontologists are eager to find fossils of the last common ancestor of chimpanzees and humans, for example. And exactly how, researchers have wondered, was *Homo sapiens* able to outcompete the Neandertals and other archaic humans? Many such mysteries about our collective past persist. Darwin's insights will no doubt continue to light the way to solving them. ■

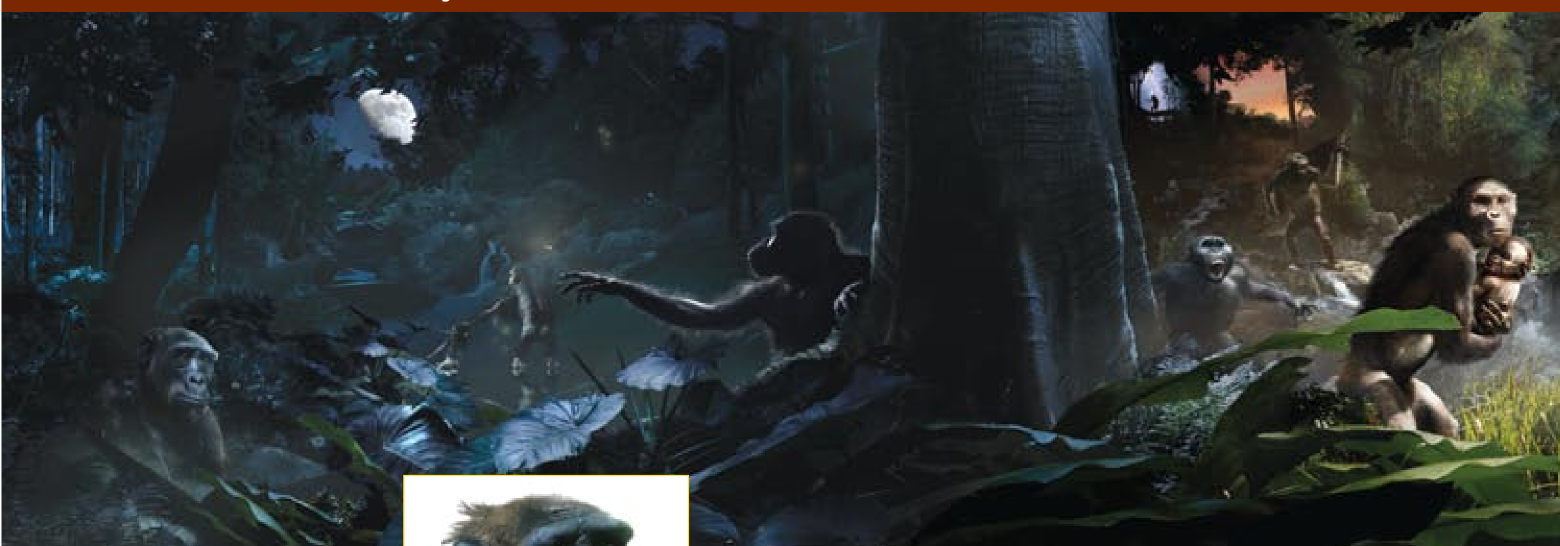
Kate Wong is a staff writer and editor.

Viktor Deak's combination of painting, drawing and sculpture with the latest computer technology produces remarkably photorealistic images of the prehistoric past. Working with anthropologists at the American Museum of Natural History, Deak illustrated *The Last Human: A Field Guide to 23 Species of Extinct Humans.* The award-winning book sold out its first edition. Born in Budapest, Hungary, in 1977, Deak immigrated to America with his parents when he was a child and grew up in the New England suburbs. He lives and works in New York City.

○○○ Skeletons in Our Closet

The tree presented here is one of many interpretations of the hominid fossil record. Some scholars parse the remains into more species; others opt for fewer. And whereas some of the relationships between species are well supported (***red solid lines***), others remain tentative (***red dashed lines***). The accompanying panorama and portraits, for their part, imagine these hominids in the flesh and highlight watershed events in the human odyssey.





Sahelanthropus tchadensis

First found: Toros-Menalla, Chad, 2001

Significance: The earliest putative hominid

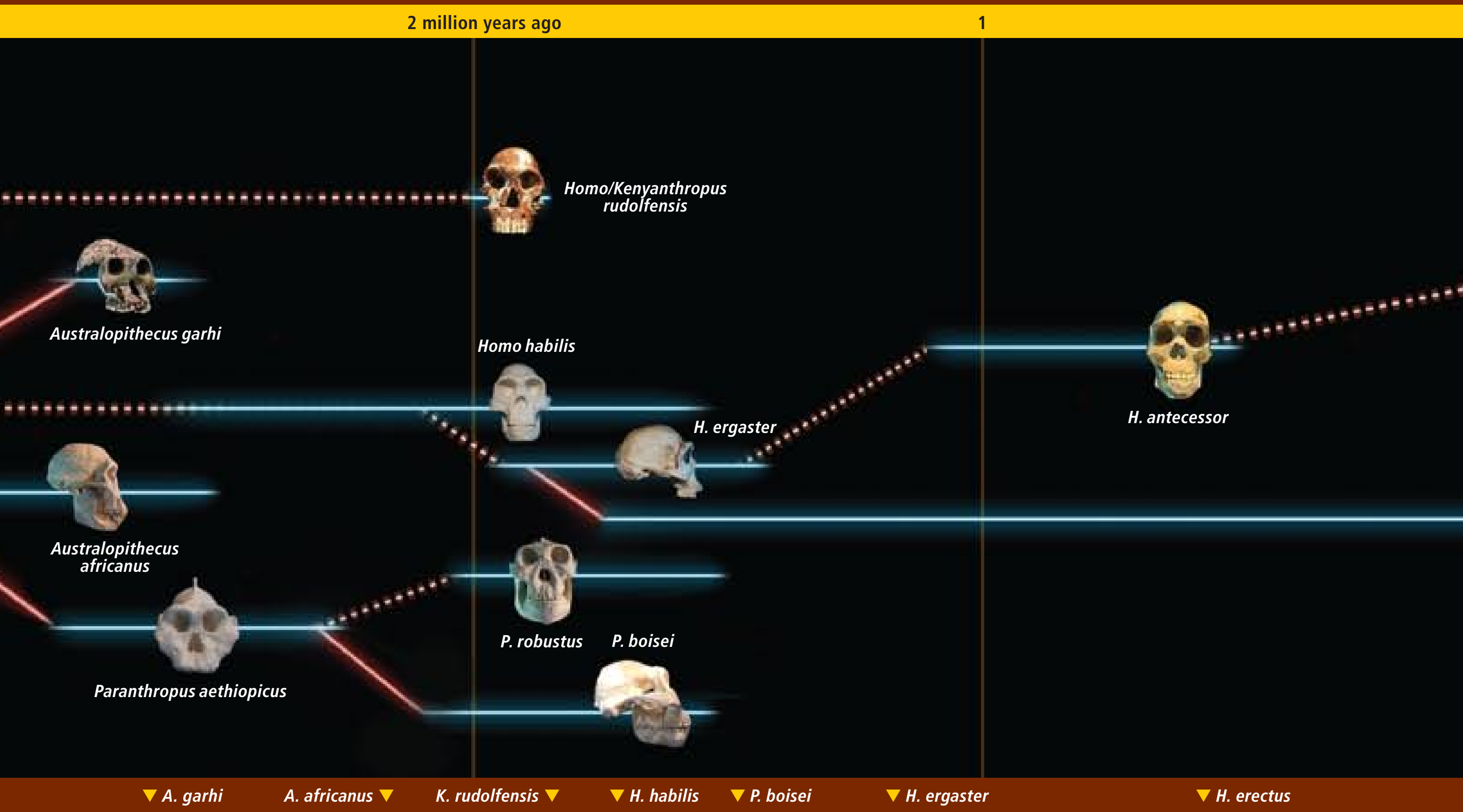
Open question: Did this creature walk upright? Thus far only skull and jaw remains have been found, although some researchers believe that details of the base of the skull suggest bipedalism.

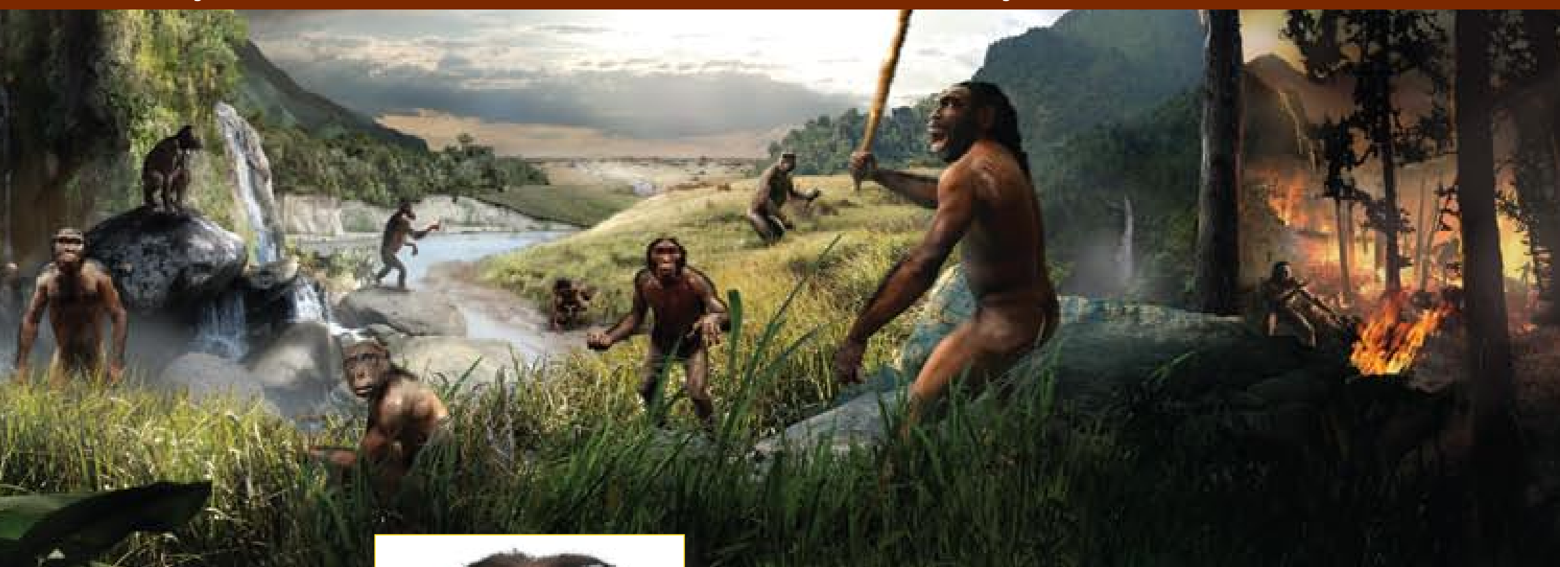
Australopithecus afarensis

First found: Hadar, Ethiopia, 1973

Significance: The ancestor of our own genus, *Homo,* as well as the genus *Paranthropus*

Open question: Did this hominid have a social structure more like that of humans, chimpanzees or gorillas?



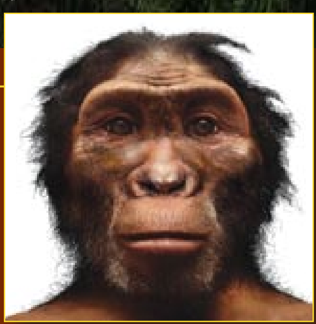


Homo habilis

First found: Olduvai Gorge, Tanzania, 1962

Significance: The first hominid known to have made stone tools

Open question: This poorly known species closely resembles *Australopithecus* and might actually belong in that genus instead of in *Homo.*

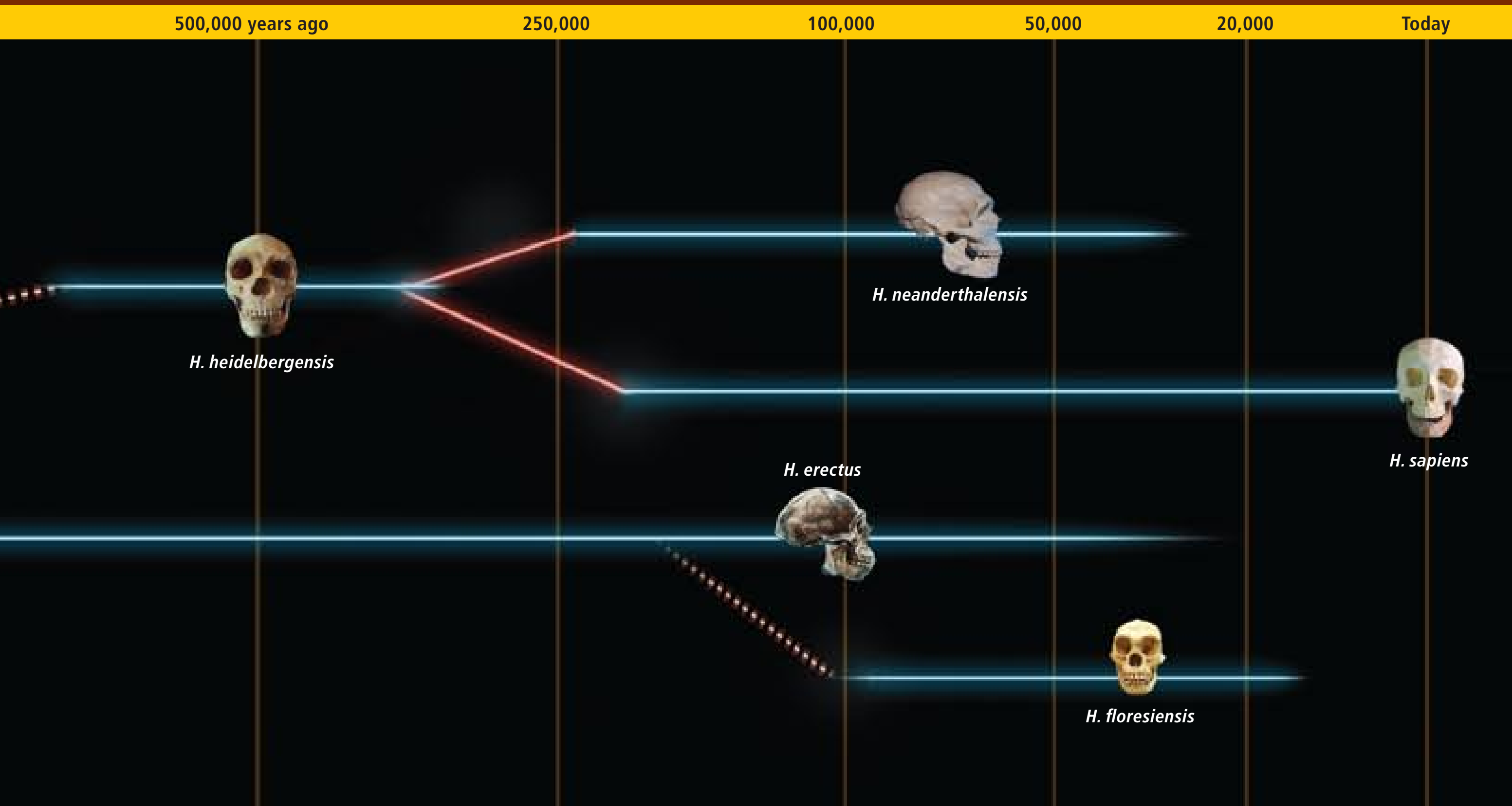


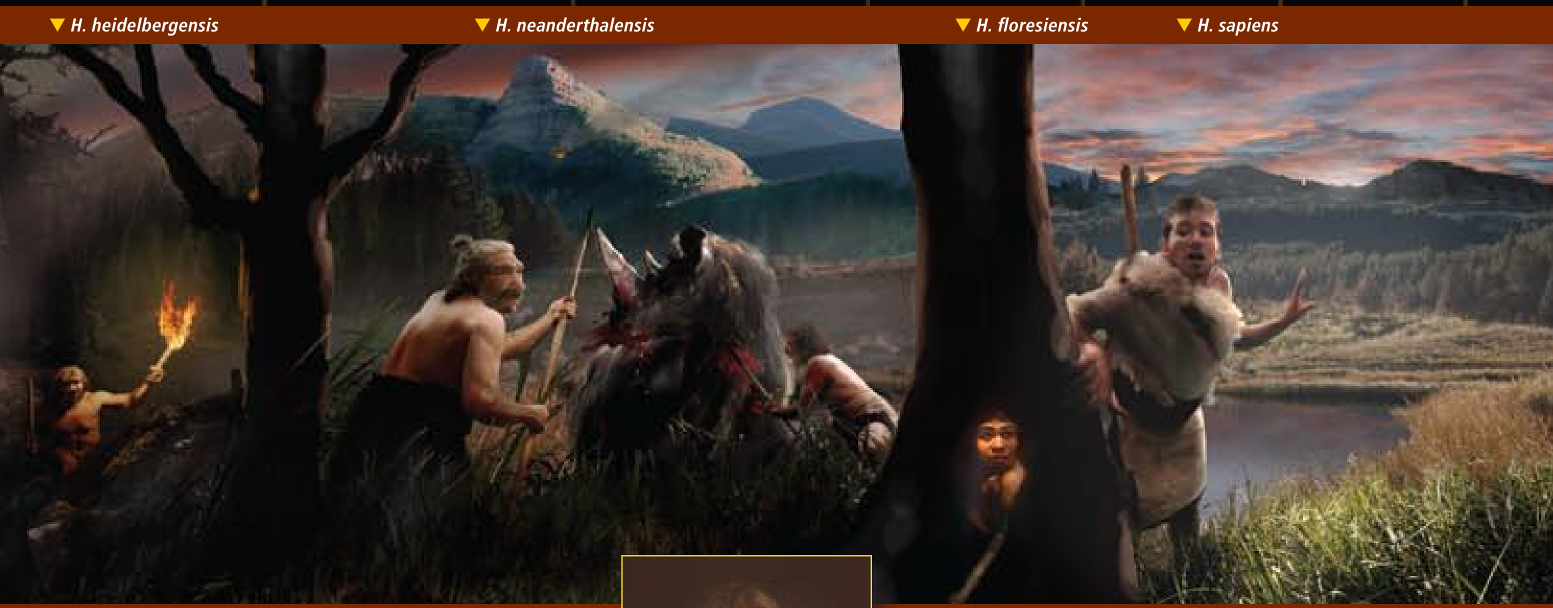
H. ergaster

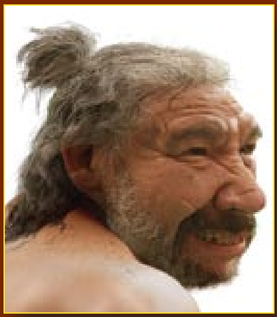
First found: Lake Turkana, Kenya, 1971

Significance: The first hominid to leave Africa

Open question: Experts do not know what finally, some five million years after the dawn of humans, prompted our ancestors to spread out from their natal continent.







H. neanderthalensis

First found: Engis, Belgium, 1829

Significance: A big-game hunter that ruled Ice Age Europe and western Asia for nearly 200,000 years

Open question: Whether or not they interbred with *H. sapiens* is a topic of debate.

H. floresiensis

First Found: Flores, Indonesia, 2004

Significance: The latest-surviving extinct hominid, with startlingly small brain and body

Open question: Who was this hominid's ancestor? A larger-bodied species of *Homo* or something more australopithecinelike?

H. sapiens

First found: Oldest known fossils discovered in Omo, Ethiopia, 1967

Significance: The only hominid to colonize every continent and the first to systematically use symbols

Open question: Did *H. sapiens* have the capacity for symbolic thought at its inception, or did this ability arise via a later genetic mutation?

THIS OLD BODY

Evolutionary hand-me-downs inherited from fish and tadpoles have left us with hernias, hiccups and other maladies • • • BY NEIL H. SHUBIN

I started teaching human anatomy at the same time my university renovated my laboratory. As it turns out, this coincidence could not have been more propitious. Teaching anatomy for the first time can be a struggle, and it is not just because there are an enormous number of names to learn. A glimpse inside the body reveals structures left inside of us during the course of evolution, which often seem a confused jumble, with arteries, nerves and other structures taking odd paths to get from one part of the body to another.

While I was struggling to understand the body's internal structures, I was given space in a 100-year-old building that needed to be renovated into a modern laboratory. When we opened the walls to look at the plumbing, wiring and other mechanicals, we saw a tangle that made no apparent sense; cables, wires and pipes took bizarre loops and turns throughout the building. Nobody in their right mind would have designed my building to conform to the snarled mess we saw when the wall was removed. Constructed in 1896, the utilities reflect an old design that has been jury-rigged for each renovation done over previous decades. If you want to understand the twisting pathways for a cable or a pipe, you have to understand their history and how they have been modified over the years. The same is true for structures in the human body.

Take the male spermatic cord. This tube connects the testes, in the scrotum, to the urethra, in the penis. In so doing, it forms a path for sperm to exit the body. The scrotum lies adjacent to the penis, so you would think that the best design would take the shortest course, a straight shot between the two structures. Not so. The spermatic cord ascends from the scrotum, then loops inside the pubic bone, descends through an opening below the hip joints and finally travels to the urethra inside the penis. This path—a historical legacy—is as much a source of vexation for medical students to understand as it is for the human males who suffer certain kinds of hernias because of it.

KEY CONCEPTS

- Routing of nerves and fluid pathways in the human body resembles the tangle of wiring and pipes in an aging house, a heritage from fish and amphibian ancestors.
- The tube through which sperm passes forms a roundabout loop that can lead to hernias, a result of major anatomical changes that occurred as we evolved from fish.
- Nerves that are inherited from fish and travel from the brain to the diaphragm can become irritated and trigger hiccups, a closing of the entryway to the windpipe, an action that itself is a hand-me-down from amphibians that breathe with both lungs and gills.

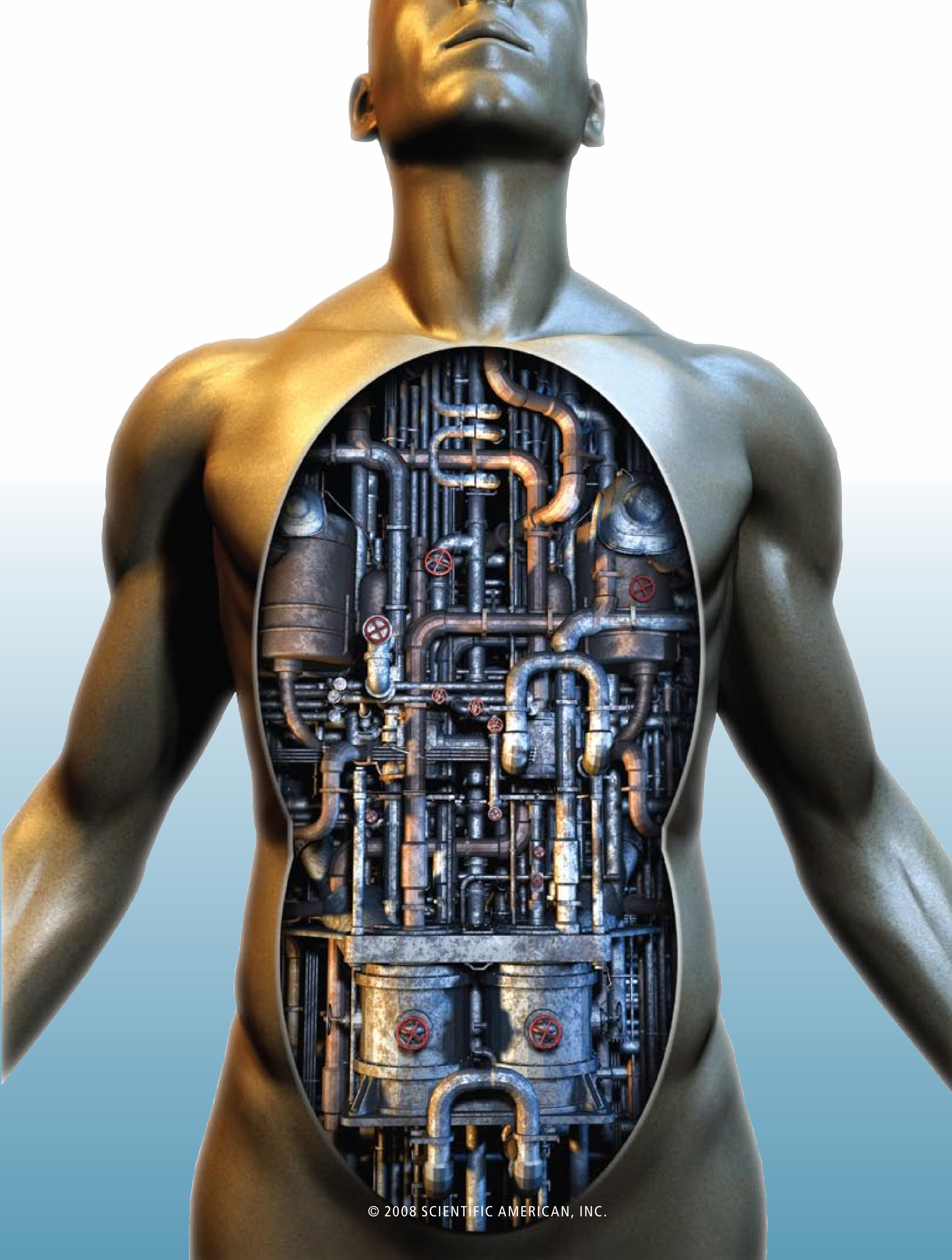
—The Editors

Piscine Inheritance

To make sense of our own bodies, we need to examine the history we share with everything from microbes and worms to fish and primates. In the case of the spermatic cord, human gonads begin development in a similar way to those of sharks, fish and other bony animals. The gonads—ovaries in females and testes in males—originally form high up in the human body, near the liver, presumably because the interactions between the tissues that develop into the gonads occur there. In adult sharks and fish, the gonads typically remain up near the liver. They probably stay in this ancestral configuration because their sperm can develop within the confines of the body cavity itself.

Mammals like us do things differently from our fish ancestors. As a male fetus develops, the gonads descend. In females, the ovaries move down from the midsection to lie near the uterus and fallopian tubes. This movement ensures that the egg does not have far to travel to be fer-

KENN BROWN *Mondolithic Studios*



THE AUTHOR

Neil H. Shubin is provost of academic affairs at the Field Museum. He is also a paleontologist, associate dean of organismal and evolutionary biology, and Robert R. Bensley Professor at the University of Chicago. He has found fossils that provide an understanding of key transition points in evolution: reptile to mammal, water to land. These discoveries have emerged from expeditions, ranging from Greenland to Morocco. In 2006 Shubin's team reported in *Nature* the discovery of fossils of *Tiktaalik,* a creature intermediate between a fish and an amphibian.

tilized. In males, the gonads descend farther, all the way to the scrotal sac, which extends from the body.

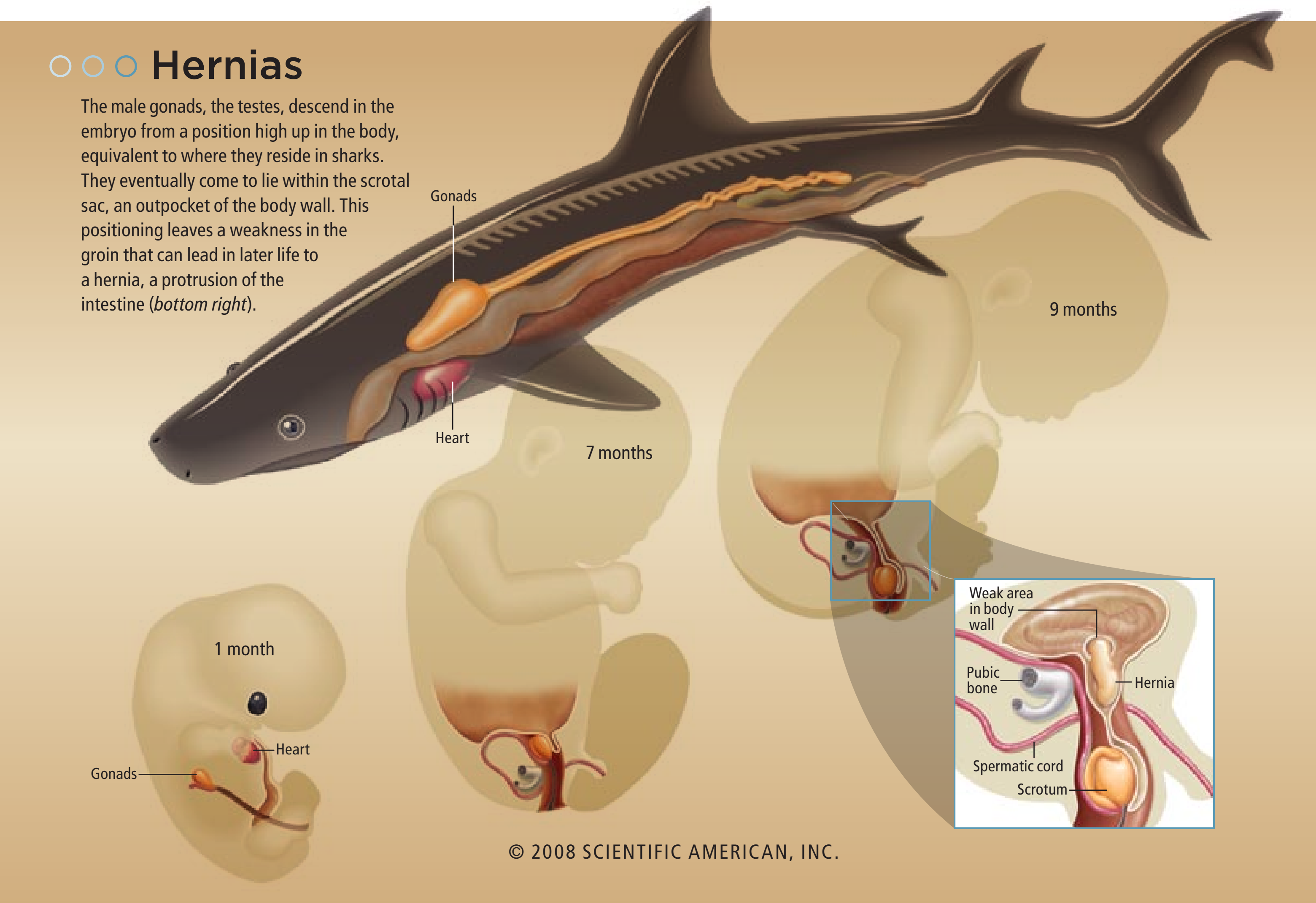
This feature is quite important for the production of healthy sperm. One possible reason is that mammals are warm-blooded and that the quantity and quality of sperm are dependent on developing in a cooler temperature than the rest of the body. Indeed, one study even suggests that a shift from tight-fitting jockeys, which can press the scrotum against the body, to boxers, which allow it to dangle, can improve some factors of sperm quality. Accordingly, the mammalian scrotum is a sac separated from the warm body that can rise and fall to control the temperature at which the sperm develops—think "cold-shower effect."

And therein lies the problem. For the testes to sit in this sac, they have to descend a long way, thereby causing the spermatic cord to take a roundabout loop. Unfortunately, for males the loop causes a weakness within the body wall near its apex. Several types of hernias can result when a little bit of gut pokes through this weak spot. These hernias can be congenital: some intestinal pieces travel with the gonads and descend through the body wall. Or they can develop later in life because of this zone of weakness. So the propensity to acquire certain kinds of hernias reflects layers of human history: our fishy past and mammalian present.

Why We Hic

The same kind of evolutionary analysis can be applied to a variety of maladies. Take hiccups, which can range from an annoyance that lasts a few minutes to a major life-altering condition that spans months or, in rare instances, years. A spasm of the muscles in the throat and chest causes a hiccup. The characteristic "hic" sound results when we sharply inspire air while the epiglottis, a flap of soft tissue at the back of the throat, closes. All these movements are completely involuntary; we "hic" without any thought on our part. Hiccups occur for many reasons: we eat too fast or too much; even more severe conditions, such as tumors in the chest area, can bring them on.

Hiccups reveal at least two layers of our history: one shared with fish, another with am-



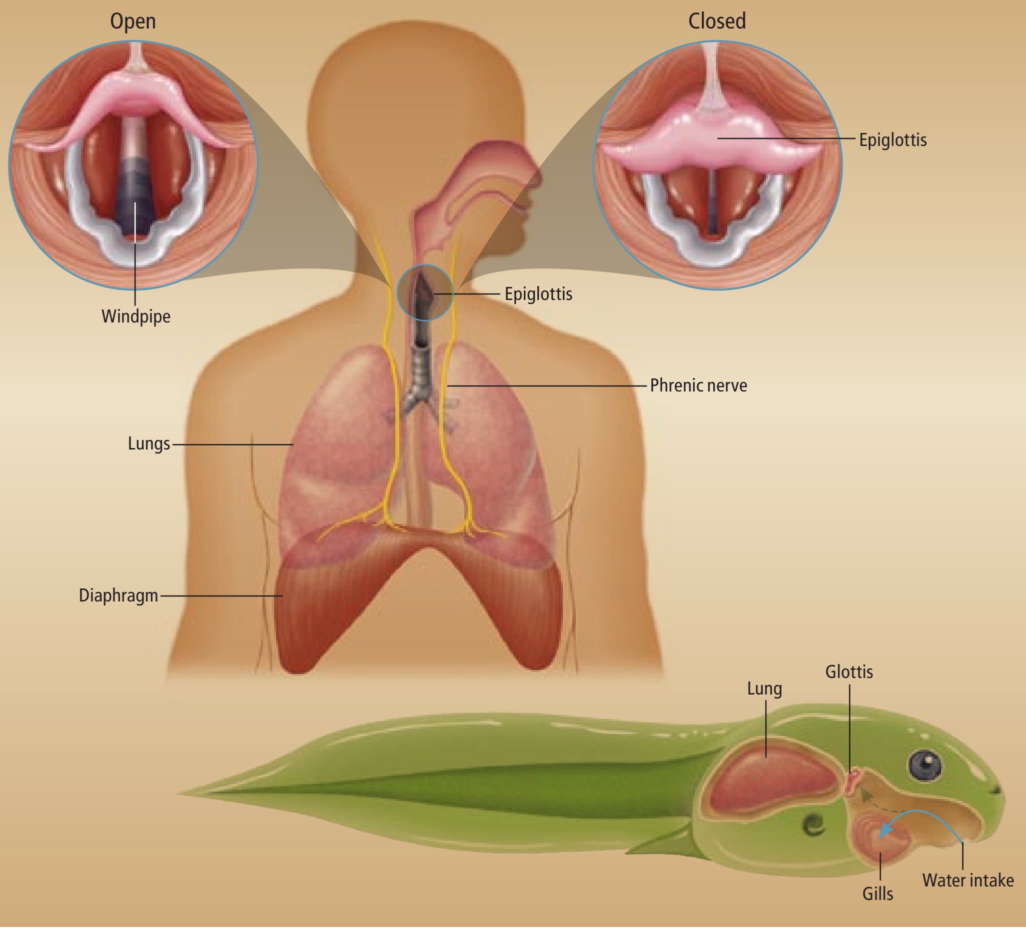
Hernias

The male gonads, the testes, descend in the embryo from a position high up in the body, equivalent to where they reside in sharks. They eventually come to lie within the scrotal sac, an outpocket of the body wall. This positioning leaves a weakness in the groin that can lead in later life to a hernia, a protrusion of the intestine (*bottom right*).

JOHN WEINSTEIN *The Field Museum* (Shubin); ALICE Y. CHEN (*illustration*)

Hiccups

The hic of hiccups can at times be caused by blockages or lesions that crimp one of the phrenic nerves, which control breathing and are an evolutionary hand-me-down from fish. These nerves relay brain signals that induce a spasm of muscles in the throat and chest, causing the epiglottis to shut the windpipe. The sharp inspiration and blocking of the throat, the hic, are a legacy of a tadpole's pumping of water into its mouth when breathing through its gills. As it ingests water, its glottis closes to prevent fluid from entering its lungs, which are used for breathing on land.



phibians, according to one well-supported hypothesis. We inherited the major nerves we use in breathing from fish. One set of nerves, the phrenic, extends from the base of the skull and travels through the chest cavity and the diaphragm, among other places. This tortuous course creates problems; anything that interrupts the path of these nerves along their length can interfere with our ability to breathe. Irritation of these nerves can even be a cause of hiccups. A more rational design of the human body would have the nerves traveling not from the neck but from a spot nearer to the diaphragm. Unluckily, we became heir to this design from fishy ancestors with gills closer to the neck, not a diaphragm well below it.

If the strange pathway of the nerves is a product of our fish origin, the hiccup itself may have arisen from the past we share with amphibians. It turns out that the characteristic pattern of muscle and nerve activity of hiccups occurs naturally in other creatures. And not just any creatures. More specifically, they turn up in tadpoles that use both lungs and gills to breathe. When tadpoles use their gills, they have a problem—they need to pump water into their mouth and throat and then across the gills, but they need to keep this water from entering their lungs. So what do they do? They shut the glottis to close off the breathing tube, while sharply inspiring. In essence, they breathe with their gills using an extended form of hiccup.

Our deep history was, at different times, spent in ancient oceans, small streams and savanna plains—and not office buildings, ski slopes or football fields. This extraordinary disconnect between our past and present means that our body falls apart in certain predictable ways. The major bones in human knees, backs and wrists arose in aquatic creatures hundreds of millions of years ago. Is it any surprise, then, that we tear cartilage in our knees and suffer back pain as we walk on two legs or develop carpal tunnel syndrome as we type, knit or write? Our fish and amphibian ancestors did not do these things.

Take the body plan of a fish, modify it using genes altered from those that build the body of a worm, dress it up to be a mammal, then tweak and twist that mammal to make a creature that walks upright, talks, thinks and has superfine control of its fingers, and we have a recipe for disaster. We can dress up this fish only so much before paying a price. In a perfectly designed world—one without an extended historic legacy—we would not have to suffer from the infirmities of hemorrhoids or hernias. Nor would our buildings be so expensive to renovate. ■

ALICE Y. CHEN

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WHAT WILL BECOME OF *HOMO SAPIENS*?

Contrary to popular belief, humans continue to evolve. Our bodies and brains are not the same as our ancestors' were—or as our descendants' will be • • • BY PETER WARD

When you ask for opinions about what future humans might look like, you typically get one of two answers. Some people trot out the old science-fiction vision of a big-brained human with a high forehead and higher intellect. Others say humans are no longer evolving physically—that technology has put an end to the brutal logic of natural selection and that evolution is now purely cultural.

The big-brain vision has no real scientific basis. The fossil record of skull sizes over the past several thousand generations shows that our days of rapid increase in brain size are long over. Accordingly, most scientists a few years ago would have taken the view that human physical evolution has ceased. But DNA techniques, which probe genomes both present and past, have unleashed a revolution in studying evolution; they tell a different story. Not only has *Homo sapiens* been doing some major genetic reshuffling since our species formed, but the rate of human evolution may, if anything, have increased. In common with other organisms, we underwent the most dramatic changes to our body shape when our species first appeared, but we continue to show genetically induced changes to our physiology and perhaps to our behavior as well. Until fairly recently in our history, human races in various parts of the world were becoming more rather than less distinct. Even today the conditions of modern life could be driving changes to genes for certain behavioral traits.

If giant brains are not in store for us, then what is? Will we become larger or smaller, smarter or dumber? How will the emergence of new diseases and the rise in global temperature shape us? Will a new human species arise one day? Or does the future evolution of humanity lie not within our genes but within our technology, as we augment our brains and bodies with silicon and steel? Are we but the builders of the next dominant intelligence on the earth—the machines?

KEY CONCEPTS

- People commonly assume that our species has evolved very little since prehistoric times. Yet new studies using genetic information from populations around the globe suggest that the pace of human evolution increased with the advent of agriculture and cities.
- If we are still evolving, what might our species look like in a millennium should we survive whatever environmental and social surprises are in store for us? Speculation ranges from the hopeful to the dystopian.

—The Editors

The Far and Recent Past

Tracking human evolution used to be the province solely of paleontologists, those of us who study fossil bones from the ancient past. The human family, called the Hominidae, goes back at least seven million years to the appearance of a small proto-human called *Sahelanthropus tchadensis*. Since then, our family has had a still disputed, but rather diverse, number of new species in it—as many as nine that we know of and others surely still hidden in the notoriously poor hominid fossil record. Because early human skeletons rarely made it into sedimentary rocks before they were scavenged, this estimate changes from year to year as new discoveries and new interpretations of past bones make their way into print [see "Once We Were Not Alone," by Ian Tattersall; Scientific American, January 2000, and "An Ancestor to Call Our Own," by Kate

NESSIM HIGSON (*photoillustration*); KEVIN SUMMERS *Getty Images* (*flower*); PAUL TAYLOR *Getty Images* (*hand*); RON LEVINE *Getty Images* (*girl*); PHOTODISC *Getty Images* (*brain*); ISTOCKPHOTO.COM (*skull and egg*)

BEYOND *HOMO SAPIENS*

Our lineage has produced new species in the past. What about the future? Speciation requires an isolating mechanism of some kind. The most common is geographic isolation, where a small population gets cut off from the larger gene pool. The very size and interconnectedness of humanity make this possibility low under present conditions, but here are some ways to bring it about:

Setting up human colonies on distant worlds.

Losing or voluntarily discarding the technology that allows the global interchange of our genes.

Breaking into isolated groups after an apocalypse such as a large asteroid hitting the earth.

Engaging in genetic engineering.

THE AUTHOR

Peter Ward has been active in paleontology, biology and astrobiology for more than 30 years. He led the University of Washington node of the NASA Astrobiology Institute, a team of more than 40 scientists and students, from 2001 to 2006. Ward is especially known as an expert on mass extinctions and the role of extraterrestrial impacts on the earth. He and his 11-year-old son recently built a reconstruction of the late Cretaceous world on a large model-train layout, replete with dinosaurs to scale, and can now attest that the extinction of the dinosaurs was caused by speeding locomotives.

Wong; Scientific American, January 2003].

Each new species evolved when a small group of hominids somehow became separated from the larger population for many generations and then found itself in novel environmental conditions favoring a different set of adaptations. Cut off from kin, the small population went its own genetic route and eventually its members could no longer successfully reproduce with the parent population.

The fossil record tells us that the oldest member of our own species lived 195,000 years ago in what is now Ethiopia. From there it spread out across the globe. By 10,000 years ago modern humans had successfully colonized each of the continents save Antarctica, and adaptations to these many locales (among other evolutionary forces) led to what we loosely call races. Groups living in different places evidently retained just enough connections with one another to avoid evolving into separate species. With the globe fairly well covered, one might expect that the time for evolving was pretty much finished.

But that turns out not to be the case. In a study published a year ago Henry C. Harpending of the University of Utah, John Hawks of the University of Wisconsin–Madison and their colleagues analyzed data from the international haplotype map of the human genome [see "Traces of a Distant Past," by Gary Stix; Scientific American, July 2008]. They focused on genetic markers in 270 people from four groups: Han Chinese, Japanese, Yoruba and northern Europeans. They found that at least 7 percent of human genes underwent evolution as recently as 5,000 years ago. Much of the change involved adaptations to particular environments, both natural and human-shaped. For example, few people in China and Africa can digest fresh milk into adulthood, whereas almost everyone in Sweden and Denmark can. This ability presumably arose as an adaptation to dairy farming.

Another study by Pardis C. Sabeti of Harvard University and her colleagues used huge data sets of genetic variation to look for signs of natural selection across the human genome. More than 300 regions on the genome showed evidence of recent changes that improved people's chance of surviving and reproducing. Examples included resistance to one of Africa's great scourges, the virus causing Lassa fever; partial resistance to other diseases, such as malaria, among some African populations; changes in skin pigmentation and development of hair follicles among Asians; and the evolution of lighter skin and blue eyes in northern Europe.

Harpending and Hawks's team estimated that over the past 10,000 years humans have evolved as much as 100 times faster than at any other time since the split of the earliest hominid from the ancestors of modern chimpanzees. The team attributed the quickening pace to the variety of environments humans moved into and the changes in living conditions brought about by agriculture and cities. It was not farming per se or the changes in the landscape that conversion of wild habitat to tamed fields brought about but the often lethal combination of poor sanitation, novel diet and emerging diseases (from other humans as well as domesticated animals). Although some researchers have expressed reservations about these estimates, the basic point seems clear: humans are first-class evolvers.

Unnatural Selection

During the past century, our species' circumstances have again changed. The geographic isolation of different groups has been broached by the ease of transportation and the dismantling of social barriers that once kept racial groups apart. Never before has the human gene pool had such widespread mixing of what were heretofore entirely separated local populations of our species. In fact, the mobility of humanity might be bringing about the homogenization of our species. At the same time, natural selection in our species is being thwarted by our technology and our medicines. In most parts of the globe, babies no longer die in large numbers. People with genetic damage that was once fatal now live and have children. Natural predators no longer affect the rules of survival.

Steve Jones of University College London has argued that human evolution has essentially ceased. At a Royal Society of Edinburgh debate in 2002 entitled "Is Evolution Over?" he said: "Things have simply stopped getting better, or worse, for our species. If you want to know what Utopia is like, just look around—this is it." Jones suggested that, at least in the developed world, almost everyone has the opportunity to reach reproductive age, and the poor and rich have an equal chance of having children. Inherited disease resistance—say, to HIV—may still confer a survival advantage, but culture, rather than genetic inheritance, is now the deciding factor in whether people live or die. In short, evolution may now be memetic—involving ideas—rather than genetic [see "The Power of Memes," by Susan Blackmore; Scientific American, October 2000].

PEPI KHARA

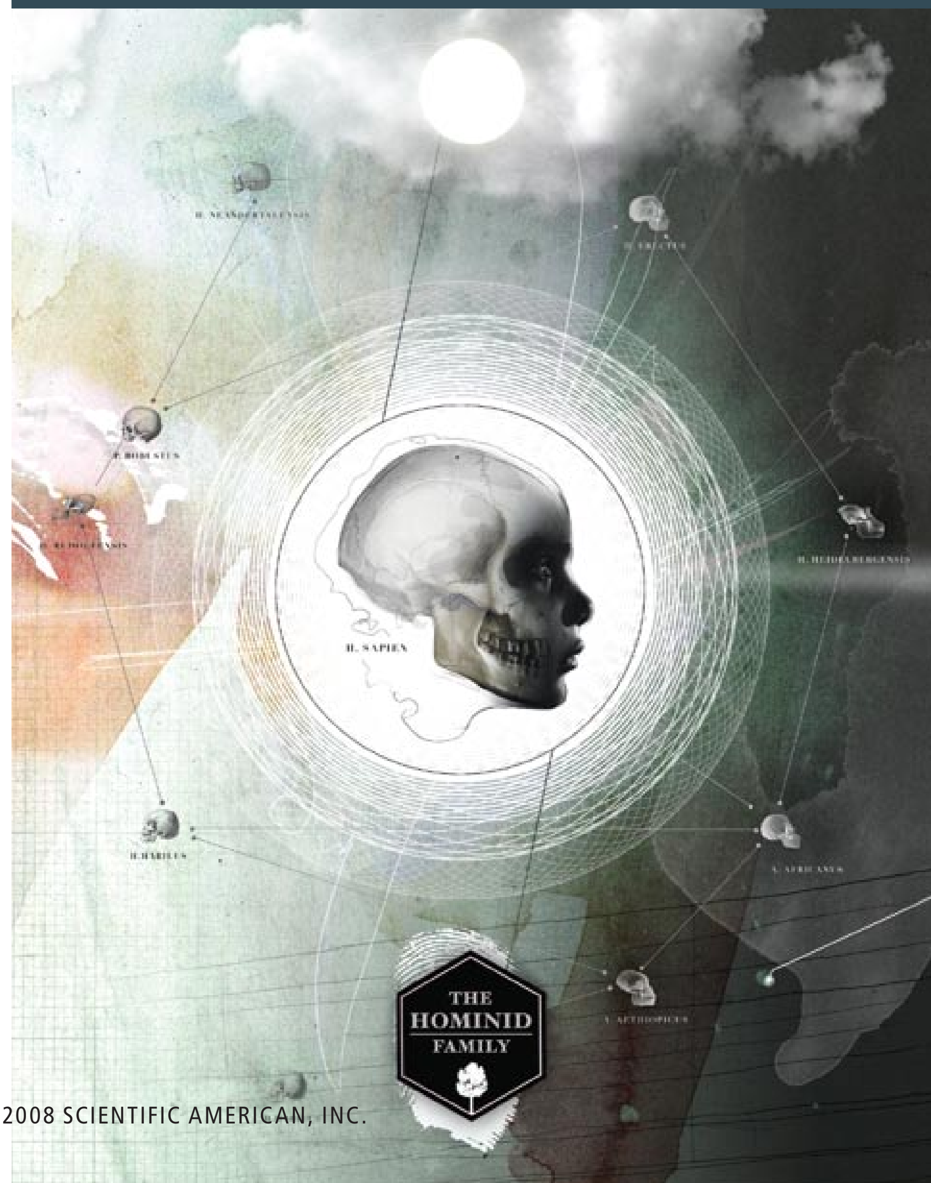
Another point of view is that genetic evolution continues to occur even today, but in reverse. Certain characteristics of modern life may drive evolutionary change that does not make us fitter for survival—or that even makes us less fit. Innumerable college students have noticed one potential way that such "inadaptive" evolution could happen: they put off reproduction while many of their high school classmates who did not make the grade started having babies right away. If less intelligent parents have more kids, then intelligence is a Darwinian liability in today's world, and average intelligence might evolve downward.

Such arguments have a long and contentious history. One of the many counterarguments is that human intelligence is made up of many different abilities encoded by a large number of genes. It thus has a low degree of heritability, the rate at which one generation passes the trait to the next. Natural selection acts only on heritable traits. Researchers actively debate just how heritable intelligence is [see "The Search for Intelligence," by Carl Zimmer; Scientific American, October 2008], but they have found no sign that average intelligence is in fact decreasing.

Even if intelligence is not at risk, some scientists speculate that other, more heritable traits could be accumulating in the human species and that these traits are anything but good for us. For instance, behavior disorders such as Tourette's syndrome and attention-deficit hyperactivity disorder (ADHD) may, unlike intelligence, be encoded by but a few genes, in which case their heritability could be very high. If these disorders increase one's chance of having children, they could become ever more prevalent with each generation. David Comings, a specialist in these two diseases, has argued in scientific papers and a 1996 book that these conditions are more common than they used to be and that evolution might be one reason: women with these syndromes are less likely to attend college and thus tend to have more children than those who do not. But other researchers have brought forward serious concerns about Comings's methodology. It is not clear whether the incidence of Tourette's and ADHD is, in fact, increasing at all. Research into these areas is also made more difficult because of the perceived social stigma that many of these afflictions attach to their carriers.

Although these particular examples do not pass scientific muster, the basic line of reasoning is plausible. We tend to think of evolution as something involving structural modification, yet it can and does affect things invisible from the outside—behavior. Many people carry the genes making them susceptible to alcoholism, drug addiction and other problems. Most do not succumb, because genes are not destiny; their effect depends on our environment. But others do succumb, and their problems may affect whether they survive and how many children they have. These changes in fertility are enough for natural selection to act on. Much of humanity's future evolution may involve new sets of behaviors that spread in response to changing social and environmental conditions. Of course, humans differ from other species in that we do not have to accept this Darwinian logic passively.

Over the past 10,000 years humans have evolved as much as 100 times faster than at any other time.



NESSIM HIGSON (*photoillustration*); ISTOCKPHOTO.COM (*skull and boy's head*)

*I*f machine efficiency became the new measure of evolutionary fitness, much of what we regard as quintessentially human would be weeded out.

Directed Evolution

We have directed the evolution of so many animal and plant species. Why not direct our own? Why wait for natural selection to do the job when we can do it faster and in ways beneficial to ourselves? In the area of human behavior, for example, geneticists are tracking down the genetic components not just of problems and disorders but also of overall disposition and various aspects of sexuality and competitiveness, many of which may be at least partially heritable. Over time, elaborate screening for genetic makeup may become commonplace, and people will be offered drugs based on the results.

The next step will be to actually change people's genes. That could conceivably be done in two ways: by changing genes in the relevant organ only (gene therapy) or by altering the entire genome of an individual (what is known as germ-line therapy). Researchers are still struggling with the limited goal of gene therapy to cure disease. But if they can ever pull off germline therapy, it will help not only the individual in question but also his or her children. The major obstacle to genetic engineering in humans will be the sheer complexity of the genome. Genes usually perform more than one function; conversely, functions are usually encoded by more than one gene. Because of this property, known as pleiotropy, tinkering with one gene can have unintended consequences.

Why try at all, then? The pressure to change genes will probably come from parents wanting to guarantee their child is a boy or a girl; to endow their children with beauty, intelligence, musical talent or a sweet nature; or to try to ensure that they are not helplessly disposed to become mean-spirited, depressed, hyperactive or even criminal. The motives are there, and they are very strong. Just as the push by parents to genetically enhance their children could be socially irresistible, so, too, would be an assault on human aging. Many recent studies suggest that aging is not so much a simple wearing down of body parts as it is a programmed decay, much of it genetically controlled. If so, the next century of genetic research could unlock numerous genes controlling many aspects of aging. Those genes could be manipulated.

Assuming that it does become practical to change our genes, how will that affect the future evolution of humanity? Probably a great deal. Suppose parents alter their unborn children to enhance their intelligence, looks and longevity. If the kids are as smart as they are long-lived—an IQ of 150 and a lifespan of 150 years—they could have more children and accumulate more wealth than the rest of us. Socially they will probably be drawn to others of their kind. With some kind of self-imposed geographic or social segregation, their genes might drift and eventually differentiate as a new species. One day, then, we will have it in our power to bring a new human species into this world. Whether we choose to follow such a path is for our descendants to decide.

The Borg Route

Even less predictable than our use of genetic manipulation is our manipulation of machines—or they of us. Is the ultimate evolution of our species one of symbiosis with machines, a human-

NESSIM HIGSON (*photoillustration*); AMANA PRODUCTIONS *Getty Images* (*woman*) machine synthesis? Many writers have predicted that we might link our bodies with robots or upload our minds into computers. In fact, we are already dependent on machines. As much as we build them to meet human needs, we have structured our own lives and behavior to meet theirs. As machines become ever more complex and interconnected, we will be forced to try to accommodate them. This view was starkly enunciated by George Dyson in his 1998 book *Darwin among the Machines:* "Everything that human beings are doing to make it easier to operate computer networks is at the same time, but for different reasons, making it easier for computer networks to operate human beings.... Darwinian evolution, in one of those paradoxes with which life abounds, may be a victim of its own success, unable to keep up with non-Darwinian processes that it has spawned."

Our technological prowess threatens to swamp the old ways that evolution works. Consider two different views of the future taken from an essay in 2004 by evolutionary philosopher Nick Bostrom of the University of Oxford. On the optimistic side, he wrote: "The big picture shows an overarching trend towards increasing levels of complexity, knowledge, consciousness, and coordinated goal-directed organization, a trend which, not to put too fine a point on it, we may label 'progress.' What we shall call the Panglossian view maintains that this past record of success gives us good grounds for thinking that evolution (whether biological, memetic or technological) will continue to lead in desirable directions."

Although the reference to "progress" surely causes the late evolutionary biologist Steven Jay Gould to spin in his grave, the point can be made. As Gould argued, fossils, including those from our own ancestors, tell us that evolutionary change is not a continuous thing; rather it occurs in fits and starts, and it is certainly not "progressive" or directional. Organisms get smaller as well as larger. But evolution has indeed shown at least one vector: toward increasing complexity. Perhaps that is the fate of future human evolution: greater complexity through some combination of anatomy, physiology or behavior. If we continue to adapt (and undertake some deft planetary engineering), there is no genetic or evolutionary reason that we could not still be around to watch the sun die. Unlike aging, extinction does not appear to be genetically programmed into any species.

The darker side is all too familiar. Bostrom (who must be a very unsettled man) offered a vision of how uploading our brains into computers could spell our doom. Advanced artificial intelligence could encapsulate the various components of human cognition and reassemble those components into something that is no longer human—and that would render us obsolete. Bostrom predicted the following course of events: "Some human individuals upload and make many copies of themselves. Meanwhile, there is gradual progress in neuroscience and artificial intelligence, and eventually it becomes possible to isolate individual cognitive modules and connect them up to modules from other uploaded minds.... Modules that conform to a common standard would be better able to communicate and cooperate with other modules and would therefore be economically more productive, creating a pressure for standardization.... There might be no niche for mental architectures of a human kind."

As if technological obsolescence were not disturbing enough, Bostrom concluded with an even more dreary possibility: if machine efficiency became the new measure of evolutionary fitness, much of what we regard as quintessentially human would be weeded out of our lineage. He wrote: "The extravagancies and fun that arguably give human life much of its meaning—humor, love, game-playing, art, sex, dancing, social conversation, philosophy, literature, scientific discovery, food and drink, friendship, parenting, sport—we have preferences and capabilities that make us engage in such activities, and these predispositions were adaptive in our species' evolutionary past; but what ground do we have for being confident that these or similar activities will continue to be adaptive in the future? Perhaps what will maximize fitness in the future will be nothing but nonstop high-intensity drudgery, work of a drab and repetitive nature, aimed at improving the eighth decimal of some economic output measure."

In short, humanity's future could take one of several routes, assuming we do not go extinct:

Stasis. We largely stay as we are now, with minor tweaks, mainly as races merge.

Speciation. A new human species evolves on either this planet or another.

Symbiosis with machines. Integration of machines and human brains produces a collective intelligence that may or may not retain the qualities we now recognize as human.

Quo vadis Homo futuris? ■

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Four Fallacies of Pop Evolutionary Psychology

Some evolutionary psychologists have made widely popularized claims about how the human mind evolved, but other scholars argue that the grand claims lack solid evidence • • • BY DAVID J. BULLER

KEY CONCEPTS

- Among Charles Darwin's lasting legacies is our knowledge that the human mind evolved by some adaptive process.
- A major, widely discussed branch of evolutionary psychology—Pop EP—holds that the human brain has many specialized mechanisms that evolved to solve the adaptive problems of our hunter-gatherer ancestors.
- The author and several other scholars suggest that some assumptions of Pop EP are flawed: that we can know the psychology of our Stone Age ancestors, that we can thereby figure out how distinctively human traits evolved, that our minds have not evolved much since the Stone Age, and that standard psychological questionnaires yield clear evidence of the adaptations.

—The Editors

Charles Darwin wasted no time applying his theory of evolution to human psychology, following *On the Origin of Species* (1859) with *The Descent of Man* (1871) and *The Expression of the Emotions in Man and Animals* (1872). Ever since, the issue hasn't been whether evolutionary theory can illuminate the study of psychology but how it will do so. Still, a concerted effort to explain how evolution has affected human behavior began only in the 1970s with the emergence of sociobiology. The core idea of sociobiology was simple: behavior has evolved under natural and sexual selection (in response to competition for survival and reproduction, respectively), just as organic form has. Sociobiology thereby extended the study of adaptation to include human behavior.

In his 1985 critique of sociobiology, *Vaulting Ambition,* philosopher Philip Kitcher noted that, whereas some sociobiology backed modest claims with careful empirical research, the theoretical reach of the dominant program greatly exceeded its evidential grasp. Kitcher called this program "pop sociobiology" because it employed evolutionary principles "to advance grand claims about human nature and human social institutions" and was "deliberately designed to command popular attention."

Times have changed. Although some self-identified sociobiologists are still around, the current fashion is evolutionary psychology. Evolutionary psychology maintains that adaptation is to be found among the psychological mechanisms that control behavior rather than among behaviors themselves. But, as the old saw goes, the more things change, the more they stay the same. Although some work in evolutionary psychology backs modest claims with careful empirical research, a dominant strain, pop evolutionary psychology, or Pop EP, offers grand and encompassing claims about human nature for popular consumption.

The most notable representatives of Pop EP are psychologists David M. Buss (a professor at the University of Texas at Austin and author of *The Evolution of Desire* and *The Dangerous Passion*) and Steven Pinker (a professor at Harvard University whose books include *How the Mind Works* and *The Blank Slate*). Their popular accounts are built on the pioneering theoretical work of what is sometimes referred to as the Santa Barbara school of evolutionary psychology, led by anthropologists Donald Symons and John Tooby and psychologist Leda Cosmides, all at the University of California, Santa Barbara.

According to Pop EP, "the human brain consists of a large collection of functionally specialized computational devices that evolved to solve

DEFINITION

As used in this article, pop evolutionary psychology, or Pop EP, refers to a branch of theoretical psychology that employs evolutionary principles to support claims about human nature for popular consumption.

GRANT DELIN

DIORAMA OF A **Stone Age man as he might have lived some 15,000 years ago was photographed at the Hall of Human Origins at the American Museum of Natural History in New York CIty.**

the adaptive problems regularly encountered by our hunter-gatherer ancestors" (from the Web site of the Center for Evolutionary Psychology at U.C.S.B.). Just as evolution by natural and sexual selection has endowed all humans with morphological adaptations such as hearts and kidneys, Pop EP says, so it has endowed all humans with a set of psychological adaptations, or "mental organs." These include psychological mechanisms, or "functionally specialized computational devices," for language, face recognition, spatial perception, tool use, mate attraction and retention, parental care and a wide variety of social relations, among other things. Collectively, these psychological adaptations constitute a "universal human nature." Individual and cultural differences are, by this account, the result of our common nature responding to variable local circumstances, much as a computer program's outputs vary as a function of its inputs. The notable exceptions to this rule involve sex differences, which evolved because males and females sometimes faced distinct adaptive problems.

POP EP SAYS

that analysis of the adaptive problems faced by our Stone Age ancestors, such as how to compete for mates and resources, yields clues to the mind's design.

BUT

without knowledge of our ancestors' psychological traits—information we don't have—we can't know how selection tinkered with these traits to create the minds we now have.

FRANK STOCKTON

Moreover, because complex adaptation is a very slow process, human nature is designed for the hunter-gatherer lifestyle led by our ancestors in the Pleistocene (the period from 1.8 million to 10,000 years ago). As Cosmides and Tooby colorfully say, "our modern skulls house a Stone Age mind." Pop EP proposes to discover our universal human nature by analyzing the adaptive problems our ancestors faced, hypothesizing the psychological mechanisms that evolved to solve them and then testing those hypotheses using standard-fare psychological evidence, such as paper-and-pencil questionnaires. Pop EP claims that a number of psychological adaptations have been discovered in this way, including evolved sex differences in mate preferences (males prefer nubility; females prefer nobility) and jealousy (men are more distressed by a mate's sexual infidelity, women by emotional infidelity).

I believe that Pop EP is misguided. The ideas suffer not so much from one fundamental flaw as from many small mistakes. Nevertheless, recent critiques of evolutionary psychology point to some general problems of Pop EP.

Fallacy 1:
Analysis of Pleistocene Adaptive Problems Yields Clues to the Mind's Design

Tooby and Cosmides have argued that because we can be quite certain that our Pleistocene ancestors had to, among other things, "select mates of high reproductive value" and "induce potential mates to choose them," we can also be sure that psychological adaptations evolved for solving these problems. But efforts to identify the adaptive problems that drove human psychological evolution confront a dilemma.

On the one horn, while it is true that our ancestors had to "induce potential mates to choose them," for example, such a description is too abstract to provide any clear indication of the nature of human psychological adaptations. All species face the problem of attracting mates. Male bowerbirds build ornately decorated bowers, male hangingflies offer captured prey, and male sedge warblers sing a wide repertoire of songs. Figuring out which strategies ancestral humans had to use requires a much more precise description of the adaptive problem for early humans.

More precise descriptions of the adaptive problems our ancestors faced, however, get impaled by the other horn of the dilemma: these descriptions are purely speculative, because we

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POP EP SAYS

that we know or can discover why distinctively human traits such as language evolved.

BUT

to discover why any trait evolved, we need to identify the adaptive functions it served among early humans, for which we have little evidence.

have little evidence of the conditions under which early human evolution occurred. The paleontological record provides a few clues about some aspects of early human life, but it is largely silent regarding the social interactions that would have been of principal importance in human psychological evolution. Nor do extant hunter-gatherer populations provide many hints about the social lives of our ancestors. Indeed, the lifestyles of these groups vary considerably, even among those who live in the regions of Africa populated by early humans.

Moreover, as biologist Richard Lewontin of Harvard has argued, the adaptive problems faced by a species are not independent of its characteristics and lifestyle. Tree bark contributes to the adaptive problems faced by woodpeckers, but stones lying at the foot of a tree do not. In contrast, for thrushes, which use stones to break snail shells, the stones are part of the adaptive problems they face, whereas tree bark is not. Similarly, our ancestors' motivational and cognitive processes would have been selectively responsive to certain features of the physical and social environments, and this selective responsiveness would have determined which environmental factors affected human evolution. So to identify the adaptive problems that shaped the human mind, we need to know something about ancestral human psychology. But we don't.

Finally, even if we could precisely identify the adaptive problems faced by our ancestors throughout human evolutionary history, we still couldn't infer much about the nature of human psychological adaptations. Selection builds solutions to adaptive problems by retaining modifications to preexisting traits. Subsequent adaptation is always a function of how preexisting traits were modifiable. To know how a solution to an adaptive problem evolved, then, it is necessary to know something about the preexisting trait that was recruited and modified to solve the problem. Without knowledge of our ancestors' psychological traits—which we don't have—we can't know how selection tinkered with them to create the minds we now possess.

Fallacy 2:
We Know, or Can Discover, Why Distinctively Human Traits Evolved

Biologists are often able to reconstruct the selection pressures that drove a species' evolution by using the comparative method to study a clade, or group of species descended from a common ancestor. Because all the species in the group are descended from a common form, differences among them may be the result of variations in the environmental demands they faced. When a trait is shared by two or more species in a clade, but not by the others, it is sometimes possible to identify environmental demands common to those species but absent among the species without the trait. Correlating trait differences with specific environmental variations, in this way, can indicate the environmental demands to which a trait is adapted.

But the comparative method offers little help for Pop EP's aspiration to reveal the adaptive history of the psychological traits—including language and forms of higher cognition—that putatively constitute human nature. Pinker, for example, has argued eloquently that language is an adaptation for verbal communication of infinite combinatorial complexity. He is probably right that language is an adaptation. But discovering why it evolved, what it is an adaptation for, requires identifying the adaptive functions that language served among early language users. To employ the comparative method to answer such questions, we need to compare some human psychological trait with its homologous form in species with whom we share a common ancestor. Here looms the problem. Among extant species, our closest relatives are the chimpanzee and the bonobo, with whom we share a common ancestor that lived approximately six million years ago. But even these, our closest relatives, don't possess forms of the complex psychological traits, such as language, whose evolution Pop EP aspires to explain. So we can't identify the environmental demands we share with our closest relatives to see what our common psychological traits are adapted to. Rather, we need to identify the environmental demands that drove our evolutionary separation from our closest living relatives during the past six million years.

What could enlighten us about these evolutionary events would be information about the ecology and lifestyle of more closely related species with whom we share some higher cognitive abilities. Then, perhaps, we could identify environmental demands shared with them but absent among the chimpanzee and the bonobo (and other primates). The species that fit this bill are the other hominins, the australopithecines and the other species in the genus *Homo*. Unfortunately, all other hominins are extinct. And dead hominins tell (virtually) no tales about their evolutionary histories [see "Once We Were Not Alone," by Ian Tattersall; Scientific American, January 2000]. So there is a dearth of evidence necessary for using the comparative method to illuminate the evolutionary history of distinctively human traits. (That is why there are several theories about the evolution of language but no suggestions about how evidence can be used to choose among them.)

The comparative method does, however, sometimes provide useful information about distinctively human adaptations. But as philosopher Jonathan Michael Kaplan of Oregon State University has pointed out, when it does so, it is not for traits that are universal among humans, but for traits that appear in only some human populations. For example, we know that the gene that produces sickle cell anemia (when a person has two copies of the gene) is an adaptation for resistance to malaria (when a person has just one copy of the gene). Our evidence derived from comparing human populations that have the gene with human populations that don't and identifying the environmental demands correlated with its presence.

Because the comparative method has illuminated such physiological adaptations, it is reasonable to suppose it could illuminate some psychological adaptations as well. But this is cold comfort to Pop EP, which claims that all human psychological adaptations are, in fact, universal among human populations. It is precisely such universal and distinctively human traits for which the comparative method offers little use. Therefore, it is unlikely that accounts of the evolution of our alleged universal human nature will ever rise above the level of speculation.

Fallacy 3:
"Our Modern Skulls House a Stone Age Mind"

Pop EP's claim that human nature was designed during the Pleistocene, when our ancestors lived as hunter-gatherers, gets it wrong on both ends of the epoch.

Some human psychological mechanisms undoubtedly did emerge during the Pleistocene. But others are holdovers of a more ancient evolutionary past, aspects of our psychology that are shared with some of our primate relatives. Evolutionary neuroscientist Jaak Panksepp of Bowling Green State University has identified seven emotional systems in humans that originated deeper in our evolutionary past than the Pleistocene. The emotional systems that he terms Care, Panic and Play date back to early primate evolutionary history, whereas the systems of Fear, Rage, Seeking and

POP EP SAYS

that modern people harbor a Stone Age mind.

BUT

it seems just as likely that the human mind had to adapt to dramatic changes brought about by the advent of agriculture and life in cities. Humans have changed physiologically since the Stone Age, so why wouldn't we have changed psychologically as well?

FRANK STOCKTON

The idea that we are stuck with a Pleistocene-adapted psychology greatly underestimates the rate at which natural and sexual selection can drive evolutionary change.

Lust have even earlier, premammalian origins.

Recognition of our deeper evolutionary history can greatly affect how we understand human psychology. Consider human mating. Buss has argued that human mating strategies were designed during the Pleistocene to solve adaptive problems that were unique in shaping human evolution. Accordingly, observing that humans pursue both short- and long-term mating (sometimes indulging in brief infidelities in the context of an ongoing mateship), he interprets these behaviors as aspects of an integrated set of psychological adaptations that unconsciously calculate the reproductive benefits of each strategy. When the potential reproductive benefits of a short-term mating opportunity are greater than the potential costs, these adaptations lead to infidelity.

If we recognize that aspects of our psychology are holdovers of prehuman evolutionary history, we get a very different picture. Indeed, because our closest relatives, the chimpanzee and bonobo, are highly promiscuous species, our lineage likely embarked on the uniquely human leg of its evolutionary journey with a mechanism of lust designed to promote promiscuous mating. Psychological characteristics that subsequently emerged during human evolutionary history were built atop that foundation. And we know that some emotional systems subsequently evolved to promote the pair bonding that is ubiquitous among human cultures but absent in our closest primate relatives. We have no reason, however, to think that mechanisms of lust and pair bonding evolved together as parts of an integrated mating strategy. Indeed, they likely evolved as separate systems, at diverse points in our lineage's evolutionary history, in response to different adaptive demands, to serve distinct purposes.

If this alternative interpretation of human mating psychology is correct, we are not "of one mind" about our sexual relationships. Rather, we possess competing psychological urges. We are pushed toward promiscuity by evolutionarily ancient mechanisms of lust and toward long-term pair bonds by more recently evolved emotional systems. Rather than being driven by an integrated Pleistocene psychology that unconsciously calculates which urge to pursue when, we are torn by independently evolved emotional mechanisms.

The view that "our modern skulls house a Stone Age mind" gets things wrong on the contemporary end of our evolutionary history as well. The idea that we are stuck with a Pleistocene-adapted psychology greatly underestimates the rate at which natural and sexual selection can drive evolutionary change. Recent studies have demonstrated that selection can radically alter the life-history traits of a population in as few as 18 generations (for humans, roughly 450 years).

Of course, such rapid evolution can occur only with significant change in the selection pressures acting on a population. But environmental change since the Pleistocene has unquestionably altered the selection pressures on human psychology. The agricultural and industrial revolutions precipitated fundamental changes in the social structures of human populations, which in turn altered the challenges humans face when acquiring resources, mating, forming alliances or negotiating status hierarchies. Other human activities—ranging from constructing shelter to preserving food, from contraception to organized education—have also consistently altered the selection pressures. Because we have clear examples of post-Pleistocene physiological adaptation to changing environmental demands (such as malaria resistance), we have no reason to doubt similar psychological evolution.

Moreover, human psychological characteristics are the product of a developmental process involving interaction between genes and the environment. Even if little genetic evolution has taken place since the Pleistocene, which is doubtful, human environments have changed in profound ways, as the examples above indicate. Any Pleistocene-selected genes we possess will interact with these new environments to produce psychological traits that may differ in important ways from those of our Pleistocene ancestors. So there is no good reason to think that all of our evolved psychological characteristics remain adapted to the lifestyle of Pleistocene hunter-gatherers.

SOME POP EP WRITINGS

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Evolutionary Psychology: The New Science of the Mind. David M. Buss. Allyn and Bacon, 2007.

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THE AUTHOR

David J. Buller is Presidential Research Professor and professor of philosophy at Northern Illinois University. He is author of *Adapting Minds: Evolutionary Psychology and the Persistent Quest for Human Nature* (MIT Press, 2005) and editor of *Function, Selection, and Design* (SUNY Press, Series in Philosophy and Biology, 1999).

Fallacy 4:
The Psychological Data Provide Clear Evidence for Pop EP

Pop EP argues that its speculations about our Pleistocene past have led to the discovery of many of the psychological adaptations that control our behavior. Because the approach has worked, it must be on to at least part of the truth about human evolutionary history. Of course, the soundness of this argument turns on the strength of the evidence for Pop EP's alleged discoveries. That evidence usually consists of standard psychological pencil-and-paper data (such as responses to forced-choice questionnaires), but it sometimes also includes a limited array of behavioral data. As I argue at length in *Adapting Minds,* however, the evidence is typically inconclusive at best. Pop EP's favored evolutionary hypotheses are, as philosopher Robert C. Richardson of the University of Cincinnati recently quipped, "speculation disguised as results." The appearance that the evidence is compelling is created less by the data themselves than by the failure to consider and adequately test viable alternative explanations. Consider a single illustration of this point.

Buss argues that jealousy evolved as an emotional alarm that signals a partner's potential infidelities and causes behavior designed to minimize losses of reproductive investment. Among our ancestors, the argument continues, infidelities entailed different reproductive costs for the two sexes. For men, a female's *sexual* infidelity signified that he might be investing parental resources in another male's offspring. For women, it was a male's *emotional* involvement with another woman that could lead to the loss of his resources. And indeed, Buss claims to have discovered the requisite sex difference in the evolved "design features" of the jealous mind: the male mind is more sensitive to cues of sexual infidelity, whereas the female mind is more sensitive to cues of emotional infidelity.

The principal data cited in support of this theory are responses to forced-choice questionnaires. One questionnaire item, for example, asks subjects which they find more upsetting: "imagining your partner forming a deep emotional attachment" to a rival or "imagining your partner enjoying passionate sexual intercourse" with a rival. Results consistently show that more men than women report the thought of a partner's sexual infidelity to be more distressing than the thought of a partner's emotional infidelity.

But such data are hardly conclusive evidence of sex-differentiated psychological adaptations. Instead both sexes could have the same evolved capacity to distinguish threatening from nonthreatening infidelities and to experience jealousy to a degree that is proportional to the perceived threat to a relationship in which one has invested mating effort. This shared capacity could generate Buss's questionnaire results because of acquired beliefs about a sex difference in the types of behavior that pose a threat to a relationship. In fact, several studies have found that it is widely believed, by both sexes, that men are more likely than women to have sex in the absence of any emotional involvement. Given this belief, men will find a woman's sexual infidelity more threatening than women will find a man's sexual infidelity, because female sexual infidelity is more likely to be accompanied by emotional involvement.

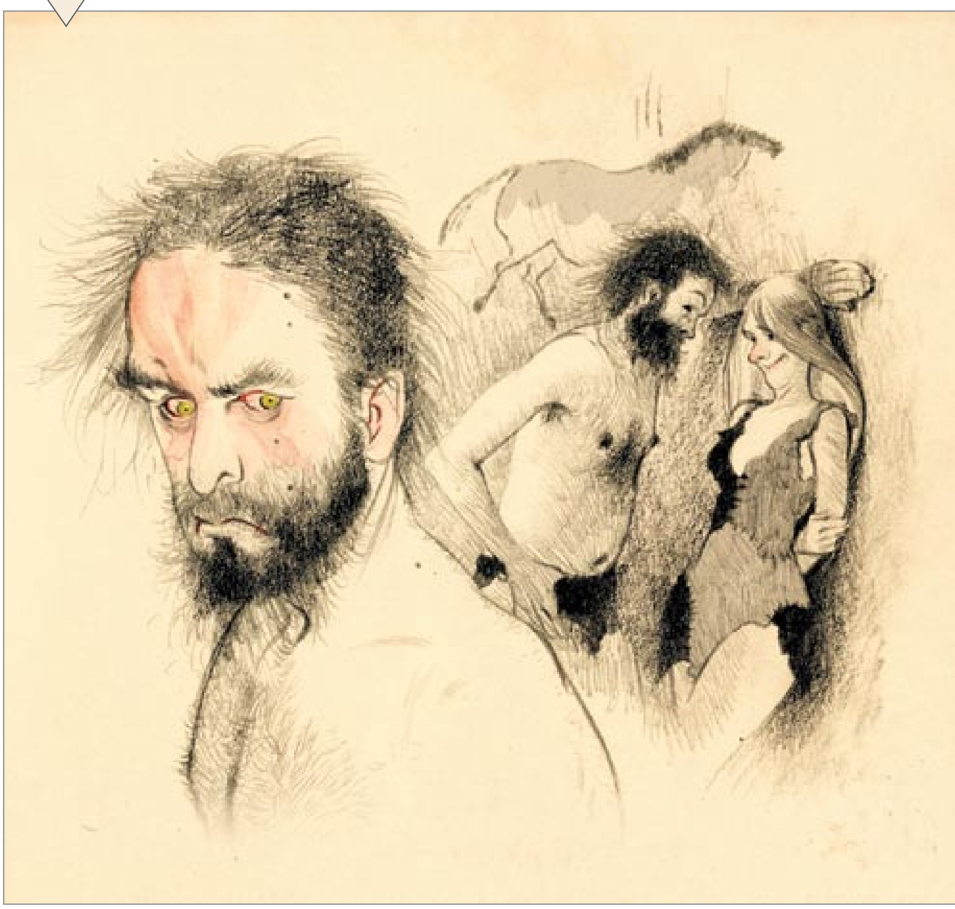
This alternative hypothesis also readily accounts for data that aren't easily accommodated by the theory that there is a sex difference in the evolved design features of the mind. First, homosexual men are even less likely than heterosexual women to find sexual infidelity more upsetting than emotional infidelity. And homosex-

POP EP SAYS

that the psychological data provide clear evidence for their claims, such as differences in the basis of jealousy in males and females.

BUT

the data are largely based on forced-answer questionnaires [*see box on opposite page*]. Such evidence is inconclusive. It gives no clear basis, for example, for thinking that males and females evolved distinct mechanisms of jealousy. Instead both sexes may possess the same mechanism, which simply responds differently when faced with different types of threat to a relationship.


FRANK STOCKTON

ual males, as a group, are also less likely than heterosexual males or females to believe that sexual infidelity poses a threat to the primary relationship. If the sexes share the same capacity for jealousy, with the degree of sexual jealousy determined by the degree of the perceived threat to a relationship, homosexual males' tendency not to find sexual infidelity threatening would cause them to depart from the male norm.

Second, the degree to which males find the prospect of a female partner's sexual infidelity upsetting varies significantly among cultures. For example, only about a quarter of German males report sexual infidelity to be more upsetting than emotional infidelity. Interestingly, Buss and his colleagues have themselves noted that the German culture has "more relaxed attitudes about sexuality, including extramarital sex, than does the American culture." So German males should be less likely than American males to believe that a female partner's sexual infidelity threatens a relationship and hence less likely to be distressed by sexual infidelity than American males. Again, this cultural difference is precisely what we should expect if degree of sexual jealousy is a function of the degree to which sexual infidelity is perceived as a threat to a relationship.

It is unclear why Pop EP resists the idea that the sexes share the same emotional mechanism of jealousy and that attitudinal differences are a function of differences in the beliefs processed by the mechanism. According to Pop EP, many cultural differences stem from a common human nature responding to variable local conditions. Yet cultural differences are often more profound than the sex differences that Pop EP has transformed into sensational theory. If cultural variation can result from a common nature responding to dissimilar inputs, surely sex differences in attitudes and behavior can, too.

Coda

Among Darwin's lasting legacies is our knowledge that the human mind evolved by some adaptive process. After all, the human brain is even more costly to run than an internal-combustion engine these days, consuming 18 percent of the body's energy intake while constituting merely 2 percent of its weight. We wouldn't have such an organ if it hadn't performed some important adaptive functions in our evolutionary past.

The challenge for evolutionary psychology is to move from this general fact to some evidentially well-supported specifics about the adaptive processes that shaped the mind. But, as we have seen, the evidence needed to substantiate accounts of adaptation in our lineage during the past couple of million years is scarce. And this isn't the kind of evidence that is likely to materialize; such evidence is lost to us, probably forever. It may be a cold, hard fact that there are many things about the evolution of the human mind that we will never know and about which we can only idly speculate.

Of course, some speculations are worse than others. Those of Pop EP are deeply flawed. We are unlikely ever to learn much about our evolutionary past by slicing our Pleistocene history into discrete adaptive problems, supposing the mind to be partitioned into discrete solutions to those problems, and then supporting those suppositions with pencil-and-paper data. The field of evolutionary psychology will have to do better. Even its very best, however, may never provide us knowledge of why all our complex human psychological characteristics evolved. ■

A Pop EP Questionnaire

To test for an evolved sex difference in jealousy, psychologist David M. Buss and his colleagues designed a questionnaire (*below*), which they administered to American subjects [see "Sex Differences in Jealousy: Evolution, Physiology, and Psychology" in *Psychological Science,* Vol. 3, No. 4; July 1992]. Their questionnaire, or a minor variant of it, was subsequently used in a number of similar studies in several societies. Results of these studies are shown in the tables at the bottom; the first column in each table lists data obtained by Buss and his colleagues in the original study.

Questionnaire

Instructions: Please think of a serious committed romantic relationship that you have had in the past, that you currently have, or that you would like to have. Imagine that you discover that the person with whom you've been seriously involved became interested in someone else. What would distress or upset you more (*circle only one*):

DILEMMA 1
(A) Imagining your partner forming a deep emotional attachment to that person.
(B) Imagining your partner enjoying passionate sexual intercourse with that other person.

DILEMMA 2
(A) Imagining your partner trying different sexual positions with that other person.
(B) Imagining your partner falling in love with that other person.

SURVEY RESULTS

Percentage choosing sexual infidelity (B) as more upsetting in Dilemma 1

	U.S.	U.S.	U.S.	U.S.	U.S.	U.S.	China	Netherlands	Germany	Korea	Japan	Average
Male	60	76	61	55	53	73	21	51	28	59	38	51
Female	17	32	18	32	23	4	5	31	16	18	13	22

Percentage choosing sexual infidelity (A) as more upsetting in Dilemma 2

	U.S.	U.S.	U.S.	U.S.	Netherlands	Germany	Korea	Japan	Average
Male	44	43	44	47	23	30	53	32	38
Female	12	11	12	12	12	8	22	15	13

MORE TO EXPLORE

The Seven Sins of Evolutionary Psychology. Jaak Panksepp and Jules B. Panksepp in *Evolution and Cognition,* Vol. 6, No. 2, pages 108–131; 2000.

Historical Evidence and Human Adaptations. Jonathan Michael Kaplan in *Philosophy of Science,* Vol. 69, No. S3, pages S294–S304; 2002. PDF available for download at **http://oregonstate.edu/~kaplanj/Kaplan-HistoricalEvidence.pdf**

Evolutionary Psychology as Maladapted Psychology. Robert C. Richardson. MIT Press, 2007.

Evolutionary Psychology. Stephen M. Downes in *The Stanford Encyclopedia of Philosophy.* Spring 2008 edition. **http://plato.stanford.edu/archives/spr2008/entries/evolutionary-psychology**

Evolution in the Everyday

Understanding of evolution is fostering powerful technologies for health care, law enforcement, ecology, and all manner of optimization and design problems • • • **BY DAVID P. MINDELL**

KEY CONCEPTS

- The theory of evolution provides humankind with more than just a scientific narrative of life's origins and progression. It also yields invaluable technologies.
- For instance, the concept of molecular clocks—based on the accumulation of mutations in DNA over the eons—underlies applications such as the DNA analyses used in criminal investigations.
- DNA analysis of how pathogens evolve produces useful information for combating the outbreak and spread of disease. Accelerated evolution in laboratories has improved vaccines and other therapeutic proteins.
- Computer scientists have adapted evolution's mechanisms of mutation and selection to solve problems.

—The Editors

Charles Darwin surely had no clue of the technological advances that his studies of beetles and birds would unleash. Our progress in comprehending the history and mechanisms of evolution has led to powerful applications that shape a wide variety of fields today.

For instance—as the *CSI* franchise of television shows has popularized—law-enforcement agencies now commonly use evolutionary analyses in their investigations. Knowledge of how different genes evolve determines the kind of information they can extract from DNA evidence.

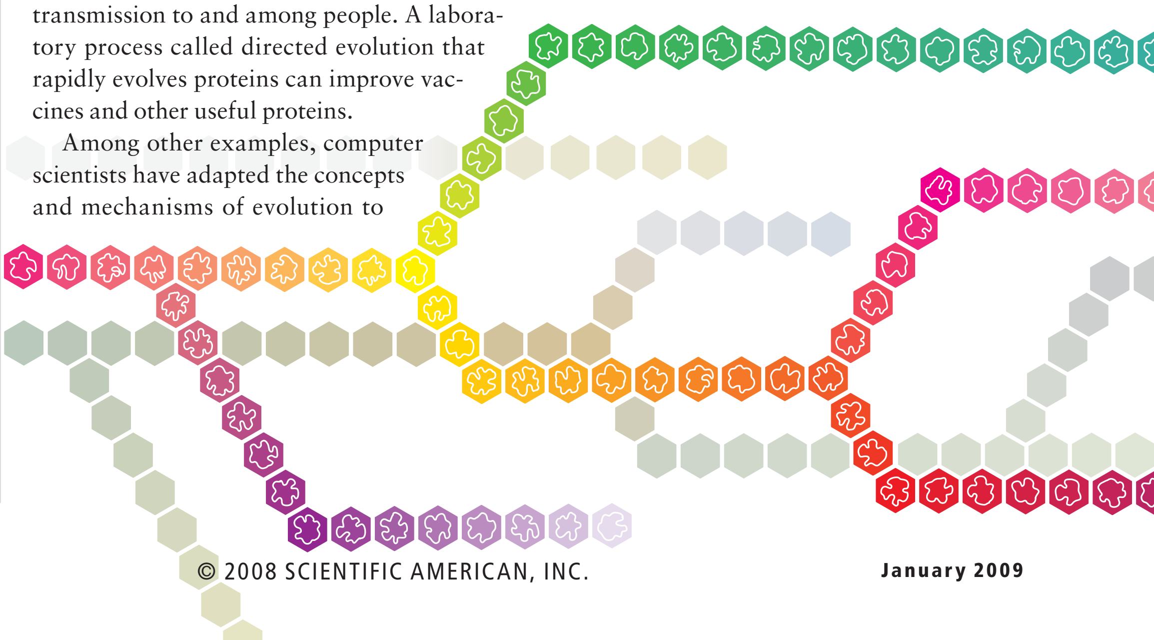
In health care, phylogenetic analysis (studies of DNA sequences to infer their evolutionary relatedness, or genealogy) of a pathogen such as bird flu or West Nile virus can lead to vaccines and to guidelines for minimizing the disease's transmission to and among people. A laboratory process called directed evolution that rapidly evolves proteins can improve vaccines and other useful proteins.

Among other examples, computer scientists have adapted the concepts and mechanisms of evolution to create a general system known as genetic programming that can solve complex optimization and design problems. And a recently developed approach known as metagenomics has revolutionized scientists' ability to survey the kinds of microbes living in a region, bringing about the most dramatic change in our understanding of microbial diversity since the advent of microscopes.

About 400 years ago English philosopher and statesman Francis Bacon commented that knowledge is power. The extremely useful techniques borne of our growing comprehension of evolution bear him out in spectacular fashion.

Beyond Reasonable Doubt

Evolutionary analyses and criminal investigations hold the same goal of revealing historical



JEN CHRISTIANSEN

World

events. Their fruitful combination awaited only the maturing of DNA-sequencing technology to provide large data sets, robust quantitative methods, and enlightened integration of science and the legal system.

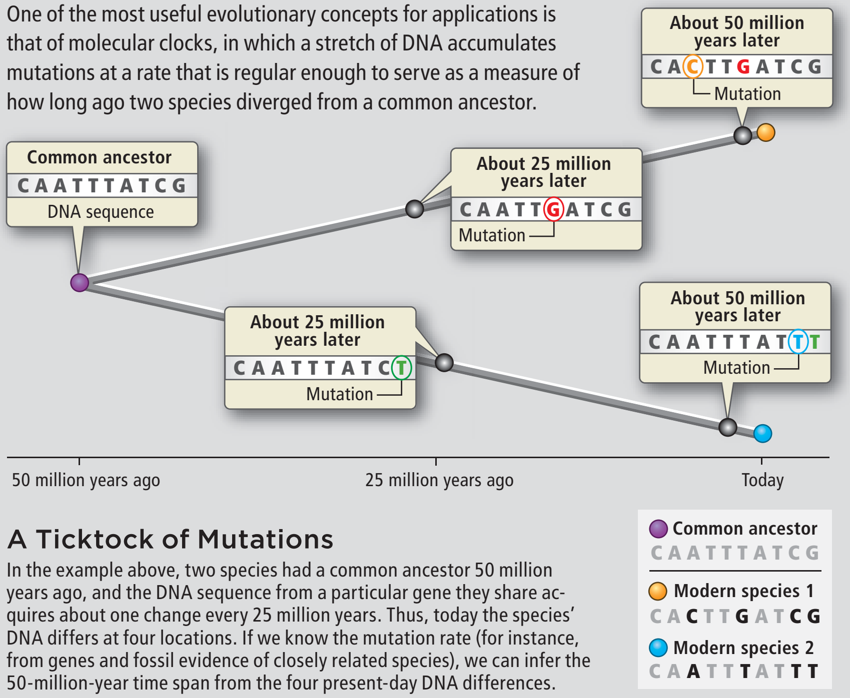
As with many applications of evolution, the concept of molecular clocks plays a vital role. Changes in many DNA sequences occur at roughly predictable rates over time, forming the basis for molecular clocks [*see box on next page*]. The clocks for two regions of DNA, however, can run at markedly different rates. In the early 1980s geneticists discovered regions of human DNA that evolve very rapidly, and scientists soon pressed these fast-evolving regions into service as genetic markers—unique identifiers of individuals, like fingerprints but with greater detail—in criminal cases and in paternity testing.

Forensic investigators assess specific genetic markers as indicators of links between suspects and crime scene evidence such as a single human hair, lip cells left on a beer can, saliva on envelope flaps and cigarette butts, as well as semen, blood, urine and feces. The most straightforward use is to demonstrate a suspect's innocence by the nonmatching of his or her markers compared with those of crime scene evidence. Indeed, the Innocence Project, a public policy organization promoting and tracking the use of genetic markers to overturn wrongful convictions, reports that since 1989, nonmatching of genetic markers has exonerated more than 220 people, many of them convicted for rape crimes and some of them on death row.

The standing of evolutionary science within the U.S. court system has completely reversed since its portrayal as an insidious scourge in the 1925 trial of Tennessee high school teacher John T. Scopes. In the 1998 criminal case of the *State of Louisiana v. Richard J. Schmidt,* the judge set precedent in ruling that phylogenetic analyses met judicial standards because they were subject to empirical testing, pub-

Molecular Clocks

One of the most useful evolutionary concepts for applications is that of molecular clocks, in which a stretch of DNA accumulates mutations at a rate that is regular enough to serve as a measure of how long ago two species diverged from a common ancestor.

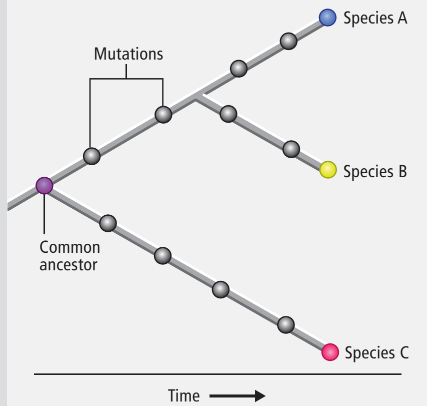


A Ticktock of Mutations

In the example above, two species had a common ancestor 50 million years ago, and the DNA sequence from a particular gene they share acquires about one change every 25 million years. Thus, today the species' DNA differs at four locations. If we know the mutation rate (for instance, from genes and fossil evidence of closely related species), we can infer the 50-million-year time span from the four present-day DNA differences.

Evolutionary Trees

Scientists can apply the molecular clock technique to a group of related species to help infer their evolutionary tree, or phylogeny. Here, for example, the DNA from species A and B differ at four locations from each other, but each differs at eight locations from species C. Thus, the lineage of species C split from that of A and B's common ancestor twice as long ago as A and B's individual lineages diverged. A, B and C could also represent strains of a virus, mutating over a time span of a few years.



lished in peer-reviewed sources and accepted within the scientific community—some of the criteria commonly known as the Daubert standard for scientific evidence, after the name of a plaintiff in an earlier precedent-setting case.

I was fortunate to be invited to participate in *Louisiana v. Schmidt* as a scientist and expert witness by Michael L. Metzker of the Baylor College of Medicine and David M. Hillis of the University of Texas at Austin. The three of us worked together on the molecular analyses.

The uncontested facts in the case are that a gastroenterologist broke into the home of his former office nurse and mistress and gave her an injection. He claimed it was a vitamin B shot. She claimed it was HIV. She had begun feeling ill several months after the injection and a blood test revealed that she had become infected with HIV, at which point she went to the district attorney's office to file charges. The DA's detectives quickly obtained a search warrant for the physician's office, where they seized his record books and a vial of blood from a refrigerator. The physician said that the blood sample, drawn from one of his HIV-positive patients, was for his own research.

The next logical step in the investigation was to perform phylogenetic analyses of the HIV lineages from the nurse and the alleged source. My collaborators and I selected two HIV genes to sequence, one relatively fast-evolving, encoding part of the viral envelope (*env*), the other slow, encoding a vital enzyme called reverse transcriptase (RT). We also had blood samples from about 30 other infected individuals to serve as a reference point.

Our analyses of the *env* gene showed the HIV sequences from the victim and the doctor's sample formed two sister clades relative to the epidemiological sample. The likelihood of two random people from the infected population having such similar viruses is extremely small. This result is consistent with the accusation that the physician used the blood sample from one of his patients to infect the nurse, but it could also be that the patient was infected with HIV from the nurse. The phylogeny inferred from the more slowly evolving RT sequences showed that viruses from the victim were younger, arising from within the clade of viruses from the alleged source. This result clearly indicated that viruses from the alleged source had infected the nurse.

The jury found the doctor guilty of attempted murder, and he was sentenced to 50 years in prison. Of course, we cannot know how much weight the jurors placed on the evolutionary evidence and how much on other items such as the physician's notebooks and behavior. But we do know that phylogenetic analyses will continue to be used in U.S. courts, thanks to the Supreme Court upholding the *Louisiana v. Schmidt* precedent in 2002.

JEN CHRISTIANSEN; SOURCE: "MOLECULAR CLOCKS," FROM THE UNDERSTANDING EVOLUTION WEB SITE, UNIVERSITY OF CALIFORNIA MUSEUM OF PALEONTOLOGY, 2008 (*http://evolution.berkeley.edu/evolibrary/article/molecclocks_01*)

Microbial Arms Race

Like crime, infectious disease will always be a fact of life for us. Parasitic viruses, bacteria, fungi and animals have been co-evolving with people throughout *Homo sapiens*'s entire history, driving evolution of our wonderfully adaptable immune systems. Human populations provide ever larger breeding grounds for microbial pathogens, and even if we do hold some at bay and drive a few to extinction, others will evolve to invade successfully and spread. We are in this arms race for the long haul.

Understanding the evolutionary history of pathogens entails determining their genealogy, often based on phylogenetic analyses of DNA, which represent our best method for identifying unknown pathogens and their genes. Learning a pathogen's genealogy allows us to form valuable working hypotheses about its means of reproduction and transmission, as well as its preferred habitats, because close relatives are more likely to share heritable life history traits than distant relatives are. In turn, we can use this key information to make recommendations about how to minimize the pathogen's transmission opportunities and, potentially, how to enhance immunity.

Understanding evolutionary mechanisms requires identifying the causes of mutation and the roles of natural selection and chance events in the origin and persistence of particular heritable changes. We may track heritable changes across genotypes and morphology (physical form), as well as across life history traits such as virulence, transmissibility, host specificity and reproductive rate. For example, growing knowledge of distantly related bacteria exchanging drug-resistance genes, a process called horizontal transfer, has led biologists to seek new kinds of antibiotics that would block the ability of these mobile genetic elements to replicate and transfer themselves.

The deadly history of human influenza epidemics and our increasing grasp of flu virus evolution illustrates some of these points in action. Phylogenetic analyses of flu virus genes sampled broadly from host species have shown us that wild birds are a primary source and that domestic pigs are often, though not always, the intermediary hosts between birds and humans. Thus, health officials now recommend that people in certain regions keep their poultry and pigs in separate enclosed facilities to prevent contact with wild birds. They advise doing surveillance for a highly pathogenic variety known as influenza A strain H5N1 and other phylogenetically identified strains not just in poultry but also in select wild species, including waterfowl and shorebirds.

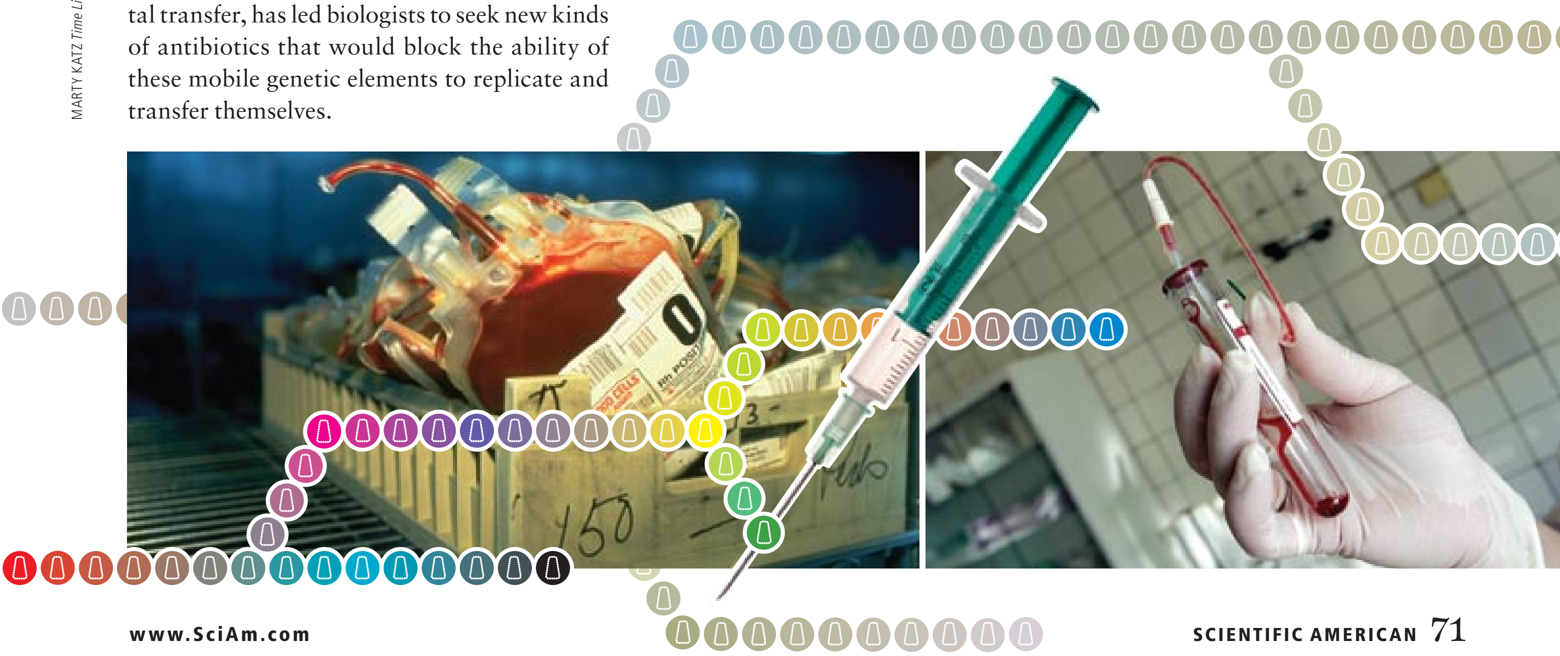
Phylogenies also demonstrate that influenza A genomes have eight unique segments that can be mixed and matched among strains from different host species. This form of recombination, known as shift, combined with mutation in DNA sequences, provides the near kaleidoscopic variation that allows reconfigured viruses to elude previously developed immune system antibodies, requiring us continually to develop new vaccines. Coupling geographic sampling with the phylogenetic history of specific segments and particular mutations known to be pathogenic helps in predicting the spread of the disease and in identifying candidates for use in vaccine development.

In 1997 scientists barely contained a potentially catastrophic outbreak in Hong Kong of H5N1, when they convinced authorities to slaughter all domestic fowl, the local virus source. Although future pandemics are a ques-

EVOLVING HIGH SPEED

Training a robot to walk as fast as possible while keeping its balance can require laborious fine-tuning of its gait for each new walking surface. Researchers at Carnegie Mellon University used an evolutionary algorithm for this task with four-legged Sony Aibos. Four of these robots tried out various gaits and shared the resulting performance data with one another. They then selected the best gaits and produced mutated "offspring" walks to evaluate next. After about 100 generations of this evolutionary process, the quadrupeds could walk 20 percent faster than they could with the scientists' best efforts at hand-tuning them.

FORENSIC SCIENCE can thank biologists' understanding of evolving DNA sequences for the powerful tool of genetic markers, which can indicate or rule out links between suspects and crime scene evidence. In a precedent-setting 1998 case, phylogenetic analysis of HIV samples strongly supported the accusation that a doctor had injected his victim with blood from an infected patient.



MARTY KATZ *Time Life Pictures/Getty Images (blood bags)*; DANIEL SAMBRAUS *(syringe)*; MAXIM MARMUR *AFP/Getty Images (test tube)*

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tion of when, not if, our knowledge about evolutionary sources, hybridization among genomes and the host-shifting capability of flu viruses helps us to minimize risk.

Evolutionary Medicine

Another way that evolution influences our health is through what might be called "unintelligent design features" of our bodies—legacies of our evolutionary past [see "This Old Body," by Neil H. Shubin, on page 50]. For instance, humans have a higher incidence of birthing problems as compared with other primates because female pelvis size in humans has not kept pace with selection for larger infant brain size. Some traits that may seem unintelligently designed, however, can actually be useful. Examples include fever, diarrhea and vomiting, which aid in purging microbial infections.

Applying an evolutionary perspective in understanding our susceptibilities and promoting health is known as evolutionary or Darwinian medicine. A vital step in this new endeavor is integration of basic evolutionary science into the curricula for medical and public health students.

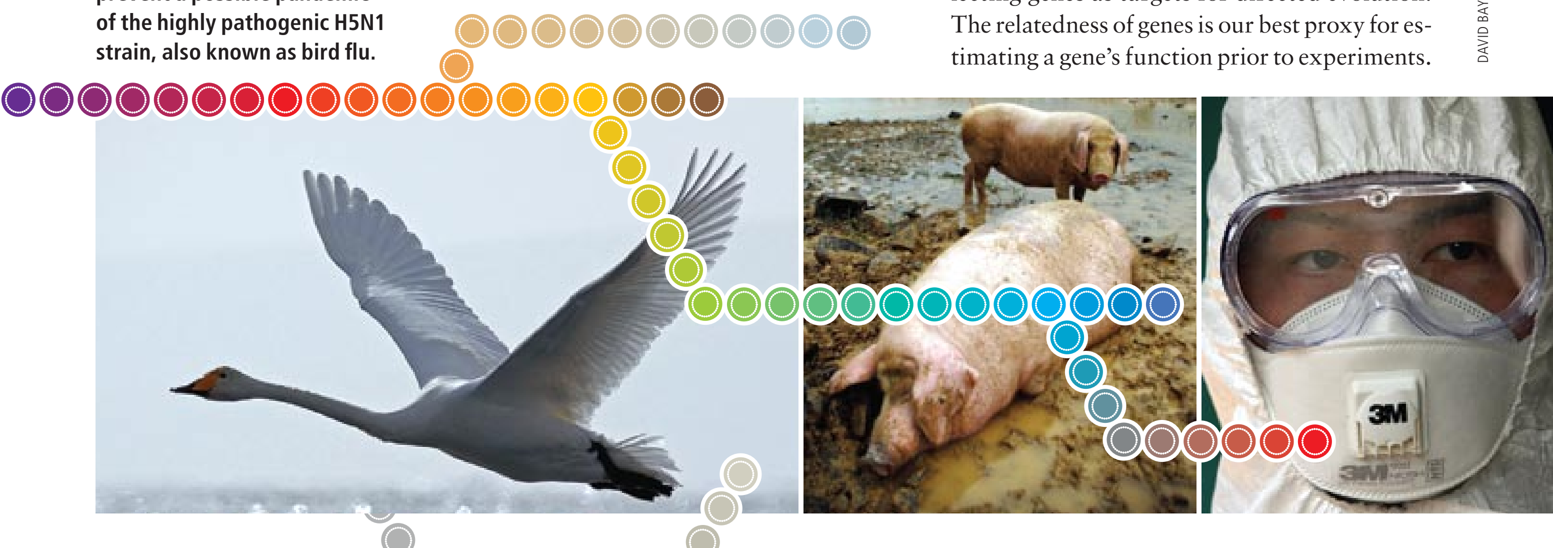
The matching of human genotypes with particular diseases has given rise to the possibility of personalized medicine, in which physicians can specify medications and dosages for individuals based on particular genetic traits. An example of this nascent approach involves the drug Herceptin (trastuzumab), which can reduce early-stage breast cancers in roughly 25 percent of cases but occasionally causes heart problems. Doctors can use information about an individual's genotype to identify the likelihood of positive response to Herceptin and whether the low probability of heart problems is a worthwhile risk [see "Gaining Ground on Breast Cancer," by Francisco J. Esteva and Gabriel N. Hortobagyi; Scientific American, June 2008].

Many people are reluctant to be genetically profiled, however, fearing unfair treatment by employers or insurance companies. In response, Congress passed the Genetic Information Nondiscrimination Act last May, outlawing such discrimination. Another concern is that race might be used as a proxy for genetic predisposition to particular diseases. Yet that kind of approach misunderstands the nature of human genetic variation, in which even closely related people may differ in their response to a drug. [For a cautionary tale on this topic, see "Race in a Bottle," by Jonathan Kahn; Scientific American, August 2007.]

In Vitro and In Silico

Evolution acting over billions of years has proved itself to be a versatile, if sometimes quirky, designer. Researchers are now borrowing from evolution's drawing board, using directed evolution to enhance useful functions of proteins. These molecular biologists intentionally mutate genes, produce the proteins the genes encode, measure the proteins' functional performance, and then select sets of top performers for subsequent bouts of mutation and testing. Repeating this cycle millions of times often yields impressive results.

Understanding of evolutionary history and mechanisms improves directed evolution in several ways. First, discovering the phylogenetic relationships of genes is an important step in determining their functions and, therefore, in selecting genes as targets for directed evolution. The relatedness of genes is our best proxy for estimating a gene's function prior to experiments.



HUMAN INFLUENZA virus strains often start out in wild birds, with domestic pigs serving as intermediary hosts between birds and humans. Understanding of this evolutionary history, revealed by analyses of virus DNA sampled from a wide variety of host species, helped scientists convince authorities in Hong Kong to slaughter all domestic fowl in 1997 to prevent a possible pandemic of the highly pathogenic H5N1 strain, also known as bird flu.

DAVID BAY (*Mindell*); CHINA PHOTOS/GETTY IMAGES (*swan*); AP PHOTO (*pigs*); MIKE CLARKE *AFP/Getty Images* (*person in mask*)

If we have experimentally determined the functions for a gene in mice, say, it is reasonable to hypothesize that the most closely related gene in humans will have similar functions.

Second, knowledge of how particular genes evolve—understanding of the mechanisms of mutation and how natural selection operates on them—informs the choice of mutations to impose in directed evolution. A protein is a chain of amino acids whose sequence ultimately determines the protein's function. Directed evolutionists may choose to alter single amino acids at random locations anywhere within the sequence or only in certain regions or even at specific sequence positions known to be functionally important. Protein-coding genes are structured in segments, which we can shuffle to try to create arrangements with novel capabilities. We can also mix the structural segments of related genes from within a gene family (phylogenetically identified) or from sister species to construct so-called chimeric proteins. Recombination and shuffling of gene segments has produced rapid evolution of proteins in nature, and mimicking this approach has proved to be powerful in the lab. Researchers have further accelerated evolutionary change by shuffling whole genomes among populations of select microbes.

Among directed evolution's successes are a vaccine against human papillomavirus and better hepatitis C vaccines. Shuffling segments of 20 different human interferons (a family of immune system proteins) has led to chimeric proteins that are 250,000 times more effective at slowing viral replication. An improved human p53 protein, a tumor suppressor, has yielded better inhibition of tumor growth in lab experiments, and researchers are working on transferring this success to individuals who have compromised p53 proteins.

Another way that scientists and engineers emulate evolution in the lab is with computer programs called evolutionary or genetic algorithms. People have used this technique extensively to search for optimal solutions to complex problems, including scheduling air traffic, forecasting weather, balancing stock portfolios and optimizing combinations of medicines, as well as for designing bridges, electronic circuits and robot-control systems [see "Evolving Inventions," by John R. Koza, Martin A. Keane and Matthew J. Streeter; Scientific American, February 2003].

The general structure of an evolutionary algorithm includes five steps:

1. Generate a population of candidate solutions.
2. Evaluate the suitability, or fitness, of each candidate solution.
3. If any candidate solution meets all the target criteria, stop the process.
4. Otherwise, select groups of relatively fit individuals in the population to be parents.
5. Subject the parents to mutational changes and "sexual" recombination of their traits to produce a new population of candidate solutions. Then begin again with step 2.

Genetic programming sometimes finds solutions very unlike typical human designs. For instance, an evolutionary computation to find orbits for constellations of communications satellites minimizing signal loss by ground-based receivers identified orbit configurations that were unusually asymmetric, with variable gaps between the individual satellite paths. These evolved optimal constellations outperformed the more symmetrical arrangements usually considered by designers.

Directed evolution of immune system proteins called interferons has produced variants that are 250,000 times more effective at slowing viral replication.

Critical Services

As humankind's numbers continue to grow and cause environmental changes at a rapid pace, concerns mount about conserving biological diversity and sustaining human populations over time. We rely on healthy ecosystems, made up of organisms and their environments, to provide us with usable water, arable land and clean air. These critical ecosystem services are essential for human well-being, yet we have little understanding of their regulation and the consequences of changes in ecosystems. What are the roles of particular species and communities within an ecosystem? How sensitive are these natural systems to loss of species and habitats? How do ecosystem changes influence local climates, pollination and seed dispersal in plants, decomposition of waste, and the emergence and spread of disease? These are difficult questions that evolutionary methods and knowledge help to answer.

Taking inventory is critical for understanding and managing resources. Yet a great many life-forms remain to be discovered and described, particularly the very small, including untold legions of viruses, bacteria and protists. The effort to determine the genealogical links among all life-forms includes extensive genetic sampling of biological diversity, within species as well as among them. With information from phylogenetic analyses of these samples, biologists can assess the relative distinctiveness of groups of organisms and delineate the evolutionary units (such as particular species or groups of species) of concern for conservation.

Many phylogenetic analyses have revealed previously unrecognized species. DNA from African elephant populations supported recognition of two distinct species in Africa rather than one, as was long believed. *Loxodonta africana* is found primarily in forest habitats, whereas the newly named *L. cyclotis* lives in the savanna. DNA analyses have also found new species of Asian soft-shelled turtles, right whales and Old World vultures, among many others.

The development of unique genetic markers for vertebrate species increasingly aids the enforcement of conservation laws by identifying protected animals or their parts being smuggled or sold illegally. This approach has helped prosecution of cases of illicit whaling, use of tiger products in Asian medicines and harvesting of caviar from protected sturgeon species.

Metagenomics

The DNA from one organism makes up one genome. Collect the DNA from an entire community of microbes of various species in some location, and you have a metagenome. Biologists can now isolate DNA fragments from such a community, determine the fragments' sequences and reassemble them into contiguous sequences—all without first requiring the difficult and labor-intensive steps involved in growing the microbes in the lab.

Metagenomic analysis of microbes in the human intestinal tract has revealed more than 100 times as many different genes as are found in our own genomes (which contain about 25,000 protein-coding genes) and about 300 previously unknown and, so far, unculturable microbial lifeforms. The known microbes and their genes play important roles in development of our immune systems, in the production of fatty acids (which power healthy intestinal cell growth), and in detoxification of ingested substances that could otherwise lead to cancerous cell growth or alter our ability to metabolize medicines. Metagenomic analyses suggest that changes in the occurrence, abundance and interactions of both known and unknown microbes play a role in human diseases such as inflammatory bowel disease or in conditions such as obesity.

Similar metagenomic analyses of the reproductive tract in females have shown that bacterial vaginosis, a disease associated with premature labor and delivery, pelvic inflammatory disease and the acquisition of sexually transmitted pathogens such as HIV, is accompanied by dramatic changes in the species composition of vaginal bacteria communities. Researchers have found many newly discovered bacterial groups in both healthy and unhealthy vaginal ecosystems. Improved treatment of bacterial vaginosis requires better understanding of how these changes in vaginal ecosystems occur and how they affect ecosystem function and disease progression.

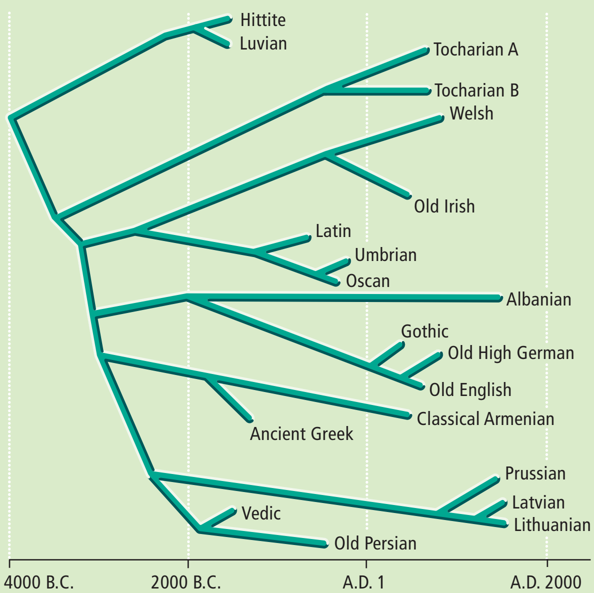
Turning to external ecosystems and sustainability, metagenomic analyses of water samples from the Pacific Ocean and from the Sargasso Sea in the North Atlantic have similarly indicated that a vast amount of oceanic biological diversity, including many viruses, remains to be discovered and understood. Scientists know relatively little about the metabolic abilities and ecological functions of these diverse microbial

The Tree of Tongues

Charles Darwin himself noted the relation between human genealogy and language change: "If we possessed a perfect pedigree of mankind, a genealogical arrangement of the races of man would afford the best classification of the various languages now spoken throughout the world; and if all extinct languages, and all intermediate and slowly changing dialects, were to be included, such an arrangement would be the only possible one."

Languages do not evolve in a strict biological sense. Yet they do change over time in a manner analogous to biological evolution, with human innovation and borrowing playing an important role. Study of the evolution of languages began in the 1950s with compilation of cognate words, those sharing common origins, among language pairs. More recently, linguists and evolutionary scientists have applied the statistical methods of maximum likelihood and Bayesian analysis (used by biologists for phylogenetic analyses of evolution) in studies of language evolution. They apply the techniques to data sets of shared cognates and language structures such as grammar and the sounds used. Analyses using evolutionary models focusing on the most slowly changing features of language structure suggest that some historical relations can be traced back 20,000 years ago or more. —***D.P.M.***

INDO-EUROPEAN LANGUAGES form evolutionary trees (*right*) when scientists apply biologists' phylogenetic methods to sets of related words and other shared characteristics. Which of the many alternative trees best represents the history of the languages, however, remains unclear.



JEN CHRISTIANSEN; SOURCE: "RECONSTRUCTING THE EVOLUTIONARY HISTORY OF INDO-EUROPEAN LANGUAGES USING ANSWER SET PROGRAMMING," BY E. ERDEM, V. LIFSCHITZ, L. NAKHLEH AND D. RINGE, IN *PRACTICAL ASPECTS OF DECLARATIVE LANGUAGES (PADL): 5TH INTERNATIONAL SYMPOSIUM, 2003;* SPRINGER, 2003 lineages and have numerous projects under way. We need to learn about them because microbial communities are largely responsible for supporting life on earth. They conduct most of the world's photosynthesis, and they make the necessary elements of carbon, nitrogen, oxygen and sulfur accessible to other life-forms, including people.

Using the evolution-based analyses of metagenomics to learn the composition of communities in a variety of circumstances is only the first step in learning what the community members do, how they interact, and how they are changed and sustained over time. Are diverse microbial communities more resilient to environmental change than less diverse ones? Are some particular groups of species of great importance in maintaining an ecosystem? What drives formation and turnover in the composition of microbial communities? The concepts and methods needed for this next level of understanding are largely within the realm of evolutionary ecology, which entails study of all interactions within and among species and populations and their environments.

We have yet to see applications arising from microbial metagenomics and evolutionary ecology, but possibilities abound. Microbes both produce and consume carbon dioxide, methane and other greenhouse gases and may play a role in determining the success of efforts to curtail global warming. Metagenomics-based systems might monitor environmental health and watch for pathogens, whether naturally emergent or introduced by terrorists. Metagenomics could diagnose a broad selection of diseases in humans and livestock, which might be treated with probiotic therapies (the introduction of beneficial microbes). Newly discovered microbes could be exploited in the development of new antibiotics, in the discovery of enzymes to extract glucose from cellulose (which could then be fermented to ethanol as a fuel), and in the bioremediation of contaminated soil or water.

Nearly all our scientific understanding stems from observing and interrogating nature at some level. Nature as teacher does not lecture or provide study guides. Instead natural systems appeal to our innate curiosity, with the awesome and strangely beautiful compelling us to learn as best we can. Evolution is the unifying principle for comprehending all life on earth, and applying its lessons about the history and mechanisms of change can promote human well-being. What was once a curiosity is now a powerful tool. ■

Metagenomic analysis has revealed about 300 previously unknown microbes living in the human gut.

MORE TO EXPLORE

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Evolution and Medicine Network. Available at **http://evolutionandmedicine.org**

The Innocence Project. Available at **http://innocenceproject.org**

THE SCIENCE OF SPORE

A computer game illustrates the difference between building your own simulated creature and real-life natural selection • • • **BY ED REGIS**

When Will Wright was developing Spore, his much acclaimed computer game, he interviewed several life scientists. He asked them how nature had actually done what he was attempting to simulate in the game—which was, among other things, the development of the earliest stages of life and its evolution. (Some billboard advertisements for the game feature the slogan "Evolution Begins at Spore.com.") Among the scientists Wright consulted were Michael Levine, a geneticist at the University of California, Berkeley; Neil H. Shubin, a paleontologist at the University of Chicago; and Hansell Stedman, a surgeon at the University of Pennsylvania School of Medicine.

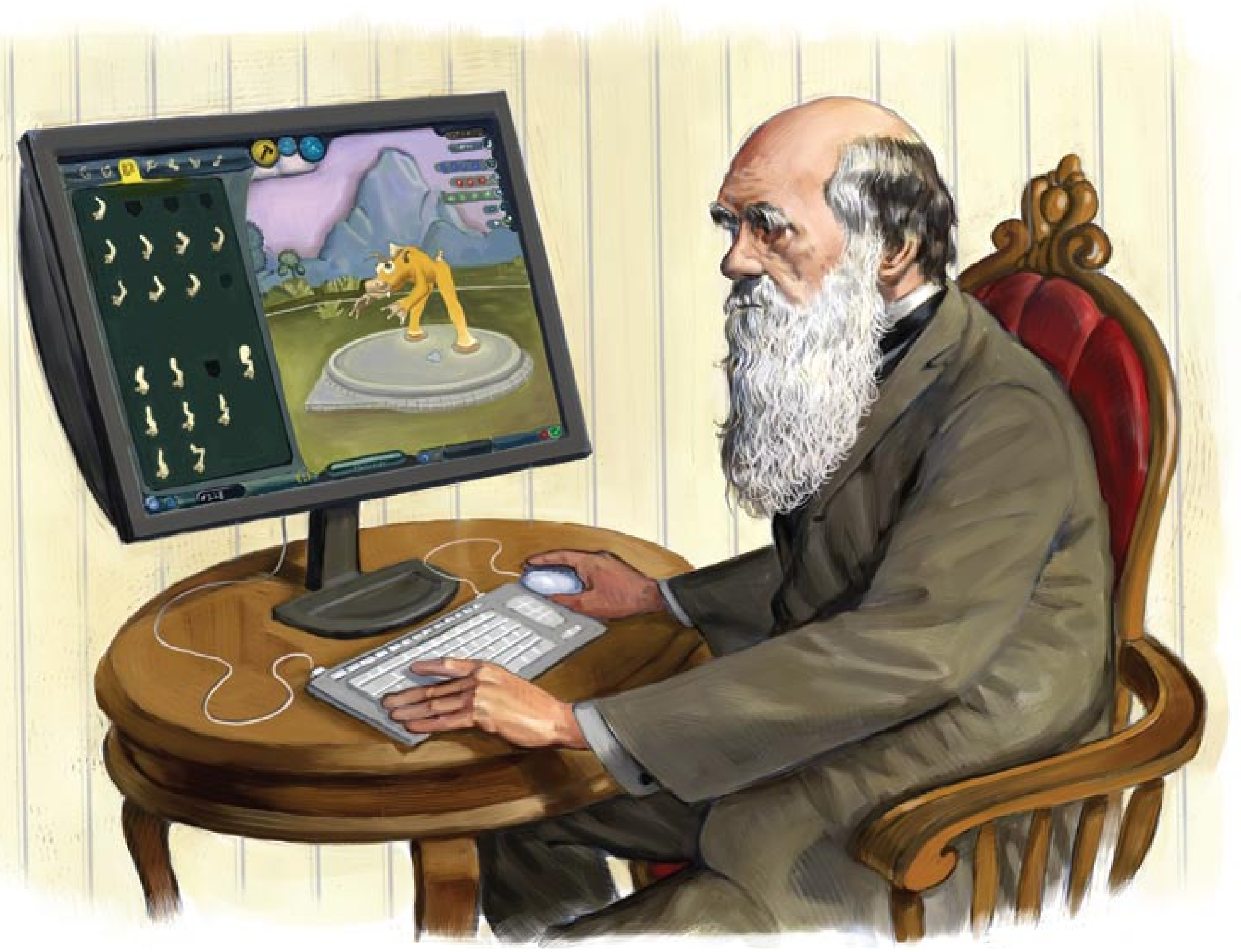
But for all the research that went into it, Spore comes off as a mixed success at replicating the inner workings of evolution by natural selection. On the plus side, in both the game and the real world, there is competition among individuals: Darwin's well-known "struggle for existence." In both, the more fit survive, and the less so die out, duplicating the basic evolutionary principle of survival of the fittest. In the game and in real life, simple entities develop into more complex ones, a pattern that is a common, though not an inevitable, feature of Darwinian evolution. Finally, in both Spore and in nature, life-forms tend to be bilaterally symmetrical, even though exceptions occur in real-life creatures such as amoebas as well as in some of Spore's unicellular organisms.

Spore encompasses five stages of development: cell, creature, tribe, civilization and space. There are some potent differences, however, between evolution as it actually operates and Spore's animated version of events. For one, in the "cell" and "creature" stages of the game, organisms win "DNA points" when they achieve certain goals. Evolving to a higher level of existence is a matter of acquiring DNA points, much as travelers might accrue frequent-flier miles in an effort to go places. In the real world, in contrast, organisms evolve through random genetic mutations, by sexual reproduction and by other mechanisms but not merely by amassing DNA.

Second, at many defining moments in the game the player is given a narrow range of alternatives and is forced to choose among them from a predefined menu of possibilities. In the cell stage, for example, you have to choose whether to develop into a carnivore or a herbivore. In the real world, the range of possibilities at any fork in the evolutionary road is vastly greater, richer and more undefined.

Generally, evolution proceeds slowly in small steps. Although theorists debate over the precise rates of evolutionary change, Spore moves along at comparative light speed, in many cases by huge leaps, as entire body parts—hands, feet, jaws, eyes, limbs—are grafted onto an organism and smoothly integrated into its functioning. These miracles are performed by a "creature editor," an application that allows the user to choose from a palette of prefabricated, preassembled body parts, each of which can be attached to the organism with a few swift clicks of the mouse. The various items in these parts bins have, of course, not themselves evolved but have been designed and stockpiled by the game's creators.

GAME CREATURE



ELECTRONIC ARTS (*Spore creation*); MATT COLLINS (*Darwin at the computer*)

Evolution is a branching process with multiple lines of descent operating simultaneously and in parallel. When played solo, Spore is essentially linear and one-dimensional, with the player controlling the activities of a single cell or creature. (At the "tribe" stage, the player controls the behavior of several tribal members, but these specimens are now biologically fixed and no longer undergo changes to their size and shape.) When the game is played online, however, the player interacts with other Spore players and can download their creations from a "Sporepedia," a large collection of living things (as well as of inanimate objects such as buildings, vehicles and even music). With this feature, Spore approaches a level of parallelism that is actually found in nature.

Which brings us to the greatest difference between Spore and evolution by natural selection, namely, that whereas evolution is an emergent phenomenon with no conscious "selector," Spore quite obviously has one: the user. It is the user who selects for or against things at every juncture: body parts, traits, behaviors, colors, textures, patterns, shapes. Spore does not in fact proceed by natural selection at all but rather by artificial selection. Indeed, putting the player in the position of an omnipotent creator makes the game more a simulation of intelligent design than of real-world Darwinian selection.

Spore may well be the ultimate computer game, the high-water mark of computer animation. You may find it mesmerizing or boring, sophisticated or silly, more Disney than Darwin.

Nevertheless, it is an amusement that holds a special appeal for some. Planetary scientist Frank Drake, author of the Drake equation, a formula for estimating the likely number of extraterrestrial civilizations in the our galaxy, says: "I think it is a good game for kids. It will plant the idea in their heads that the creatures of Earth (and elsewhere) have not always been the same, that species have come and gone and that, in general, the complexity of living things has increased over time. This in turn should encourage many of them to study science, and that, in the end, could be the greatest benefit of the game." ■

THE AUTHOR

Ed Regis has written seven science books, including the recent *What Is Life?: Investigating the Nature of Life in the Age of Synthetic Biology*, which is about the attempt to build an artificial living cell. He and his wife live in the mountains in Maryland near Camp David.

The Latest Face of Creationism

Creationists who want religious ideas taught as scientific fact in public schools continue to adapt to courtroom defeats by hiding their true aims under ever changing guises

• • • BY GLENN BRANCH & EUGENIE C. SCOTT

Professors routinely give advice to students but usually while their charges are still in school. Arthur Landy, a distinguished professor of molecular and cell biology and biochemistry at Brown University, recently decided, however, that he had to remind a former premed student of his that "without evolution, modern biology, including medicine and biotechnology, wouldn't make sense."

The sentiment was not original with Landy, of course. Thirty-six years ago geneticist Theodosius Dobzhansky, a major contributor to the foundations of modern evolutionary theory, famously told the readers of *The American Biology Teacher* that "nothing in biology makes sense, except in the light of evolution." Back then, Dobzhansky was encouraging biology teachers to present evolution to their pupils in spite of religiously motivated opposition. Now, however, Landy was addressing Bobby Jindal—the governor of the state of Louisiana—on whose desk the latest antievolution bill, the so-called Louisiana Science Education Act, was sitting, awaiting his signature.

Remembering Jindal as a good student in his genetics class, Landy hoped that the governor would recall the scientific importance of evolution to biology and medicine. Joining Landy in his opposition to the bill were the American Institute of Biological Sciences, which warned that "Louisiana will undoubtedly be thrust into the national spotlight as a state that pursues politics over science and education," and the American Association for the Advancement of Science, which told Jindal that the law would "unleash an assault against scientific integrity." Earlier, the National Association of Biology Teachers had urged the legislature to defeat the bill, pleading "that the state of Louisiana not allow its science curriculum to be weakened by encouraging the utilization of supplemental materials produced for the sole purpose of confusing students about the nature of science."

But all these protests were of no avail. On June 26, 2008, the governor's office announced that Jindal had signed the Louisiana Science Education Act into law. Why all the fuss? On its face, the law looks innocuous: it directs the state board of education to "allow and assist teachers, principals, and other school administrators to create and foster an environment within public elementary and secondary schools that promotes critical thinking skills, logical analysis, and open and objective discussion of scientific theories being studied," which includes providing "support and guidance for teachers regarding effective ways to help students understand, analyze, critique, and objectively review scientific theories being studied." What's not to like? Aren't critical thinking, logical analysis, and open and objective discussion exactly what science education aims to promote?

KEY CONCEPTS

- Creationists continue to agitate against the teaching of evolution in public schools, adapting their tactics to match the roadblocks they encounter.
- Past strategies have included portraying creationism as a credible alternative to evolution and disguising it under the name "intelligent design."
- Other tactics misrepresent evolution as scientifically controversial and pretend that advocates for teaching creationism are defending academic freedom.

—The Editors

ZACHARY ZAVISLAK (*photograph*); KURSTEN BRACCHI (*styling*)

INJECTING RELIGION into the science curricula of public schools is often a hidden goal of state legislation addressing the teaching of evolution.

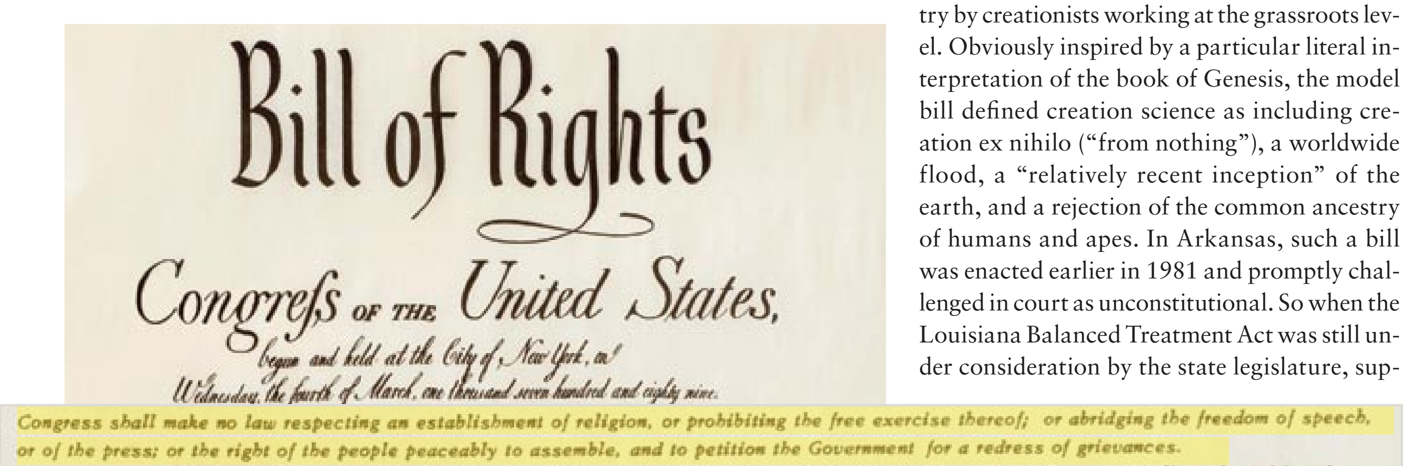
As always in the contentious history of evolution education in the U.S., the devil is in the details. The law explicitly targets evolution, which is unsurprising—for lurking in the background of the law is creationism, the rejection of a scientific explanation of the history of life in favor of a supernatural account involving a personal creator. Indeed, to mutate Dobzhansky's dictum, nothing about the Louisiana law makes sense except in the light of creationism.

Creationism's Evolution

Creationists have long battled against the teaching of evolution in U.S. public schools, and their strategies have evolved in reaction to legal setbacks. In the 1920s they attempted to ban the teaching of evolution outright, with laws such as Tennessee's Butler Act, under which teacher John T. Scopes was prosecuted in 1925. It was not until 1968 that such laws were ruled to be unconstitutional, in the Supreme Court case *Epperson v. Arkansas*. No longer able to keep evolution out of the science classrooms of the public schools, creationists began to portray creationism as a scientifically credible alternative, dubbing it creation science or scientific creationism. By the early 1980s legislation calling for equal time for creation science had been introduced in no fewer than 27 states, including Louisiana. There, in 1981, the legislature passed the Balanced Treatment for Creation-Science and Evolution-Science in Public School Instruction Act, which required teachers to teach creation science if they taught evolution.

The Louisiana Balanced Treatment Act was based on a model bill circulated across the country by creationists working at the grassroots level. Obviously inspired by a particular literal interpretation of the book of Genesis, the model bill defined creation science as including creation ex nihilo ("from nothing"), a worldwide flood, a "relatively recent inception" of the earth, and a rejection of the common ancestry of humans and apes. In Arkansas, such a bill was enacted earlier in 1981 and promptly challenged in court as unconstitutional. So when the Louisiana Balanced Treatment Act was still under consideration by the state legislature, sup-

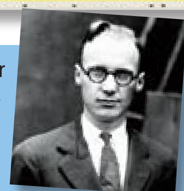
ESTABLISHMENT CLAUSE of the U.S. Constitution's First Amendment is now understood to require the separation of church and state. It has led the Supreme Court to strike down as unconstitutional laws aimed at teaching creationism in public schools—which is why creationists now disguise that aim.



It's Your Move

This time line notes some key events in the seesawing history of the battle between creationists and evolutionists. It highlights the way creationist tactics have shifted in response to evolution's advances in classrooms and to court rulings that have banned religious proselytizing in public schools.

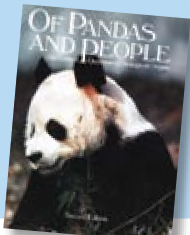
Late 1910s and early 1920s: As high school attendance rises, more American students become exposed to evolution.



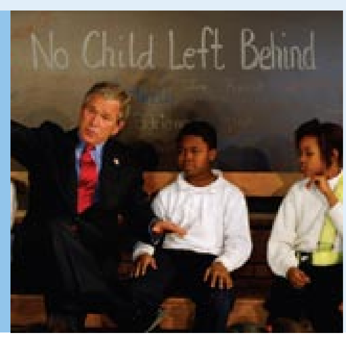
1925: Butler Act in Tennessee outlaws teaching of human evolution. Teacher John T. Scopes (*above*) is prosecuted and convicted under the law, although the conviction is later overturned on a technicality.

1958: Biological Sciences Curriculum Study (BSCS) is founded with funds from a federal government concerned about science education in the wake of Sputnik. BSCS's textbooks emphasize evolution, which was largely absent from textbooks after the Scopes trial; commercial publishers follow suit.

1989: *Of Pandas and People,* the first book systematically to use the term "intelligent design" is published; it touts the notion as an alternative to evolution.



2001: Passage of the No Child Left Behind Act cements the importance of state science standards, which have become a new battleground between creationism and evolution (because inclusion of evolution in science standards increases the likelihood that evolution will be taught).



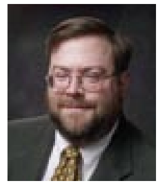
ISTOCKPHOTO.COM (*Bill of Rights*); AP PHOTO (*Scopes*); LAWRENCE JACKSON AP Photo (*George W. Bush with students*) porters, anticipating a similar challenge, immediately purged the bill's definition of creation science of specifics, leaving only "the scientific evidences for creation and inferences from those scientific evidences." But this tactical vagueness failed to render the law constitutional, and in 1987 the Supreme Court ruled in *Edwards v. Aguillard* that the Balanced Treatment Act violated the Establishment Clause of the First Amendment to the Constitution, because the act "impermissibly endorses religion by advancing the religious belief that a supernatural being created humankind."

Creationism adapts quickly. Just two years later a new label for creationism—"intelligent design"—was introduced in the supplementary textbook *Of Pandas and People,* produced by the Foundation for Thought and Ethics, which styles itself a Christian think tank. Continuing the Louisiana Balanced Treatment Act's strategy of reducing overt religious content, intelligent design is advertised as not based on any sacred texts and as not requiring any appeal to the supernatural. The designer, the proponents say, might be God, but it might be space aliens or time-traveling cell biologists from the future. Mindful that teaching creationism in the public schools is unconstitutional, they vociferously reject any characterization of intelligent design as a form of creationism. Yet on careful inspection, intelligent design proves to be a rebranding of creationism—silent on a number of creation science's distinctive claims (such as the young age of the earth and the historicity of Noah's flood) but otherwise riddled with the same scientific errors and entangled with the same religious doctrines.

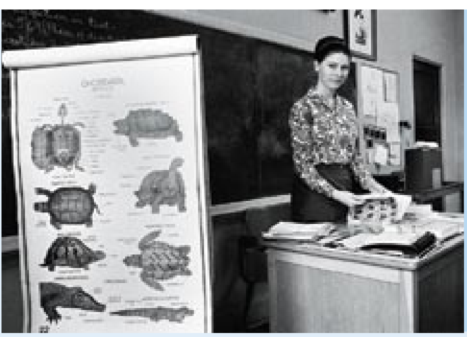
Such a careful inspection occurred in a federal courtroom in 2005, in the trial of *Kitzmiller v. Dover Area School District.* At issue was a policy in a local school district in Pennsylvania requiring a disclaimer to be read aloud in the classroom alleging that evolution is a "Theory ... not a fact," that "gaps in the Theory exist for which there is no evidence," and that intelligent design as presented in *Of Pandas and People* is a credible scientific alternative to evolution. Eleven local parents filed suit in federal district court, arguing that the policy was unconstitutional. After a trial that spanned a biblical 40 days, the judge agreed, ruling that the policy violated the Establishment Clause and writing, "In making this determination, we have addressed the seminal question of whether [intelligent design] is science. We have concluded that it is not, and moreover that [intelligent design] cannot uncouple itself from its creationist, and thus religious, antecedents."

The expert witness testimony presented in the *Kitzmiller* trial was devastating for intelligent design's scientific pretensions. Intelligent design was established to be creationism lite: at the trial philosopher Barbara Forrest, co-author of *Creationism's Trojan Horse: The Wedge of Intelligent Design,* revealed that references to creationism in *Of Pandas and People* drafts were replaced with refer-

THE AUTHORS




Glenn Branch and **Eugenie C. Scott** are deputy director and executive director, respectively, of the National Center for Science Education (NCSE) in Oakland, Calif., where they work to defend the teaching of evolution in the public schools. Together they edited ***Not in Our Classrooms: Why Intelligent Design Is Wrong for Our Schools.*** Branch is trained in philosophy and is a longtime observer of pseudoscience of all kinds. Scott, a physical anthropologist by training and a former university professor, is internationally known as a leading authority on the antievolution movement and has received many awards and honorary degrees for her work at NCSE.



1968:
Supreme Court rules in case of *Epperson v. Arkansas* that laws barring the teaching of evolution in public schools are unconstitutional. Teacher Susan Epperson is shown at the left in 1966.

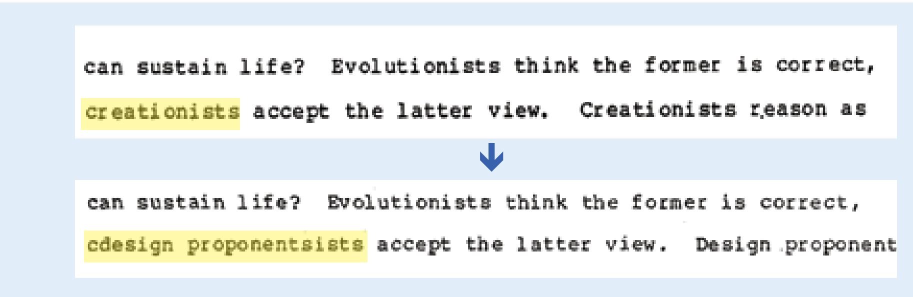
1981: Louisiana passes the Balanced Treatment for Creation-Science and Evolution-Science in Public School Instruction Act. Also in the 1980s legislators in more than 25 states introduce bills calling for "creation science" to have equal time with evolution.

1987: Supreme Court rules in the case of *Edwards v. Aguillard* that the Louisiana Balanced Treatment Act violates the Establishment Clause of the First Amendment.

2005:
Decision in *Kitzmiller v. Dover Area School District* rules that teaching intelligent design in the public schools is unconstitutional. The photograph at the right captures plaintiff Tammy Kitzmiller during a break from the trial.

June 2008:
Governor Bobby Jindal (*right*) signs the Louisiana Science Education Act into law. Marketed as supporting critical thinking in classrooms, the law threatens to open the door for the teaching of creationism and for scientifically unwarranted critiques of evolution in public school science classes.

AP PHOTO (*Epperson*); CAROLYN KASTER *AP Photo* (*Kitzmiller*); RICHARD CUMMINS *Corbis* (*Louisiana state seal*); BILL HABER *AP Photo* (*Jindal*); G. PAUL BISHOP (*Branch*); STEVE MIRSKY (*Scott*)


can sustain life? Evolutionists think the former is correct,
creationists accept the latter view. Creationists reason as

can sustain life? Evolutionists think the former is correct,
cdesign proponentsists accept the latter view. Design proponent

NONSENSE PHRASE "cdesign proponentists" resulted when the words "design proponents" were substituted incompletely for "creationists" in the manuscript for *Of Pandas and People.* This and other evidence revealed that references to creationism were systematically replaced with references to "intelligent design" after the Supreme Court ruled in 1987 that teaching creationism in public schools is unconstitutional. The discovery helped to convince a federal district court in 2005 to declare the teaching of intelligent design unconstitutional as well.

COURTESY OF NICK MATZKE (*text from* Of Pandas and People)

ences to design shortly after the 1987 *Edwards* decision striking down Louisiana's Balanced Treatment Act was issued. She even found a transitional form, where the replacement of "creationists" by "design proponents" was incomplete—"cdesign proponentsists" was the awkward result. More important, intelligent design was also established to be scientifically bankrupt: one of the expert witnesses in the trial, biochemist Michael Behe, testified that no articles have been published in the scientific research literature that "provide detailed rigorous accounts of how intelligent design of any biological system occurred"—and he was testifying in *defense* of the school board's policy.

Donning a Fake Mustache

Failing to demonstrate the scientific credibility of their views, creationists are increasingly retreating to their standard fallback strategy for undermining the teaching of evolution: misrepresenting evolution as scientifically controversial while remaining silent about what they regard as the alternative. This move represents only a slight rhetorical shift. From the Scopes era onward, creationists have simultaneously employed three central rhetorical themes, sometimes called the three pillars of creationism, to attack evolution: that evolution is unsupported by or actually in conflict with the facts of science; that teaching evolution threatens religion, morality and society; and that fairness dictates the necessity of teaching creationism alongside evolution. The fallback strategy amounts to substituting for creationism the scientifically unwarranted claim that evolution is a theory in crisis.

Creationists are fond of asserting that evolution is a theory in crisis because they assume that there are only two alternatives: creationism (whether creation science or intelligent design) and evolution. Evidence against evolution is thus evidence for creationism; disproving evolution thus proves creationism. The judge in *McLean v. Arkansas,* the 1981 case in which Arkansas's Balanced Treatment Act was ruled to be unconstitutional, succinctly described the assumption as "a contrived dualism." Yet by criticizing evolution without mentioning creationism, proponents of the fallback strategy hope to encourage students to acquire or retain a belief in creationism without running afoul of the Establishment Clause. Creationism's latest face is just like its earlier face, only now thinly disguised with a fake mustache.

Underscoring the conscious decision to emphasize the supposed evidence against evolution, the Institute for Creation Research, which promotes creation science, candidly recommended immediately after the *Edwards* decision that "school boards and teachers should be strongly encouraged at least to stress the scientific evidences and arguments *against evolution* in their classes … even if they don't wish to recognize these as evidences and arguments *for creation.*" Similarly, the Discovery Institute, the de facto institutional headquarters of intelligent design, saw the writing on the wall even before the decision in the *Kitzmiller* ruling that teaching intelligent design in the public schools is unconstitutional. Although a widely discussed internal memorandum—"The Wedge Document"—had numbered among its goals the inclusion of intelligent design in the science curricula of 10 states, the Discovery Institute subsequently retreated to a strategy to undermine the teaching of evolution, introducing a flurry of labels and slogans—"teach the controversy," "critical analysis" and "academic freedom"—to promote its version of the fallback strategy.

"Academic freedom" was the creationist catchphrase of choice in 2008: the Louisiana Science Education Act was in fact born as the Louisiana Academic Freedom Act, and bills invoking the idea were introduced in Alabama, Florida, Michigan, Missouri and South Carolina, although, as of November, all were dead or stalled [*see box on page 84*]. And academic freedom was a central theme of the first creationist movie to tarnish the silver screen: *Expelled: No Intelligence Allowed*. (Science columnist Michael Shermer eviscerated *Expelled* in his review in the June 2008 issue of *Scientific American,* and the magazine's staff added commentary on www.SciAm.com.) Portraying the scientific community as conspiring to persecute scientists for their views on creationism, *Expelled* was ostensibly concerned with academic freedom mainly at the college level, but it was used to lobby for the academic freedom legislation in Missouri and Florida aimed at the public schools.

(The movie, by the way, was a critical failure and jam-packed with errors.)

The appeal of academic freedom as a slogan for the creationist fallback strategy is obvious: everybody approves of freedom, and plenty of people have a sense that academic freedom is desirable, even if they do not necessarily have a good understanding of what it is. The concept of academic freedom is primarily relevant to college teaching, and the main organization defending it, the American Association of University Professors, recently reaffirmed its opposition to antievolution laws such as Louisiana's, writing, "Such efforts run counter to the overwhelming scientific consensus regarding evolution and are inconsistent with a proper understanding of the meaning of academic freedom." In the public schools, even if there is no legal right to academic freedom, it is sound educational policy to allow teachers a degree of latitude to teach their subjects as they see fit—but there are limits. Allowing teachers to instill scientifically unwarranted doubts about evolution is clearly beyond the pale. Yet that is what the Louisiana Science Education Act was evidently created, or designed, to do.

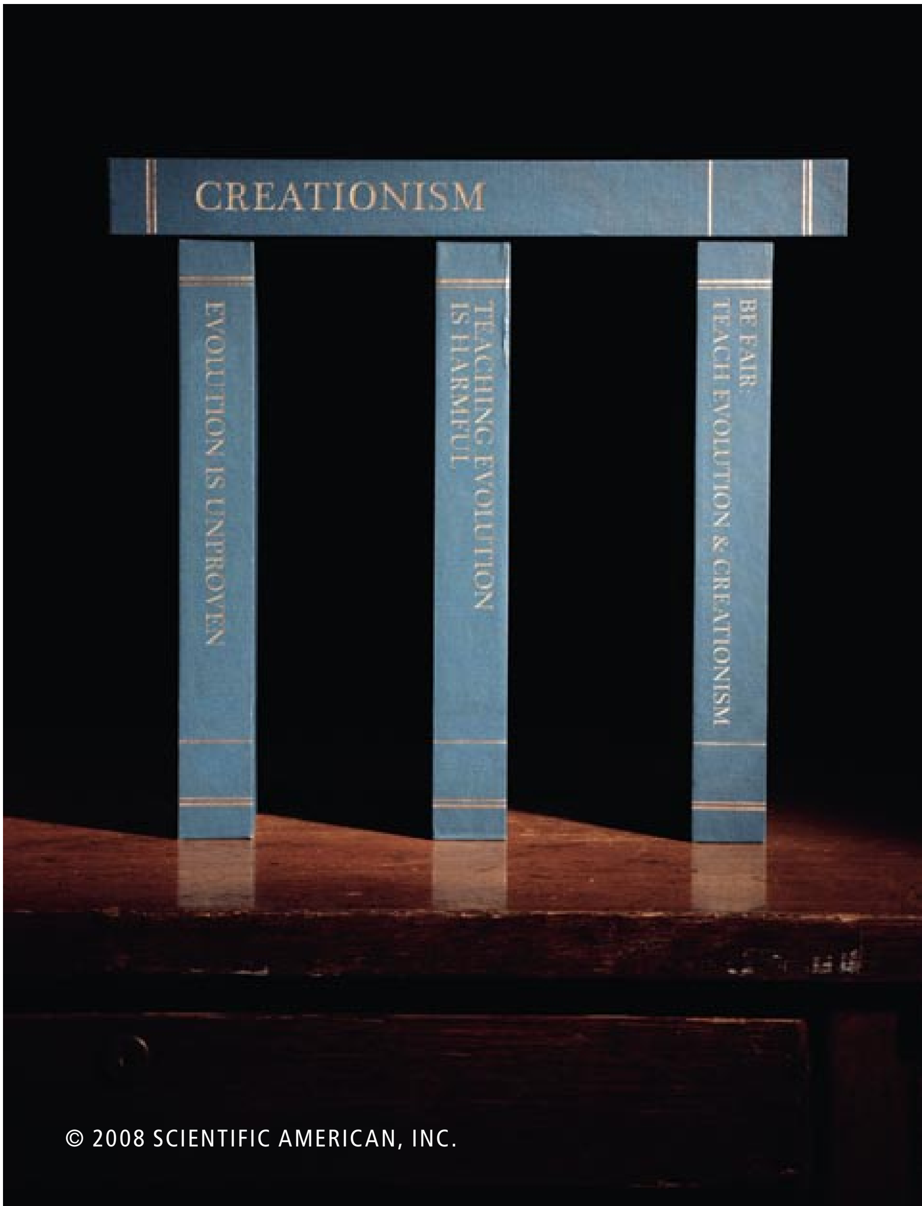
The Worm in the Apple

The real purpose of the law—as opposed to its ostensible support for academic freedom—becomes evident on analysis. First, consider what the law seeks to accomplish. Aren't teachers in the public schools *already* exhorted to promote critical thinking, logical analysis and objective discussion of the scientific theories that they discuss? Yes, indeed: in Louisiana, policies established by the state board of education already encourage teachers to do so, as critics of the bill protested during a legislative hearing.

So what is the law's true intent? That only a handful of scientific topics—"biological evolution, the chemical origins of life, global warming, and human cloning"—are explicitly mentioned is a hint. So is the fact that the bill was introduced at the behest of the Louisiana Family Forum, which seeks to "persuasively present biblical principles in the centers of influence on issues affecting the family through research, communication and networking." And so is the fact that the group's executive director was vocally dismayed when those topics were temporarily deleted from the bill.

Second, was there in fact a special need for the Louisiana legislature to encourage teachers to promote critical thinking with respect to evolution in particular? No evidence seems to have been forthcoming. Patsye Peebles, a veteran science teacher in Baton Rouge, commented, "I was a biology teacher for 22 years, and I never needed the legislature to tell me how to present anything. This bill doesn't solve any of the problems classroom teachers face, and it will make it harder for us to keep the focus on accurate science in science classrooms." And of course, the National Association of Biology Teachers, representing more than 9,000 biology educators across the country, took a firm stand against the bill. In neighboring Florida, the sponsors of similar bills alleged that there were teachers who were prevented from or penalized for "teaching the 'holes'" in evolution. But no such teachers were ever produced, and the state department of education and local newspapers were unable to confirm that the claimed incidents of persecution ever occurred.

And, third, what are these "holes" in evolu-



ASSERTIONS dubbed the "three pillars of creationism" underlie many antievolution campaigns. Because portraying creationism as scientifically credible has failed as a tactic for inserting religion into public schools, creationists are increasingly focusing on insisting that evolutionary theory is flawed, dangerous to religion, morality and society, and taught dogmatically.

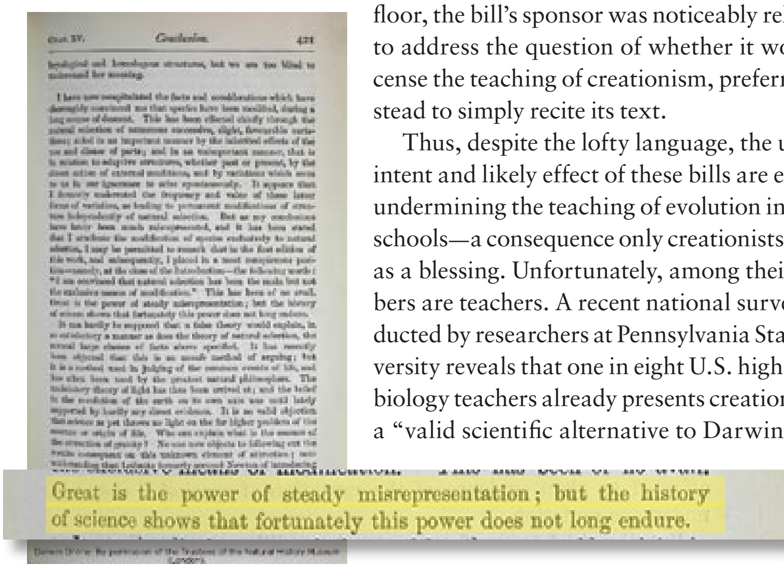
ZACHARY ZAVISLAK (*photograph*); KURSTEN BRACCHI (*styling*)

Antievolution Bills of 2008

Several states aside from Louisiana entertained antievolution bills last year. Clearly, efforts to push such legislation continue unabated.

STATE (BILL)	OSTENSIBLE AIM	STATUS
Alabama (HB 923)	Support academic freedom	Died May 2008
Florida (HB 1483)	Foster critical analysis	Died May 2008
Florida (SB 2692)	Support academic freedom	Died May 2008
Michigan (SB 1361)	Support academic freedom	In committee when this issue went to press
Michigan (HB 6027)	Support academic freedom	Identical to SB 1361; in commitee when this issue went to press
Missouri (HB 2554)	Promote teaching of evolution's strengths and weaknesses	Died May 2008
South Carolina (SB 1386)	Promote teaching of evolution's strengths and weaknesses	Died June 2008

SIXTH EDITION of *On the Origin of Species* includes Charles Darwin's lament over the power of "steady misrepresentation." He took comfort in science's past victories over falsehood, but the authors of this article argue that science is not enough to combat campaigns designed to mislead schoolchildren; activism is needed as well.



tion, anyhow? The savvier supporters of bills such as Florida's and Louisiana's realize that it is crucial to disclaim any intention to promote creationism. But because there is no scientifically credible challenge to evolution, only long-ago-debunked creationist claptrap [see "15 Answers to Creationist Nonsense," by John Rennie; Scientific American, June 2002], the supporters of such bills are forced to be evasive when asked about what material would be covered.

In Florida, for example, a representative of the Discovery Institute dithered when asked whether intelligent design constituted "scientific information" in the sense of the bill, saying, "In my personal opinion, I think it does. But the intent of this bill is not to settle that question," and adding, unhelpfully, "The intent of this bill is … it protects the 'teaching of scientific information.'" Similarly, during debate on the Senate floor, the bill's sponsor was noticeably reluctant to address the question of whether it would license the teaching of creationism, preferring instead to simply recite its text.

Thus, despite the lofty language, the ulterior intent and likely effect of these bills are evident: undermining the teaching of evolution in public schools—a consequence only creationists regard as a blessing. Unfortunately, among their numbers are teachers. A recent national survey conducted by researchers at Pennsylvania State University reveals that one in eight U.S. high school biology teachers already presents creationism as a "valid scientific alternative to Darwinian explanations for the origin of species," with about the same percentage emphasizing that "many reputable scientists" view creationism as a scientifically valid alternative to evolution.

Not all creationist teachers are as extreme as John Freshwater, a Mount Vernon, Ohio, middle school teacher who became immersed in legal troubles over his religious advocacy in the classroom, which included not only teaching creationism but also, allegedly, using a high-voltage electrical apparatus to brand his students with a cross. But even the less zealous will probably take laws such as Louisiana's as a license to miseducate. Such laws are also likely to be used to bully teachers who are not creationists: nationally, three in 10 already report pressure to present creationism or downplay evolution.

These bills will also further encourage school districts where creationists are politically powerful to adopt antievolution policies. A statement by a member of the Livingston Parish School Board who supported the Louisiana bill is instructive. After saying "both sides—the creationism side and the evolution side—should be presented," he explained that the bill was needed because "teachers are scared to talk about" creation. How plausible is it, then, that the law's provision that it is not to be "construed to promote any religious doctrine" will be honored in practice? As conservative columnist John Derbyshire commented, "the Act will encourage Louisiana local school boards to unconstitutional behavior. That's what it's *meant* to do."

The Future of Steady Misrepresentation

What are the legal prospects of the creationist fallback strategy? A case in Georgia, *Selman v. Cobb County School District,* is suggestive, if not decisive. In 2002 the Cobb County board of education, bowing to the demands of local creationists, decided to require warning labels for biology textbooks. Using a phrase employed by creationists even before the Scopes trial in 1925, the labels described evolution as "a theory, not a fact," while remaining silent about creationism. Five parents in the county filed suit in federal district court, arguing that the policy requiring the labels was unconstitutional, and the trial judge agreed, citing the abundant history linking the warning labels with creationist activity in Cobb County in particular and linking the fallback strategy with creationism in general. The case was vacated on appeal because of concerns about the evidence submitted at trial, remanded

DARWIN ONLINE *University of Cambridge (page from* On the Origin of Species*)*; ZACHARY ZAVISLAK *(textbook photograph)*; KURSTEN BRACCHI *(textbook styling)* to the trial court and settled on terms favorable to the parents. It remains to be seen whether the fallback strategy will survive constitutional scrutiny elsewhere—but it is likely that it will be challenged, whether in Louisiana or elsewhere.

In the meantime, it is clear why the Louisiana Science Education Act is pernicious: it tacitly encourages teachers and local school districts to miseducate students about evolution, whether by teaching creationism as a scientifically credible alternative or merely by misrepresenting evolution as scientifically controversial. Vast areas of evolutionary science are for all intents and purposes scientifically settled; textbooks and curricula used in the public schools present precisely such basic, uncomplicated, uncontroversial material. Telling students that evolution is a theory in crisis is—to be blunt—a lie.

Moreover, it is a dangerous lie, because Dobzhansky was right to say that nothing in biology makes sense except in the light of evolution: without evolution, it would be impossible to explain why the living world is the way it is rather than otherwise. Students who are not given the chance to acquire a proper understanding of evolution will not achieve a basic level of scientific literacy. And scientific literacy will be indispensable for workers, consumers and policymakers in a future dominated by medical, biotechnological and environmental concerns.

In the sesquicentennial year of *On the Origin of Species,* it seems fitting to end with a reference to Charles Darwin's seminal 1859 book. In the first edition of *Origin of Species,* Darwin was careful to acknowledge the limits to his project, writing, "I am convinced that natural selection has been the main but not the exclusive means of modification." Nevertheless, he was misinterpreted as claiming that natural selection was entirely responsible for evolution, provoking him to add a rueful comment to the sixth edition: "Great is the power of steady misrepresentation; but the history of science shows that fortunately this power does not long endure."

The enactment of the Louisiana Science Education Act, and the prospect of similar legislation in the future, confirms Darwin's assessment of the power of steady misrepresentation. But because the passage of such antievolution bills ultimately results from politics rather than science, it will not be the progress of science that ensures their failure to endure. Rather it will take the efforts of citizens who are willing to take a stand and defend the uncompromised teaching of evolution. ■

What to Do

If controversy over the teaching of evolution erupts in your area, here are some actions you can take:

- ✔ Resolving the controversy requires thinking politically, which means forming coalitions. Join with like-minded science educators, scientists, members of the clergy and other citizens to convince policymakers not to accede to creationist proposals.
- ✔ Keep in mind that the goal is not only to keep creationism out of the science classroom but also to ensure that evolution is taught properly—without qualifiers such as "only a theory" and unaccompanied by specious "evidence against evolution."
- ✔ Be ready to rebut assertions that evolution is a theory in crisis; that evolution is a threat to religion, morality and society; and that it is only fair to teach "both sides" of the issue.
- ✔ Arrange for defenders of evolution to write letters to the editor and op-eds, attend and speak at meetings of the board of education or legislature, and work to turn out the vote on Election Day.

Adapted from "Defending the Teaching of Evolution: Strategies and Tactics for Activists," by Glenn Branch, in *Not in Our Classrooms: Why Intelligent Design Is Wrong for Our Schools.* Edited by Eugenie C. Scott and Glenn Branch. Beacon, 2006.

MORE TO EXPLORE

Analyzing Critical Analysis: The Fallback Antievolutionist Strategy. Nicholas J. Matzke and Paul R. Gross in *Not in Our Classrooms: Why Intelligent Design Is Wrong for Our Schools.* Edited by Eugenie C. Scott and Glenn Branch. Beacon, 2006.

Evolution: The Triumph of an Idea. Carl Zimmer. Harper Perennial, 2006.

Creationism's Trojan Horse: The Wedge of Intelligent Design. Revised edition. Barbara Forrest and Paul R. Gross. Oxford University Press, 2007.

The Devil in Dover: An Insider's Story of Dogma v. Darwin in Small-Town America. Lauri Lebo. New Press, 2008.

Evolution vs. Creationism: An Introduction. Second edition. Eugenie C. Scott. Greenwood, 2009.

A Theory of a Deadly Fusion

The ability to spread underlies the killing power of cancer. The process occurs, John Pawelek thinks, when tumor cells fuse with white blood cells—an idea that, if right, could yield new therapies BY CHARLES Q. CHOI

On a cold, gray Saturday morning at Yale University in February 1993, instead of just reading his laboratory's article in a cancer journal and scanning past the rest—cancer is a profoundly wide field, and there is much to read—cancer biologist John Pawelek made time to finish the entire issue. That simple decision changed the course of his research, toward a controversial explanation for the deadliest aspect of the disease—namely, why it spreads.

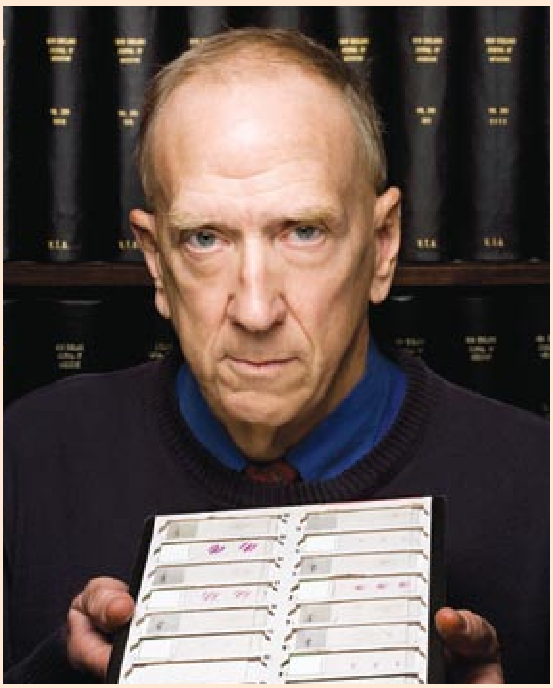
The issue contained a letter from three Czech doctors asking whether the fusion of tumor cells and white blood cells could cause cancers to spread, or metastasize. At the time, Pawelek was also reading a book by evolutionary biologist Lynn Margulis, who pioneered the idea that life on earth was revolutionized by ancient cells engulfing one another and fusing together, forming hybrids that had better chances at survival. "I was really excited by the connection," he recalls. "Since there was a precedent for hybridization in evolution, why not in cancer?"

In the past 15 years Pawelek and his colleagues have shown that cancer cells can fuse with white blood cells and become highly metastatic in lab animals. Now they are searching for the same activity in humans. The leading cause of death in cancer is metastasis—tumors are generally treatable as long as they have not moved to vital organs. So if the research reveals that such hybrids help cancer spread, it could open up new avenues to fighting cancer. As Pawelek puts it: "You have to know how metastasis starts to properly fight it."

But maddeningly little is known about what makes cancer spread. Explaining the capabilities that metastatic cells possess—to break away from their original tumors, migrate past other cells, travel around the body via lymph or blood vessels, invade tissues, and grow—would involve understanding how cells interact with one another. "And we don't yet have good biological tools to investigate the interactions between different cell types and organs," explains cancer geneticist Bert Vogelstein of Johns Hopkins University.

One theory behind the origin of metastasis is that mutations in one or a few genes cause tumor cells to gain the ability to migrate. Another idea suggests that no specific mutations are needed—rather cancer cells eventually accumulate abnormal numbers of chromosomes that break down the constraints that keep any normal cell from metastasizing. In Pawelek's view, these theories do not explain how cancer cells would acquire the right genetic changes in the right order needed to spread successfully.

Instead the 66-year-old Pawelek suggests that cancer cells spread after fusing with white blood cells known as macrophages. Like metastatic cells, macrophages can roam around and infiltrate most parts of the body and are naturally resistant to toxic drugs. "Metastasis is a very different phase from ordinary cancer and to me is almost like a new disease superimposed on a preexisting cancer cell—maybe cancer cells inherit all these traits at once by hybridizing with white blood cells," Pawelek speculates. Moreover, macrophages regularly engulf germs and unhealthy cells—they might occasionally fuse with tumor cells instead of destroying them, much as ancient cells once

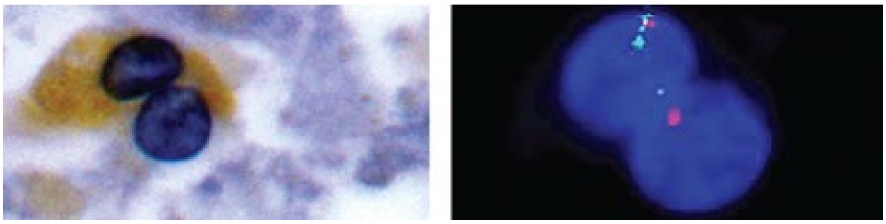


ETHAN HILL

JOHN PAWELEK

FUSION POWER: Proposes that tumors start to spread, or metastasize, after fusing with white blood cells. In the photograph, he is holding malignant melanoma samples that he will analyze for signs of such fusion.

FATAL SPREAD: The American Cancer Society expects 1.4 million new cases of cancer in the U.S. in 2008 (globally, at least 12 million). For breast cancer, the five-year survival rate is 98 percent before it spreads, 26.7 percent after; for prostate cancer, 100 percent before, 31.9 percent after.



METASTATIC MATING? After receiving a bone marrow transplant from her son, a female patient developed cancer cells in her kidney (*blue in optical photograph at left*). A fluorescence image of those cells (*right*) reveals Y chromosomes (*red*), suggesting that her carcinoma resulted from a hybridization of her cells and her son's bone marrow cells.

FROM "FUSION OF TUMOUR CELLS WITH BONE MARROW-DERIVED CELLS: A UNIFYING EXPLANATION FOR METASTASIS," BY JOHN M. PAWELEK AND ASHOK K. CHAKRABORTY, IN *NATURE REVIEWS CANCER*, VOL. 8; MAY 2008

joined together into symbiotic relationships a billion years ago, he reasons.

In their first experiments, Pawelek and his colleagues took a strain of mouse melanoma cells known to be only weakly metastatic and fused them with mouse macrophages by exposing them to polyethylene glycol, which can dissolve cell membranes. They implanted these hybrids in roughly 5,000 mice. "These were massive experiments that took four years to accomplish, and we were just going on faith," Pawelek recounts. The results were striking—roughly 55 percent of the hybrid cells proved "really, really deadly, very metastatic," he declares, in contrast to melanoma cells fused with one another—none of them became metastatic. "I was convinced we were on to something."

Pawelek and his colleagues have also found molecular similarities between metastatic cells and macrophages, such as activation of genes linked with movement. In addition, they discovered that these cancer cells apparently produce organelles known as autophagosomes, with which the cells can digest chunks of themselves. Macrophages often produce autophagosomes as a means to snack on themselves while traveling, and cancer cells may do the same.

Pawelek is not the first scientist drawn to the fusion theory. Its earliest proponent was German pathologist Otto Aichel, who proposed it in 1911. It revived again some 50 years later, thanks to experiments showing that implanted tumor cells could spontaneously fuse with cells in lab animals and spread. About the mid-1980s, however, interest faded. David Goldenberg, who conducted some of those studies and is now president of the Garden State Cancer Center in Belleville, N.J., suggests that attention waned because although scientists could see hybrids of foreign and host cells, the tools at the time could not show that such fusions were actually taking place in natural settings. After all, if fusions were happening in cancer patients, both the tumor cells and macrophages would be virtually genetically identical, making it hard to prove that metastatic cells were hybrids.

But now Pawelek believes that technology has caught up and that the evidence lies with cancer patients who received bone marrow transplants. Radiation therapy and chemotherapy kill off bone marrow, which supplies white blood cells to the body. Donated bone marrow would naturally be genetically distinct from the patient, making it possible to see if tumor cells of the host fused with macrophages from the donor.

So far Pawelek and his colleagues have found two possible examples. In one, a boy with type O blood received a bone marrow transplant from his type A brother, and when the bone marrow recipient later developed kidney cancer, the scientists found tumor cells that possessed blood type A. In the other example, a woman who received a bone marrow transplant from her son later developed kidney cancer, and the new tumor contained cells with the male Y chromosome. In both the human examples, however, the investigators could not confirm that the cells contained the host's genome. It therefore remains possible that these cells were not hybrids but simply came from the donor. On future samples, Pawelek hopes to use forensic DNA analysis techniques that can detect genes from both host and donor in the same cells.

Any searches for hybrids are highly vulnerable to error, cautions stem cell biologist Irving Weissman of Stanford University. "I've seen this kind of thing over and over again—when you think you've seen a hybrid, it turns out there's almost always a cell with another cell adhering to it or very close to it." (Pawelek insists the researchers took care to ensure such mistakes were not made.)

Weissman also cites other studies that show hybrids are actually less cancerous, not more, when tumor cells are fused with normal cells, apparently because the infusion of healthy DNA helps to suppress malignant activity. Pawelek suggests that the cell type used may partially explain this discrepancy—fusions with white blood cells show enhanced malignancy, whereas cell types such as epithelial cells can suppress tumors.

But even if Pawelek shows that the fused cells become metastatic, Vogelstein says, researchers still have to see whether these hybrids account for a significant fraction of metastases or whether other mechanisms trigger most spreading cancers.

If Pawelek is right, investigators will have new ways to combat cancer. For instance, they could aim to develop drugs based on antibodies that attack fused cells that may have unique chemical signatures or to devise therapies that block molecules linked with cell fusion. "Even if he's wrong," Vogelstein remarks, "the pursuit of unconventional ideas often leads to novel insights."

In the meantime, Pawelek's work has inspired other labs—75 scientists attended the first meeting on cell fusion and cancer in Sweden in October 2007, where Pawelek was a featured speaker. The hybrid theory, it seems, is spreading once more. ■

Charles Q. Choi is a frequent contributor.

New Designs Going Up

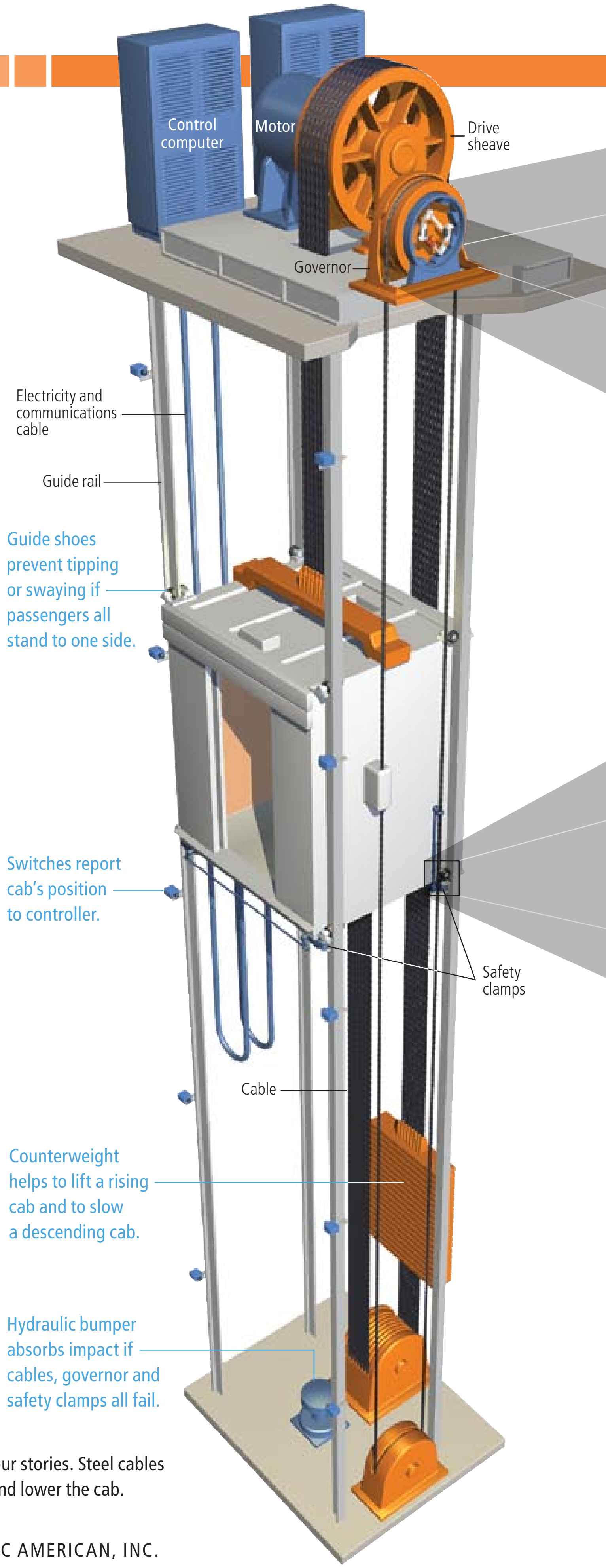
By Mark Fischetti

Elevator installation is a mature business, yet change is under way as office space and energy get pricey. Most buildings that are taller than four stories use traction elevators [*see illustration on this page*]. A motor at the top of the shaft turns a sheave—essentially a pulley—that raises and lowers cables attached to the cab and a counterweight. Gears connect the motor and sheave in slower systems. Faster elevators are gearless; the sheave is coupled directly.

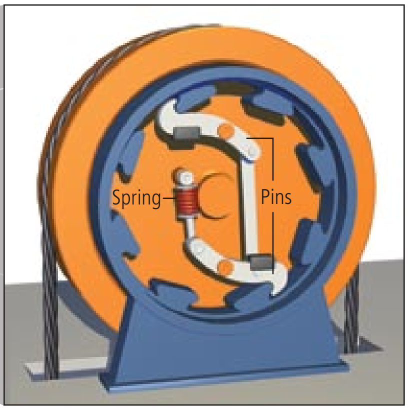
Either way, the machinery typically fills an entire room above or beside the top of the shaft, occupying what could be prime penthouse space. But innovations are allowing builders to squeeze the equipment into the head of the shaft itself or against a side wall. “We are steadily shifting to gearless, machine room–less designs,” says Jeff Blain, senior project manager at Schindler Elevator in New York City. Some companies are using permanent-magnet gearless motors, which are smaller than traditional designs but have become just as powerful. And Otis Elevator in Farmington, Conn., has switched from wound steel cables to flat steel belts, allowing the sheave and motor to be downsized.

At the same time, manufacturers are exploiting gravity to save energy. A counterweight chosen to weigh about as much as a cab with 40 to 45 percent of a full load lessens the motor output needed. But when an empty elevator must go up, the heavier counterweight’s fall provides too much energy; massive resistors dissipate the excess energy as heat. The same resistance is needed when a full cab (heavier than the counterweight) is descending. New regenerative drives, however, convert the wasted energy into electricity. “We feed that energy back into the building’s electric grid for reuse,” says Leandre Adifon, vice president of elevator systems engineering and development at Otis.

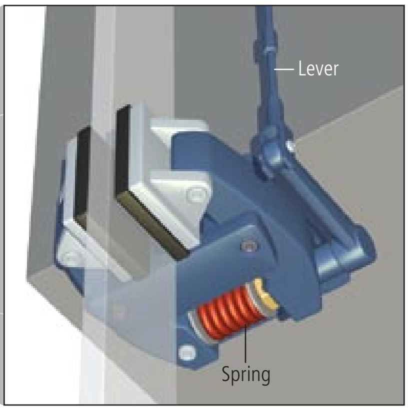
Improved dispatch technology is upping human efficiency in buildings with multiple shafts. Office buildings are cramming more people into existing floors, but the increased population can slow elevator service. To compensate, installers are replacing the “up” and “down” push buttons in foyers with numbered display screens or touch pads. Would-be passengers push the floor number they want, and a computer tells them which elevator to take, grouping people going to the same or neighboring floors. The computer dispatches the elevators so each one travels to a small set of nearby floors, instead of randomly traveling far up and down. The scheme decreases wait time and energy consumption.



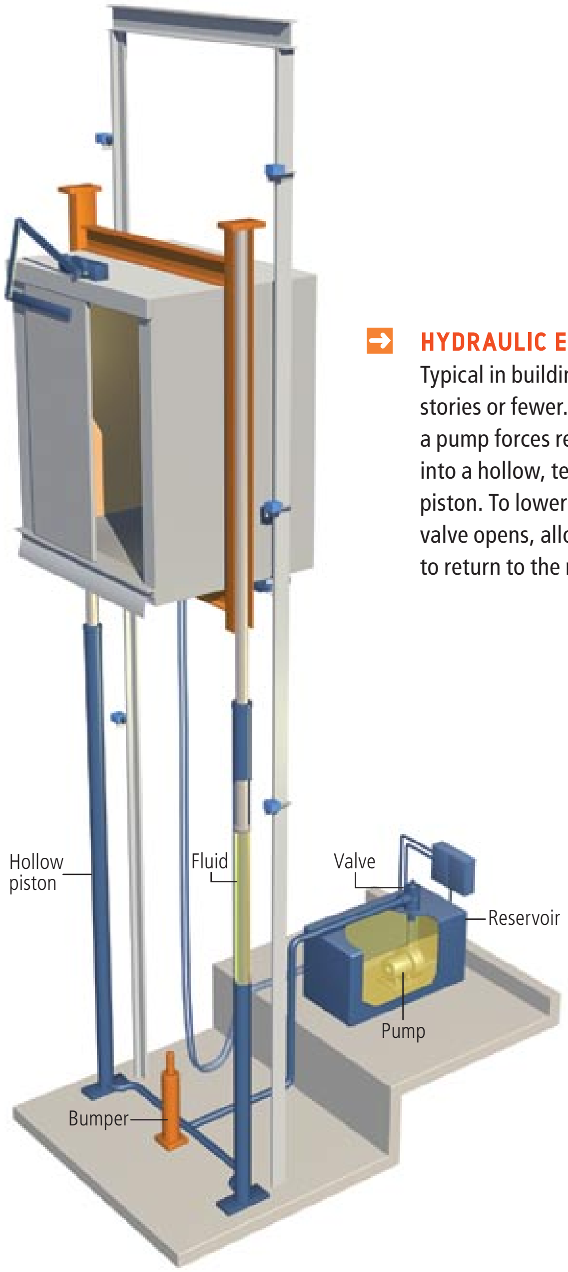
TRACTION ELEVATOR
Installed in most buildings taller than four stories. Steel cables held by friction in a drive sheave raise and lower the cab.



GOVERNOR is spun by a cable attached to the cab. If the cab drops too quickly, weighted pins swing outward because of centrifugal force, overcoming the spring so that hooked arms grab the sheave, locking it and yanking a lever that engages safety clamps.



SAFETY CLAMP pincers grab the rail when yanked by the governor lever.



HYDRAULIC ELEVATOR Typical in buildings four stories or fewer. To lift the cab, a pump forces reservoir fluid into a hollow, telescoping piston. To lower the cab, the valve opens, allowing the fluid to return to the reservoir.

DID YOU KNOW ...

FAST FACT: Toshiba Elevator claims to have the fastest passenger elevator, installed in Taipei 101, the 101-story building in Taiwan. Top climbing speed is 3,314 feet (1,010 meters) per minute, or roughly 100 floors in 26 seconds. A blower system adjusts the atmospheric pressure inside the cab to minimize ear popping.

SAFETY FIRST: An elevator cable is rated to hold 125 percent of the maximum full-car weight, and five or more cables suspend most cabs. Steel rope has become so strong that a one-half- or five-eighths-inch diameter is sufficient for a 3,500-pound load, typical in mid-rise buildings. New, flat, high-strength steel belts of similar strength may be less than one-fourth-inch thick.

SO INCLINED: Certain elevators made by Otis move laterally as they rise, to follow the contour of unusual structures. Angled cables pull cabs along rails inclined at 39 degrees (from the horizontal) in the pyramidal Luxor Hotel in Las Vegas and at 30 degrees in the Eiffel Tower in Paris.

GEORGE RETSECK

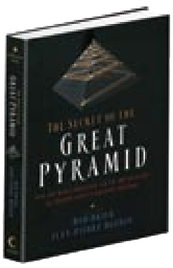
SEND TOPIC IDEAS *to workingknowledge@SciAm.com*

Ancient Engineering ▪ Waste Not ▪ Earth Rising

BY MICHELLE PRESS

➔ THE SECRET OF THE GREAT PYRAMID: HOW ONE MAN'S OBSESSION LED TO THE SOLUTION OF ANCIENT EGYPT'S GREATEST MYSTERY

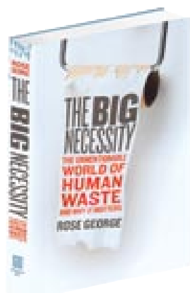
by Bob Brier and Jean-Pierre Houdin. Smithsonian Books, 2008 ($24.95)



Egyptologist Bob Brier tells the story of Jean-Pierre Houdin, a French architect who spent several years sitting in front of his computer for 10 hours a day puzzling out a solution for the building of the Great Pyramid of Giza. Using three-dimensional architectural software, Houdin constructed 3-D models of the interior of the pyramid. The images rotating on his screen provided evidence of a mile-long ramp corkscrewing up the *inside* of the pyramid that had remained undetected for 4,500 years. His theory solves many mysteries about the huge structure and has won supporters. But proof awaits permission from the Egyptian authorities to look for the ramp, most likely using thermal photography.

➔ THE BIG NECESSITY: THE UNMENTIONABLE WORLD OF HUMAN WASTE AND WHY IT MATTERS

by Rose George. Metropolitan Books, 2008 ($26)



Four in 10 people have no access to any latrine, toilet, bucket or box. They defecate in narrow alleyways, in forests, by train tracks. The disease toll of this human excrement is astounding, killing more people worldwide than any other single cause. Modern sanitation, where it exists, has added 20 years to the average human life. But population growth in the First World has taxed sanitation systems: 90 percent of the globe's sewage ends up untreated in oceans, rivers and lakes.

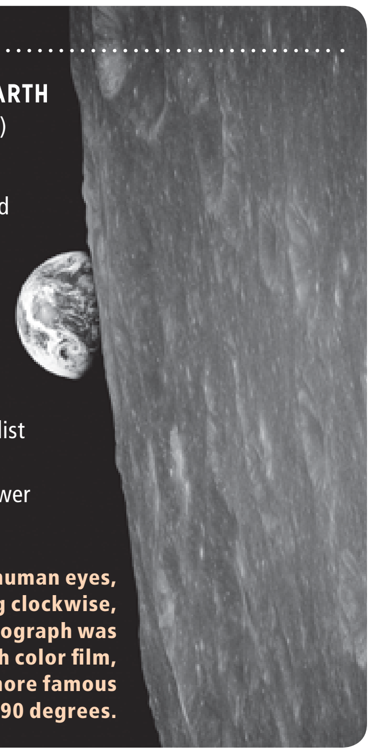
Rose George, a journalist, unreels these shocking statistics in lively, unflinching style as she details this enormous problem that is seldom discussed, hidden in a "social straitjacket of denial." The book is not all gloom and doom. She lays out possible remedies, from the biogas digesters that turn waste into fuel in China to the agricultural use of sludge in the U.S. And she is not without humor, most notably as she investigates the robo toilets of Japan that wash and dry the private parts and even check blood pressure.

EXCERPT

➔ EARTHRISE: HOW MAN FIRST SAW THE EARTH

by Robert Poole. Yale University Press, 2008 ($26)

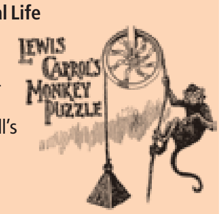
"This book is about that extraordinary moment in 1968 when humankind first saw the whole Earth, and about everything that flowed into and out of it. It is an alternative history of the space age, written from a viewpoint looking back at the Earth. Confidence in the progress of science and technology was never higher than at the time of the first journeys to the Moon; afterwards came the first 'Earth Day,' the crisis of confidence, and the environmentalist renaissance. At the very apex of human progress the question was asked, 'Where next?', and the answer came, 'Home.' Earthrise was an epiphany in space."



EARTHRISE, seen for the first time by human eyes, December 24, 1968, as *Apollo 8,* orbiting clockwise, emerged from behind the moon. The photograph was taken before the astronauts could reload with color film, which, a few minutes later, captured the more famous "Earthrise" image, generally shown rotated 90 degrees.

NOTABLE BOOKS: MATH + LIFE

1 **Lewis Carroll in Numberland: His Fantastical Mathematical Logical Life**
by Robin Wilson. W. W. Norton, 2008 ($24.95)
A biography that examines inspirations and sources for Lewis Carroll's fantastical writings.



2 **The Great Equations: Breakthroughs in Science from Pythagoras to Heisenberg**
by Robert P. Crease. W. W. Norton, 2009 ($24.95)
Places 10 great equations in historical context.

3 **Professor Stewart's Cabinet of Mathematical Curiosities**
by Ian Stewart. Basic Books, 2008 (paperbound, $16.95)
Logic puzzles, geometric puzzles, numerical puzzles, odd items of mathematical culture, things to do, and things to make.

4 **Geekspeak: How Life + Mathematics = Happiness**
by Graham Tattersall. Collins, 2008 ($19.95)
Common sense + straightforward arithmetic + a little questioning of received wisdom = empowerment.

5 **Rock, Paper, Scissors: Game Theory in Everyday Life**
by Len Fisher. Basic Books, 2008 ($15.95)
How game theory can add to our chances of solving personal and global problems.

NASA (*moon and Earth*); *SAM LOYD'S CYCLOPEDIA OF 5000 PUZZLES, TRICKS, AND CONUNDRUMS WITH ANSWERS* (*monkey puzzle*)

Q How does **solar power** work?

A. Paul Alivisatos, deputy director of Lawrence Berkeley National Laboratory and a leader of the Helios solar energy research project there, shines some light on the matter:

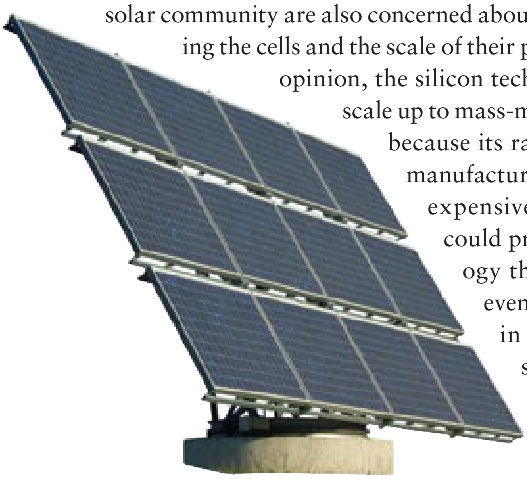
When the sun strikes a solar panel, the energy of the sunlight liberates electrons in the solar cells, producing an electric current that we can harness to power pocket calculators, homes, even science stations on Mars.

In a traditional crystalline silicon cell, the atoms in the silicon crystal are bound by shared electrons. When light is absorbed, some of the electrons in those bonds are excited up to a higher energy level. Those electrons can then move around the crystal more freely than when they were bound, allowing them to flow as an electric current.

Imagine that you have a ledge—a shelf on the wall—and you take a ball and throw it up onto that ledge. That is akin to promoting an electron to a higher energy level. A photon, an indivisible packet of light energy, enters the silicon crystal and bumps the electron up onto the ledge (the higher energy level), where it stays until we come and collect the energy by using the electricity.

Researchers are constantly looking for new approaches, and refining existing ones, to boost the efficiency of this process. The power efficiency of a crystalline silicon cell is in the 22 to 23 percent range, meaning the cells convert that much of the light energy striking them into electricity. The cells that you might be able to afford to put on your rooftop are less efficient than that, somewhere between 15 and 18 percent. The best-performing solar cells, such as the ones that go on satellites, approach 50 percent efficiency.

This conversion rate is one important measure, but we in the solar community are also concerned about the cost of making the cells and the scale of their production. In my opinion, the silicon technology does not scale up to mass-market size ideally because its raw materials and manufacturing processes are expensive. If researchers could produce a technology that scaled better, even one less efficient in energy conversion than crystalline silicon, we might be able to make millions of acres of the stuff to generate a great deal of energy. Many companies and universities are experimenting with a variety of materials, such as plastics and nanoparticles, to achieve this goal.



Q Why does **my voice sound so different** when it is recorded and played back?

Timothy E. Hullar, an otologist and assistant professor at the Washington University School of Medicine in St. Louis, replies:

Sound can reach the inner ear by way of two separate paths, and those paths in turn affect what we perceive. Air-conducted sound is transmitted from the surrounding environment through the external auditory canal, eardrum and middle ear to the cochlea, the fluid-filled spiral in the inner ear. Bone-conducted sound reaches the cochlea directly through the tissues of the head.

When you speak, sound energy spreads in the air around you and reaches your cochlea through your external ear by air conduction. Sound also travels from your vocal cords and other structures directly to the cochlea, but the mechanical properties of your head enhance its deeper, lower-frequency vibrations. The voice you hear when you speak is the combination of sound carried along both paths. When you listen to a recording of yourself speaking, the bone-conducted pathway that you consider part of your "normal" voice is eliminated, and you hear only the air-conducted component in unfamiliar isolation. You can experience the reverse effect by putting in earplugs so you hear only bone-conducted vibrations.

Some people have abnormalities of the inner ear that enhance their sensitivity to this component so much that the sound of their own breathing becomes overwhelming, and they may even hear their eyeballs moving in their sockets. ■

HAVE A QUESTION?... *Send it to experts@SciAm.com or go to* **www.SciAm.com/asktheexperts**

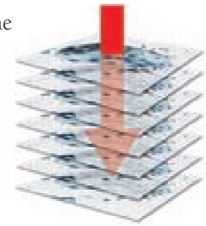
MARTIN RUEGNER (*solar cell*); COLORBLIND (*woman speaking*)

The PC becomes a microscope: focusing up and down, zooming in and out, viewing fluorescence...

On her personal computer, without need of a microscope, a researcher analyzes a fluorescence-stained section of mouse kidney. This "digital slide" was scanned from an original glass slide by Hamamatsu's *NanoZoomer Digital Pathology* system.

Digital slides: making research easier

The problem with a glass microscope slide is, there's only one original. For others to view it, you need to send them the slide—and they need to have a microscope.



On a PC, focus up and down to examine different depths in the sample.

Now, Hamamatsu's *NanoZoomer* can turn a glass slide into a very unique electronic image...

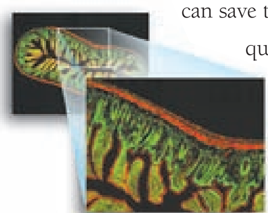
One that can be easily viewed on any PC. And which contains *depth of information* to allow focusing up and down. And which can be further magnified to analyze details.

These ultra-high resolution digital-slide files now permit easy duplication, simpler cataloging and quick transmission to anyone in the world!

Hamamatsu is opening the new frontiers of Light

Fluorescence images that don't fade

Previously, glass fluorescence slides could not be archived because of fading. But now NanoZoomer can save the original image quality indefinitely!



Easily zoom in to see greater detail.

These digital slides can also include *location guides* to direct the viewer to a specific point of interest—a very valuable feature, especially in research areas such as drug development, gene expression and protein localization.

NanoZoomer Digital Pathology: one more way Hamamatsu is opening the new frontiers of Light.

http://jp.hamamatsu.com/en/rd/publication/

HAMAMATSU

The Frontiers of Light