SCIENTIFIC AMERICAN PRESENTS

EXPLORING

Intelligence

A Search in the Human, Animal, Machine and Extraterrestrial Domains

QUARTERLY $5.95

IQ: What Your Score Really Means

Multiple Intelligences

Giftedness and Savants

Smart Drugs in Your Kitchen

Animal Thinking and Empathy

Game-Playing Computers

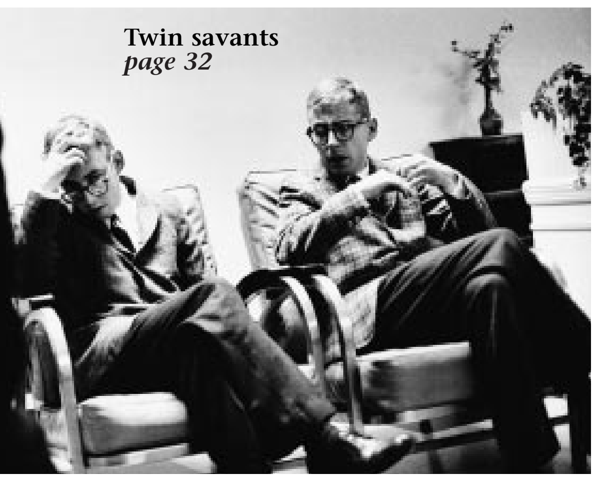
SETI Today

SCIENTIFIC AMERICAN PRESENTS EXPLORING INTELLIGENCE Quarterly Volume 9, Number 4

SCIENTIFIC AMERICAN PRESENTS
Winter 1998 Volume 9 Number 4

EXPLORING Intelligence

A Search in the Human, Animal, Machine and Extraterrestrial Domains



Twin savants
page 32

Scientific American Presents (ISSN 1048-0943), Volume 9, Number 4, Winter 1998, published quarterly by Scientific American, Inc., 415 Madison Avenue, New York, NY 10017-1111. Periodicals Publication Rate. Postage paid at New York, N.Y., and at additional mailing offices. Canadian BN No. 127387652RT; QST No. Q1015332537. Subscription rates: one year $19.80 (outside U.S. $23.80). To purchase additional quantities: 1 to 9 copies: U.S. $5.95 each plus $2.00 per copy for postage and handling (outside U.S. $5.00 P & H); 10 to 49 copies: $5.35 each, postpaid; 50 copies or more: $4.75 each, postpaid. Send payment to Scientific American, Dept. SAQ, 415 Madison Avenue, New York, NY 10017-1111. Postmaster: Send address changes to Scientific American Presents, Box 5063, Harlan, IA 51593. Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 247-7631.

COVER ILLUSTRATION BY WATERS DESIGN ASSOCIATES, INC.

SCIENTIFIC AMERICAN PRESENTS

Exploring Intelligence is published by the staff of SCIENTIFIC AMERICAN, with project management by:

SCIENTIFIC AMERICAN, INC.
415 Madison Avenue • New York, NY 10017-1111
(212) 754-0550

PRINTED IN U.S.A.

Intelligence Considered

by Philip Yam, *issue editor*

THE ESTATE OF KEITH HARING

***Untitled,* Keith Haring**

What does it mean to have brainpower? A search for a definition of intelligence

For the past several years, the Sunday newspaper supplement *Parade* has featured a column called "Ask Marilyn." People are invited to query Marilyn vos Savant, who at age 10 had tested at a mental level of someone about 23 years old; that gave her an intelligence quotient of 228—the highest score ever recorded. IQ tests ask you to complete verbal and visual analogies, to envision paper after it has been folded and cut, and to deduce numerical sequences, among other similar tasks. So it is a bit perplexing when vos Savant fields such queries from the average Joe (whose IQ is 100) as, What's the difference between love and infatuation? Or what is the nature of luck and coincidence? It's not obvious how the capacity to visualize objects and to figure out numerical patterns suits one to answer questions that have eluded some of the best poets and philosophers.

Clearly, intelligence encompasses more than a score on a test. Just what does it mean to be smart? How much of intelligence can be specified, and how much can we learn about it from neurobiology, genetics, ethology, computer science and other fields?

The defining term of intelligence in humans still seems to be the IQ score, even though IQ tests are not given as often as they used to be. The test comes primarily in two forms: the Stanford-Binet Intelligence Scale and the Wechsler Intelligence Scales (both come in adult and children's versions). Generally costing several hundred dollars, they are usually given only by psychologists, although variations of them populate bookstores and the World Wide Web. (Superhigh scores like vos Savant's are no longer possible, because scoring is now based on a statistical population distribution among age peers, rather than simply dividing the mental age by the chronological age and multiplying by 100.) Other standardized tests, such as the Scholastic Assessment Test (SAT) and the Graduate Record Exam (GRE), capture the main aspects of IQ tests.

Such standardized tests may not assess all the important elements necessary to succeed in school and in life, argues Robert J. Sternberg. In his article "How Intelligent Is Intelligence Testing?", Sternberg notes that traditional tests best assess analytical and verbal skills but fail to measure creativity and practical knowledge, components also critical to problem solving and life success. Moreover, IQ tests do not necessarily predict so well once populations or situations change. Research has found that IQ predicted leadership skills when the tests were given under low-stress conditions, but under high-stress conditions, IQ was negatively correlated with leadership—that is, it predicted the opposite. Anyone who has toiled through college entrance exams will testify that test-taking skill also matters, whether it's knowing when to guess or what questions to skip.

Sternberg has developed tests to measure the creative and practical sides of the mind. Some schools and businesses use them, and Sternberg has published work showing their predictive value in subsequent tasks, but they have yet to gain much acceptance in the mainstream testing business.

Still, conventional standardized testing has leveled the field for most people—whatever their shortcomings, the exams provide some standard by which universities can select students. Contrast this with the time before World War II, when family background and attendance at elite prep schools were key requirements for selective colleges.

That tests cannot capture all of a person's skills in a neat number is an important crux of the article by Howard Gardner. In "A Multiplicity of Intelligences," he espouses his view, developed in part after working with artists and musicians who had suffered strokes, that human intelligence is best thought of as consisting of several components, perhaps as many as nine. Components such as spatial and bodily-kinesthetic, embodied by, say, architect Frank Lloyd Wright and hockey player Wayne Gretzky, elude test measures. Gardner's classifications are not arbitrary; he draws from evolution, brain function, developmental biology and other disciplines.

Gardner has been quite influential in education circles, where his theory is often required study for teachers-to-be. He feels, however, that some of his ideas are being misinterpreted. He mentions Daniel Goleman's best-seller, *Emotional Intelligence,* the central concept of which is based on multiple-intelligences theory. Gardner maintains that the theory should not be used to create a value system, as suggested in Goleman's book. People with high emotional quotients aren't necessarily well adjusted and kind to others—think Hannibal Lecter.

In Defense of IQ

In sharp contrast to Sternberg and Gardner is Linda S. Gottfredson. In "The General Intelligence Factor," she makes the case for the psychologist's *g*—that is, a single factor for brains. Other elements, such as linguistic ability and mathematical skill, fall below *g* in the hierarchy of human skills. She argues that IQ scores are important predictors for both academic and life success and draws on biology to bolster her ideas.

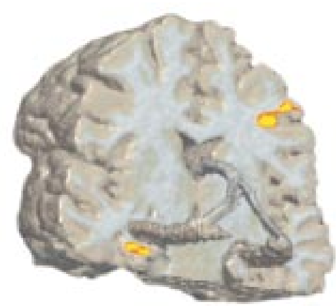
The concept of *g* has a long and stormy history. First proposed in the early part of this century, it has waxed and waned in popularity. Among the public and the media, the concept took a hard hit in 1981, when Stephen Jay Gould published his now classic *The Mismeasure of Man*. In it, he argues that early researchers (perhaps unconsciously) biased their measurements of intelligence based on race and points to shortcomings of those trying to substantiate *g*. For instance, he takes to task Catherine M. Cox's 1926 publication of deduced IQ scores of past historical figures. Gould notes that Cox drew her assumptions based on written biographical accounts of a person's deeds. Unfortunately, the existence of such biographies correlated with the prominence of the family—poorer families were less likely to have documentation of their chil-

Sir Francis Galton	200
Johann Wolfgang von Goethe	185
Francois-Marie Arouet Voltaire	170
Alfred Lord Tennyson	155
William Wordsworth	150
Sir Walter Scott	150
Lord Byron	150
Abraham Lincoln	125
George Washington	125
Nicolaus Copernicus	105
Michael Faraday	105

ESTIMATED IQ SCORES of eminent historical figures were published in 1926 by Catherine M. Cox in The Early Mental Traits of Three Hundred Geniuses. *Although such lists generate interest, poor assumptions often underlie the analyses, rendering the results highly questionable and largely irrelevant.*

dren's accomplishments. Hence, pioneering British physicist Michael Faraday, from a modest background, gets a surprisingly low childhood IQ score of 105.

Psychometricans (psychologists who apply statistics to measure intelligence) have a hostile view of Gould. According to critics, many of whom recently have written new reviews for the rerelease of *Mismeasure,* Gould does not grasp factor analysis—the statistical technique used to extract *g*. In a 1995 review published in the journal *Intelligence,* John B. Carroll of the University of North Carolina at Chapel Hill writes that "it is indeed odd that Gould continues to place the burden of his critique on factor analysis, the nature and purpose of which, I believe, he still fails to understand." This is one of the milder criticisms leveled at Gould by psychometricians.



JAMES B. BREWER

BRAIN ACTIVITY recorded by James B. Brewer and his colleagues at Stanford University is revealed by functional magnetic resonance imaging. It shows part of the neural areas that operate during recall of a visual scene (above). *Such imaging techniques are enabling neurobiologists to pinpoint functions within the brain.*

The stormy debate about *g* stems from its political, racial and eugenics overtones. Historically, the idea of IQ has been used to justify excluding certain immigrant groups, to maintain status quo policies and even to sterilize some people. Scientists who hold views that intelligence is strongly hereditary are often vilified by the general population, sometimes rightly and sometimes wrongly. One researcher who has a bad public image that is not on par with the opinion of professional peers is Arthur R. Jensen of the University of California at Berkeley: even those working psychologists who disagree with him consider his investigations to be solid research.

Modern genetic studies threaten to inflame the racial controversy even more. For example, this past May, Robert Plomin of the Institute of Psychiatry in London and several collaborators reported the discovery of a gene variation that is statistically linked with high intelligence. The variation lies in chromosome 6, within a gene that encodes for a receptor for an insulinlike growth factor (specifically, IGF-2), which might affect the brain's metabolic rate.

In some respects, the discovery is not truly surprising. Obviously, some people are born smarter than others. But note who Plomin and his colleagues used as subjects: 50 students with high SAT scores. Strictly speaking, the researchers found a gene for performance on the SAT. True, SATs correlate with IQ scores, which in turn reflect *g*—which not everyone agrees is the sole indicator of smarts. Complicating the analyses is the fact that average SAT scores have been variable; they dipped in the 1980s but are now swinging back up. That could be the result of better schooling, because the SAT measures achievement more than inherent learning capacities (for which IQ tests are designed). But even IQ scores have not been as stable as was once thought. James R. Flynn of the University of Otago in New Zealand discovered that worldwide, IQ scores have been rising by about three points per decade—by a full standard deviation (15 points) in the past 50 years.

Are we truly smarter than our grandparents? Researchers aren't sure just what has caused the rise. (Flynn himself, who is profiled in the January 1999 issue of *Scientific American,* doesn't think the rise is real.) Genetics clearly cannot operate on such a short time scale. Ulric Neisser of Cornell University thinks it may have to do with the increasing visual complexity of modern life. Images on television, billboards and computers have enriched the visual experience, making people more capable in handling the spatial aspects of the IQ tests. So even though genes might play a substantial role in individual differences in IQ, the environment dictates how those genes are expressed.

In part to probe the genetic-environment mechanisms, the American Psychological Association (APA) convened a task force of mainstream psychologists. They published a 1995 report, *Intelligence: Knowns and Unknowns,* which concluded that almost nothing can be said about the reason for the 15-point IQ difference between black and white Americans: "There is certainly no such support for a genetic interpretation. At this time, no one knows what is responsible for the differential."

The APA report was sparked by the publication of *The Bell Curve,* by Charles Murray and Richard J. Herrnstein. The report actually does not disagree with the data presented in the book about IQ scores and the notion of *g*. The interpretation of the data, however, is a different story. To many scholars, *The Bell Curve* played on psychometric data to advance a politically conservative agenda—arguing, for instance, that *g* is largely inherited and that thus enrichment programs for disadvantaged youth are doomed to failure. As staff writer Tim Beardsley points out in "For Whom Did the Bell Curve Toll?", several interpretations are possible, and other studies have produced results that run counter to the dreary conclusions offered by Murray and Herrnstein. Although it engendered heated debate, the book ultimately had little impact on government policy.

Function and Form

Even those who fall on the right end of the bell curve, however, do not necessarily have it easy. In "Uncommon Talents: Gifted Children, Prodigies and Savants," Ellen Winner explores the nature of children who are so mentally advanced that schools often do not know how to educate them. These whiz kids are expected to achieve on their own even though they often are misunderstood, ridiculed and neglected. Many are unevenly gifted, excelling in one field but doing average in others. The most extreme cases are the so-called savants (formerly called idiot savants), who can perform astounding feats of calculation and memory despite having autism or autismlike symptoms. Studies of such people offer valuable insights into how the human brain works.

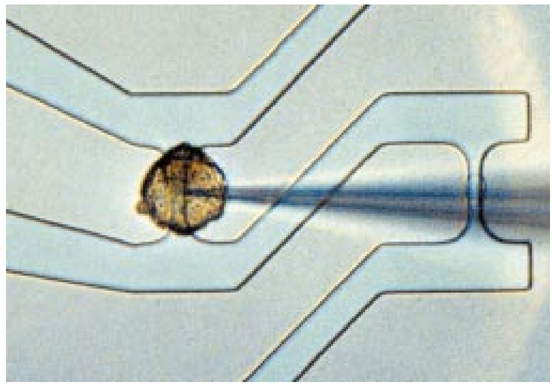
Observations of brain-damaged patients have done much to identify the discrete functional areas of the brain [see past SCIENTIFIC AMERICAN articles, such as "The Split Brain Revisited," by Michael S. Gazzaniga, July 1998; "Emotion, Memory and the Brain," by Joseph LeDoux, June 1994; and the special issue *Mind and Brain*, September 1992]. Modern imaging technology, such as positron-emission tomography (PET) and functional magnetic resonance imaging (fMRI), have helped investigators to map cognitive function with structure [see "Visualizing the Mind," by Marcus E. Raichle; SCIENTIFIC AMERICAN, April 1994]. With such imaging, researchers can see how the brain "lights up" when certain cognitive tasks are performed, such as reciting numbers or recalling a visual scene.

Structure and function are of particular interest to neurobiologists trying to boost the brainpower of the common person. Several researchers in fact have ties to pharmaceutical companies hoping to capitalize on what would seem to be a huge market in cognitive enhancers. In "Seeking 'Smart' Drugs," staff writer Marguerite Holloway reviews the diverse approaches. If you're a sea slug or a fruit fly, scientists can do wonders for your memory. Humans have somewhat limited choices at the moment; the vast majority of compounds now sold have no solid clinical basis. For instance, package labels of the popular herb gingko biloba overstate its efficacy: a study has shown that it has some modest benefits in Alzheimer's patients, but no study has indicated that gingko definitely helps healthy individuals. Prospective compounds, including modified estrogen and nerve growth factors, seem promising, but the best smart drug may already be in your kitchen: sugar, the energy source of neurons.

The exploration of human intelligence naturally raises the question of how humans got to be intelligent in the first place. In "The Emergence of Intelligence" (updated since its appearance in the October 1994 issue of *Scientific American*), William H. Calvin puts forth a kind of *2001: A Space Odyssey* hypothesis: that ballistic movement, whether it's pitching a baseball or throwing sticks and stones at black monoliths, is the key to intelligence, because a degree of foresight and planning is required to hit the target. And these ingredients may have permitted language, music and creativity to emerge, differentiating us from the rest of the world's fauna.

Do Animals Think?

That's not to say that animals aren't intelligent. In "Reasoning in Animals," James L. Gould and Carol Grant Gould make a persuasive case that animals have some ability to solve problems. The examples they cite and the studies they describe make it unlikely that strict behaviorism—that animals' actions are dictated by conditioned responses—can explain it all. Of course, not everything an animal does is an act of cognition: many of the actions of animals are accomplished and restricted by instinct and genes.



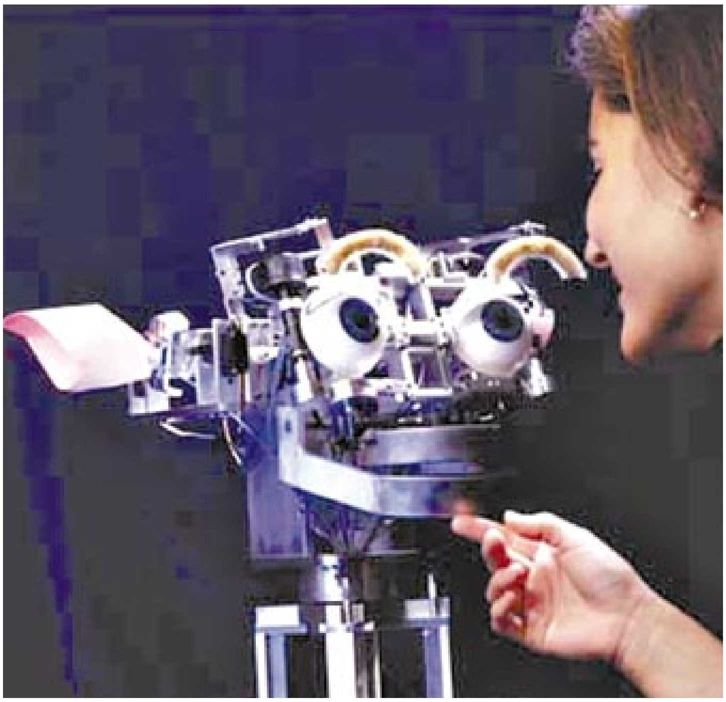
PETER FROMHERZ *Max Planck Institute of Biochemistry*

NEURON TRANSISTOR, using a leech ganglion, unites carbon with silicon. The nerve cell (green), *about 80 microns wide, fires depending on the signals sent to the transistor. The fuzzy object piercing the nerve cell is a micromanipulator.*

Language plays a role in the development of cognitive abilities, too, as suggested by Irene M. Pepperberg's article, "Talking with Alex: Logic and Speech in Parrots." Alex is the famous Grey parrot that can make requests and provide answers in a seemingly reasoned way. Alex is unique in part because he's a bird: other communicating animals have been primates, such as the chimpanzees Washoe and Kanzi and the gorilla Koko. Rigorously speaking, these animals are communicating through learned symbols and sounds; whether they are truly engaging in language, which permits planning and abstraction, remains to be proved.

Besides language, another hallmark of intelligence may be self-awareness. Many investigators have grappled with human consciousness from a scientific perspective [see "The Puzzle of Conscious Experience," by David J. Chalmers; SCIENTIFIC AMERICAN, December 1995; and "The Problem of Consciousness," by Francis Crick and Christof Koch; SCIENTIFIC AMERICAN, September 1992]. But how can you tell if an animal is self-aware? In the late 1960s Gordon G. Gallup, Jr., devised a now classic test using mirrors. Gallup painted a red dot on the faces of anesthetized animals and then observed them when they awoke and noticed themselves in the mirror. An animal that would start poking at the red spot on its face seemingly indicated an awareness that it was seeing itself in the mirror, not another creature. Of all the animals tested in this way, only humans, chimpanzees and orangutans pass.

With self-awareness comes the ability to take into account another creature's feelings—at least, that's the way it works in humans. Taking the pro side of the debate, "Can Animals Empathize?", Gallup reasons that chimps and orangutans have a sense of self, which they might use to model other creature's mental states.



SAM OGDEN

HUMANOID ROBOT KISMET of the Massachusetts Institute of Technology interacts socially with humans with emotive expressions. It belongs to the Cog project, which seeks in part to develop a robot that behaves as if it were conscious without necessarily being so.

Daniel J. Povinelli, however, remains skeptical (in the best traditions of scientific open-mindedness, he adopts the "maybe not" view). He tells how he tested chimpanzees under a variety of clever conditions to see if they understand that another creature cannot see them. It turns out that chimps will beg for food from a blindfolded person (who does not see the chimps) as well as from a sighted individual. Such results suggest that chimps do not reason about another animal's state of mind—or even their own. That they pass the mirror test suggests to Povinelli that they are not necessarily self-aware. Instead they learn that the mirror images are the *same* as themselves.

I, Robot

If our closest relatives aren't self-aware, is there any chance that a computer can be? In seeking to make a machine that can pass the so-called Turing test—that is, produce responses that would be indistinguishable from those of humans—artificial intelligence has proved to be a substantial disappointment. Yet passing the Turing test may be an unfair measure of AI progress. In "On Computational Wings: Rethinking the Goals of Artificial Intelligence," Kenneth M. Ford and Patrick J. Hayes maintain that the obsession with the Turing test has led AI researchers down the wrong road. They draw an analogy with artificial flight: engineers for centuries tried to produce flying machines by mimicking the way birds soar. But modern aircraft obviously do not fly like birds, and fortunately so. From this argument, Ford and Hayes note that AI is effectively all around us—in instrumentation, in data-recognition tasks, in "expert" systems such as medical-diagnostic programs and in search software, such as intelligent agents, which roam cyberspace to retrieve information [see "Intelligent Software," by Pattie Maes; SCIENTIFIC AMERICAN, September 1995].

Several more formal AI projects exist. One is that of Douglas B. Lenat of Cycorp in Austin, Tex., who for more than a decade has been working on CYC, a project that aims to create a machine that can share and manage information that we humans might consider common sense [see "Artificial Intelligence," by Douglas B. Lenat; SCIENTIFIC AMERICAN, September 1995]. Another is that of Rodney Brooks and Lynn Andrea Stein of the Massachusetts Institute of Technology, whose team has produced Cog, a humanoid robot that its makers hope to endow with abilities of a conscious human, without its necessarily being conscious.

A realm of AI that sparks intense, though perhaps unjustified, feelings of anxiety and human pride is game-playing machines. In "Computers, Games and the Real World," Matthew L. Ginsberg summarizes the main contests that machines are playing and how they fare against human competitors. Garry Kasparov's loss in a six-game match against IBM's Deep Blue last year may have inspired some soul searching. The point of game-playing computers, however, is not so much to best their makers as to explore which types of calculation are best suited to the architecture of the silicon chip. As Ginsberg reminds us, computers are designed not to replace us humans but to help us.

Indeed, life without computers is now hard to imagine. And the machines will get more ubiquitous. In "Wearable Intelligence," Alex P. Pentland explains how devices such as keyboards, monitor screens, wireless transmitters and receivers are getting so small that we can physically wear them. Imagine reading e-mail on special eyeglasses as you walk down the street, generating power in your shoes that is converted to electricity that powers your personal-area network for cellular communications. Two M.I.T. students, Thad Starner and Steve Mann, have spent time in such cyborg existences—Starner has been doing it since 1992. They look like less slick versions of the futuristic Borg creatures seen on the *Star Trek* series.

A true melding of mind and machine is still far away, although the appeal apparently is irresistible. British Telecommunications has a project called Soul Catcher; the goal is to develop a computer that can be slipped into the brain to augment memory and other cognitive functions. Hans Moravec of Carnegie Mellon University and others have argued, somewhat disturbingly, that it should be possible to remove the brain and download its contents into a computer—and with it, one hopes, personality and consciousness.

Connecting neurons to silicon is only in its infancy. Peter Fromherz and his colleagues at the Max Planck Institute of Biochemistry in Martinsried-München, Germany, have managed to connect the two and caused the neuron to fire when instructed by the computer chip. Granted, the neuron used in the experiment came from a leech. But in principle "there are no show-stoppers" to neural chips, says computer scientist Chris Diorio of the University of Washington, adding that "the electronics part is the easy part." The difficulty is the interface.

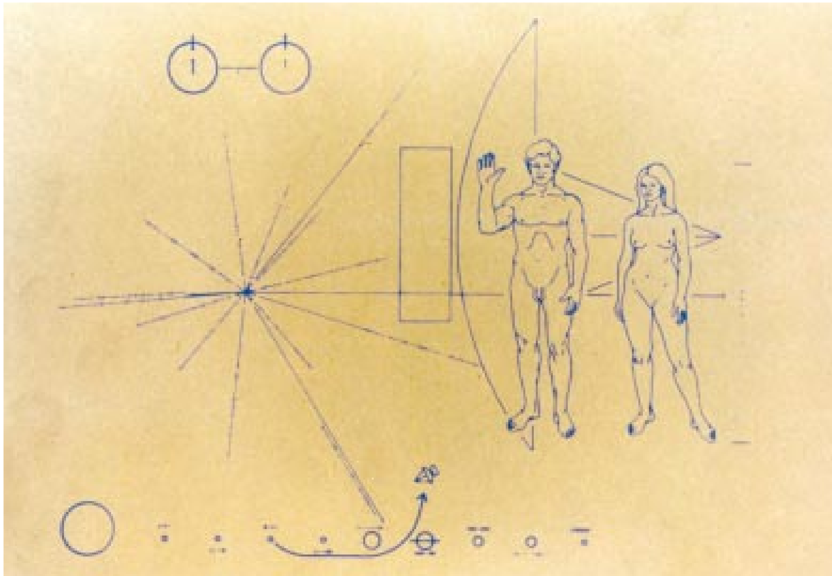
Diorio was one of the organizers of a weeklong meeting this past August sponsored by Microsoft Research and the University of Washington that explored how biology might help create intelligent computer systems. Expert systems, notes co-organizer Eric Horvitz of Microsoft Research, do quite well in their rather singular tasks but cannot match an invertebrate in behavioral flexibility. "A leech becomes more risk taking when hungry," he notes. "How do you build a circuit that takes risk?" The hydrocarbon basis of neurons might also mean that the brain is more efficient with its constituent materials than a computer is with its silicon. "If we knew what a synapse was doing, we could mimic it," Diorio says, but "we don't have the mathematical foundation yet."

Beyond Earth

While we have much to learn from the neurons on Earth, we stand to gain even more if we could find neurons from other planets. In "Is There Intelligent Life Out There?", Guillermo A. Lemarchand reviews the history of the search for extraterrestrial intelligence, or SETI. The odds say that other technological civilizations are out there, so why haven't we made contact yet, government conspiracies notwithstanding? The answer is simple: astronomers have looked at only a tiny fraction of the sky—some 10^{-16} of it. Almost all SETI funds have come from private sources, and time on radio telescopes is limited.

One ingenious attempt to enlist help from amateurs is SETI@home. Interested parties would download a special screen saver for personal computers that, when running, would sift through data gathered from the Arecibo Radio Observatory in Puerto Rico (specifically, from Project SERENDIP). In other words, as you take a break from work, your PC would look for artificial signals from space. Organizers estimate that 50,000 machines running the screen saver would rival all current SETI projects. At press time, investigators were still completing the software and looking for sponsorship: they need at least $200,000 to proceed to the final phases. Check it out at http://setiathome.ssL.berkeley.edu/ on the World Wide Web.

Of course, there's the chance that we have already received alien greetings but haven't recognized them as such. In Lemarchand's view, sending salutations of our own may be the best way to make first contact. He proposes relying on a supernova, on the assumption that other civilizations would also turn their sights onto such relatively rare stellar explosions. Radio telescopes on Earth could send signals to nearby star systems that have good views of both Earth and the supernova.


NASA

LUNCH INVITATION? A few researchers worried that calling attention to ourselves, such as with the gold plaque on the Pioneer spacecraft, might bring extraterrestrial aliens intent on consuming humans. SETI scientists disagree, and some advocate sending more greetings from Earth.

Defining Intelligence

In the end, most of us would feel rather confident in identifying intelligent signals, be they from space, a machine, an animal or other people. An exact definition of intelligence is probably impossible, but the data at hand suggest at least one: an ability to handle complexity and solve problems in some useful context—whether it is finding the solution to the quadratic equation or obtaining just-out-of-arm's-reach bananas. The other issues surrounding intelligence—its neural and computational basis, its ultimate origins, its quantification—remain incomplete, controversial and, of course, political.

No one would argue that it doesn't pay to be smart. The role that intelligence plays in modern society depends not on the amount of knowledge gained about it but on the values that a society chooses to emphasize—for the U.S., that includes fairness, equal opportunity, basic rights and tolerance. That intelligence studies could pervert these values is, ultimately, the root of anxiety about such research. Vigilance is critical and so is the need for a solid base of information by which to make informed judgments—a base to which, I hope, this issue has contributed. SA

HUMAN

How Intelligent Is

by Robert J. Sternberg

A typical American adolescent spends more than 5,000 hours in high school and several thousand more hours studying in the library and at home. But for those students who wish to go on to college, much of their fate is determined in the three or so hours it takes to complete the Scholastic Assessment Test (SAT) or the American College Test (ACT). Four years later they may find themselves in a similar position when they apply to graduate, medical, law or business school.

The stakes are high. In their 1994 book *The Bell Curve,* Richard J. Herrnstein and Charles Murray pointed out a correlation between scores on such tests and a variety of measures of success, such as occupational attainment. They suggested that the U.S. is developing a "cognitive elite"—consisting of high-ability people in prestigious, lucrative jobs—and a larger population of low-ability people in dead-end, low-wage positions. They suggested an invisible hand of nature at work.

But to a large extent, the hand is neither invisible nor natural. We have decided as a society that people who score well on these high-stakes tests will be granted admission to the best schools and, by extension, to the best access routes to success. People have used other criteria, of course: caste at birth, membership in governmental party, religious affiliation. A society can use whatever it wishes—even height, so that very soon people in prestigious occupations would be tall. (Oddly enough, to some extent Americans and many people in other societies already use this criterion.) Why have the U.S. and other countries chosen to use ability tests as a basis to open and close the access gates? Are they really the measures that should be used? The answers lie in how intelligence testing began.

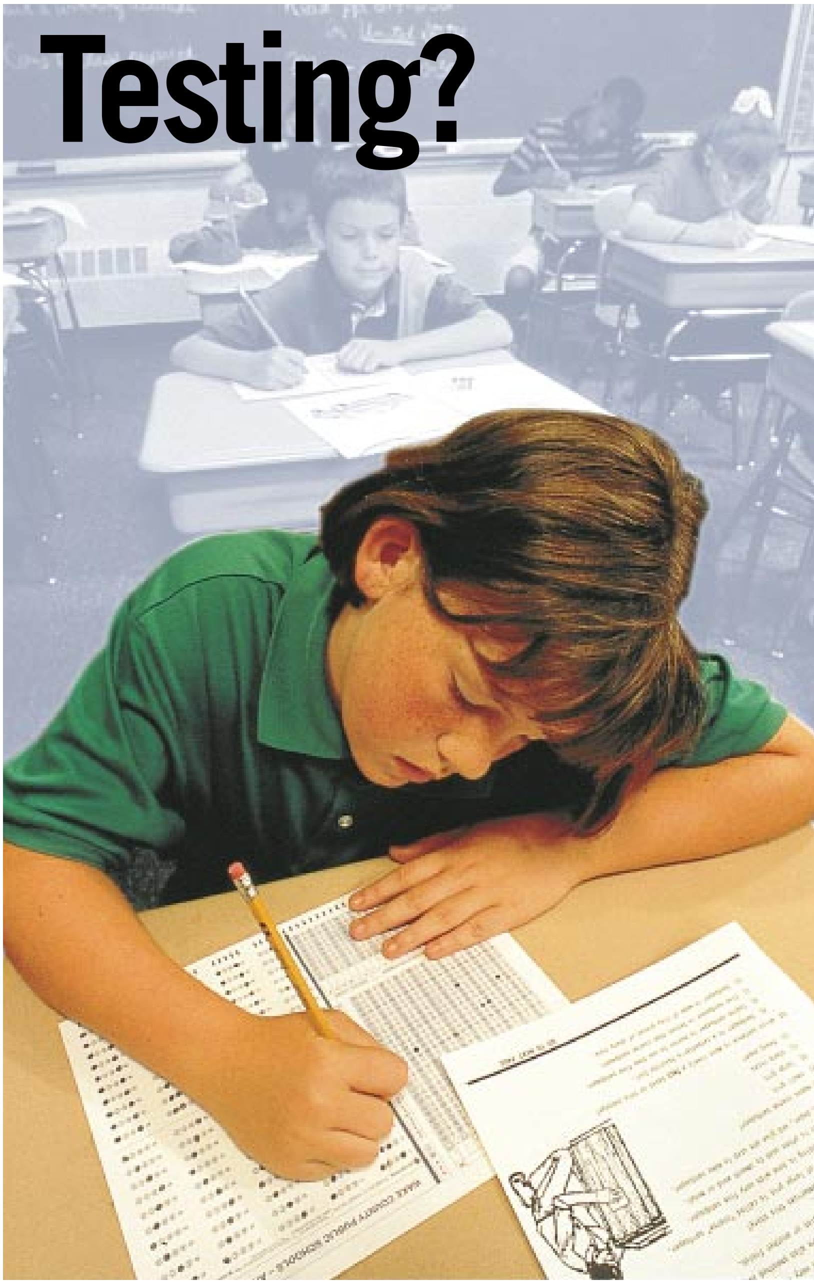
A Brief History of Testing

Sir Francis Galton, a cousin of Charles Darwin, made the first scientific attempt to measure intelligence. Between 1884 and 1890 Galton ran a service at the South Kensington Museum in London, where, for a small fee, people could have their intelligence checked. The only problem was that Galton's tests were ill chosen. For example, he contrived a whistle that would tell him the highest pitch a person could perceive. Another test used several cases of gun cartridges filled with layers of either shot, wool or wadding. The cases were identical in appearance and differed only in weight. The test was to pick up the cartridges and then to discriminate the lighter from the heavier. Yet another test was of sensitivity to the smell of roses.

James McKeen Cattell, a psychologist at Columbia University, was so impressed with Galton's work that in 1890 he devised similar tests to be used in the U.S. Unfortunately for him, a student of his, Clark Wissler, decided to see whether scores on such tests were actually meaningful. In particular, he wanted to know if the scores were related either to one another or to college grades. The answer to both questions proved to be no—so if the tests didn't predict school performance or even each other, of what use were they? Understandably, interest in Galton's and Cattell's tests waned.

A Frenchman, Alfred Binet, got off to a better start. Commissioned to devise a

Intelligence Testing?



CHARLES GUPTON *The Stock Market*

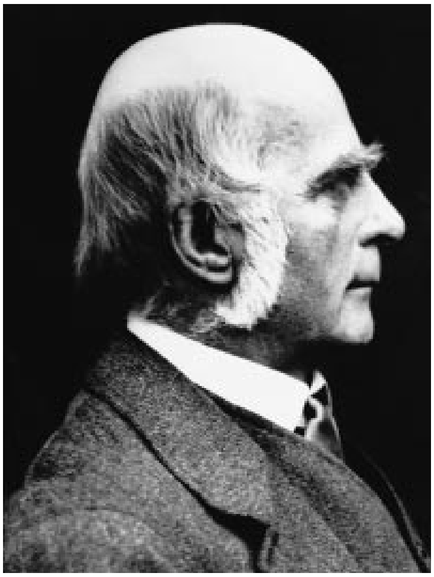
Conventional measures, such as SATs and IQ tests, miss critical abilities essential to academic and professional success

means to predict school performance, he cast around for test items. Together with his colleague Theodore Simon, he developed a test of intelligence, published in 1905, that measured things such as vocabulary ("What does *misanthrope* mean?"), comprehension ("Why do people sometimes borrow money?") and verbal relations ("What do an orange, an apple and a pear have in common?"). Binet's tests of judgment were so successful at predicting school performance that a variant of them, called the Stanford-Binet Intelligence Scale (fourth edition), is still in use today. (Louis Terman of Stanford University popularized the test in the U.S.—hence the name.) A competing test series, the Wechsler Intelligence Scales, measures similar kinds of skills.

It is critical to keep in mind that Binet's mission was linked to school performance and, especially, to distinguishing children who were genuinely mentally retarded from those who had behavior problems but who were able to think just fine. The result was that the tests were designed, and continue to be designed, in ways that at their best predict school performance.

During World War I, intelligence testing really took off: psychologists were asked to develop a method to screen soldiers. That led to the Army Alpha (a verbal test) and Beta (a performance test with pantomimed directions instead of words), which were administered in groups. (Psychologists can now choose between group or individually administered tests, although the individual tests generally give more reliable scores.) In 1926 a new test was introduced, the forerunner to today's SAT. Devised by Carl C. Brigham of Princeton University, the test provided verbal and mathematical scores.

Shortly thereafter, a series of tests evolved, which today are used to measure various kinds of achievements and abilities, including IQ (intelligence quotient), "scholastic aptitude," "academic aptitude" and related constructs. Although the names of these tests vary, scores on all of them tend to correlate highly



CORBIS-BETTMANN

SIR FRANCIS GALTON made the first scientific attempt to measure intelligence. His tests included determining the pitch of whistles and the weight of gun cartridges. They were not particularly useful.

CORBIS-BETTMANN

ALFRED BINET developed the examination that is the forerunner of the modern IQ test. He devised questions that probed vocabulary, comprehension and verbal abilities to predict school performance.

with one another, so for the purposes of this article I will refer to them loosely as conventional tests of intelligence.

What Tests Predict

Typically, conventional intelligence tests correlate about 0.4 to 0.6 (on a 0 to 1 scale) with school grades, which statistically speaking is a respectable level of correlation. A test that predicts performance with a correlation of 0.5, however, accounts for only about 25 percent of the variation in individual performances, leaving 75 percent of the variation unexplained. (In statistics, the variation is the square of the correlation, so in this case, $0.5^2 = 0.25$.) Thus, there has to be much more to school performance than IQ.

The predictive validity of the tests declines when they are used to forecast outcomes in later life, such as job performance, salary or even obtaining a job in the first place. Generally, the correlations are only a bit over 0.3, meaning that the tests account for roughly 10 percent of variation in people's performance. That means 90 percent of the variation is unexplained. Moreover, IQ prediction becomes less effective once populations, situations or tasks change. For instance, Fred Fiedler of the University of Washington found that IQ positively predicts leadership success under conditions of low stress. But in high-stress situations, the tests negatively predict success. Some intelligence tests, including both the Stanford-Binet and Wechsler, can yield multiple scores. But can prediction be improved?

Curiously, whereas many kinds of technologies, such as computers and communications, have moved forward in leaps and bounds in the U.S. and around the world, intelligence testing remains almost a lone exception. The content of intelligence tests differs little from that used at the turn of the century. Edwin E. Ghiselli, an American industrial psychologist, wrote an article in 1966 bemoaning how little the predictive value of intelligence tests had improved in 40 years. More than 30 years later the situation remains unchanged.

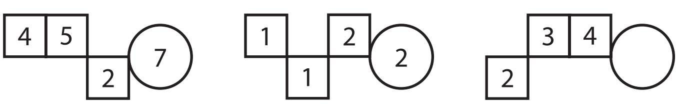
Improving Prediction

We *can* do better. In research with Michael Ferrari of the University of Pittsburgh, Pamela R. Clinkenbeard of the University of Wisconsin–Whitewater and Elena L. Grigorenko of Yale University, I showed that a test that measured not only the conventional memory and analytical abilities but also creative and prac-

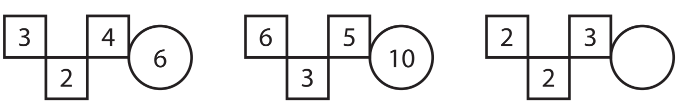
QUESTIONS REPRESENTATIVE OF IQ and other standardized tests include mathematical deduction and computation, spatial visualization and verbal analogies.

1. The same mathematical rules apply within each row to produce the numbers in the circles. The upper row, for instance, might mean multiplication, whereas the lower row means subtraction. Deduce the rules for the items below and write the answer in the circle.

A.

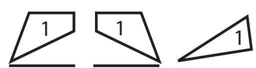


B.

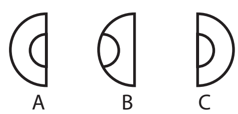


2. Two of the shapes represent mirror images of the same shape. Underline that pair.

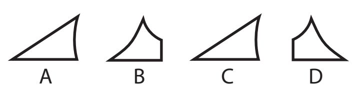
Example:



A.



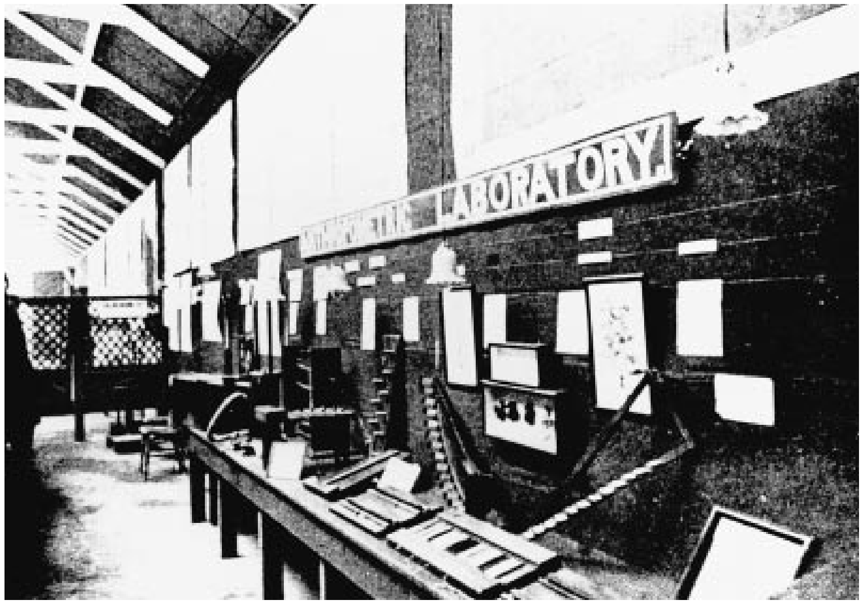
B.



Answers: 1A. 5; 1B. 3; 2A. A and C; 2B. B and D

Courtesy of *Self-Scoring IQ Tests,* by Victor Serebriakoff and Barnes & Noble and Robinson Publishing

INTELLIGENCE TESTING by Galton took place between 1884 and 1890 at the South Kensington Museum in London.



ARCHIVES OF THE HISTORY OF AMERICAN PSYCHOLOGY, UNIVERSITY OF AKRON

tical thinking abilities could improve prediction of course grades for high school students in an introductory psychology course. (A direct comparison of correlations between this test and conventional tests is not possible because of the restricted sample, which consisted of high-ability students selected by their schools.)

In these broader tests, individuals had to solve mathematical problems with newly defined operators (for example, X glick $Y = X + Y$ if $X < Y$, and $X - Y$ if $X \geq Y$), which require a more flexible kind of thinking. And they were asked to plan routes on maps and to solve problems related to personal predicaments, which require a more everyday, practical kind of thinking. Here is one example:

The following question gives you information about the situation involving a high school student. Read the question carefully. Choose the answer that provides the best solution, given the specific situation and desired outcomes.

John's family moved to Iowa from Arizona during his junior year in high school. He enrolled as a new student in the local high school two months ago but still has not made friends and feels bored and lonely. One of his favorite activities is writing stories. What is likely to be the most effective solution to this problem?

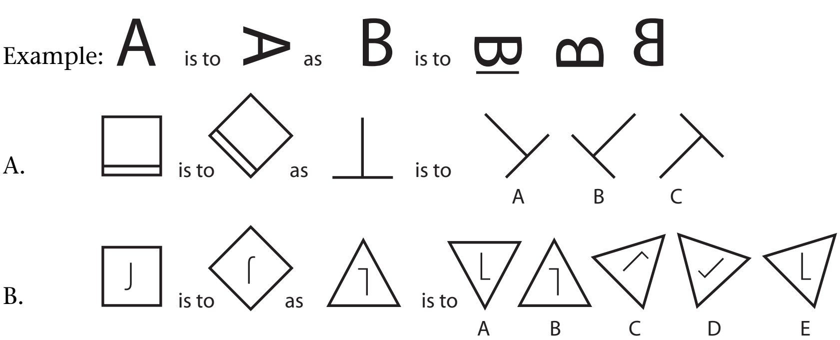
A. Volunteer to work on the school newspaper staff
B. Spend more time at home writing columns for the school newsletter
C. Try to convince his parents to move back to Arizona
D. Invite a friend from Arizona to visit during Christmas break

Best answer: A

Creativity can similarly be measured. For example, in another study, Todd Lubart, now at René Descartes University–Paris V, and I asked individuals to perform several creative tasks. They had to write short stories based on bizarre titles such as *The Octopus's Sneakers* or *3853*, draw pictures of topics such as the earth seen from an insect's point of view or the end of time, come up with exciting advertisements for bow ties, doorknobs or other mundane products, and solve quasiscientific problems, such as how someone might find among us extraterrestrial aliens seeking to escape detection. The research found that creative intelligence was relatively domain-specific—that is, people who are creative in one area are not necessarily creative in another—and that creative performance is only weakly to moderately correlated with the scores of conventional measures of IQ.

The implications for such testing extend to teaching. The achievement of students taught in a way that allowed them to make the most of their distinctive pattern of abilities was significantly higher than that of students who were taught in the conventional way, empha-

3. Underline the analogous shape.



4. Complete each analogy by underlining two words from those in the parentheses.

A. dog is to puppy as (pig, cat, kitten)
B. circle is to globe as (triangle, square, solid, cube)

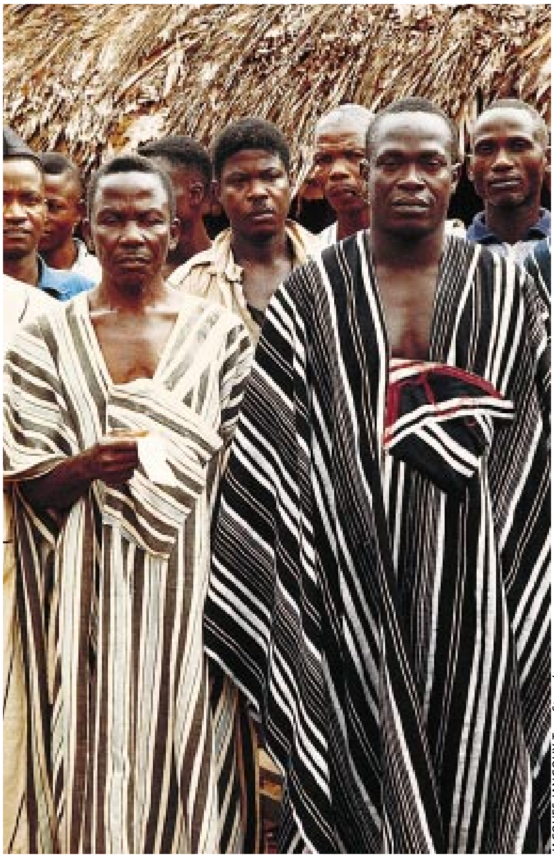
5. Underline the two words whose meanings do not belong with the others.

A. shark, sea lion, cod, whale, flounder
B. baize, paper, felt, cloth, tinfoil
C. sword, arrow, dagger, bullet, club

Answers: 3A. B; 3B. E; 4A. Cat, kitten; 4B. Square, cube; 5A. Sea lion, whale (others are fish); 5B. Cloth, tinfoil (others are made of compressed fibers); 5C. Arrow, bullet (others are used by the hand) sizing memory. Indeed, further research done by Bruce Torff of Hofstra University, Grigorenko and me has shown that the achievements of all students improve, on average, when they are taught to think analytically, creatively and practically about the material they learn, even if they are tested only for memory performance.

Interestingly, whereas individuals higher in conventional (memory and analytical) abilities tended to be primarily white, middle- to upper-middle-class and in "better" schools, students higher in creative and practical abilities tended to be racially, socioeconomically and educationally more diverse, and group differences were not significant. Group differences in conventional test scores—which are common and tend to favor white students—therefore may be in part a function of the narrow range of abilities that standard tests favor.

Tests can also be designed to improve prediction of job performance. Richard K. Wagner of Florida State University and I have shown that tests of practical intelligence in the workplace can predict job performance as well as or better than IQ tests do, even though these tests do not correlate with IQ. In such a test, managers might be told that they have a number of tasks to get done in the next three weeks but do not have time to do them all and so must set priorities. We have devised similar tests for salespeople, students and, most recently, military leaders (in a collaborative effort with psychologists at the U.S. Military Academy at West Point). Such tests do not replace conventional intelligence tests, which also predict job performance, but rather supplement them.



JACQUES JANGOUX *Tony Stone Images*

KPELLE OF WESTERN AFRICA illustrate the shortcoming of translating Western IQ tests for different cultures. The Kpelle would sort items based on functionality—such as "apple" with "eat"—whereas standard tests seek to sort based on category—"apple" with "orange."

A Question of Culture

Cultural prerogatives also affect scores on conventional tests. Grigorenko and I, in collaboration with Kate Nokes and Ruth Prince of the University of Oxford, Wenzel Geissler of the Danish Bilharziasis Laboratory in Copenhagen, Frederick Okatcha of Kenyatta University in Nairobi and Don Bundy of the University of Cambridge, designed a test of indigenous intelligence for Kenyan children in a rural village. The test required them to perform a task that is adaptive for them: recognizing how to use natural herbal medicines to fight illnesses. Children in the village knew the names of many such medicines and in fact treated themselves once a week on average. (Western children, of course, would know none of them.) The children also took conventional IQ tests.

Scores on the indigenous intelligence test correlated significantly but negatively with vocabulary scores on the Western tests. In other words, children who did better on the indigenous tests actually did worse on the Western tests, and vice versa. The reason may be that parents tend to value indigenous education or Westernized education but not both, and they convey those particular values to their children.

People from different cultures may also interpret the test items differently. In 1971 Michael Cole, now at the University of California at San Diego, and his colleagues studied the Kpelle, who live in western Africa. Cole's team found that what the Kpelle considered to be a smart answer to a sorting problem, Westerners considered to be stupid, and vice versa. For instance, given the names of categories such as fruits and vegetables, the Kpelle would sort functionally (for instance, "apple" with "eat"), whereas Westerners would sort categorically ("apple" with "orange," nested under the word "fruit").

Westerners do it the way they learn in school, but the Kpelle do it the way they (and Westerners) are more likely to do it in everyday life. People are more likely to think about eating an apple than about sorting an apple into abstract taxonomic categories.

Right now conventional Western tests appear in translated form throughout the world. But the research results necessarily raise the question of whether simply translating Western tests for other cultures makes much sense.

Toward a Better Test

If we can do better in testing than we currently do, then, getting back to the original question posed at the beginning of the article, how have we gotten to where we are? Several factors have conspired to lead us as a society to weigh conventional test scores heavily:

1. *The appearance of precision.* Test scores look so precise that institutions and the people in them often accord them more weight then they probably deserve.

2. *The similarity factor.* A fundamental principle of interpersonal attraction is that people tend to be attracted to those who are similar to them. This principle applies not only in intimate relationships but in work relationships as well. People in positions of power look for others like themselves; because they needed high test scores to get where they are, they tend to seek others who have high test scores.

3. *The publication factor.* Ratings of institutions, such as those published annually in *U.S. News and World Report,* create intense competition among colleges and universities to rank near the top. The institutions cannot control all the factors that go into the ranking. But test scores are relatively easier to control than, say, scholarly publications of faculty, so institutions start to weigh test scores more heavily to prop up their rat-

The following task represents a work-related situation, followed by a series of items that are relevant to handling the situation. Briefly scan all the items and then rate the quality of each item on the 1 to 7 scale provided.

An employee who reports to one of your subordinates has asked to talk with you about waste, poor management practices and possible violations of both company policy and the law on the part of your subordinate. You have been in your present position only a year, but in that time you have had no indications of trouble about the subordinate in question. Neither you nor your company has an "open door" policy, so it is expected that employees should take their concerns to their immediate supervisors before bringing a matter to the attention of anyone else. The employee who wishes to meet with you has not discussed this matter with her supervisors because of its delicate nature.

1——————2——————3——————4——————5——————6——————7

1	2	3	4	5	6	7
extremely bad			neither good nor bad			extremely good

1. Refuse to meet with the employee unless the individual first discusses the matter with your subordinate.
2. Meet with the employee but only with your subordinate present.
3. Schedule a meeting with the employee and then with your subordinate to get both sides of the story.
4. Meet with the employee and then investigate the allegations if an investigation appears warranted before talking with your subordinate.
5. Find out more about the employee, if you can, before making any decisions.
6. Refuse to meet with the employee and inform your subordinate that the employee has attempted to sidestep the chain of command.
7. Meet with your subordinate first before deciding whether to meet with the employee.
8. Reprimand the employee for ignoring the chain of command.
9. Ask a senior colleague whom you respect for advice about what to do in this situation.
10. Turn the matter over to an assistant.

ROBERT J. STERNBERG

PREDICTING JOB PERFORMANCE can be accomplished with tests of practical intelligence, which require solving real-world problems. Such tests do not correlate with IQ, however.

ings. Publication of mastery-test scores by states also increases the pressure on the public schools to teach to the tests.

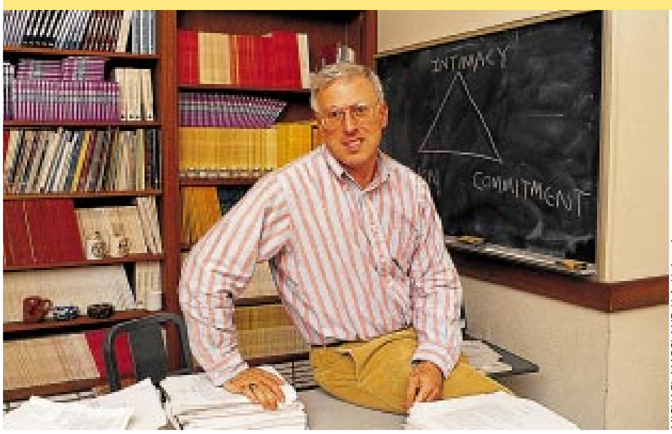
4. *Confirmation bias.* Once people believe in the validity of the tests, they tend to set up situations that confirm their beliefs. If admissions officials believe, for example, that students with test scores below a certain point cannot successfully do the work in their institution, they may not admit students with scores below that point. The result is that the institutions never get a chance to see if others could successfully do the work.

Given the shortcomings of conventional tests, there are those who would like to get rid of standardized testing altogether. I believe this course of action would be a mistake. Without test scores, we are likely to fall into the trap of overweighting factors that should matter less or not at all, whether it is political pull or socioeconomic status or just plain good looks. Societies started using tests to increase, not to decrease, equity for all.

Others would like to use *only* performance-based measures, such as having children do actual science experiments. The problem with such measures is that, despite their intuitive appeal, they are no less culturally biased than conventional tests and have serious problems of statistical reliability and validity that have yet to be worked out.

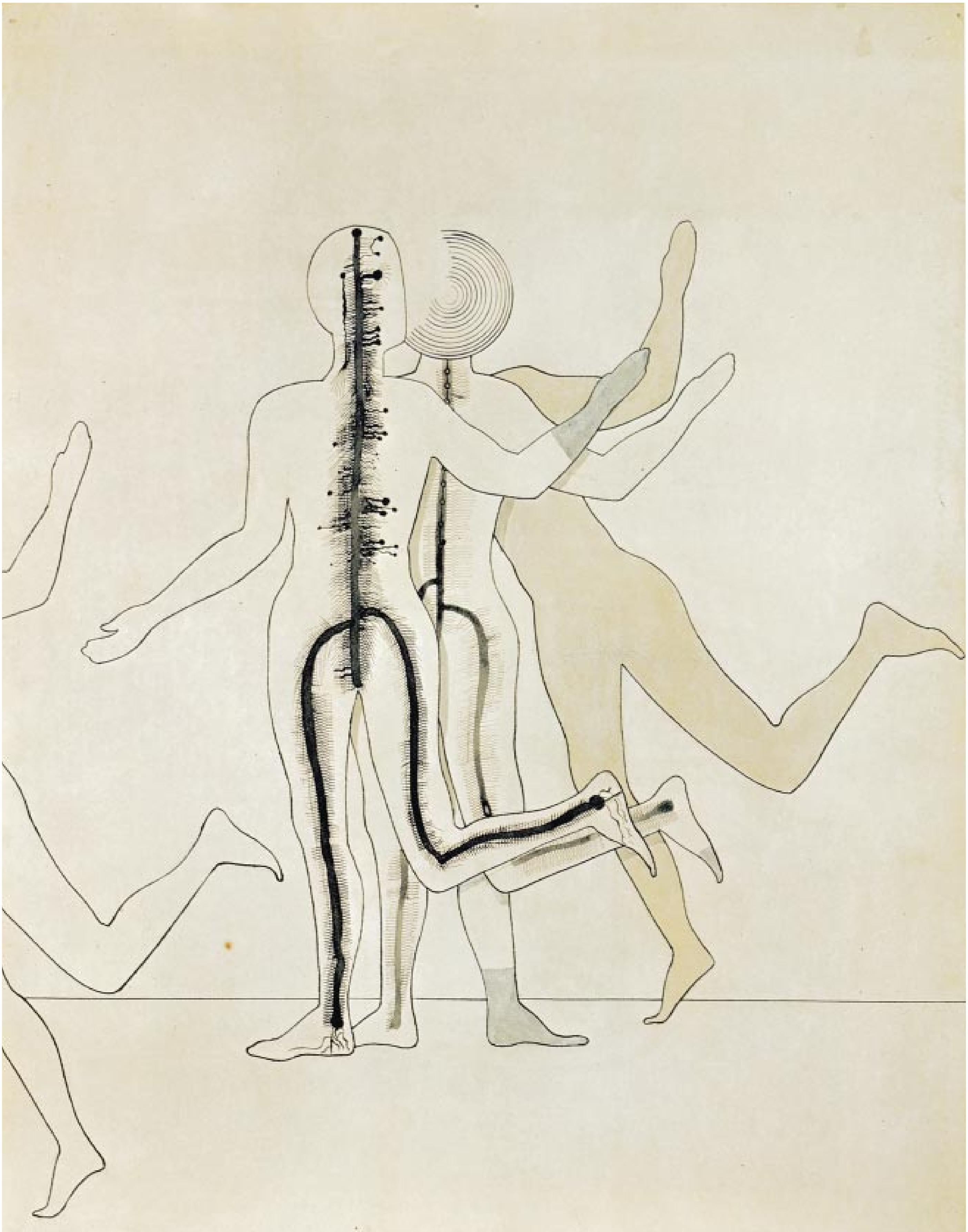
A sensible plan would be to continue to use conventional tests but to supplement them with more innovative tests, some of which are already available and others of which have to be invented. Unlike most kinds of companies involved in technology, testing firms spend little or nothing on basic research, and their applied work is often self-serving. Given the monopoly a few companies have in the testing industry and the importance of tests, we might think as a society of strongly encouraging or even requiring the testing companies to modify their approach. Or the public could fund research on its own. The innovations should be not just in the vehicles for testing (such as computerized testing) but in the very content of the tests. The time has come to move testing beyond the horse and buggy. We have the means; we just need the will. SA

About the Author



MICHAEL MARSLAND *Yale University*

ROBERT J. STERNBERG wrote his own version of an intelligence test when he was just 13. "I wish I still had a copy," he says. "It's probably as good as anything I've published since." Then, as now, Sternberg believed that the standard tests were not good measures of intelligence. But his research was canceled by the school psychologist. "For some reason, the guy didn't like the idea of a 13-year-old giving IQ tests to his classmates," he recalls. "But some people still don't like my ideas, so nothing really changes in life." Now Sternberg is professor of psychology and education at Yale University, where he had been an undergraduate. In addition to intelligence, Sternberg also studies love, creativity, conflict resolution and other psychology issues. "I'm a dabbler," he admits. But a dabbler with a mission. "I want to have people view intelligence more broadly," Sternberg says. "If you can open people's eyes and get them to question what they've been doing or how they've been thinking about things, it's really rewarding."



A Man Can Conceal Another, **by Max Ernst**

A Multiplicity of Intelligences

Rather than having just an intelligence defined by IQ, humans are better thought of as having eight, maybe nine, kinds of intelligences, including musical, spatial and kinesthetic

by Howard Gardner

As a psychologist, I was surprised by the huge public interest in *The Bell Curve,* the 1994 book on human intelligence by the late Harvard University psychologist Richard J. Herrnstein and policy analyst Charles Murray. Most of the ideas in the book were familiar not only to social scientists but also to the general public. Indeed, educational psychologist Arthur R. Jensen of the University of California at Berkeley as well as Herrnstein had written popularly about the very same ideas in the late 1960s and the early 1970s. Perhaps, I reasoned, every quarter-century a new generation of Americans desires to be acquainted with "the psychologist's orthodoxy" about intelligence—namely, that there is a single, general intelligence, often called *g,* which is reflected by an individual's intelligence quotient, or IQ.

This concept stands in contrast to my own view developed over the past decades: that human intelligence encompasses a far wider, more universal set of competences. Currently I count eight intelligences, and there may be more. They include what are traditionally regarded as intelligences, such as linguistic and logical-mathematical abilities, but also some that are not conventionally thought of in that way, such as musical and spatial capacities. These intelligences, which do not always reveal themselves in paper-and-pencil tests, can serve as a basis for more effective educational methods.

Defining Brainpower

The orthodox view of a single intelligence, widely, if wrongly, accepted today in the minds of the general population, originated from the energies and convictions of a few researchers, who by the second decade of this century had put forth its major precepts. In addition to its basic assumption, the orthodoxy also states that individuals are born with a certain intelligence or potential intelligence, that this intelligence is difficult to change and that psychologists can assess one's IQ using short-answer tests and, perhaps, other "purer" measures, such as the time it takes to react to a sequence of flashing lights or the presence of a particular pattern of brain waves.

Soon after this idea had been proposed—I like to call it "hedgehog orthodoxy"—more "foxlike" critics arose. From outside psychology, commentators such as American newspaper columnist Walter Lippmann challenged the criteria used to assess intelligence, contending that it was more complex and less fixed than the psychometricians had proposed.

From within psychology, scientists questioned the notion of a single, overarching intelligence. According to their analyses, intelligence is better thought of as a set of several factors. In the 1930s Louis L. Thurstone of the University of Chicago said it makes more sense to think of seven, largely independent "vectors of the mind." In the 1960s Joy P. Guilford of the University of Southern California enunciated 120 factors, later amended to 150. Scottish investigator Godfrey Thomson of the University of Edinburgh spoke around the 1940s of a large number of loosely coupled faculties. And in our own day, Robert J. Sternberg of Yale University has proposed a triarchic theory of intellect. These arches comprise a component that deals with standard computational skill, a component that is sensitive to contextual factors and a component that is involved with novelty.

Somewhat surprisingly, all these commentators—

whether in favor of or opposed to the notion of single intelligence—share one conviction. They all believe that the nature of intelligence will be determined by testing and analyzing the data thus secured. Perhaps, reason orthodox defenders like Herrnstein and Murray, performance on a variety of tests will yield a strong general factor of intelligence. And indeed, there is evidence for such a "positive manifold," or high correlation, across tests. Perhaps, counter pluralists like Thurstone and Sternberg, the right set of tests will demonstrate that the mind consists of a number of relatively independent factors, with strength in one area failing to predict strength or weakness in other areas.

But where is it written that intelligence needs to be determined on the basis of tests? Were we incapable of making judgments about intellect before Sir Francis Galton and Alfred Binet cobbled together the first set of psychometric items a century ago? If the dozens of IQ tests in use around the world were suddenly to disappear, would we no longer be able to assess intellect?

Break from Orthodoxy

Nearly 20 years ago, posing these very questions, I embarked on quite a different path into the investigation of intellect. I had been conducting research primarily with two groups: children who were talented in one or more art form and adults who had suffered from strokes that compromised specific capacities while sparing others. Every day I saw individuals with scattered profiles of strengths and weaknesses, and I was impressed by the fact that a strength or a deficit could cohabit comfortably with distinctive profiles of abilities and disabilities across the variety of humankind.

On the basis of such data, I arrived at a firm intuition: human beings are better thought of as possessing a number of relatively independent faculties, rather than as having a certain amount of intellectual horsepower, or IQ, that can be simply channeled in one or another direction. I decided to search for a better formulation of human intelligence. I defined an intelligence as "a psychobiological potential to solve problems or to fashion products that are valued in at least one cultural context." In my focus on fashioning products and cultural values, I departed from orthodox psychometric approaches, such as those adopted by Herrnstein, Murray and their predecessors.

Criteria for an Intelligence

1. *Potential isolation by brain damage.* For example, linguistic abilities can be compromised or spared by strokes.

2. *The existence of prodigies, savants and other exceptional individuals.* Such individuals permit the intelligence to be observed in relative isolation.

3. *An identifiable core operation or set of operations.* Musical intelligence, for instance, consists of a person's sensitivity to melody, harmony, rhythm, timbre and musical structure.

4. *A distinctive developmental history within an individual, along with a definable nature of expert performance.* One examines the skills of, say, an expert athlete, salesperson or naturalist, as well as the steps to attaining such expertise.

5. *An evolutionary history and evolutionary plausibility.* One can examine forms of spatial intelligence in mammals or musical intelligence in birds.

6. *Support from tests in experimental psychology.* Researchers have devised tasks that specifically indicate which skills are related to one another and which are discrete.

7. *Support from psychometric findings.* Batteries of tests reveal which tasks reflect the same underlying factor and which do not.

8. *Susceptibility to encoding in a symbol system.* Codes such as language, arithmetic, maps and logical expression, among others, capture important components of respective intelligences.

To proceed from an intuition to a definition of a set of human intelligences, I developed criteria that each of the candidate intelligences had to meet [*see box at left*]. These criteria were drawn from several sources:

• Psychology: The existence of a distinct developmental history for a capacity through which normal and gifted individuals pass as they grow to adulthood; the existence of correlations (or the lack of correlations) between certain capacities.

• Case studies of learners: Observations of unusual humans, including prodigies, savants or those suffering from learning disabilities.

• Anthropology: Records of how different abilities are developed, ignored or prized in different cultures.

• Cultural studies: The existence of symbol systems that encode certain kinds of meanings—language, arithmetic and maps, for instance.

• Biological sciences: Evidence that a capacity has a distinct evolutionary history and is represented in particular neural structures. For instance, various parts of the left hemisphere dominate when it comes to motor control of the body, calculation and linguistic ability; the right hemisphere houses spatial and musical capacities, including the discrimination of pitch.

The Eight Intelligences

Armed with the criteria, I considered many capacities, ranging from those based in the senses to those having to do with planning, humor and even sexuality. To the extent that a candidate ability met all or most of the criteria handily, it gained plausibility as an intelligence. In 1983 I concluded that seven abilities met the criteria sufficiently well: linguistic, logical-mathematical, musical, spatial, bodily-kinesthetic (as exemplified by athletes, dancers and other physical performers), interpersonal (the ability to read other people's moods, motivations and other mental states), and intrapersonal (the ability to access one's own feelings and to draw on them to guide behavior). The last two can generally be considered together as the basis for emotional intelligence (although in my version, they focus more on cognition and understanding than on feelings). Most standard measures of intelligence primarily probe linguistic and logical intelligence; some survey spatial intelligence. The other four are almost entirely ignored. In 1995, invoking new data that fit the criteria, I added an eighth intelligence—that of the naturalist, which permits the recognition and categorization of natural objects. Examples are Charles Darwin, John James Audubon and Rachel Carson. I am currently considering the possibility of a ninth: existential intelligence, which captures the human proclivity to raise and ponder fundamental questions about existence, life, death, finitude. Religious and philosophical thinkers such as the Dalai Lama and Søren A. Kierkegaard exemplify this kind of ability. Whether existential intelligence gets to join the inner sanctum depends on whether convincing evidence accrues about the neural basis for it.

The theory of multiple intelligences (or MI theory, as it has come to be called) makes two strong claims. The first is that all humans possess all these intelligences: indeed, they can collectively be considered a definition of *Homo sapiens,* cognitively speaking. The second claim is that just as we all look different and have unique personalities and temperaments, we also have different profiles of intelligences. No two individuals, not even identical twins or clones, have exactly the same amalgam of profiles, with the same strengths and weaknesses. Even in the case of identical genetic heritage, individuals undergo different experiences and seek to distinguish their profiles from one another.

Within psychology, the theory of multiple intelligences has generated controversy. Many researchers are nervous about the movement away from standardized tests and the adoption of a set of criteria that are unfamiliar and less open to quantification. Many also balk at the use of the word "intelligence" to describe some of the abilities, preferring to define musical or bodily-kinesthetic intelligences as talents. Such a narrow definition, however, devalues those capacities, so that orchestra conductors and dancers are talented but not smart. In my view, it would be all right to call those abilities talents, so long as logical reasoning and linguistic facility are then also termed talents.

Some have questioned whether MI theory is empirical. This criticism, however, misses the mark. MI theory is based completely on empirical evidence. The number of intelligences, their delineation, their subcomponents are all subject to alteration in the light of new findings. Indeed, the existence of the naturalist intelligence could be asserted only after evidence had accrued that parts of the temporal lobe are dedicated to the naming and recognition of natural things, whereas others are attuned to human-made objects. (Good evidence for a neural foundation comes from clinical literature, which reported instances in which brain-damaged individuals lost the capacity to identify living things but could still name inanimate objects. Experimental findings by Antonio R. Damasio of the University of Iowa, Elizabeth Warrington of the Dementia Research Group at National Hospital in London and others have confirmed the phenomenon.)

Much of the evidence for the personal intelligences has come from research in the past decade on emotional intelligence and on the development in children of a "theory of mind"—the realization that human beings have intentions and act on the basis of these intentions. And the intriguing finding by Frances H. Rauscher of the University of Wisconsin–Oshkosh and her colleagues of the "Mozart effect"—that early musical experiences may enhance spatial capacities—raises the possibility that musical and spatial intelligences draw on common abilities.

It is also worth noting that the movement toward multiple intelligences is quite consistent with trends in related sciences. Neuroscience recognizes the modular nature of the brain; evolutionary psychology is based on the notion that different capacities have evolved in specific environments for specific purposes; and artificial intelligence increasingly embraces expert systems rather than general problem-solving mechanisms. Within science, the believers in a single IQ or general intelligence are increasingly isolated, their positions more likely to be embraced by those, like Herrnstein and Murray, who have an ideological ax to grind.

If some psychologists expressed skepticism about the theory of multiple intelligences, educators around the world have embraced it. MI theory not only comports with their intuitions that children are smart in different ways; it also holds out hope that more students can be reached more effectively if their favored ways of knowing are taken into account in curriculum, instruction and assessment. A virtual cottage industry has arisen to create MI schools, classrooms, curricula, texts, computer systems and the like. Most of this work is well intentioned, and some of it has proved quite effective in motivating students and in giving them a sense of involvement in intellectual life.

Various misconceptions, however, have arisen: for example, that every topic should be taught in seven or eight ways or that the purpose of school is to identify (and broadcast) students' intelligences, possibly by administering an octet of new standardized tests. I have begun to speak out against some of these less advisable beliefs and practices.

My conclusion is that MI theory is best thought of as a tool rather than as an educational goal. Educators need to determine, in conjunction with their communities, the goals that they are seeking. Once these goals have been articulated, then MI theory can provide powerful support. I believe schools should strive to develop individuals of a certain sort—civic-minded, sensitive to the arts, deeply rooted in the disciplines. And schools should probe pivotal topics with sufficient depth so that students end up with a comprehensive understanding of them. Curricular and assessment approaches founded on MI theory, such as Project Spectrum at the Eliot-Pearson Preschool at Tufts University, have demonstrated considerable promise in helping schools to achieve these goals.

All humans possess all these intelligences: indeed, they can collectively be considered a definition of *Homo sapiens*, cognitively speaking.

The Future of MI

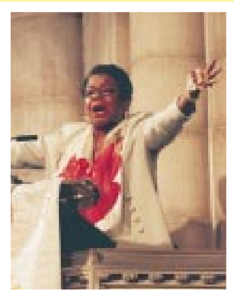
Experts have debated various topics in intelligence—including whether there is one or more—for nearly a century, and it would take a brave seer to predict that these debates will disappear. (In fact, if past cycles repeat themselves, a latter-day Herrnstein and Murray will author their own *Bell Curve* around 2020.) As the person most closely associated with the theory of multiple intelligences, I record three wishes for this line of work.

The first is a broader but not infinitely expanded view of intelligence. It is high time that intelligence be widened to incorporate a range of human computational capacities, including those that deal with music, other persons and skill in deciphering the natural world.

A Sampling of Intelligences

The examples of each intelligence are meant for illustrative purposes only and are not exclusive—one person can excel in several categories. Note also that entire cultures might encourage the development of one or another intelligence; for instance, the seafaring Puluwat of the Caroline Islands in the South Pacific cultivate spatial intelligence and excel at navigation, and the Manus children of New Guinea learn the canoeing and swimming skills that elude the vast majority of seafaring Western children.

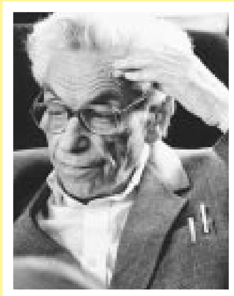
Maya Angelou



1. LINGUISTIC
A mastery and love of language and words with a desire to explore them.

Poets, writers, linguists: T. S. Eliot, Noam Chomsky, W. H. Auden

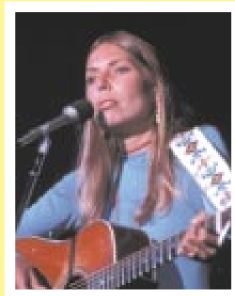
Paul Erdös



2. LOGICAL-MATHEMATICAL
Confronting and assessing objects and abstractions and discerning their relations and underlying principles.

Mathematicians, scientists, philosophers: Stanislaw Ulam, Alfred North Whitehead, Henri Poincaré, Albert Einstein, Marie Curie

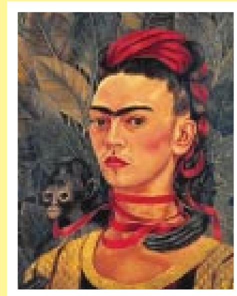
Joni Mitchell



3. MUSICAL
A competence not only in composing and performing pieces with pitch, rhythm and timbre but also in listening and discerning. May be related to other intelligences, such as linguistic, spatial or bodily-kinesthetic.

Composers, conductors, musicians, music critics: Ludwig van Beethoven, Leonard Bernstein, Midori, John Coltrane

Frida Kahlo



4. SPATIAL
An ability to perceive the visual world accurately, transform and modify perceptions and re-create visual experiences even without physical stimuli.

Architects, artists, sculptors, mapmakers, navigators, chess players: Michelangelo, Frank Lloyd Wright, Garry Kasparov, Louise Nevelson, Helen Frankenthaler

Alvin Ailey

5. BODILY-KINESTHETIC
Controlling and orchestrating body motions and handling objects skillfully.

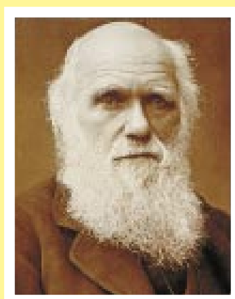
Dancers, athletes, actors: Marcel Marceau, Martha Graham, Michael Jordan

Margaret Mead

6. and 7. PERSONAL INTELLIGENCES
Accurately determining moods, feelings and other mental states in oneself (intrapersonal intelligence) and in others (interpersonal) and using the information as a guide for behavior.

Psychiatrists, politicians, religious leaders, anthropologists: Sigmund Freud, Mahatma Gandhi, Eleanor Roosevelt

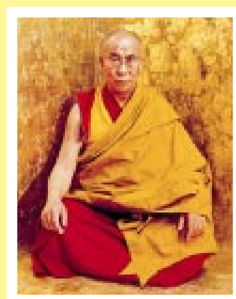
Charles Darwin



8. NATURALIST
Recognizing and categorizing natural objects.

Biologists, naturalists: Rachel Carson, John James Audubon

Dalai Lama



9. EXISTENTIAL
(possible intelligence): Capturing and pondering the fundamental questions of existence. More evidence, however, is needed to determine whether this is an intelligence.

Spiritual leaders, philosophical thinkers: Jean-Paul Sartre, Søren A. Kierkegaard

EMILE WAMSTEKER *AP Photo* (Angelou); GEORGE CSICSERY, from the documentary film *N Is a Number: A Portrait of Paul Erdös* (Erdös); HENRY DILTZ *Corbis* (Mitchell); ART RESOURCE (*Self-Portrait with a Monkey,* 1940) (Kahlo); NORMAND MAXON *Alvin Ailey American Dance Theater* (Ailey); APA/ARCHIVE PHOTOS (Mead); POPPERFOTO/ARCHIVE PHOTOS (Darwin); MICHAEL O'NEIL *Outline* (Dalai Lama)

But it is important that intelligence not be conflated with other virtues, such as creativity, wisdom or morality.

I also contend that intelligence should not be so broadened that it crosses the line from description to prescription. I endorse the notion of emotional intelligence when it denotes the capacity to compute information about one's own or others' emotional life. When the term comes to encompass the kinds of persons we hope to develop, however, then we have crossed the line into a value system—and that should not be part of our conception of intelligence. Thus, when psychologist and *New York Times* reporter Daniel Goleman emphasizes in his recent best-seller, *Emotional Intelligence,* the importance of empathy as part of emotional intelligence, I go along with him. But he also urges that individuals care for one another. The possession of the capacity to feel another's suffering is not the same as the decision to come to her aid. Indeed, a sadistic individual might use her knowledge of another's psyche to inflict pain.

My second wish is that society shift away from standardized, short-answer proxy instruments to real-life demonstrations or virtual simulations. During a particular historical period, it was perhaps necessary to assess individuals by administering items that were themselves of little interest (for example, repeating numbers backward) but that were thought to correlate with skills or habits of importance. Nowadays, however, given the advent of computers and virtual technologies, it is possible to look directly at individuals' performances—to see how they can argue, debate, look at data, critique experiments, execute works of art, and so on. As much as possible, we should train students directly in these valued activities, and we should assess how they carry out valued performances under realistic conditions. The need for ersatz instruments, whose relation to real-world performance is often tenuous at best, should wane.

My third wish is that the multiple-intelligences idea be used for more effective pedagogy and assessment. I have little sympathy with educational efforts that seek simply to "train" the intelligences or to use them in trivial ways (such as singing the math times tables or playing Bach in the background while one is doing geometry). For me, the educational power of multiple intelligences is exhibited when these faculties are drawn on to help students master consequential disciplinary materials.

It is high time that the view of intelligence be widened to incorporate a range of human computational capacities.

I explain how such an approach might work in my book, *A Well-Disciplined Mind*, which will appear in the spring of 1999. I focus on three rich topics: the theory of evolution (as an example of scientific truth), the music of Mozart (as an example of artistic beauty), and the Holocaust (as an example of immorality in recent history). In each case, I show how the topic can be introduced to students through a variety of entry points drawing on several intelligences, how the subject can be made more familiar through the use of analogies and metaphors drawn from diverse domains, and how the core ideas of the topic can be captured not merely through a single symbolic language but rather through a number of complementary model languages or representations.

Pursuing this approach, the individual who understands evolutionary theory, for instance, can think of it in different ways: in terms of a historical narrative, a logical syllogism, a quantitative examination of the size and dispersion of populations in different niches, a diagram of species delineation, a dramatic sense of the struggle among individuals (or genes or populations), and so on. The individual who can think of evolution in only one way—using only one model language—actually has only a tenuous command of the principal concepts of the theory.

The issue of who owns intelligence has been an important one in our society for some time—and it promises to be a crucial and controversial one for the foreseeable future. For too long, the rest of society has been content to leave intelligence in the hands of psychometricians. Often these test makers have a narrow, overly scholastic view of intellect. They rely on a set of instruments that are destined to valorize certain capacities while ignoring those that do not lend themselves to ready formulation and testing. And those with a political agenda often skirt close to the dangerous territory of eugenics.

MI theory represents at once an effort to base the conception of intelligence on a much broader scientific basis, one that offers a set of tools to educators that will allow more individuals to master substantive materials in an effective way. Applied appropriately, the theory can also help each individual achieve his or her human potential at the workplace, in avocations and in the service of the wider world. SA

About the Author

HOWARD GARDNER is pure Harvard. He started his career as a student there in 1961 and went on to complete a Ph.D. and a postdoctoral fellowship at Harvard Medical School. Now Gardner is a professor of education and co-director of Harvard's Project Zero—an umbrella project that encompasses some two dozen different studies related to cognition and creativity. At one time a serious pianist, Gardner has always been involved in the arts. His interest in psychology and the arts led him to do postdoctoral work in neurology, studying how artists and musicians are affected after a stroke. At Project Zero, Gardner met his wife, Ellen Winner, who was studying children's understanding of metaphor. Gardner has four children, all of whom are somehow involved in the arts—one plays piano, another plays bass, one is a photographer and the oldest is an arts administrator.

Gardner has written several books on multiple-intelligences theory and other topics, including *Frames of Mind*, *The Mind's New Science* and *The Unschooled Mind*. Ironically, the popular misinterpretation of his MI theory has inspired Gardner to study ethics. "I've learned that when you develop ideas, you have to have a certain sense of responsibility for how they're used," he says.

COURTESY OF HOWARD GARDNER

The General Intelligence Factor

Despite some popular assertions, a single factor for intelligence, called g, can be measured with IQ tests and does predict success in life

by Linda S. Gottfredson

No subject in psychology has provoked more intense public controversy than the study of human intelligence. From its beginning, research on how and why people differ in overall mental ability has fallen prey to political and social agendas that obscure or distort even the most well-established scientific findings. Journalists, too, often present a view of intelligence research that is exactly the opposite of what most intelligence experts believe. For these and other reasons, public understanding of intelligence falls far short of public concern about it. The IQ experts discussing their work in the public arena can feel as though they have fallen down the rabbit hole into Alice's Wonderland.

The debate over intelligence and intelligence testing focuses on the question of whether it is useful or meaningful to evaluate people according to a single major dimension of cognitive competence. Is there indeed a general mental ability we commonly call "intelligence," and is it important in the practical affairs of life? The answer, based on decades of intelligence research, is an unequivocal yes. No matter their form or content, tests of mental skills invariably point to the existence of a global factor that permeates all aspects of cognition. And this factor seems to have considerable influence on a person's practical quality of life. Intelligence as measured by IQ tests is the single most effective predictor known of individual performance at school and on the job. It also predicts many other aspects of well-being, including a person's chances of divorcing, dropping out of high school, being unemployed or having illegitimate children.

By now the vast majority of intelligence researchers take these findings for granted. Yet in the press and in public debate, the facts are typically dismissed, downplayed or ignored. This misrepresentation reflects a clash between a deeply felt ideal and a stubborn reality. The ideal, implicit in many popular critiques of intelligence research, is that all people are born equally able and that social inequality results only from the exercise of unjust privilege. The reality is that Mother Nature is no egalitarian. People are in fact unequal in intellectual potential—and they are born that way, just as they are born with different potentials for height, physical attractiveness, artistic flair, athletic prowess and other traits. Although subsequent experience shapes this potential, no amount of social engineering can make individuals with widely divergent mental aptitudes into intellectual equals.

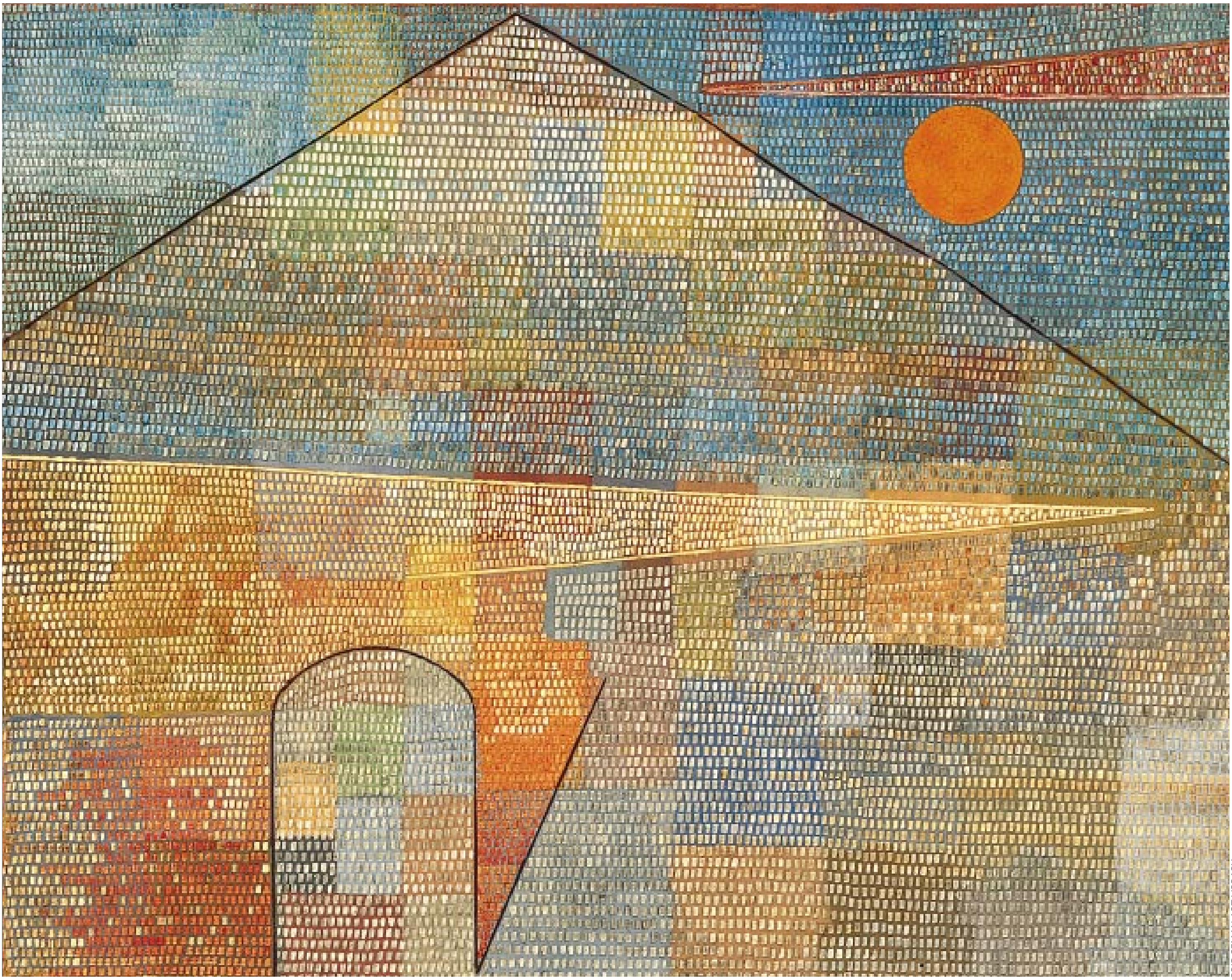
Of course, there are many kinds of talent, many kinds of mental ability and many other aspects of personality and character that influence a person's chances of happiness and success. The functional importance of general mental ability in everyday life, however, means that without onerous restrictions on individual liberty, differences in mental competence are likely to result in social inequality. This gulf between equal opportunity and equal outcomes is perhaps what pains Americans most about the subject of intelligence. The public intuitively knows what is at stake: when asked to rank personal qualities in order of desirability, people put intelligence second only to good health. But with a more realistic approach to the intellectual differences between people, society could better accommodate these differences and minimize the inequalities they create.

Extracting *g*

Early in the century-old study of intelligence, researchers discovered that all tests of mental ability ranked individuals in about the same way. Although mental tests are often designed to measure specific domains of cognition—verbal fluency, say, or mathematical skill, spatial visualization or memory—people who do well on one kind of test tend to do well on the others, and people who do poorly generally do so across the board. This overlap, or intercorrelation, suggests that all such tests measure some global element of intellectual ability as well as specific cognitive skills. In recent decades, psychologists have devoted much effort to isolating that general factor, which is abbreviated *g*, from the other aspects of cognitive ability gauged in mental tests.

The statistical extraction of *g* is performed by a technique called factor analysis. Introduced at the turn of the century by British psychologist Charles Spearman, factor analysis determines the minimum number of underlying dimensions necessary to explain a pattern of correlations among measurements. A general factor suffusing all tests is not, as is sometimes argued, a necessary outcome of factor analysis. No general factor has been found in the analysis of personality tests, for example; instead the method usually yields at least five dimensions (neuroticism, extraversion, conscientiousness, agreeableness and openness to ideas), each relating to different subsets of tests. But, as Spearman observed, a general factor does emerge from analysis of mental ability tests, and leading psychologists, such as Arthur R. Jensen of the University of California at Berkeley and John B. Carroll of the University of North Carolina at Chapel Hill, have confirmed his findings in the decades since. Partly because of this research, most intelligence experts now use *g* as the working definition of intelligence.

The general factor explains most differences among individuals in performance on diverse mental tests. This is



BRIDGEMAN ART LIBRARY

***Ad Parnassum*, by Paul Klee**

HIERARCHICAL MODEL of intelligence is akin to a pyramid, with g at the apex; other aptitudes are arrayed at successively lower levels according to their specificity.

true regardless of what specific ability a test is meant to assess, regardless of the test's manifest content (whether words, numbers or figures) and regardless of the way the test is administered (in written or oral form, to an individual or to a group). Tests of specific mental abilities do measure those abilities, but they all reflect *g* to varying degrees as well. Hence, the *g* factor can be extracted from scores on any diverse battery of tests.

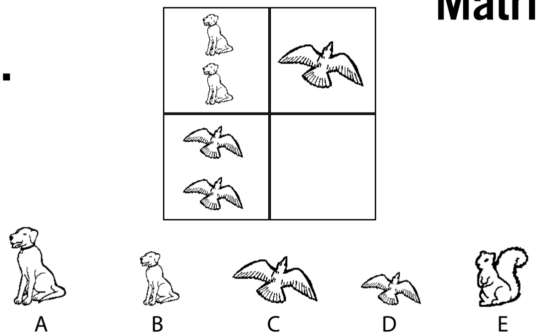
Conversely, because every mental test is "contaminated" by the effects of specific mental skills, no single test measures only *g*. Even the scores from IQ tests—which usually combine about a dozen subtests of specific cognitive skills—contain some "impurities" that reflect those narrower skills. For most purposes, these impurities make no practical difference, and *g* and IQ can be used interchangeably. But if they need to, intelligence researchers can statistically separate the *g* component of IQ. The ability to isolate *g* has revolutionized research on general intelligence, because it has allowed investigators to show that the predictive value of mental tests derives almost entirely from this global factor rather than from the more specific aptitudes measured by intelligence tests.

In addition to quantifying individual differences, tests of mental abilities have also offered insight into the meaning of intelligence in everyday life. Some tests and test items are known to correlate better with *g* than others do. In these items the "active ingredient" that demands the exercise of *g* seems to be complexity. More complex tasks require more mental manipulation, and this manipulation of information—discerning similarities and inconsistencies, drawing inferences, grasping new concepts and so on—constitutes intelligence in action. Indeed, intelligence can best be described as the ability to deal with cognitive complexity.

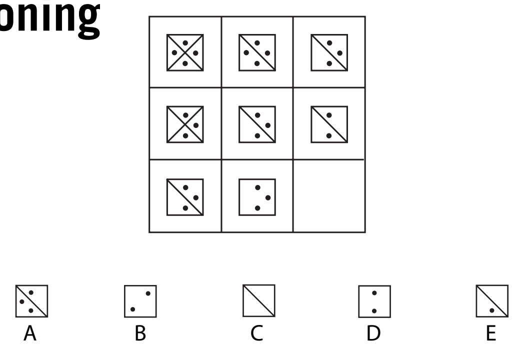
This description coincides well with lay perceptions of intelligence. The *g* factor is especially important in just the kind of behaviors that people usually associate with "smarts": reasoning, problem solving, abstract thinking, quick learning. And whereas *g* itself describes mental aptitude rather than accumulated knowledge, a person's store of knowledge tends to correspond with his or her *g* level, probably because that accumulation represents a previous adeptness in learning and in understanding new information. The *g* factor is also the one attribute

Matrix Reasoning

1.



2.



Number Series

3. 2, 4, 6, 8, _, _

4. 3,6,3,6, _,_

5. 1,5,4,2,6,5, _, _

6. 2,4,3,9,4,16, _,_

Analogies

7. brother: sister → father: ______

A. child B. mother C. cousin D. friend

8. joke: humor → law: ______

A. lawyer B. mercy C. courts D. justice

LINDA S. GOTTFREDSON

Answers: 1. A; 2. D; 3. 10, 12; 4. 3, 6; 5. 3, 7; 6. 5, 25; 7. B; 8. D

SAMPLE IQ ITEMS resembling those on current tests require the test taker to fill in the empty spaces based on the pattern in the images, numbers or words. Because they can vary in complexity, such tasks are useful in assessing g *level.*

that best distinguishes among persons considered gifted, average or retarded.

Several decades of factor-analytic research on mental tests have confirmed a hierarchical model of mental abilities. The evidence, summarized most effectively in Carroll's 1993 book, *Human Cognitive Abilities,* puts *g* at the apex in this model, with more specific aptitudes arrayed at successively lower levels: the so-called group factors, such as verbal ability, mathematical reasoning, spatial visualization and memory, are just below *g,* and below these are skills that are more dependent on knowledge or experience, such as the principles and practices of a particular job or profession.

Some researchers use the term "multiple intelligences" to label these sets of narrow capabilities and achievements. Psychologist Howard Gardner of Harvard University, for example, has postulated that eight relatively autonomous "intelligences" are exhibited in different domains of achievement. He does not dispute the existence of *g* but treats it as a specific factor relevant chiefly to academic achievement and to situations that resemble those of school. Gardner does not believe that tests can fruitfully measure his proposed intelligences; without tests, no one can at present determine whether the intelligences are indeed independent of *g* (or each other). Furthermore, it is not clear to what extent Gardner's intelligences tap personality traits or motor skills rather than mental aptitudes.

Other forms of intelligence have been proposed; among them, emotional intelligence and practical intelligence are perhaps the best known. They are probably amalgams either of intellect and personality or of intellect and informal experience in specific job or life settings, respectively. Practical intelligence like "street smarts," for example, seems to consist of the localized knowledge and know-how developed with untutored experience in particular everyday settings and activities—the so-called school of hard knocks. In contrast, general intelligence is not a form of achievement, whether local or renowned. Instead the *g* factor regulates the rate of learning: it greatly affects the rate of return in knowledge to instruction and experience but cannot substitute for either.

The Biology of *g*

Some critics of intelligence research maintain that the notion of general intelligence is illusory: that no such global mental capacity exists and that apparent "intelligence" is really just a by-product of one's opportunities to learn skills and information valued in a particular cultural context. True, the concept of intelligence and the way in which individuals are ranked according to this criterion could be social artifacts. But the fact that *g* is not specific to any particular domain of knowledge or mental skill suggests that *g* is independent of cultural content, including beliefs about what intelligence is. And tests of different social groups reveal the same continuum of general intelligence. This observation suggests either that cultures do not construct *g* or that they construct the same *g*. Both conclusions undercut the social artifact theory of intelligence.

Moreover, research on the physiology and genetics of *g* has uncovered biological correlates of this psychological phenomenon. In the past decade, studies by teams of researchers in North America and Europe have linked several attributes of the brain to general intelligence. After taking into account gender and physical stature, brain size as determined by magnetic resonance imaging is moderately correlated with IQ (about 0.4 on a scale of 0 to 1). So is the speed of nerve conduction. The brains of bright people also use less energy during problem solving than do those of their less able peers. And various qualities of brain waves correlate strongly (about 0.5 to 0.7) with IQ: the brain waves of individuals with higher IQs, for example, respond more promptly and consistently to simple sensory stimuli such as audible clicks. These observations have led some investigators to posit that differences in *g* result from differences in the speed and efficiency of neural processing. If this theory is true, environmental conditions could influence *g* by modifying brain physiology in some manner.

Studies of so-called elementary cognitive tasks (ECTs), conducted by Jensen and others, are bridging the gap between the psychological and the physiological aspects of *g*. These mental tasks have no obvious intellectual content and are so simple that adults and most children can do them accurately in less than a second. In the most basic reaction-time tests, for example, the subject must react when a light goes on by lifting her index finger off a home button and immediately depressing a response button. Two measurements are taken: the number of milliseconds between the illumination of the light and the subject's release of the home button, which is called decision time, and the number of milliseconds between the subject's release of the home button and pressing of the response button, which is called movement time.

In this task, movement time seems independent of intelligence, but the decision times of higher-IQ subjects are slightly faster than those of people with lower IQs. As the tasks are made more complex, correlations between average decision times and IQ increase. These results further support the notion that intelligence equips individuals to deal with complexity and that its influence is greater in complex tasks than in simple ones.

The ECT-IQ correlations are comparable for all IQ levels, ages, genders and racial-ethnic groups tested. Moreover, studies by Philip A. Vernon of the University of Western Ontario and others have shown that the ECT-IQ overlap results almost entirely from the common *g* factor in both measures. Reaction times do not reflect differences in motivation or strategy or the tendency of some individuals to rush through tests and daily tasks—that penchant is a personality trait. They actually seem to measure the speed with which the brain apprehends, integrates and evaluates information. Research on ECTs and brain physiology has not yet identified the biological determinants of this processing speed. These studies do suggest, however, that *g* is as reliable and global a phenomenon at the neural level as it is at the level of the complex information processing required by IQ tests and everyday life.

The existence of biological correlates of intelligence does not necessarily mean that intelligence is dictated by genes. Decades of genetics research have shown, however, that people are born with different hereditary potentials for intelligence and that these genetic endowments are responsible for much of the variation in mental ability among individuals. Last spring an international team of scientists headed by Robert Plomin of the Institute of Psychiatry in London announced the discovery of the first gene linked to intelligence. Of course, genes have their effects only in interaction with environments, partly by enhancing an individual's exposure or sensitivity to formative experiences. Differences in general intelligence, whether measured as IQ or, more accurately, as *g* are both genetic and environmental in origin—just as are all other psychological traits and attitudes studied so far, including personality, vocational interests and societal attitudes. This is old news among the experts. The experts have, however, been startled by more recent discoveries.

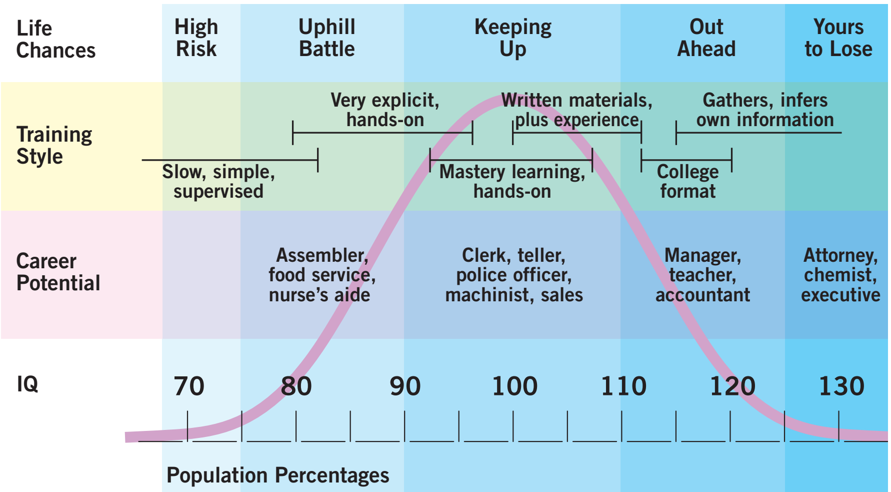
One is that the heritability of IQ rises with age—that is to say, the extent to which genetics accounts for differences in IQ among individuals increases as people get older. Studies comparing identical and fraternal twins, published in the past decade by a group led by Thomas J. Bouchard, Jr., of the University of Minnesota and other scholars, show that about 40 percent of IQ differences among preschoolers stems from genetic differences but that heritability rises to 60 percent by adolescence and to 80 percent by late adulthood. With age, differences among individuals in their developed intelligence come to mirror more closely their genetic differences. It appears that the effects of environment on intelligence fade rather than grow with time. In hindsight, perhaps this should have come as no surprise. Young children have the circumstances of their lives imposed on them by parents, schools and other agents of society, but as people get older they become more independent and tend to seek out the life niches that are most congenial to their genetic proclivities.

A second big surprise for intelligence experts was the discovery that environments shared by siblings have little to do with IQ. Many people still mistakenly believe that social, psychological and economic differences among families create lasting and marked differences in IQ. Behavioral geneticists refer to such environmental effects as "shared" because they are common to siblings who grow up together. Research has shown that although shared environments do have a modest influence on IQ in childhood, their effects dissipate by adolescence. The IQs of adopted children, for example, lose all resemblance to those of their adoptive family members and become more like the IQs of the biological parents they have never known. Such findings suggest that siblings either do not share influential aspects of the rearing environment or do not experience them in the same way. Much behavioral genetics research currently focuses on the still mysterious processes by which environments make members of a household less alike.

g on the Job

Although the evidence of genetic and physiological correlates of *g* argues powerfully for the existence of global intelligence, it has not quelled the critics of intelligence testing. These skeptics argue that even if such a global entity exists, it has no intrinsic functional value and becomes important only to the extent that people treat it as such: for example, by using IQ scores to sort, label and assign students and employees. Such concerns over the proper use of mental tests have prompted a great deal of research in recent decades. This research shows that although IQ tests can indeed be misused, they measure a capability that does in fact affect many kinds of performance and many life outcomes, independent of the tests' interpretations or applications. Moreover, the research shows that intelligence tests measure the capability equally well for all native-born English-speaking groups in the U.S.

If we consider that intelligence manifests itself in everyday life as the ability to deal with complexity, then it is easy to see why it has great functional or practical importance. Children, for example, are regularly exposed to complex tasks once they begin school. Schooling requires above all that students learn, solve problems and think abstractly. That IQ is quite a good predictor of differences in educational achievement is therefore not surprising.



Population Percentages

	High Risk	Uphill Battle	Keeping Up	Out Ahead	Yours to Lose
Total population distribution	5	20	50	20	5
Out of labor force more than 1 month out of year (men)	22	19	15	14	10
Unemployed more than 1 month out of year (men)	12	10	7	7	2
Divorced in 5 years	21	22	23	15	9
Had illegitimate children (women)	32	17	8	4	2
Lives in poverty	30	16	6	3	2
Ever incarcerated (men)	7	7	3	1	0
Chronic welfare recipient (mothers)	31	17	8	2	0
High school dropout	55	35	6	0.4	0

Adapted from *Intelligence*, Vol. 24, No. 1; January/February 1997

JOHN MENGEL *Ponzi & Weill*

CORRELATION OF IQ SCORES with occupational achievement suggests that g reflects an ability to deal with cognitive complexity. Scores also correlate with some social outcomes (the percentages apply to young white adults in the U.S.).

When scores on both IQ and standardized achievement tests in different subjects are averaged over several years, the two averages correlate as highly as different IQ tests from the same individual do. High-ability students also master material at many times the rate of their low-ability peers. Many investigations have helped quantify this discrepancy. For example, a 1969 study done for the U.S. Army by the Human Resources Research Office found that enlistees in the bottom fifth of the ability distribution required two to six times as many teaching trials and prompts as did their higher-ability peers to attain minimal proficiency in rifle assembly, monitoring signals, combat plotting and other basic military tasks. Similarly, in school settings the ratio of learning rates between "fast" and "slow" students is typically five to one.

The scholarly content of many IQ tests and their strong correlations with educational success can give the impression that *g* is only a narrow academic ability. But general mental ability also predicts job performance, and in more complex jobs it does so better than any other single personal trait, including education and experience. The army's Project A, a seven-year study conducted in the 1980s to improve the recruitment and training process, found that general mental ability correlated strongly with both technical proficiency and soldiering in the nine specialties studied, among them infantry, military police and medical specialist. Research in the civilian sector has revealed the same pattern. Furthermore, although the addition of personality traits such as conscientiousness can help hone the prediction of job performance, the inclusion of specific mental aptitudes such as verbal fluency or mathematical skill rarely does. The predictive value of mental tests in the work arena stems almost entirely from their measurement of *g*, and that value rises with the complexity and prestige level of the job.

Half a century of military and civilian research has converged to draw a portrait of occupational opportunity along the IQ continuum. Individuals in the top 5 percent of the adult IQ distribution (above IQ 125) can essentially train themselves, and few occupations are beyond their reach mentally. Persons of average IQ (between 90 and 110) are not competitive for most professional and executive-level work but are easily trained for the bulk of jobs in the American economy. In contrast, adults in the bottom 5 percent of the IQ distribution (below 75) are very difficult to train and are not competitive for any occupation on the basis of ability. Serious problems in training low-IQ military recruits during World War II led Congress to ban enlistment from the lowest 10 percent (below 80) of the population, and no civilian occupation in modern economies routinely recruits its workers from that range. Current military enlistment standards exclude any individual whose IQ is below about 85.

The importance of *g* in job performance, as in schooling, is related to complexity. Occupations differ considerably in the complexity of their demands, and as that complexity rises, higher *g* levels become a bigger asset and lower *g* levels a bigger handicap. Similarly, everyday tasks and environments also differ significantly in their cognitive complexity. The degree to which a person's *g* level will come to bear on daily life depends on how much novelty and ambiguity that person's everyday tasks and surroundings present and how much continual learning, judgment and decision making they require. As gamblers, employers and bankers know, even marginal differences in rates of return will yield big gains—or losses—over time. Hence, even small differences in *g* among people can exert large, cumulative influences across social and economic life.

In my own work, I have tried to synthesize the many lines of research that document the influence of IQ on life outcomes. As the illustration on the opposite page shows, the odds of various kinds of achievement and social pathology change systematically across the IQ continuum, from borderline mentally retarded (below 70) to intellectually gifted (above 130). Even in comparisons of those of somewhat below average (between 76 and 90) and somewhat above average (between 111 and 125) IQs, the odds for outcomes having social consequence are stacked against the less able. Young men somewhat below average in general mental ability, for example, are more likely to be unemployed than men somewhat above average. The lower-IQ woman is four times more likely to bear illegitimate children than the higher-IQ woman; among mothers, she is eight times more likely to become a chronic welfare recipient. People somewhat below average are 88 times more likely to drop out of high school, seven times more likely to be jailed and five times more likely as adults to live in poverty than people of somewhat above-average IQ. Below-average individuals are 50 percent more likely to be divorced than those in the above-average category.

These odds diverge even more sharply for people with bigger gaps in IQ, and the mechanisms by which IQ creates this divergence are not yet clearly understood. But no other single trait or circumstance yet studied is so deeply implicated in the nexus of bad social outcomes—poverty, welfare, illegitimacy and educational failure—that entraps many low-IQ individuals and families. Even the effects of family background pale in comparison with the influence of IQ. As shown most recently by Charles Murray of the American Enterprise Institute in Washington, D.C., the divergence in many outcomes associated with IQ level is almost as wide among siblings from the same household as it is for strangers of comparable IQ levels. And siblings differ a lot in IQ—on average, by 12 points, compared with 17 for random strangers.

An IQ of 75 is perhaps the most important threshold in modern life. At that level, a person's chances of mastering the elementary school curriculum are only 50–50, and he or she will have a hard time functioning independently without considerable social support. Individuals and families who are only somewhat below average in IQ face risks of social pathology that, while lower, are still significant enough to jeopardize their well-being. High-IQ individuals may lack the resolve, character or good fortune to capitalize on their intellectual capabilities, but socioeconomic success in the postindustrial information age is theirs to lose.

What Is versus What Could Be

The foregoing findings on *g*'s effects have been drawn from studies conducted under a limited range of circumstances—namely, the social, economic and political conditions prevailing now and in recent decades in developed countries that allow considerable personal freedom. It is not clear whether these findings apply to populations around the world, to the extremely advantaged and disadvantaged in the developing world or, for that matter, to people living under restrictive political regimes. No one knows what research under different circumstances, in different eras or with different populations might reveal.

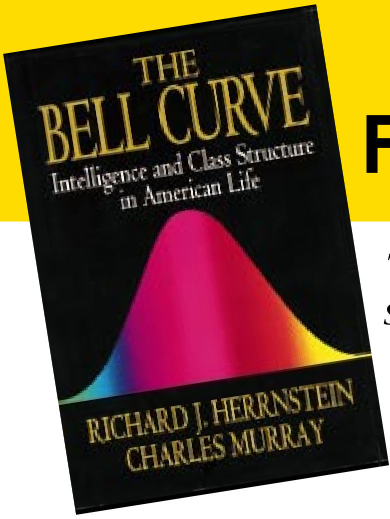
But we do know that, wherever freedom and technology advance, life is an uphill battle for people who are below average in proficiency at learning, solving problems and mastering complexity. We also know that the trajectories of mental development are not easily deflected. Individual IQ levels tend to remain unchanged from adolescence onward, and despite strenuous efforts over the past half a century, attempts to raise *g* permanently through adoption or educational means have failed. If there is a reliable, ethical way to raise or equalize levels of *g*, no one has found it.

Some investigators have suggested that biological interventions, such as dietary supplements of vitamins, may be more effective than educational ones in raising *g* levels. This approach is based in part on the assumption that improved nutrition has caused the puzzling rise in average levels of both IQ and height in the developed world during this century. Scientists are still hotly debating whether the gains in IQ actually reflect a rise in *g* or are caused instead by changes in less critical, specific mental skills. Whatever the truth may be, the differences in mental ability among individuals remain, and the conflict between equal opportunity and equal outcome persists. Only by accepting these hard truths about intelligence will society find humane solutions to the problems posed by the variations in general mental ability. SA

About the Author


COURTESY OF LINDA S. GOTTFREDSON

LINDA S. GOTTFREDSON is professor of educational studies at the University of Delaware, where she has been since 1986, and co-directs the Delaware–Johns Hopkins Project for the Study of Intelligence and Society. She trained as a sociologist, and her earliest work focused on career development. "I wasn't interested in intelligence per se," Gottfredson says. "But it suffused everything I was studying in my attempts to understand who was getting ahead." This "discovery of the obvious," as she puts it, became the focus of her research. In the mid-1980s, while at Johns Hopkins University, she published several influential articles describing how intelligence shapes vocational choice and self-perception. Gottfredson also organized the 1994 treatise "Mainstream Science on Intelligence," an editorial with more than 50 signatories that first appeared in the *Wall Street Journal* in response to the controversy surrounding publication of *The Bell Curve*. Gottfredson is the mother of identical twins—a "mere coincidence," she says, "that's always made me think more about the nature and nurture of intelligence." The girls, now 16, follow Gottfredson's Peace Corps experience of the 1970s by joining her each summer for volunteer construction work in the villages of Nicaragua.



For Whom Did the Bell Curve Toll?

The most controversial social science book in decades shook up readers. Researchers are less easily impressed

by Tim Beardsley, *staff writer*

That Richard J. Herrnstein and Charles Murray's 1994 book *The Bell Curve* should become a commercial blockbuster was perhaps unsurprising, given its user-friendly presentation and its incendiary subject matter. The 800-page volume argued that American society is increasingly dividing into a wealthy "cognitive elite" and a dull, growing underclass. Because the authors believe that cognitive ability is largely inherited and that it strongly predicts important social outcomes such as avoidance of poverty and criminality, they foresaw the emergence of a "custodial state" in which the elite keep the underclass underfoot. African-Americans, in Herrnstein and Murray's vision, seemed doomed to remain disproportionately in the underclass, because that group is cognitively disadvantaged for reasons that are "very likely" to be in part genetic.

Among the authors' recommendations for adapting to these inevitable trends were dismantling affirmative action and the welfare safety net and shifting funds from educational programs for disadvantaged children to programs for the gifted—changes that some might argue would speed stratification. The book has so far sold more than 500,000 copies.

Whether *The Bell Curve* will have an influence on social science or real-world policy comparable to its popularity seems doubtful. Murray wrote in an afterword to the paperback edition (Herrnstein died before the book was published) that the relationships between IQ and social behaviors presented in *The Bell Curve* are "so powerful they will revolutionize sociology." But thoughtful critics who have now had a chance to reanalyze crucial data say new findings weaken or contradict most of *The Bell Curve*'s more abrasive conclusions.

Observers of the education scene see little evidence, moreover, that the book has had any effect on policy decisions, although it may in some minds have legitimized the status quo between the haves and have-nots. The U.S. Congress, which might have been expected to give the book a hearing, has paid little attention to education policy in recent years. *The Bell Curve*'s discussion of racial genetics probably ensured that politicians would avoid allying themselves with its message, says educational evaluation expert Ernest R. House of the University of Colorado. What is left, as the dust settles, are some innocuous facts about intelligence that, while perhaps news to some, are hardly revolutionary, in the judgment of Christopher Jencks of Harvard University, an editor (with Meredith Phillips) of a new book, *The Black-White Test Score Gap*.

Starting with what is relatively uncontroversial, most scholars accept that the quantity measured by IQ tests, known as general intelligence, is a meaningful construct that can predict mental performance—even though there are substantial differences of opinion over its precise theoretical status, and nobody knows its material basis. Most agree, too, that in today's society some nontrivial proportion of the variation in IQ scores between individuals can be ascribed to different inherited genes. That proportion is called heritability.

Researchers differ, however, in their estimates of IQ's heritability and the implications of that effect. Herrnstein and Murray adopted a "middling value" of 60 percent, while maintaining that it might be as high as 80 percent. Others disagree. In a recent book that reanalyzes *The Bell Curve*'s major arguments, *Intelligence, Genes and Success,* statisticians and geneticists Michael Daniels, Bernie Devlin and Kathryn Roeder argue that the figure is actually about 48 percent.

The difference arises because estimates of the heritability of IQ turn largely on the similarity in IQ of twins who are reared apart. Most twin studies ignore the possibility that sharing a uterus for nine months may account for some later similarities in IQ. In reality, that effect appears to be substantial, and a statistical analysis that compensates for it (by comparing monozygotic and fraternal twins as well as other siblings) produces the lower estimate of the heritability of IQ.

But that is not all that Daniels and his co-authors find fault with in *The Bell Curve*'s use of heritability. The book erred in using a "broad" definition of heritability as a basis for speculation about genetically based cognitive stratification, they say. They argue that for this purpose a "narrow" definition of heritability is the mathematically correct one and estimate its value at only 34 percent, a figure that makes the emergence of cognitive castes "almost impossible." (The narrow definition, unlike the broad one, excludes interactions among genes.)

Raising IQ with the Environment

More fundamentally, and contrary to *The Bell Curve,* scholars point out that even if individual heritability of IQ were very large, it might nonetheless be susceptible to environmental improvements. "A heritability estimate does not in any way 'constrain' the effects of a changed environment," notes psychologist Douglas Wahlsten of the University of Alberta.

Wahlsten gives the example of the inherited disease phenylketonuria, which can cause brain damage. It is successfully treated by avoiding the amino acid phenylalanine in the diet. Likewise, Wahlsten cites studies in France showing that infants adopted from a family having low socioeconomic status into one of high socioeconomic status had childhood IQ scores that were 12 to 16 points higher than others who remained in poverty with their biological mothers. In contrast to *The Bell*

BOOK JACKET OF *THE BELL CURVE* © 1994 SIMON & SCHUSTER, INC., REPRODUCED WITH PERMISSION OF THE FREE PRESS, A DIVISION OF SIMON & SCHUSTER

Curve's judgment that "changing cognitive ability through environmental intervention has proved to be extraordinarily difficult," Wahlsten concludes that even modest environmental improvements can have substantial effects on ability test scores and that lasting gains in a child's environment can exert "quite a large" effect.

Some such effects have been documented by Craig T. Ramey of the University of Alabama at Birmingham. Ramey has demonstrated how a preschool educational intervention for the first five years of life significantly boosted IQ scores of at-risk children throughout school years and into adolescence, with an average increase of five points still apparent at age 15. The most disadvantaged children showed gains twice as large. Academic achievement (as distinct from IQ) scores of at-risk kids show even clearer benefits of preschool that persist well into the teenage years. But *The Bell Curve* shrugs off these benefits.

The book's pessimistic assessment of the prospects for educational interventions is its fatal flaw, according to psychologist Richard E. Nisbett of the University of Michigan. The authors "are probably right that there are limits to how much you can change IQ, but they may be far wider than implied in the book," Nisbett says. Christopher Winship of Harvard and Sanders Korenman of the City University of New York find that conventional education itself boosts IQ by perhaps two to four points a year, an estimate they say argues in favor of the public investment. *The Bell Curve* argued that education had little or no effect on IQ. Perhaps the best conclusion is that the factors that feed into a measured IQ score are not fully understood.

A major problem that psychologists note for *The Bell Curve*'s argument is that unstandardized intelligence scores have been increasing rapidly for several decades in industrial countries, a phenomenon known as the Flynn effect. Because some environmental influence must have caused the effect—it is too rapid for genetic changes to account for—environmental improvements that boost mental abilities must be possible.

Not So Black-and-White

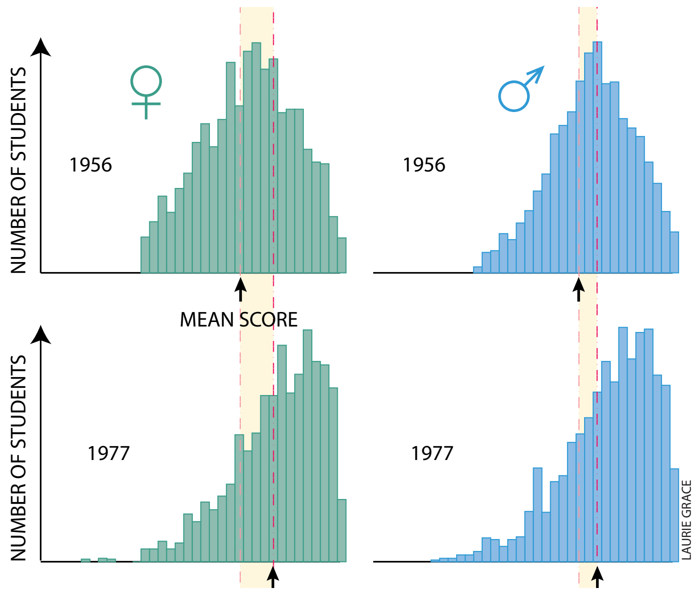
One of the most painful issues that Herrnstein and Murray explored was the lower measured average scores of African-Americans on IQ tests, as compared with Caucasians. *The Bell Curve*'s half-acceptance of a genetic influence was surely one reason for its notoriety (the question is entirely different from that of heritability of IQ between individuals). Yet according to Nisbett, the evidence—which includes adoption studies and other types—"offers almost no support for genetic explanations of the IQ differences between blacks and whites."

The test-score gap could be eliminated through practicable improvements in the educational systems, contend Jencks and Phillips in *The Black-White Test Score Gap*. They cite three principal arguments.

First, when black or mixed-race children are raised in white rather than black homes, their preadolescent test scores rise dramatically. That shows that improvements are feasible. The scores tend to fall again during adolescence, but the reasons may not be irremediable. Second, the Flynn effect argues against genetically based IQ differences between races. Third, black-white differences in academic achievement have already narrowed by almost half during this century, now being closer to 10 than to the usually cited 15 points.

The Bell Curve elaborates on its racial claims by suggesting that black-white differences in earnings are no greater than expected because of IQ differences, a key plank in the book's attack on affirmative action. But an analysis by Alexander L. Cavallo of the University of Chicago and others, which looks at the sexes separately, contests this conclusion. After allowing for ability, it seems, black males earn substantially less than white males (in females the gap is in the opposite direction). Much of the differential, Cavallo asserts, is "contributed by factors that may be influenced by racial discrimination," a conclusion that undercuts *The Bell Curve*'s argument.

Researchers of a different political stripe from Herrnstein and Murray have also found important qualifications to several more of *The Bell Curve*'s slew of conclusions about the predictive effect of IQ on life chances. Economist John Cawley of the University of Chicago and his co-authors of a chapter in *Intelligence, Genes and Success* analyze the same data studied by Herrnstein and Murray but conclude that they "dramatically overstate" how much of the variation in wages between individuals can be explained by intelligence. Sociologist Lucinda A. Manolakes of the State University of New York at Stony Brook likewise judges IQ to "be only one of many variables" that affect criminality.



FLYNN EFFECT: means of raw IQ scores have increased worldwide, including those of third-graders in Edmonton, Alberta.

The list goes on. Winship and Korenman confirm an influence of IQ on adult social outcomes such as earnings and avoidance of poverty. But they also find that family background turns out to have effects comparable with those of IQ, when proper allowance is made for the confounding effect of education. IQ is "not the dominant determinant."

Stephen Fienberg of Carnegie Mellon University, one of the editors of *Intelligence, Genes and Success,* notes that "everyone knows that smart people do better in life." But academics say that "IQ matters in a much more nuanced way" than Herrnstein and Murray maintain, according to Fienberg. The nuances make it harder to issue policy recommendations.

The publicity firestorm over Herrnstein and Murray's claims seems to have died down in the past year. Jencks and Nisbett both allow that *The Bell Curve* focused attention on the importance of thinking about intelligence in debates about public policy. Many readers, though, are likely to have come to cruder conclusions, such as that science has shown attempts to help at-risk youth to be a waste of time. Nothing could be further from the truth. SA

Uncommon Talents:

Gifted Children, Prodigies and Savants

Possessing abilities well beyond their years, gifted children inspire admiration, but they also suffer ridicule, neglect and misunderstanding

by Ellen Winner


WANG SHIQIANG

One evening a few years ago, while I was attending a concert, a young boy in the audience caught my attention. As the orchestra played a Mozart concerto, this nine-year-old child sat with a thick, well-thumbed orchestral score opened on his lap. As he read, he hummed the music out loud, in perfect tune. During intermission, I cornered the boy's father. Yes, he told me, Stephen was really reading the music, not just looking at it. And reading musical scores was one of his preferred activities, vying only with reading college-level computer programming manuals. At an age when most children concentrate on fourth-grade arithmetic and the nuances of playground etiquette, Stephen had already earned a prize in music theory that is coveted by adults.

Gifted children like Stephen are fascinating but also intimidating. They have been feared as "possessed," they have been derided as oddballs, they have been ridiculed as nerds. The parents of such young people are often criticized for pushing their children rather than allowing them a normal, well-balanced childhood. These children are so different from others that schools usually do not know how to educate them. Meanwhile society expects gifted children to become creative intellectuals and artists as adults and views them as failures if they do not.

Psychologists have always been interested in those who deviate from the norm, but just as they know more about psychopathology than about leadership and courage, researchers also know far more about retardation than about giftedness. Yet an understanding of the most talented minds will provide both the key to educating gifted children and a precious glimpse of how the human brain works.

The Nature of Giftedness

Everyone knows children who are smart, hard-working achievers—youngsters in the top 10 to 15 percent of all students. But only the top 2 to 5 percent of children are gifted. Gifted children (or child prodigies, who are just extreme versions of gifted children) differ from bright children in at least three ways:

• *Gifted children are precocious*. They master subjects earlier and learn more quickly than average children do.

• *Gifted children march to their own drummer*. They make discoveries on their own and can often intuit the solution to a problem without going through a series of logical, linear steps.

• *Gifted children are driven by "a rage to master."* They have a powerful interest in the area, or domain, in which they have high ability—mathematics, say, or art—and they can readily focus so intently on work in this domain that they lose sense of the outside world.

These are children who seem to teach themselves to read

***Pull Harder*, Wang Yani**

GIFTED CHILD ARTIST WANG YANI from China painted at a nearly adult skill level at the age of five, when she completed this painting in 1980. As a child, she produced a prodigious number of works, at one point finishing 4,000 paintings within the space of three years.

as toddlers, who breeze through college mathematics in middle school or who draw more skillfully as second-graders than most adults do. Their fortunate combination of obsessive interest and an ability to learn easily can lead to high achievement in their chosen domain. But gifted children are more susceptible to interfering social and emotional factors than once was thought.

The first comprehensive study of the gifted, carried out over a period of more than 70 years, was initiated at Stanford University in the early part of this century by Lewis M. Terman, a psychologist with a rather rosy opinion of gifted children. His study tracked more than 1,500 high-IQ children over the course of their lives. To qualify for the study, the "Termites" were first nominated by their teachers and then had to score 135 or higher on the Stanford-Binet IQ test (the average score is 100). These children were precocious: they typically spoke early, walked early and read before they entered school. Their parents described them as being insatiably curious and as having superb memories.

Terman described his subjects glowingly, not only as superior in intelligence to other children but also as superior in health, social adjustment and moral attitude. This conclusion easily gave rise to the myth that gifted children are happy and well adjusted by nature, requiring little in the way of special attention—a myth that still guides the way these children are educated today.

In retrospect, Terman's study was probably flawed. No child entered the study unless nominated by a teacher as one of the best and the brightest; teachers probably overlooked those gifted children who were misfits, loners or problematic to teach. And the shining evaluations of social adjustment and personality in the gifted were performed by the same admiring teachers who had singled out the study subjects. Finally, almost a third of the sample came from professional, middle-class families. Thus, Terman confounded IQ with social class.

The myth of the well-adjusted, easy-to-teach gifted child persists despite more recent evidence to the contrary. Mihaly Csikszentmihalyi of the University of Chicago has shown that children with exceptionally high abilities in any area—not just in academics but in the visual arts, music, even athletics—are out of step with their peers socially. These children tend to be highly driven, independent in their thinking and introverted. They spend more than the usual amount of time alone, and although they derive energy and pleasure from their soli-

DRAWING SAVANT NADIA was a "low-functioning" autistic child, whose mental age was three years and three months when she was six. But this sketch by Nadia, done at age five and a half in 1973, exhibits a command of line, foreshortening and motion reminiscent of adult Renaissance masters.

tary mental lives, they also report feeling lonely. The more extreme the level of gift, the more isolated these children feel.

Contemporary researchers have estimated that about 20 to 25 percent of profoundly gifted children have social and emotional problems, which is about twice the normal rate; in contrast, moderately gifted children do not exhibit a higher than average rate. By middle childhood, gifted children often try to hide their abilities in the hopes of becoming more popular. One group particularly at risk for such underachievement is academically gifted girls, who report more depression, lower self-esteem and more psychosomatic symptoms than academically gifted boys do.

The combination of precocious knowledge, social isolation and sheer boredom in many gifted children is a tough challenge for teachers who must educate them alongside their peers. Worse, certain gifted children can leap years ahead of their peers in one area yet fall behind in another. These children, the unevenly gifted, sometimes seem hopelessly out of sync.

The Unevenly Gifted

Terman was a proponent of the view that gifted children are globally gifted—evenly talented in all academic areas. Indeed, some special children have exceptional verbal skills as well as strong spatial, numerical and logical skills that enable them to excel in mathematics. The occasional child who completes college as an early teen—or even as a preteen—is likely to be globally gifted. Such children are easy to spot: they are all-around high achievers. But many children exhibit gifts in one area of study and are unremarkable or even learning disabled in others. These may be creative children who are difficult in school and who are not immediately recognized as gifted.

Unevenness in gifted children is quite common. A recent survey of more than 1,000 highly academically gifted adolescents revealed that more than 95 percent show a strong disparity between mathematical and verbal interests. Extraordinarily strong mathematical and spatial abilities often accompany average or even deficient verbal abilities. Julian Stanley of Johns Hopkins University has found that many gifted children selected for special summer programs in advanced math have enormous discrepancies between their math and verbal skills. One such eight-year-old scored 760 out of a perfect score of 800 on the math part of the Scholastic Assessment Test (SAT) but only 290 out of 800 on the verbal part.

In a retrospective analysis of 20 world-class mathematicians, psychologist Benjamin S. Bloom, then at the University of Chicago, reported that none of his subjects had learned to read before attending school (yet most academically gifted children do read before school) and that six had had trouble learning to read. And a retrospective study of inventors (who presumably exhibit high mechanical and spatial aptitude) showed that as children these individuals struggled with reading and writing.

Indeed, many children who struggle with language may have strong spatial skills. Thomas Sowell of Stanford University, an economist by training, conducted a study of late-talking children after he raised a son who did not begin to speak until almost age four. These children tended to have high spatial abilities—they excelled at puzzles, for instance—and most had relatives working in professions that require strong spatial

TYPICAL DRAWING by a five-year-old of average ability lacks detail and is highly schematic.

WOLFGANG AMADEUS MOZART is among the best-known child prodigies. He began picking out tunes on the piano at three years of age; by four he could tell if a violin was a quarter tone out of tune, and by eight he could play without hesitation a complex piece he had never seen before. Mozart began composing at the age of five, when he wrote two minuets for the harpsichord. Even as a young child, he could play pieces perfectly from memory, having heard them only once, and improvise on a theme without ever repeating himself.

THOMAS ALVA EDISON exemplifies the unevenly gifted individual. Edison was a prolific inventor, obtaining 1,093 patents for innovations ranging from the phonograph to the incandescent light. As a child, he was obsessed with science and spent much time tinkering in a chemistry laboratory in his parents' cellar. Edison had some difficulties learning, though, especially in the verbal areas; he may have had symptoms of dyslexia. The coexistence of strong spatial-logical skills with a weakness in language is common in the unevenly gifted.

skills. Perhaps the most striking finding was that 60 percent of these children had engineers as first- or second-degree relatives.

The association between verbal deficits and spatial gifts seems particularly strong among visual artists. Beth Casey of Boston College and I have found that college art students make significantly more spelling errors than college students majoring either in math or in verbal areas such as English or history. On average, the art students not only misspelled more than half of a 20-word list but also made the kind of errors associated with poor reading skills—nonphonetic spellings such as "physicain" for "physician" (instead of the phonetic "fisician").

The many children who possess a gift in one area and are weak or learning disabled in others present a conundrum. If schools educate them as globally gifted, these students will continually encounter frustration in their weak areas; if they are held back because of their deficiencies, they will be bored and unhappy in their strong fields. Worst, the gifts that these children do possess may go unnoticed entirely when frustrated, unevenly gifted children wind up as misfits or troublemakers.

Savants: Uneven in the Extreme

The most extreme cases of spatial or mathematical gifts coexisting with verbal deficits are found in savants. Savants are retarded (with IQs between 40 and 70) and are either autistic or show autistic symptoms. "Ordinary" savants usually possess one skill at a normal level, in contrast to their otherwise severely limited abilities. But the rarer savants—fewer than 100 are known—display one or more skills equal to prodigy level.

Savants typically excel in visual art, music or lightning-fast calculation. In their domain of expertise, they resemble child prodigies, exhibiting precocious skills, independent learning and a rage to master. For instance, the drawing savant named Nadia sketched more realistically at ages three and four than any known child prodigy of the same age. In addition, savants will often surpass gifted children in the accuracy of their memories.

Savants are like extreme versions of unevenly gifted children. Just as gifted children often have mathematical or artistic genius and language-based learning disabilities, savants tend to exhibit a highly developed visual-spatial ability alongside severe deficits in language. One of the most promising biological explanations for this syndrome posits atypical brain organization, with deficits in the left hemisphere of the brain (which usually controls language) offset by strengths in the right hemisphere (which controls spatial and visual skills).

According to Darold A. Treffert, a psychiatrist now in private practice in Fond du Lac, Wis., the fact that many savants were premature babies fits well with this notion of left-side brain damage and resultant right-side compensation. Late in pregnancy, the fetal brain undergoes a process called pruning, in which a large number of excess neurons die off [see "The Developing Brain," by Carla J. Shatz; Scientific American,

BILL EPPRIDGE *Life Magazine* ©TIME, Inc.

CALENDRICAL CALCULATORS GEORGE AND CHARLES, identical twins, are the most famous of such savants. Each could instantly compute the day of the week on which any given date, past or future, would fall. The twins were born in 1939 three months premature and retarded; their IQs tested between 40 and 70. Such an extraordinary ability to calculate in an otherwise extremely mentally disabled child mirrors the milder unevenness of gifts seen in children highly talented in mathematics but learning disabled in language.

September 1992]. But the brains of babies born prematurely may not have been pruned yet; if such brains experience trauma to the left hemisphere near the time of birth, numerous uncommitted neurons elsewhere in the brain might remain to compensate for the loss, perhaps leading to a strong right-hemisphere ability.

Such trauma to a premature infant's brain could arise many ways—from conditions during pregnancy, from lack of oxygen during birth, from the administration of too much oxygen afterward. An excess of oxygen given to premature babies can cause blindness in addition to brain damage; many musical savants exhibit the triad of premature birth, blindness and strong right-hemisphere skill.

Gifted children most likely possess atypical brain organization to some extent as well. When average students are tested to see which part of their brain controls their verbal skills, the answer is generally the left hemisphere only. But when mathematically talented children are tested the same way, both the left and right hemispheres are implicated in controlling language—the right side of their brains participates in tasks ordinarily reserved for the left. These children also tend not to be strongly right-handed, an indication that their left hemisphere is not clearly dominant.

The late neurologist Norman Geschwind of Harvard Medical School was intrigued by the fact that individuals with pronounced right-hemisphere gifts (that is, in math, music, art) are disproportionately nonright-handed (left-handed or ambidexterous) and have higher than average rates of left-hemisphere deficits such as delayed onset of speech, stuttering or dyslexia. Geschwind and his colleague Albert Galaburda theorized that this association of gift with disorder, which they called the "pathology of superiority," results from the effect of the hormone testosterone on the developing fetal brain.

Geschwind and Galaburda noted that elevated testosterone can delay development of the left hemisphere of the fetal brain; this in turn might result in compensatory right-hemisphere growth. Such "testosterone poisoning" might also account for the larger number of males than females who exhibit mathematical and spatial gifts, nonright-handedness and pathologies of language. The researchers also noted that gifted children tend to suffer more than the usual frequency of immune disorders such as allergies and asthma; excess testosterone can interfere with the development of the thymus gland, which plays a role in the development of the immune system.

Testosterone exposure remains a controversial explanation for uneven gifts, and to date only scant evidence from the study of brain tissue exists to support the theory of damage and compensation in savants. Nevertheless, it seems certain that gifts are hardwired in the infant brain, as savants and gifted children exhibit extremely high abilities from a very young age—before they have spent much time working at their gift.

Emphasizing Gifts

Given that many profoundly gifted children are unevenly talented, socially isolated and bored with school, what is the best way to educate them? Most gifted programs today tend to target children who have tested above 130 or so on standard IQ tests, pulling them out of their regular classes for a few hours each week of general instruction or interaction. Unfortunately, these programs fail the most talented students.

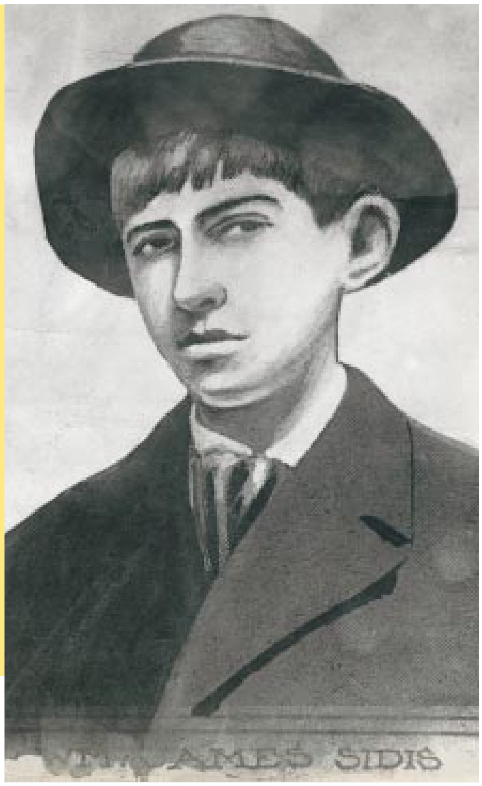
Generally, schools are focusing what few resources they have for gifted education on the moderately academically gifted. These children make up the bulk of current "pull-out" programs: bright students with strong but not extraordinary abilities, who do not face the challenges of precocity and isolation to the same degree as the profoundly gifted. These children—and indeed most children—would be better served if schools instead raised their standards across the board.

Other nations, including Japan and Hungary, set much higher academic expectations for their children than the U.S. does; their children, gifted or not, rise to the challenge by succeeding at higher levels. The needs of moderately gifted children could be met by simply teaching them a more demanding standard curriculum.

The use of IQ as a filter for gifted programs also tends to tip these programs toward the relatively abundant, moderately academically gifted while sometimes overlooking profoundly but unevenly gifted children. Many of those children do poorly on IQ tests, because their talent lies in either math or language, but not both. Students whose talent is musical, artistic or athletic are regularly left out as well. It makes more sense to identify the gifted by examining past achievement in specific areas rather than relying on plain-vanilla IQ tests.

Schools should then place profoundly gifted children in advanced courses in their strong areas only. Subjects in which a student is not exceptional can continue to be taught to the student in the regular classroom. Options for advanced classes include arranging courses especially for the gifted, placing gifted students alongside older students within their schools, registering them in college courses or enrolling them in accelerated summer programs that teach a year's worth of material in a few weeks.

Profoundly gifted children crave challenging work in their domain of expertise and the companionship of individuals with similar skills. Given the proper stimulation and opportunity, the extraordinary minds of these children will flourish. SA



WHEN BRILLIANCE ISN'T ENOUGH: William James Sidis (1898–1944) was profoundly gifted as a child, reading and spelling at the age of two, inventing a new table of logarithms at eight, speaking six languages by 10. By age 11 he was enrolled at Harvard University, delivering lectures on mathematics to the faculty. But Sidis's father had driven him mercilessly as a child, denying him any youthful pleasures and letting the media hound him. He grew deeply bitter and resentful of his father and lost all interest in mathematics after graduating from Harvard at 16. This talented young man spent the rest of his life in mindless clerical jobs, and his interests became obsessive and autisticlike: at 28 he wrote a comprehensive book on the classification of streetcar transfer slips. He died, alone, from a brain hemorrhage at 46.

BROWN BROTHERS

About the Author

COURTESY OF ELLEN WINNER

ELLEN WINNER was a student of literature and painting before she decided to explore developmental psychology. Her inspiration was Harvard University's Project Zero, which researched the psychological aspects of the arts. Her graduate studies allowed her to combine her interests in art and writing with an exploration of the mind. She received her Ph.D. in psychology from Harvard in 1978 and is currently professor of psychology at Boston College as well as senior research associate with Project Zero.

One of Winner's greatest pleasures is writing books; she has authored three, one on the psychology of the arts, another on children's use of metaphor and irony and, most recently, *Gifted Children: Myths and Realities*. "I usually have several quite different projects going at once, so I am always juggling," she remarks. She is especially intrigued by unusual children—children who are gifted, learning disabled, gifted and learning disabled, nonright-handed or particularly creative. "The goal is to understand cognitive development in its typical and atypical forms."

When she has time to play, Winner devours novels and movies and chauffeurs her 13-year-old son on snowboarding dates. She is married to the psychologist Howard Gardner and has three grown stepchildren.

1942; PHOTOGRAPH BY DAVID HEALD, © THE SOLOMON R. GUGGENHEIM FOUNDATION, NEW YORK

***Untitled (Pharmacy),* by Joseph Cornell**

Seeking "Smart" Drugs

New treatments for Alzheimer's disease and other neural disorders are pointing to drugs that could boost memory in young, healthy individuals

by Marguerite Holloway, *staff writer*

The ancient bards didn't need them. Their well-toned memories bespoke tomes: the *Iliad* and the *Odyssey,* the *Ṛg Veda* and the Mahābhārata, among thousands of hours of other recited epics. But in our era, filled with more information in more forms than we could ever productively use, we seem to want them. Just as we want beauty sculpted not by our genetic heritage or by our exertion but rather by the scalpel or by silicone, we desire brains that are artificially boosted: we want drugs that make us think more quickly, that enable us to remember more readily, that give us a competitive edge.

The pursuit of these "smart" drugs has been celebrated since the early 1990s, when books and bars (many of them in California) offered recommendations for diets or formulas or herbs such as ginkgo biloba that could better one's brain. In the intervening years, a huge market for these items has sprung up, facilitated by the ease of sales over the Internet. In Japan alone, for instance, there are now 20 or so such compounds available and at least $2 billion in sales every year.

"Ninety-nine percent of that is hype," says James L. McGaugh, head of the Center for the Neurobiology of Learning and Memory at the University of California at Irvine. And, to him, worrisome hype. "We don't know how many of these drugs work and how they interact with other drugs, so there is the purely biological danger," McGaugh explains.

Nevertheless, the public obsession with smart drugs mirrors a scientific one. And what McGaugh and neuroscientists the world over are studying could one day lead to clinically tested drugs to enhance memory. The first wave of these are being designed to help older people who are losing their ability to remember or those suffering from dementia. The only two drugs approved by the U.S. Food and Drug Administration to boost memory, in fact, are Tacrine and Donepezil, both for Alzheimer's patients. Several new compounds for this disease are in the final stage of testing and may soon be on the market. Hundreds more are being investigated. And behind this first wave—but well off in the future—is the tsunami of promise that such compounds could work in anyone.

The cognitive enhancers under study work in many different ways because research on memory is as rich and varied as memories themselves. Scientists have looked at short-term (or "working") memory, long-term memory, emotional memory and olfactory memory; they have examined the molecular and genetic webs of memory, the role of hormones in memory, and the regions of the brain that light up in tomographic scans when a person remembers a sound as opposed to words. In each of these areas, neuroscientists garnered great insights over the past few decades, offering the possibility that some of the gears of memory could be oiled or recast.

In spite of the advances and the optimism engendered, though, many investigators note that memory is so complex and so intertwined with other mental activities that it is unlikely that one drug could be precise enough to just help you find your glasses or remember names at a cocktail party. "It really calls for a carefully balanced approach, recognizing that many of the mechanisms that may be critical for memory may also be critical for transmissions that are deleterious," observes Ira B. Black of Robert Wood Johnson Medical School.

Further, augmenting short-term memory, say, or increasing attention span does not necessarily translate into greater intelligence. "It doesn't make you smart," McGaugh cautions. "If you attend to the wrong things in life, that makes you dumb." Larry Cahill, a colleague of McGaugh's at Irvine, adds his own caveat, borrowed from philosopher and psychologist William James: "'Selection is the very keel on which our mental ship is built.' In other words, if we remembered everything we would 'be as ill off as if we remembered nothing.'"

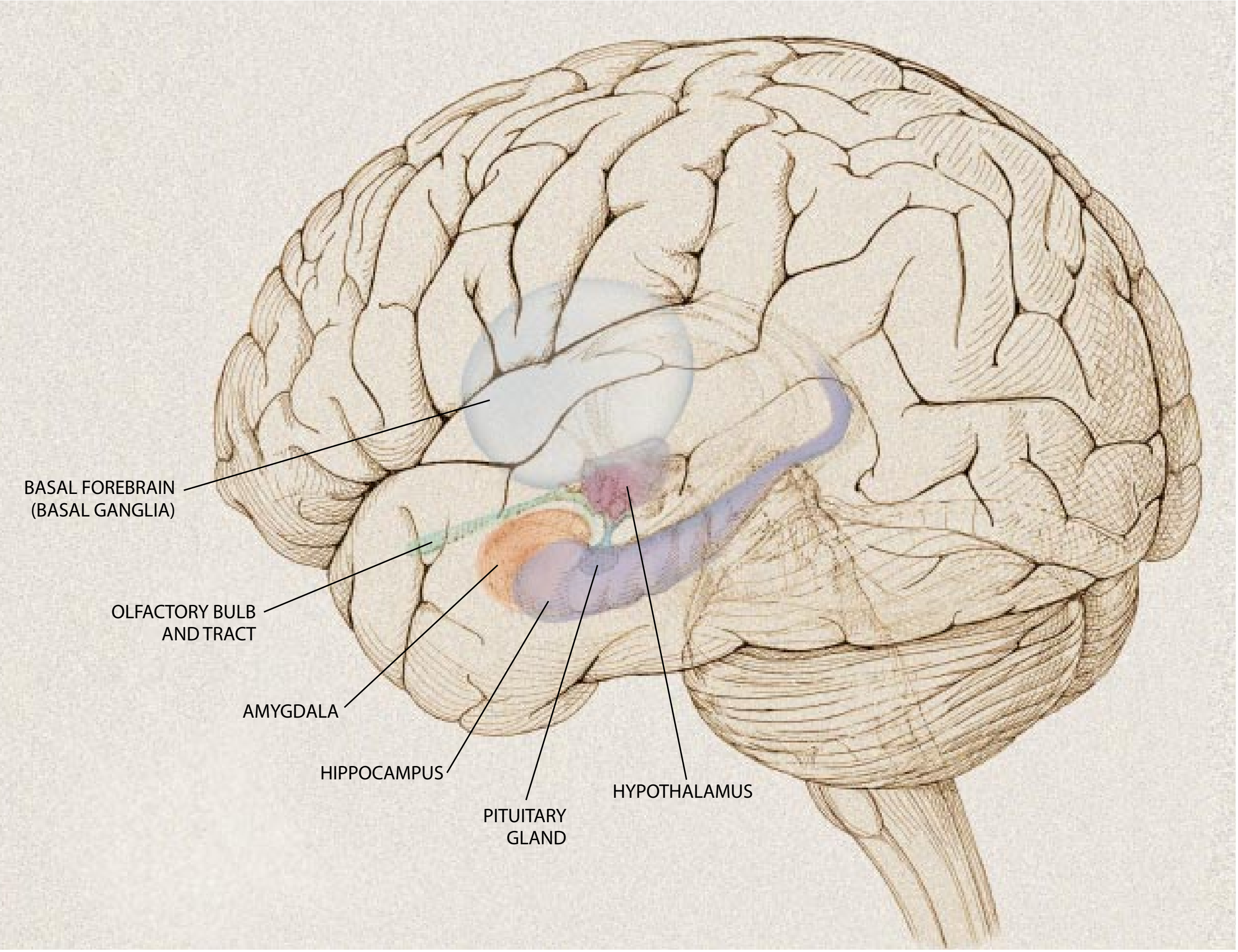
We could end up worshipping intelligence even more than we already do—but using it even less.

Transmitter Turn-ons

How we recall anything comes down to the basic currency of the nervous system: the giving and taking of neurotransmitters. These chemical messengers are released from a nerve cell into a tiny space called the synapse. On the far side of this gap sit other nerve cells studded with receptors shaped to receive specific neurotransmitters. Once these receptors have caught the molecules wafting across the synapse, they trigger chemical changes that allow information—in electrical form—to travel down the receiving neuron to its end, where, in turn, more neurotransmitters set sail across a synapse. Understanding which transactions control memory is a matter of figuring out which of the brain's 100 billion neurons—each making an average of 10,000 connections to other neurons—and which of the 50 or so neurotransmitters are involved.

Researchers have known since the 1950s that the hippocampus—part of the limbic system, which controls emotion and sits under the cerebral cortex on top of the brain stem—is crucial for memory. And since the 1980s they have known that the neurotransmitter glutamate, which binds to so-called NMDA receptors, underlies a form of learning in the hippocampus. Called long-term potentiation, it is thought to bring about memory by strengthening the path of communication

MEMORY FORMATION includes many areas of the brain, but central to this activity is the hippocampus. Nestled in the innermost part of the brain, the hippocampus, along with the amygdala and other structures, makes up the limbic system—the center of emotional response. The amygdala and hippocampus also sit next to the olfactory nerve, which explains why smells can conjure up strong emotions and memories. Stress hormones released by the hypothalamus, the pituitary gland and the adrenal glands, which sit atop the kidneys, orchestrate some forms of memory as well.



between neurons—just as walking the same route through a forest again and again etches a permanent trail.

Several efforts to develop cognitive enhancers center on NMDA receptors—in particular, making them more active and, hence, more likely to establish long-term potentiation. Gary S. Lynch of U.C. Irvine, for instance, is investigating drugs—named ampakines—that interact with a particular kind of NMDA receptor called AMPA.

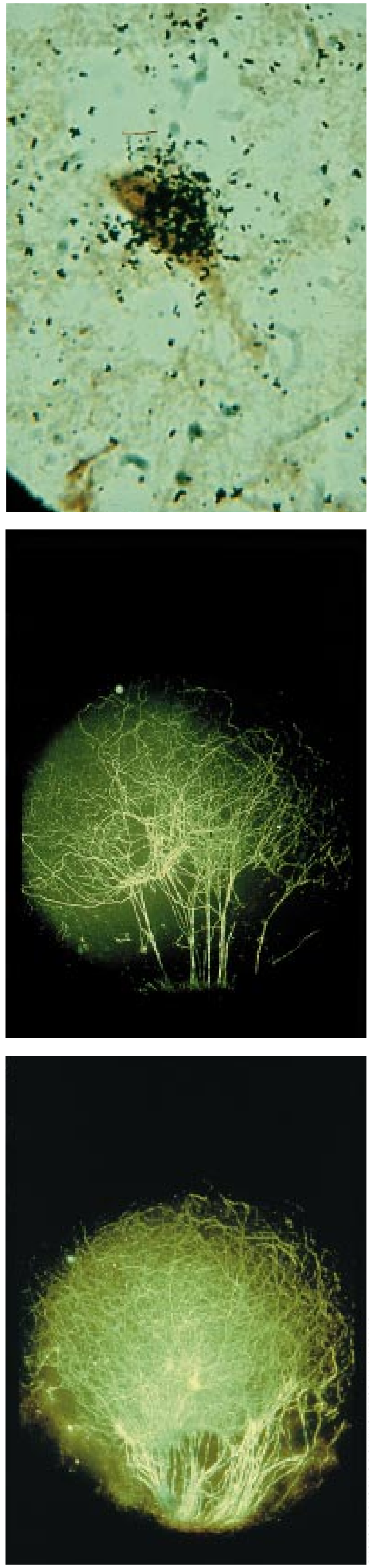
NMDA receptors may also respond to neurotropins, compounds crucial for the survival and differentiation of neurons. In a surprising finding a few years ago, Black and his co-workers discovered that brain-derived neurotrophic factor—the king of the nerve growth factors—increases synaptic strength between neurons in the hippocampus. "We sort of wandered into the area [of cognitive enhancers] through the back door," Black explains. It now appears the hippocampus is lousy with neurotropins and that—at least in petri dishes and in rats—brain-derived neurotrophic factor may act on NMDA receptors.

Jump-Starting Genes

For the moment, Black is just figuring out the fundamentals. Getting large compounds across the blood-brain barrier and into the brain is very hard. So Black and others are studying how to coax genes to turn on and produce growth factor in the right place. For example, James W. Simpkins, Edwin M. Meyer and their colleagues at the University of Florida at Gainesville are using a viral infection as the shuttle to carry a nerve growth factor gene into the brains of laboratory animals. They watch to see which neurons take up the gene and generate nerve growth factor, which ones take it up but do not do anything with it and which ones ignore it altogether. "We're asking fundamental questions," Simpkins says. "How can we get the gene to the central nervous system? How can we enhance the hit?"

Genes, of course, orchestrate every mnemonic—and every other—physiological activity, whether it is the creation of nerve growth factor or of more NMDA receptors. By documenting the molecular and genetic machinations of memory, researchers at several institutions are hoping to find other forms of memory boosters. Work on marine snails done by Eric R. Kandel's team at Columbia University and on fruit flies by Timothy Tully's group at Cold Spring Harbor Laboratory in New York State has pinpointed a gene, known as *CREB,* that appears to be central to some kinds of memory formation. With it, total recall. Without it, none. The hope is that years from now, cognitive enhancers could perhaps tickle silent *CREB*s into life and, consequently, improve memory.

CREB may prove to be just one way of manipulating the same process. Researchers at the University of Toronto reported recently in *Science* that long-term potentiation in the hippocampus can be forestalled by blocking the action of a particular enzyme dubbed Src. Src belongs to a class of enzymes



PHOTOGRAPHS BY C. DOMINIQUE TORAN-ALLERAND

RECEPTORS FOR ESTROGEN and nerve growth factor (dark spots in top image) *have been found in mice on the same neurons in the basal forebrain, a region damaged in Alzheimer's disease. This discovery suggests that estrogen may keep this—and perhaps other—parts of the brain healthy. Indeed, in the presence of small amounts of estrogen, nerve cells flourish* (middle); *higher amounts yield even healthier and more robust cells* (bottom). *Studies are now being conducted to see whether estrogen can prevent Alzheimer's disease or can improve memory function in women with the disease.*

The Proustian Connection: Popping a Madeleine

It is no surprise that smell triggers what are sometimes described as the most powerful memories: the olfactory nerve is just two synapses away from the amygdala, the center of human emotions, and just three from the hippocampus, headquarters of at least some forms of memory. Many researchers have been intrigued by this proximity, among them Rachel S. Herz of the Monell Chemical Senses Center in Philadelphia.

Herz recently examined whether smell could serve as a form of cognitive enhancer in emotional situations. She tested students who were about to take an exam and who were, as a consequence, exceedingly anxious. One set of nervous students was given a list of words to remember at the same time that they were exposed to a smell; the other group saw the same words, but their room remained odorless. A week later Herz found that those reexposed to the smell had 50 percent better recall than the control subjects did.

In another experiment, Herz tried to determine whether memory evoked by smell was more accurate than memory evoked by other cues, such as images. She found that odor did not increase accuracy but rather the emotional intensity of the recollection. So if your cognitive enhancer of choice proves to be perfume or whatever spice you have on the shelf, beware: your emotions may get the better of you. *—M.H.*

Those reexposed to the smell had 50 percent better recall.

PATTI MURRAY *Earth Scenes*

PEPPERMINT is among the scents used in experiments to evoke emotional memory.

that had been shown by Kandel and others to be important to long-term potentiation. Now it appears that Src regulates—no surprise—NMDA receptors.

Hormonal Clout

Still, not all roads lead to NMDA. Estrogen, one of the strongest and most promising cognitive enhancers currently being studied, seems to work in a different way. In the early 1990s C. Dominique Toran-Allerand of Columbia University noticed that many neurons in the basal forebrain—an area not far from the limbic system and one that is devastated by Alzheimer's disease—had receptors for both estrogen and nerve growth factor. She hypothesized that these acetylcholine-producing (or cholinergic, as they are called) neurons needed estrogen and nerve growth factor to stay healthy. Her next thought was to consider what a sudden shortage of estrogen would do to these neurons. (Previous work had shown that the neurotransmitter acetylcholine is pivotal to memory, although how it works remains mysterious. Research had also established that people with Alzheimer's have damaged cholinergic neurons and low levels of acetylcholine. The two drugs mentioned earlier—Tacrine and Donepezil—work by attacking the enzymes that break down acetylcholine.)

Toran-Allerand's findings fit nicely with those of a few other researchers as well as with anecdotal reports that more women than men develop Alzheimer's. The large clinical trials needed to examine rigorously the protective effects of estrogen have just begun: the Women's Health Initiative-Memory Study enrolled 6,000 women and will have data in 2005, and a study of 900 women whose relatives have Alzheimer's is under way at Johns Hopkins University, in conjunction with Columbia University and the Mayo Clinic. But in the past few years, several small studies have found that estrogen replacement therapy not only reduces the risk of developing Alzheimer's but also improves short-term memory in women with the disorder and in normally functioning postmenopausal women.

Men have a source of estrogen as well: testosterone is converted to its female counterpart in the brain. Unlike women, however, men do not experience a precipitous hormonal decline in their later years. Nevertheless, work by Simpkins and his colleagues shows that estrogen enhances short- and long-term memory in animals of both sexes and that it protects the brain from damage such as that caused by the loss of oxygen during stroke. So Simpkins and his team are developing nonfeminizing estrogens that could be used in men and that could reduce the estrogen-associated risk of cancer in women. "Our approach has been to discover estrogenlike compounds that are cognitive enhancers but, and we believe more important, are neuroprotective compounds," Simpkins explains.

A host of other hormones play a critical role in memory as well. Researchers studying stress responses, including McGaugh and Benno Roozendaal of U.C. Irvine, know that stress hormones such as corticosteroids can lead to powerful memory formation. Cahill is among the many neuroscientists looking at how such arousal lays down memory, which hormones do what and how to exploit this system. He is currently setting up clinical trials to test a beta blocker, Inderal, that could dull unpleasant memories in people who suffer post-traumatic stress disorder. (Cahill is quick to point out that Inderal was listed as a cognitive enhancer in *Smart Drugs and Nutrients,* the book that started the U.S. craze. "We have shown in humans that it is quite bad for memory," he laughs.)

STORYTELLING is an ancient tradition. The poets who recited the great Indian and Greek epics needed no "smart" drugs to keep their memories powerful. James L. McGaugh of the University of California at Irvine passes on this thought from a friend: "All one needs to strengthen memory is application—application of the seat of the pants to the seat of the chair."

INSTITUTE OF ORIENTAL STUDIES, ST. PETERSBURG, RUSSIA/GIRAUDON/SUPERSTOCK

As cognitive enhancers, stress hormones pose a bit of a paradox. They can be good for memory, but they take their toll on the body. The same holds true of a few of the other legal and widespread smart drugs, such as caffeine, which enhances mental alertness but can cause gastrointestinal problems. It seems that caffeine works as a stimulant because it blocks one of the receptors for adenosine—a neurotransmitter that seems, among other actions, to dull concentration.

Taking Taboos

A cup of coffee with sugar in it would work even better. "Perhaps the smartest smart drug out there is glucose," Cahill comments—although excess can be unhealthy. The first clue that sugar is a smart drug came from stress studies. Among the hormones released during stress is epinephrine, which causes blood levels of glucose to shoot up. Paul E. Gold and others at the University of Virginia at Charlottesville found that rodents and people of all ages show memory improvement when given sugar. Gold also reports that glucose enhances some forms of cognition in people with Alzheimer's disease or Down syndrome. Again, all the studies so far have been small and are not yet conclusive.

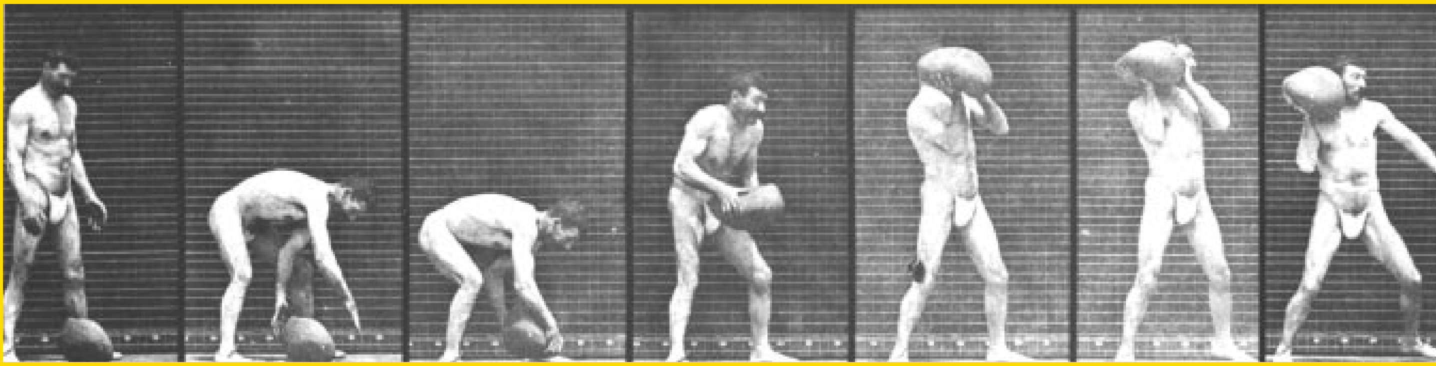
According to Gold, it appears that glucose directly triggers the production of acetylcholine. Several other researchers have fingered the hormone insulin, rather than sugar, as the crucial memory enhancer. Regardless, it would appear that a hit of jelly beans could be salubrious.

And while you are at it, a nicotine patch could help. Various studies have found that nicotine improves people's short-term memory. Nicotine, like other pleasure-inducing drugs, is an analogue of a naturally occurring neurotransmitter: it resembles acetylcholine and binds to the acetylcholine nicotinic receptor. Because of the importance of cholinergic neurons in Alzheimer's disease, some researchers have focused on understanding the nicotinic receptors. Meyer is one of these scientists, and after eight years of study, he has synthesized a drug that—to his surprise—proved to be a potent cognitive enhancer in a small group of young, healthy men. "We didn't expect the drug to work in normal people, because you don't see Alzheimer's agents working in non-Alzheimer folks," Meyer says. More evidence, he adds, that "no one really knows how memory works."

Which is why the wait for the right brain boosters may be a long one. But they are on their way, and given society's desire for elixirs and quick fixes, it is worth thinking about what it would mean to rely even more on drugs, who would be able to afford them and what memory—and perhaps intelligence—would mean to us if we had dominion over it.

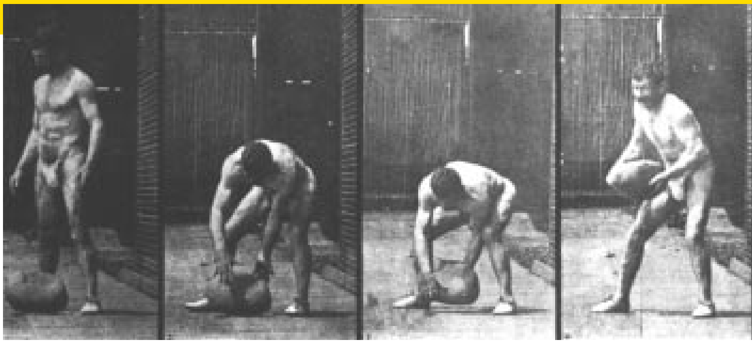
The idea of helping people who have impairments get some relief is exciting. The idea of raising a normal, healthy person's IQ a few points for certain tasks seems fair enough. But farther down this slippery slope lies the possibility of dramatically augmenting someone's intelligence—or, at least, that of someone who can afford it. That possibility seems less fair and much more likely to institutionalize fully the social and economic stratification that already exists.

Paradoxically, such smart drugs could even inculcate intellectual lassitude, much as the good feeling from a mood enhancer or antidepressant allows some people to avoid grappling with emotional problems. We could end up worshipping intelligence even more than we already do—but using it even less. "We should take care not to make the intellect our god," Albert Einstein wrote in *Out of My Later Life*. "It has, of course, powerful muscles, but no personality." SA



The Emergence of Intelligence

by William H. Calvin



To most observers, the essence of intelligence is cleverness, a versatility in solving novel problems. Foresight is also said to be an essential aspect of intelligence—particularly after an encounter with one of those terminally clever people who are all tactics and no strategy. Other observers will add creativity to the list. Personally, I like the way neurobiologist Horace Barlow of the University of Cambridge frames the issue. He says intelligence is all about making a guess that discovers some new underlying order. This idea neatly covers a lot of ground: finding the solution to a problem or the logic of an argument, happening on an appropriate analogy, creating a pleasing harmony or guessing what's likely to happen next. Indeed, we all routinely predict what comes next, even when passively listening to a narrative or a melody. That's why a joke's punch line or a P.D.Q. Bach musical parody brings you up short—you were subconsciously predicting something else and were surprised by the mismatch.

We will never agree on a universal definition of intelligence because it is an open-ended word, like consciousness. Both intelligence and consciousness concern the high end of our mental life, but they are frequently confused with more elementary mental processes, such as ones we use to recognize a friend or to tie a shoelace. Of course, such simple neural mechanisms are probably the foundations from which our abilities to handle logic and metaphor evolved. But how did that occur? That is both an evolutionary question and a neurophysiological one. Both kinds of answers are needed to understand our own intelligence. They might even help explain how an artificial or an exotic intelligence could evolve.

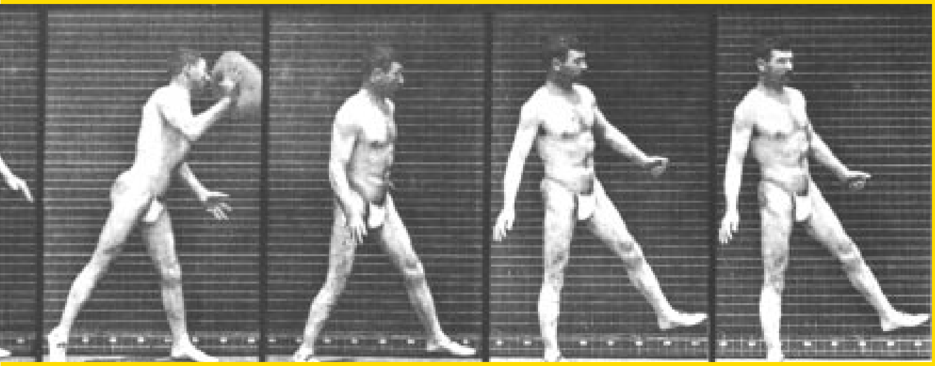
Did our intelligence arise from having more of what other animals have? The two-millimeter-thick cerebral cortex is the part of the brain most involved with making novel associations. Ours is extensively wrinkled, but were it flattened out, it would occupy four sheets of typing paper. A chimpanzee's cortex would fit on one sheet, a monkey's on a postcard, a rat's on a stamp. But a purely quantitative explanation seems incomplete. I will argue that our intelligence arose primarily through the refinement of some brain specialization, such as that for language. This specialization allowed a quantum leap in cleverness and foresight during the evolution of humans from apes. If, as I suspect, the specialization involved a core facility common to language, the planning of hand movements, music and dance, it has even greater explanatory power.

A particularly intelligent person often seems "quick" and capable of juggling many ideas at once. Indeed, the two strongest influences on your IQ score are how many novel questions you can answer in a fixed length of time and how good you are at simultaneously manipulating half a dozen mental images—as in those analogy questions: A is to B as C is to (D, E or F).

Versatility is another characteristic of intelligence. Most animals are narrow specialists, especially in matters of diet: the mountain gorilla consumes 23 kilograms (50 pounds) of green leaves each and every day. In comparison, a chimpanzee switches around a lot—it will eat fruit, termites, leaves and even a small monkey or piglet if it is lucky enough to catch one. Omnivores have more basic moves in their general behavior because their ancestors had to switch between many different food sources. They need more sensory templates, too—mental search images of things such as foods and predators for which they are "on the lookout." Their behavior emerges through the matching of these sensory templates to responsive movements.

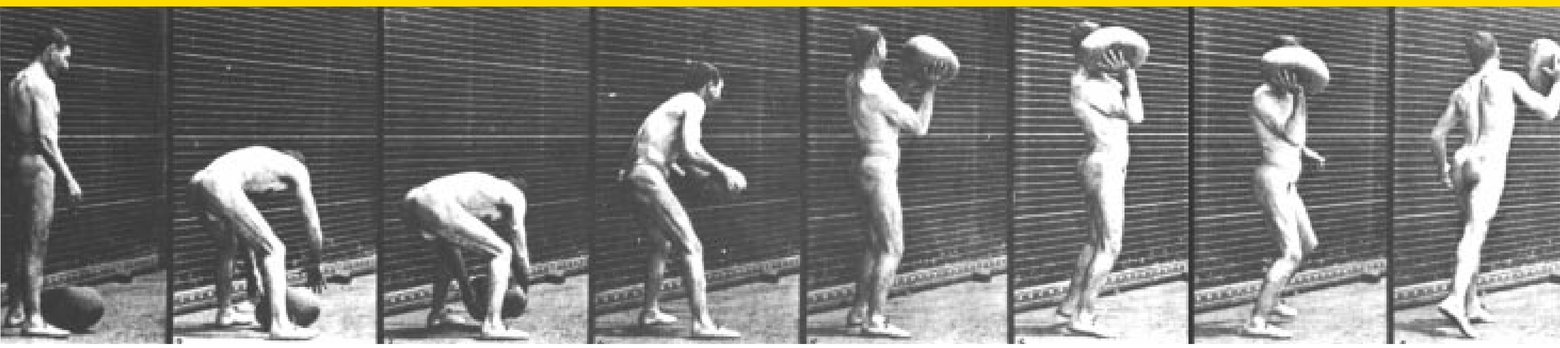
Sometimes animals try out a new combination of search image and movement during play and find a use for it later. Many animals are playful only as juveniles; being an adult is a serious business (they have all those young mouths to feed). Having a long juvenile period, as apes and humans do, surely aids intelligence. A long life further promotes versatility by affording more opportunities to discover new behaviors.

A social life also gives individuals the chance to mimic the useful discoveries of others. Researchers have seen a troop



Language, foresight, musical skills and other hallmarks of intelligence may all be linked to the human ability to create rapid movements such as throwing

DOVER PUBLICATIONS



THROWING A STONE requires a surprising amount of brainpower. The complex sequence of movements is shown in a famous series of photographs taken by Eadweard Muybridge in the 1880s. The improvement of throwing abilities in early hominids may have enhanced the dexterity of their mouth movements as well and led to the development of language.

of monkeys in Japan copy one inventive female's techniques for washing sand off food. Moreover, a social life is full of interpersonal problems to solve, such as those created by pecking orders, that go well beyond the usual environmental challenges to survival and reproduction.

Yet versatility is not always a virtue, and more of it is not always better. When the chimpanzees of Uganda arrive at a grove of fruit trees, they often discover that the efficient local monkeys are already speedily stripping the trees of edible fruit. The chimps can turn to termite fishing, or perhaps catch a monkey and eat it, but in practice their population is severely limited by that competition, despite a brain twice the size of their specialist rivals.

The Impact of Abrupt Climate Change

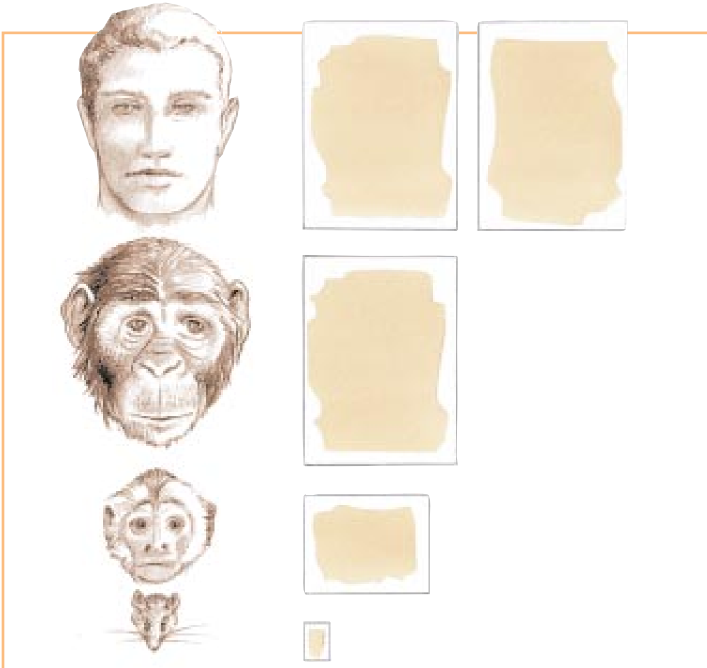
Versatility becomes advantageous, however, when the weather changes abruptly. The fourfold expansion of the hominid brain started 2.5 million years ago, when the ice ages began. Ice cores from Greenland show that warming and cooling episodes occurred every several thousand years, superimposed on the slower advances and retreats of the northern ice sheets. The vast rearrangements in ocean currents lasted for centuries, with sudden transitions that took less than a decade.

The abrupt coolings most likely devastated the ecosystems on which our ancestors depended. Because of lower temperatures and less rainfall, the forests in Africa dried up and animal populations began to crash. Lightning strikes ignited giant forest fires, denuding large areas even in the tropics. There was very little food after the fires. Once the grasses reemerged on the burnt landscape, however, the surviving grazing animals had a boom time. Within several centuries, a succession of forests came back in many places, featuring species more appropriate to the cooler climate.

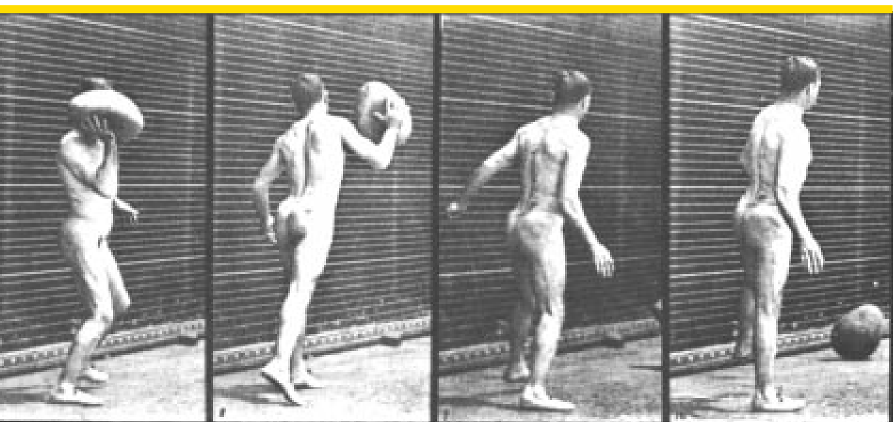
Cool, crash and burn. The progenitors of modern humans lived through hundreds of such episodes, but each was a population bottleneck that eliminated most of their relatives. Had the cooling taken a few centuries to happen, the forests could have gradually shifted, and our ancestors would not have been treated so harshly. The higher-elevation plant species would have slowly marched down the hillsides to occupy the valley floors. Hominid generations could have made their living in the way their parents taught them, culturally adapting to the new milieu. But when the cooling and drought were abrupt, it was one unlucky generation that suddenly had to improvise amid crashing populations and burning ecosystems. We are the improbable descendants of those who survived—probably because they had ways of coping with these episodes that the other great apes did not exploit.

Improvising meant learning to eat grass—or managing regularly to eat animals that eat grass. The trouble is that such animals are fast and wary, whether rabbit or antelope. Small or big, they are best tackled by cooperative groups. But sharing a rabbit leaves everyone hungry, so the hunters would have tried for the bigger animals that cluster in herds. And that had an interesting consequence. If a single hunter killed a big animal, it was too much to eat; best to give most of the meat away and count on reciprocity when someone else succeeded. Sharing food also meant fewer fights and more time available to seek out scarce food.

Each population bottleneck temporarily exaggerated the importance of such traits as cooperation, altruism and hunting abilities. Even if each episode changed the inborn predilections of the hominids by only a small amount, the hundreds of repetitions of this scenario may explain some of the differences between human abilities and those of our closest relatives among the great apes. It is tempting to say that the abrupt coolings pumped up brain size, but what makes for better survival is something much more specific: hunting abilities and perhaps altruism. What might they have to do with intelligence?



Relative Size of Cerebral Cortex



Syntax and Structured Thought

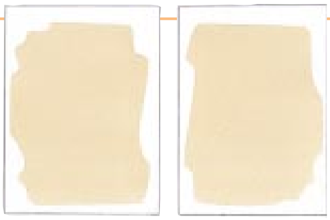
One of the improvements that occurred during the ice ages was the capacity for human language. In most of us, the brain area critical to language is located just above our left ear. Monkeys lack this left lateral language area: their vocalizations (and simple emotional utterances in humans) employ a more primitive language area near the corpus callosum, the band of fibers connecting the cerebral hemispheres.

Language is the most defining feature of human intelligence: without syntax—the orderly arrangement of verbal ideas—we would be little more clever than a chimpanzee. For a glimpse of life without syntax, look to the case of Joseph, an 11-year-old deaf boy. Because he could not hear spoken language and had never been exposed to fluent sign language, Joseph did not have the opportunity to learn syntax during the critical years of early childhood. As neurologist Oliver Sacks described him: "Joseph saw, distinguished, categorized, used; he had no problems with perceptual categorization or generalization, but he could not, it seemed, go much beyond this, hold abstract ideas in mind, reflect, play, plan. He seemed completely literal—unable to juggle images or hypotheses or possibilities, unable to enter an imaginative or figurative realm.... He seemed, like an animal, or an infant, to be stuck in the present, to be confined to literal and immediate perception, though made aware of this by a consciousness that no infant could have."

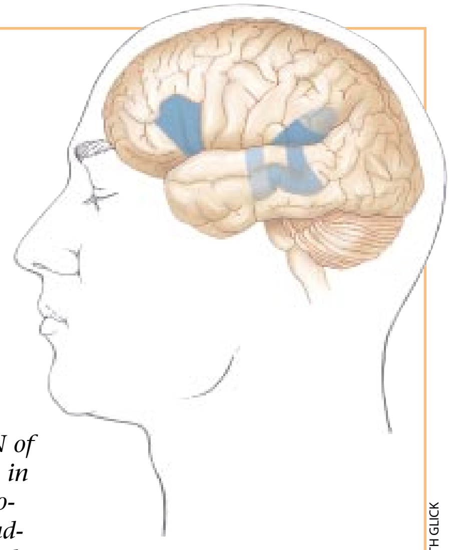
To understand why humans are so intelligent, we need to understand how our ancestors remodeled the apes' symbolic repertoire and enhanced it by inventing syntax. Wild chimpanzees use about three dozen different vocalizations to convey about three dozen different meanings. They may repeat a sound to intensify its meaning, but they do not string together three sounds to add a new word to their vocabulary. Humans also use about three dozen vocalizations, called phonemes. Yet only their combinations have content: we string together meaningless sounds to make meaningful words. Furthermore, human language uses strings of strings, such as the word phrases that make up this sentence.

Our closest animal cousins, the common chimpanzee and the bonobo (pygmy chimpanzee), can achieve surprising levels of language comprehension when motivated by skilled teachers. Kanzi, the most accomplished bonobo, can interpret sentences he has never heard before, such as "Go to the office and bring back the red ball," about as well as a two-and-a-half-year-old child. Neither Kanzi nor the child constructs such sentences independently, but they can demonstrate by their actions that they understand them.

With a year's experience in comprehension, a child starts constructing sentences that nest one word phrase inside anoth-



CEREBRAL CORTEX is the deeply convoluted surface region of the brain that is most strongly linked to intelligence (below). *A human's cerebral cortex, if flattened, would cover four pages of typing paper* (left); *a chimpanzee's would cover only one page; a monkey's would cover a postcard; and a rat's would cover a postage stamp.*



SPECIALIZED SEQUENCING REGION of the left cerebral cortex is involved both in listening to spoken language and in producing oral-facial movements. The shading in the illustration at the right, based on the data of George A. Ojemann of the University of Washington, reflects the amount of involvement in these activities.

DANA BURNS-PIZER AND JUDITH GLICK

er. The rhyme about the house that Jack built ("This is the farmer sowing the corn / That kept the cock that crowed in the morn /…That lay in the house that Jack built") is an example of such a sentence. Syntax has treelike rules of reference that enable us to communicate quickly—sometimes with fewer than 100 sounds strung together—who did what to whom, where, when, why and how. Even children of low intelligence seem to acquire syntax effortlessly, although intelligent deaf children like Joseph may miss out.

Something very close to syntax also seems to contribute to another outstanding feature of human intelligence: the ability to plan ahead. Aside from hormonally triggered preparations for winter, animals exhibit surprisingly little evidence of advance planning. For instance, some chimpanzees use long twigs to pull termites from their nests. Yet as author Jacob Bronowski observed, none of the termite-fishing chimps "spends the evening going round and tearing off a nice tidy supply of a dozen probes for tomorrow."

Human planning abilities may stem from our talent for building narratives. We can borrow the mental structures for syntax to judge combinations of possible actions. To some extent, we do this by talking silently to ourselves, making narratives out of what might happen next and then applying syntaxlike rules of combination to rate a scenario as unlikely, possible or likely. Narratives are also a major foundation for ethical choices: we imagine a course of action and its effects on others, then decide whether or not to do it. But our thinking is not limited to languagelike constructs. Indeed, we may shout "Eureka!" when feeling a set of mental relationships click into place yet have trouble expressing them verbally.

Ballistic Movements and Their Relatives

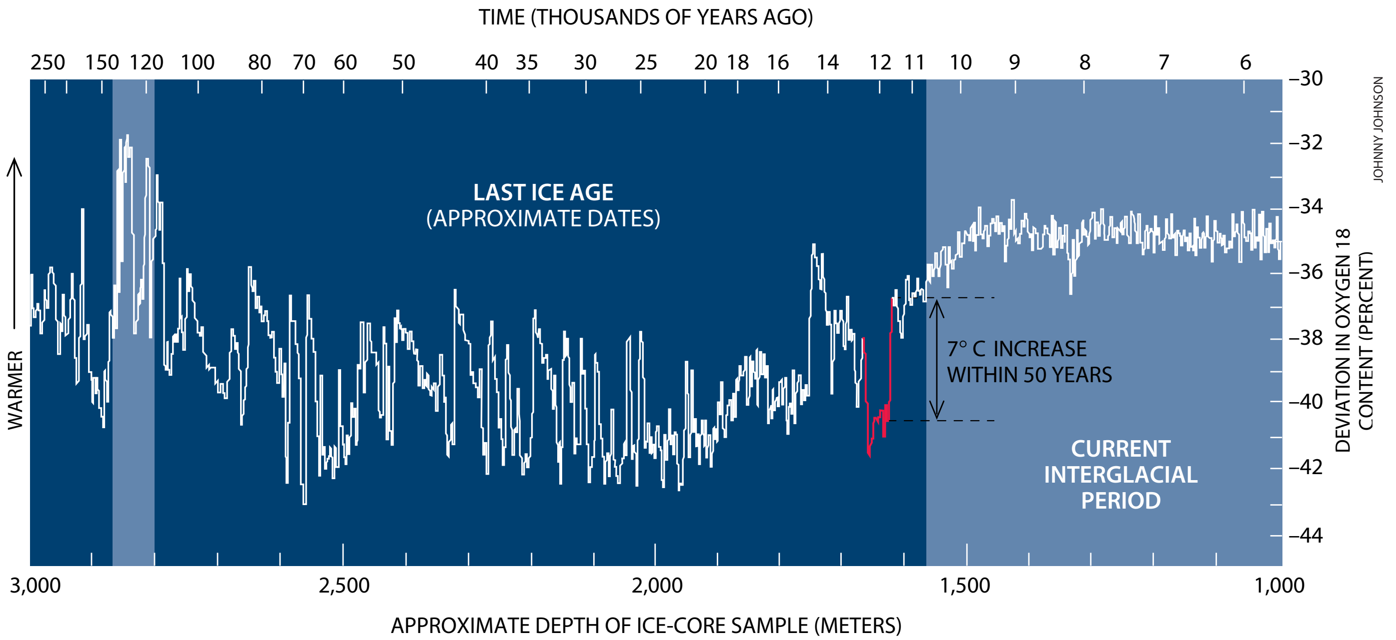
Language and intelligence are so powerful that we might think evolution would naturally favor their increase. But as Harvard University evolutionary biologist Ernst Mayr once said, most species are not intelligent, which suggests "that high intelligence is not at all favored by natural selection"—or that it is very hard to achieve. So we must consider indirect ways of achieving it, rather than general principles.

Evolution often follows indirect routes rather than "progressing" via adaptations. To account for the breadth of our higher intellectual functions (syntax, planning, logic, games with rules, music), we need to look at improvements in common-core facilities. Humans certainly have a passion for stringing things together: words into sentences, notes into melodies, steps into dances, narratives into games with rules of procedure. Might stringing things together be a core facility of the brain?

As improbable as the idea initially seems, the brain's planning of ballistic movements may have once promoted language, music and intelligence. Such movements are extremely rapid actions of the limbs that, once initiated, cannot be modified. Striking a nail with a hammer is an example. Apes have only elementary forms of the ballistic arm movements at which humans are expert—hammering, clubbing and throwing. Perhaps it is no coincidence that these movements are important to the manufacture and use of tools and hunting weapons: in a setting such as cool-crash-and-burn, hunting and toolmaking were important additions to hominids' basic survival strategies.

Compared with most movements, ballistic ones require a surprising amount of planning. Slow movements leave time for improvisation: when raising a cup to your lips, if the cup is lighter than you remembered, you can correct its trajectory before it hits your nose. Thus, a complete advance plan is not needed. You start in the right general direction and then correct your path. For sudden limb movements lasting less than one fifth of a second, feedback corrections are largely ineffective because reaction times are too long. The brain has to plan every detail of the movement. Hammering, for example, requires planning the exact sequence of activation for dozens of muscles.

The problem of throwing is compounded by the briefness of the launch window—the range of time in which a projectile can be released to hit a target. Because the human sense of



RAPID CLIMATE CHANGES may have promoted behavioral versatility in the ancestors of modern humans. Studies of Greenland ice cores show that during the last ice age, average temperatures were subject to abrupt fluctuations. During one climatic oscillation (red line), *the average temperature rose 13 degrees Fahrenheit (seven degrees Celsius) in the space of a few decades. This graph is based on work by Willi Dansgaard of the University of Copenhagen and his colleagues.*

timing is inevitably jittery, when the distance to a target doubles, the launch window becomes eight times narrower, and shrinking the timing jitter requires the activity of 64 times as many neurons. These neurons function as independent timing mechanisms working in concert, like a chorus of medieval singers reciting a plainsong in unison.

If mouth movements rely on the same core facility for sequencing as ballistic hand movements do, then improvements in dexterity might improve language, and vice versa. Accurate throwing abilities, which would have helped early hominids survive the cool-crash-and-burn episodes in the tropics, would also open up the possibility of eating meat regularly and of being able to survive winter in a temperate zone. The gift of speech would be an incidental benefit—a free lunch, as it were, because of the linkage.

There certainly seems to be a sequencer common to both hand movements and language. Much of the brain's coordination of movement occurs at a subcortical level in the basal ganglia or the cerebellum, but novel movements tend to depend on the premotor and prefrontal cortex. Two major lines of evidence point to cortical specialization for sequencing, and both of them suggest that the lateral language area has much to do with it. Doreen Kimura of the University of Western Ontario has found that stroke patients with language problems (aphasia) resulting from damage to left lateral brain areas also have considerable difficulty executing novel sequences of hand and arm movements (apraxia). By electrically stimulating the brains of patients being operated on for epilepsy, George A. Ojemann of the University of Washington has also shown that at the center of the left lateral areas specialized for language lies a region involved in listening to sound sequences. This perisylvian region seems equally involved in producing oral-facial movement sequences—even nonlanguage ones.

These discoveries reveal that the "language cortex," as people sometimes think of it, serves a far more generalized function than had been suspected. It is concerned with novel sequences of various kinds: both sensations and movements, for both the hands and the mouth. The big problem with fashioning new sequences and producing original behaviors is safety. Even simple reversals in order can be dangerous, as in "Look after you leap." Our capacity to make analogies and mental models gives us a measure of protection, however. Humans can simulate future courses of action and weed out the nonsense off-line; as philosopher Karl Popper said, this "permits our hypotheses to die in our stead." Creativity—indeed, the entire high end of intelligence and consciousness—involves playing mental games that improve the quality of our plans. What kind of mental machinery might it take to do something like that?

Natural Selection in the Brain

By 1874, just 15 years after Charles Darwin published *On the Origin of Species by Means of Natural Selection,* American psychologist William James was talking about mental processes operating in a Darwinian manner. In effect, he suggested, ideas might somehow "compete" with one another in the brain, leaving only the best or "fittest." Just as Darwinian evolution shaped a better brain in two million years, a similar Darwinian process operating within the brain might shape intelligent solutions to problems on the timescale of thought and action.

Researchers have demonstrated that a Darwinian process operating on a timescale of days governs the immune system. Through a series of cellular generations spanning several weeks, the immune system produces defensive antibody molecules that are better and better "fits" against invaders. By abstracting the essential features of a Darwinian process from what is known about species evolution and immune responses, we can see that any "Darwin machine" must have six properties.

First, it must operate on patterns of some type; in genetics, they are strings of DNA bases, but the patterns of brain activity associated with a thought might qualify. Second,

DUOMO

BALLISTIC ARM MOVEMENTS, such as those displayed by New York Yankees pitcher David Wells, are so rapid that the brain must plan the sequence of muscle contractions in advance. Some of the neural mechanisms that plan such movements may also facilitate other types of planning.

copies must somehow be made of these patterns. Third, patterns must occasionally vary, either through mutations, copying errors or a reshuffling of their parts. Fourth, variant patterns must compete to occupy some limited space (as when bluegrass and crabgrass compete for my backyard). Fifth, the relative reproductive success of the variants must be influenced by their environment; this result is what Darwin called natural selection. And finally, the makeup of the next generation of patterns must depend on which variants survive to be copied. The patterns of the next generation will be variations based on the more successful patterns of the current generation. Many of the new variants will be less successful than their parents, but some may be more so.

Let us consider how these principles might apply to the evolution of an intelligent guess inside the brain. Thoughts are combinations of sensations and memories—in a way, they are movements that have not happened yet (and maybe never will). They take the form of cerebral codes, which are spatiotemporal activity patterns in the brain that each represent an object, an action or an abstraction. I estimate that a single code minimally involves a few hundred cortical neurons within a millimeter of one another, either keeping quiet or firing in a musical pattern.

Evoking a memory is simply a matter of reconstituting such an activity pattern, according to the cell-assembly hypothesis of psychologist Donald O. Hebb [see "The Mind and Donald O. Hebb," by Peter M. Milner; SCIENTIFIC AMERICAN, January 1993]. Long-term memories are frozen patterns waiting for signals of near resonance to reawaken them, like ruts in a washboarded road waiting for a passing car to re-create a bouncing spatiotemporal pattern.

Some "cerebral ruts" are permanent, whereas others are short-lived. Short-term memories are just temporary alterations in the strengths of synaptic connections between neurons, left behind by the last spatiotemporal pattern to occupy a patch of cortex; they fade in a matter of minutes. The transition from short- to long-term memory is not well understood, but it appears to involve structural alterations in which the synaptic connections between neurons are made strong and permanent, hardwiring the pattern of neural activity into the brain.

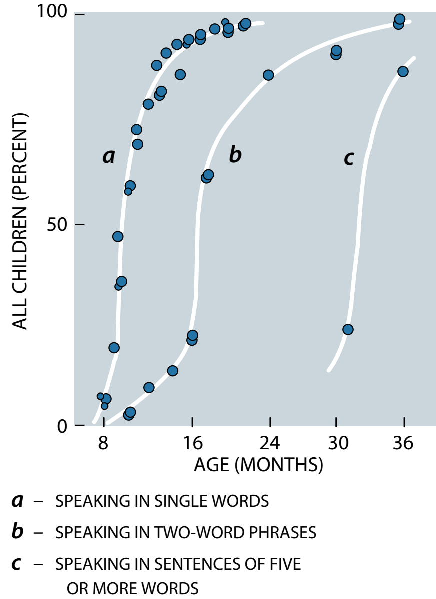
A Darwinian model of mind suggests that an activated memory can compete with others for "workspace" in the cortex. Both the perceptions of the thinker's current environment and the memories of past environments may bias that competition and shape an emerging thought. An active cerebral code moves from one part of the brain to another by making a copy of itself, much as a fax machine re-creates a pattern on a distant sheet of paper. The cerebral cortex also has circuitry for copying spatiotemporal patterns in an adjacent region less than a millimeter away, although present imaging techniques lack enough resolution to see it in progress. Repeated copying of the minimal pattern could colonize a region, rather the way that a crystal grows or wallpaper repeats an elementary pattern.

The picture that emerges from these theoretical considerations is one of a quilt, some patches of which enlarge at the expense of their neighbors as one code copies more successfully than another. As you try to decide whether to pick an apple or a banana from the fruit bowl, so my theory goes, the cerebral code for "apple" may be having a cloning competition with the one for "banana." When one code has enough active copies to trip the action circuits, you might reach for the apple. But the banana codes need not vanish: they could linger in the background as subconscious thoughts. Our conscious thought may be only the currently dominant pattern in the copying competition, with many other variants competing for dominance, one of which will win a moment later when your thoughts seem to shift focus.

It may be that Darwinian processes are only the frosting on the cognitive cake, that much of our thinking is routine or rule-bound. But we often deal with novel situations in creative ways, as when you decide what to fix for dinner tonight: You survey what's already in the refrigerator and on the kitchen

MICHAEL NICHOLS

KANZI, A BONOBO, has been reared at Georgia State University in a language-using environment. By pointing at symbols that represent words, Kanzi constructs requests much like those of a two-year-old child. His comprehension is as good as that of a two-and-a-half-year-old. Language experiments with bonobos investigate how much of syntax is uniquely human.



JOHNNY JOHNSON

ACQUISITION OF LANGUAGE by children occurs quickly and naturally through exposure to adults. By the age of three years, the great majority of children are able to construct simple sentences.

shelves. You think about a few alternatives, keeping track of what else you might have to fetch from the grocery store. All of this can flash through your mind within seconds—and that's probably a Darwinian process at work.

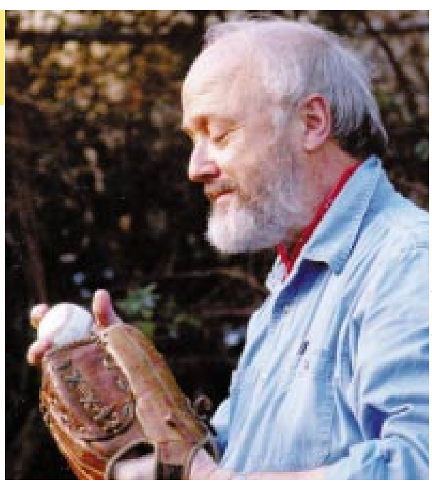
Bootstrapping Intelligence

In both its phylogeny and ontogeny, human intelligence first solves movement problems and only later graduates to ponder more abstract ones. An artificial or extraterrestrial intelligence freed of the necessity of finding food and avoiding predators might not need to move—and so might lack the "what happens next" orientation of human intelligence. It is difficult to estimate how often high intelligence might emerge, given how little we know about the demands of long-term species survival and the courses evolution can follow. We can, however, evaluate the prospects of a species by asking how many elements of intelligence each has amassed. Chimps and bonobos may be missing a few of the elements—the ability to construct nested sentences, for example—but they are doing better than the present generation of artificial-intelligence programs.

Why aren't there more species with such complex mental states? There might be a hump to get over: a little intelligence can be a dangerous thing. A beyond-the-apes intelligence must constantly navigate between the twin hazards of dangerous innovation and a conservatism that ignores what the Red Queen explained to Alice in *Through the Looking Glass:* "It takes all the running you can do, to keep in the same place." Foresight is our special form of running, essential for the intelligent stewardship that Stephen Jay Gould of Harvard warns is needed for longer-term survival: "We have become, by the power of a glorious evolutionary accident called intelligence, the stewards of life's continuity on earth. We did not ask for this role, but we cannot abjure it. We may not be suited to it, but here we are." SA

About the Author

WILLIAM H. CALVIN's career has taken a Darwinian course: his scientific interests have evolved significantly over the past four decades. He studied physics as an undergraduate at Northwestern University but devoted his spare time to a research project exploring how the brain processes color vision. This project led to graduate work in neuroscience at the Massachusetts Institute of Technology and Harvard Medical School, then to a Ph.D. in physiology and biophysics from the University of Washington in 1966. His early research focused on neuron-firing mechanisms. "I wiretapped neurons, trying to figure out how they transformed information," he says. But in the 1980s he took on a bigger question—how the human brain evolved—and his interests broadened to include anthropology, zoology and psychology. He has written several acclaimed books, including *The Cerebral Code, How Brains Think* and (with George A. Ojemann) *Conversations with Neil's Brain.* "The puzzles I'm trying to solve require information from many different fields," he says. Calvin is currently a theoretical neurophysiologist on the faculty of the University of Washington School of Medicine.



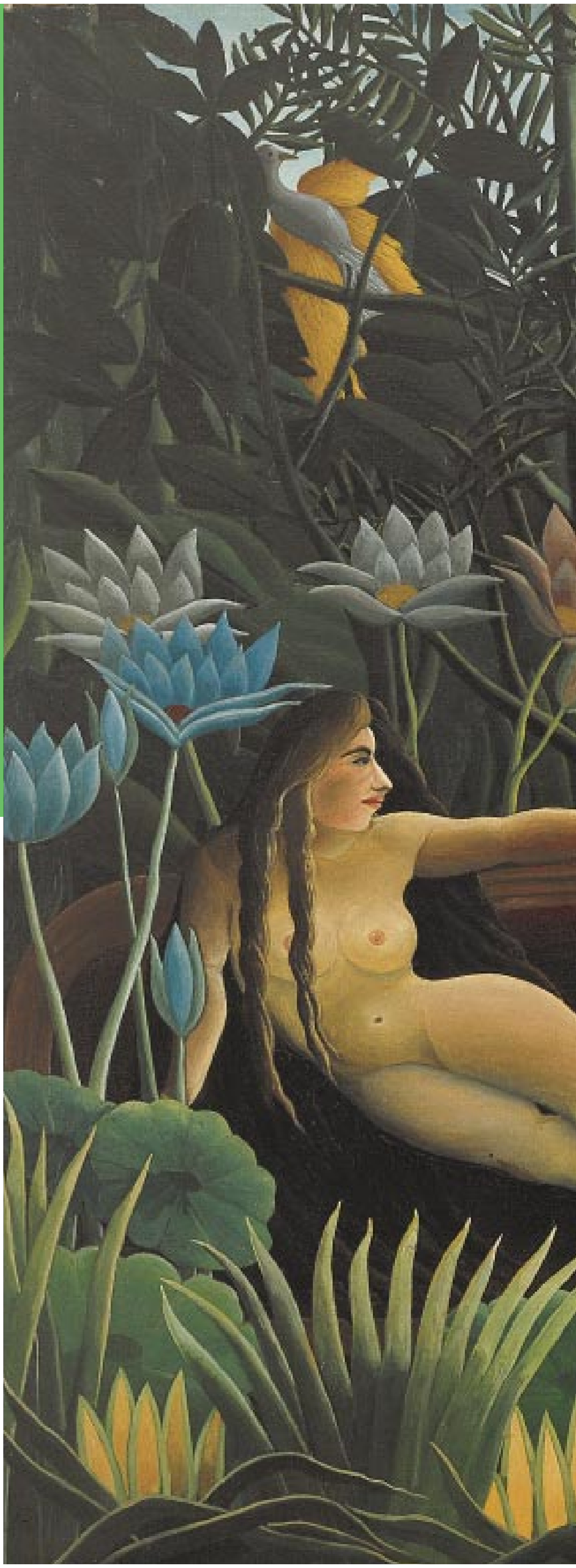
DOUG VANDERHOOF *Modern Media*

ANIMAL

Reasoning in Animals

A mounting body of evidence suggests that a number of species can infer concepts, formulate plans and employ simple logic in solving problems

by James L. Gould and Carol Grant Gould



COURTESY OF THE MUSEUM OF MODERN ART, NEW YORK

The ability to think and plan is taken by many of us to be the hallmark of the human mind. Reason, which makes thinking possible, is often said to be uniquely human and thus sets us apart from the beasts. In the past two decades, however, this comfortable assumption of intellectual superiority has come under increasingly skeptical scrutiny. Most researchers now at least entertain the once heretical possibility that some animals can indeed think. At the same time, several of the apparent mental triumphs of our species—language, for instance—have turned out to owe as much to innate programming as to raw cognitive power.

This reversal of fortune for the status of human intellectual uniqueness follows nearly a century of academic neglect. The most devastating and long-lasting blow to the idea of animal intelligence stemmed from the 1904 incident of Clever Hans the horse. Oskar Pfungst, the researcher who unraveled the mystery of an animal that seemed as intelligent as many humans, described the situation vividly: "At last the thing so long sought for was apparently found: a horse that could solve arithmetical problems—an animal, which thanks to long training, mastered not merely rudiments, but seemingly arrived at

***The Dream,* by Henri Rousseau**

a power of abstract thought which surpassed, by far, the highest expectation of the greatest enthusiast." Hans could also read and understand spoken German.

After expert groups had tested the horse (often in the absence of his owner, Mr. von Osten) and agreed that no trickery could be involved, Pfungst undertook to study the animal in detail. After many months, he discovered the true source of Hans's cleverness: the animal watched for slight involuntary cues that invariably arose from his audience as he approached the correct number of taps of his hoof.

The consequence of a mere horse having "tricked" the philosophical establishment was a wholesale retreat from work on animal thinking: before the incident, it had been common to attribute reason and thought to animals. British comparative psychologist George J. Romanes, in his 1888 book *Animal Intelligence,* set the bar so low that even shellfish could be said to be rational, as when "we find, for instance, that an oyster profits by individual experience, or is able to perceive new relations and suitably to act upon the result of its perceptions." In short, Romanes felt that if instinct is not at work, reason must be.

As a result of the Clever Hans incident, however, the behaviorist school of psychology came to dominate experiments on animal behavior in the English-speaking world. This reactionary perspective denied the existence of instinct, consciousness, thought and free will not only in animals but in humans as well. As the founder of behaviorism, American psychologist John B. Watson, put it in 1912 (in characteristically uncompromising terms), "Consciousness is neither a definite nor a usable concept.... [B]elief in the existence of consciousness goes back to the ancient days of superstition and magic."

For Watson, all human and animal behavior was the result of conditioning—even breathing and the circulation of the blood. From his perspective, humans do not really think, although they may form "verbal habits"—highly rational ones—with proper training. In the absence of words, Watson believed, animals could not possibly think. Species-specific behaviors—nest building by birds, for instance—were a result of the particular anatomy of a species, the habitat into which it was born and the experiences individuals typically underwent as they grew up.

And contrary to Romanes's view, the behaviorist felt that even learning can be mindlessly automatic, requiring no comprehension on the part of the "student." Classical conditioning simply associates an innate stimulus-response reflex with a novel stimulus. Thus, it is possible to teach a dog that a bell or a flashing light means food. The other form of learning in the behaviorist worldview—operant conditioning—merely requires animals to discover by trial and error which of their movements are rewarded and to use these data to fashion novel behavior patterns. No understanding is needed in either case. Even the subsequent discovery of species-specific learning programs (learning that is initiated and controlled by instinct) did little to alter this passive-learning-machine view of animals, although it did deliver a fatal blow to behaviorism itself [see "Learning by Instinct," by James L. Gould and Peter Marler; SCIENTIFIC AMERICAN, January 1987].

The pervasive behaviorist taboo against investigating whether animals can think, however, has persisted. Only the publication of Donald R. Griffin's highly provocative and controversial 1976 book, *The Question of Animal Awareness,* has begun to erode it. Like most of our colleagues trained in the "don't ask, don't tell" intellectual atmosphere of the first three quarters of the century, we were astonished at first that anyone would risk raising this academically dangerous issue—least of all someone with Griffin's distinguished scientific credentials. His 1984 *Animal Thinking* and 1992 *Animal Minds* have widened the scope of his assault on conventional wisdom, but the shocked outrage in academia seems to have subsided into a civilized mixture of skepticism and interest. Maybe, after all, some animals might sometimes formulate simple plans. But how can we know?

What Criteria for Thought?

The kinds of behavior that Romanes found convincing no longer seem very persuasive. For instance, the highly complex nest-building routines in birds and insects are known to be largely or entirely innate: individuals reared in isolation will nonetheless select appropriate nest sites, gather suitable material and fashion it into the kind of nest that wild-reared individuals of the species create. True, nest building often improves with practice and site selection benefits from experience, but the basic elements of the behavior are in place before the animal sets to work. Indeed, it is possible that the kinds of complex adaptive behavior that so impress us are just the types of behavior that *must* be innate, simply because they would be impossible to learn from scratch.

And as the behaviorists showed, learning can be automatic, too. In fact, conditioning seems to involve an innate and complex weighing of probabilities—computing the chance that a particular stimulus predicts the prompt appearance of an innate cue versus the chance it does not. Although it is possible that a duckling imprinting on its parents understands what it is doing and why, the behavior of a young bird following a toy train that was presented during the animal's critical period does not suggest any necessary comprehension. Thus, learning to modify behavior in the face of experience is not by itself clear evidence of thinking.

Similarly, the frequently cited cases of apparent insight in animals, such as the outbreak of cream-robbing behavior among blue tits in England in the 1930s, may not mean what they seem to mean. When unhomogenized milk was delivered to the doorstep early each morning, a layer of cream would rise to the top of the glass bottles. Blue tits, British cousins of the chickadee, would remove the foil cap and sample the cream before the bottles were taken in. The inviting idea that some cagey

COURTESY OF THE NEW YORK PUBLIC LIBRARY

MR. VON OSTEN AND CLEVER HANS, his horse, stunned the world in the 1900s with the claim that Hans could do arithmetic, spell and even understand German. Hans was actually responding to subtle cues of the people observing him.

bird had figured out this ploy and taught it to its friends ignores the natural history of the species: tits make their living peeling bark off trees to find insect larvae. So compulsive is their need to peel that hand-reared tits often strip the wallpaper from their owners' rooms in a presumably unrewarded search for insects. Perhaps the first blue tit to harvest cream from a milk bottle was outstandingly stupid rather than amazingly bright, having mistaken a bottle for a tree trunk.

Another common example is termite fishing among chimpanzees. Some adult chimps strip long twigs of leaves and insert them into the holes in termite mounds. When they withdraw the twig, they eat the termites that cling to it. Photographs frequently show a younger chimp appearing to study the behavior before trying it. But observations of lab-born chimpanzees reveal that chimps in general are obsessed with putting long, thin objects into holes—pencils into electrical outlets, for instance. As with the blue tits, the behavior seems to be innate, and only knowing the proper place to perform it need be conditioned.

Early Hints of Thinking

To infer that an animal can think, therefore, enough must be known about the natural history and innate behavioral propensities of the species, as well as the individual history of the animal in question, to be able to exclude both instinct and conditioning as the source of a novel behavior. Before the current rebirth of interest in animal thinking, a few controversial studies suggested that animals might be able to plan actions in advance. They guide much of the experimental thinking that continues today.

In 1914 German psychologist Wolfgang Köhler was working at a primate research center on the Canary Islands. He presented his captive chimps with novel problems; often the pattern of solution suggested insight rather than trial and error. For instance, when Köhler first hung a bunch of bananas out of reach, the chimpanzee being observed made a few useless leaps, then went off to a corner and "sulked." But in time he looked back at the bananas, then around the large outdoor enclosure at the various objects he had to play with, back to the bananas, back to one specific toy (a box), then ran directly to the box, dragged it under the fruit, climbed on top, leaped up and grabbed the prize.

In other variations the bananas were mounted higher, and the same pattern of seemingly sudden insight appeared, whether it involved stacking boxes, joining sticks to make a pole long enough to knock down the fruit or using a single stick from atop one box. Criticisms of Köhler's work focused on two important points: the prior experience of these wild-caught animals was unknown (so they might be remembering a solution they had learned in the wild), and lab-reared chimps spontaneously pile boxes (which they then climb and use as jumping platforms) and also fit sticks together to make poles.

Well-controlled planning tests that avoided these problems were performed by Edward C. Tolman of the University of California at Berkeley in the 1940s. He would allow a rat to explore an experimental maze with no differential reinforcement—a T-maze, for example, with the same food reward at the end of each arm—but something the animal did not need to learn, and had not been trained to learn, would be different at each end. In one instance, the left arm ended in a dark, narrow box, whereas the right arm terminated in a wide, white box. (Rats inherently prefer dark, narrow boxes.) On another day the rat was taken to a different room, placed in a dark,

COURTESY OF THE NEW YORK PUBLIC LIBRARY

PROBLEM SOLVING IN CHIMPS, in this case, stacking boxes to reach bananas, was first documented by Wolfgang Köhler around the time of World War I.

narrow box and electroshocked. On a subsequent day the rat was returned to the original maze. Conditioning theory predicts that the rat, not having been trained to any behavior in the maze, would explore at random. Alternatively, it might have learned the location of the innately preferred dark, narrow box. The rat, however, went directly to the right end of the maze and its white box.

The rat, Tolman concluded, had used two independent and apparently unrelated experiences to form a plan on the third day. He called this plan a "cognitive map." Applying this perspective to Köhler's chimps, even if they had previously played with boxes and sticks in another context, to move the box under the bananas without any apparent trial and error would require enough insight to link the knowledge of what could be done with boxes to information on the desirability of bananas. In the absence of trial-and-error conditioning, the chimps had to conceive and execute a simple plan. This, at its most basic level, is evidence of animal thought.

Skeptics, however, found elaborate explanations for Tolman's results. For instance, one critic countered that rats are afraid of mazes; hence, removal of the rat from the maze when it reached one of the end boxes was actually a reward that triggered learning. When returned to the maze, the rat knew its best chance of a reward (escape) was to go to the box it had been taken from before. By chance, that was the white box.

Cognitive Maps

Although there is good evidence for cognitive maps in creatures as phylogenetically remote as honeybees and jumping spiders, work on animal thinking has centered on birds and primates. One important line of evidence is the apparent ability of some animals to form concepts. The remarkable abilities of Alex the parrot, studied by Irene M. Pepperberg of the University of Arizona, provide one clear example (see her article on page 60). Another, involving pigeons, was pioneered by the late Richard J. Herrnstein of Harvard University (perhaps now better known as the co-author of *The Bell Curve*). His technique was to provide lab-reared pigeons with a carousel of slides, half with some example of the class of target objects—trees, perhaps, or fish or oak leaves. The birds were then rewarded with food for pecking at any slide that contained, say, a tree. Learning was slow until the birds appeared to figure out what the rewarded slides had in common. Under some conditions, the pigeons would resort to memorizing the full rewarded set of slides, revealing an astonishing ability to recall hundreds of pictures. In most cases, however, they caught on to the common feature, demonstrating their knowledge by responding correctly to an entirely new set of slides.

Because of the huge range of variation among possible examples, a concept such as "tree" is difficult to formulate. There is no list of necessary and sufficient features, because we (and pigeons) recognize trees both with and without leaves, with and without central trunks, with and without substantial side branching, close up and far away, isolated or in dense stands, with standard green or ornamental reddish leaves, and so on. For humans (and presumably for birds), a concept includes a list of properties that have individually predictive probabilities: leaves are highly correlated, for instance, whereas long, thin extensions have a lower (but still positive) association value. A tree is any object that has a sufficient "score" of individual properties—one high enough to exclude telephone poles and television antennas. Many philosophers used to accept concept formation as proof of thought; with the data on pigeons in hand, some have backed away from that criterion.

Many birds formulate and use mental maps of their home area. The ability to devise a novel route to get from one familiar location to another is often taken as a literal example of a cognitive map. Whereas many, perhaps most, birds have local-area maps, few are as spectacular as those of the African honeyguide, which makes its living feeding on the larvae and wax of bees.

The honeyguide has formed a symbiotic relationship with both honey badgers (powerful, intelligent animals that are very fond of honey) and humans. The bird locates a potential hive opener—badger or human—and attempts to "recruit" it through highly visible and audible displays. One of the two most common signals it uses is an onomatopoeic call that resembles the sound of tearing bark. Having engaged the attention of a suitable helper, the honeyguide makes short flights in the approximate direction of its target and calls again; if the helper fails to follow, the bird returns and tries again, perhaps with a shorter flight and louder calls this time. Once at the nest (which is generally a quarter- to a half-mile away), the honeyguide waits while the badger or human it has led there breaks open the hive. The bird moves in for the larvae and wax after the hive opener has left.

Numerous experiments have shown that honeyguides know the location of several hives and usually guide their accomplices to the nearest one—generally, by as direct a route as the landscape allows. In one of the most interesting experiments, the human "helper" followed the bird but insisted on walking steadily past the tree containing the hive. The honeyguide would first attempt to draw the person back to the tree; next the bird would change tactics and try to lead the human


J. MARKHAM *Bruce Coleman Inc.*

CREAM-ROBBING BEHAVIOR of blue tits, an outbreak of which occurred in 1930s Britain, was probably not as ingenious as it first seemed: the birds naturally peel bark off trees in search of insect larvae.

on to another hive in the approximate direction of travel. The seemingly inescapable conclusion is that honeyguides know the location of many colonies over a fairly wide area.

Distracting Predators and Getting Food

Flexibility in the use of innate alternatives may also be evidence for simple thinking. Two groups of ground-nesting birds, killdeers and plovers, have a variety of distraction ruses that are used to lure potential predators away from their eggs. Each display begins with the bird leaving the nest and moving inconspicuously to a location well away from its eggs. The set of possible performances ranges from simply calling from a highly visible spot to the complex feigning of a broken wing. There is even a highly realistic rodent-imitation ploy in which the bird scoots through the underbrush rustling provocatively and uttering mouselike squeaks. Each species also has a separate "startle" display designed to keep harmless animals such as deer from stumbling into the nest.

Anecdotal reports have suggested that the decision to leave the nest to perform a display, as well as which display to employ, are suited to the degree of predator threat. A fox heading directly toward the nest, for example, is more likely to get the high-intensity broken-wing performance. Carolyn Ristau of Columbia University put this reported ability to gauge threats to a test by having distinctively dressed humans walk in straight lines near plover nests. Some were told to scan the ground carefully, apparently searching for nests, whereas others were instructed to pay no attention to the ground. As time went on, the plovers began to discriminate between the potential hunters and the seemingly harmless humans: they did not even bother to leave the nest for the latter group but performed elaborate distraction displays for the former. Some degree of understanding seems evident in this ability to judge which innate response to select.

Two well-studied cases of unusual foraging behavior in birds also suggest an ability to plan. One involves green herons, birds that capture fish using several (presumably inborn) approaches. In addition, occasional herons have been observed bait fishing. They toss a morsel of food or a small twig into the water, and when a curious fish rises to investigate, the bird grabs it. Bait fishing has been observed in a few widely scattered spots in the U.S. and in a park in Japan. It appears on its own, seems (except once in Japan) not to spread to other birds and then vanishes. Given the high success rate of the technique, and yet the rarity of its use, it is improbable that bait fishing is genetically programmed; most likely the trick has been independently invented by many different herons.

A more controlled study on the ontogeny of novel foraging techniques was performed by Bernd Heinrich of the University of Vermont. He maintained five hand-reared ravens in a flight enclosure and thus knew just what kinds of learning opportunities had been available to the birds. He tested them with pieces of meat hung by strings from perches. The strings were far too long to allow a raven on the perch to simply reach down and grab the meat. The birds attempted to capture the food in midair by flying up to it, but it was secured too well for this approach to work. After repeated failed attempts, the ravens, like Köhler's chimps, ignored the food.

Six hours after the test began, one raven suddenly solved the problem: it reached down, pulled up as much string as it could manage, trapped this length of string in a pile between its foot and the perch, reached down again, trapped the next length of string under its claws and so on until it had hauled the meat up to the perch. Again, as with Köhler's chimps, there was no period of trial and error.

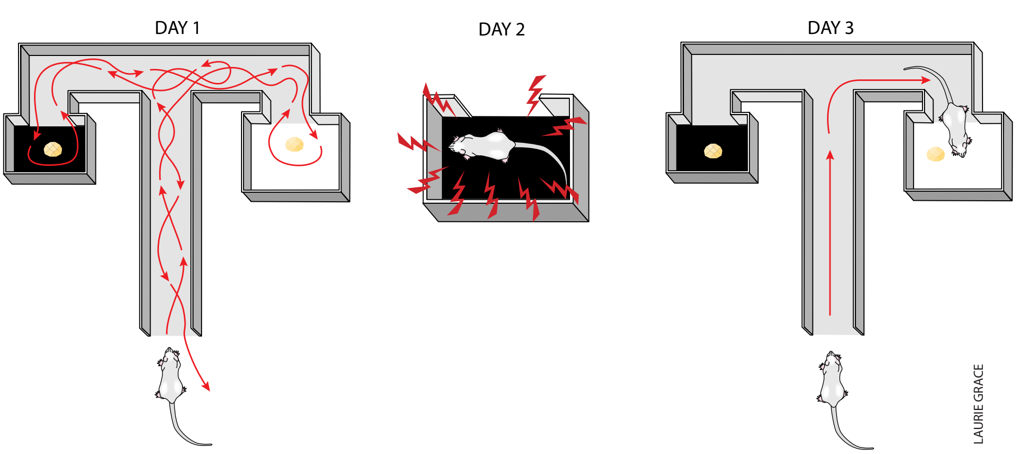
After several days, a second raven solved the problem. Even though it had had ample opportunity to observe the first bird's repeated successes, this individual pulled up the string, then stepped along the perch, arraying the string in a line rather than a pile. It trapped the string under a foot, reached down and moved over again and again until the string was stretched out along the perch and the meat was within reach. Other birds' solutions of the problem involved looping the string onto the perch. One bird never discovered how to obtain the meat; interestingly, this was also the one individual that never learned that flying away with the tied-down meat led to a nasty jerk when the food reached the end of its tether.

TERMITE FISHING by chimpanzees is accomplished by inserting a stripped twig into a termite mound and then eating the insects that cling to it. As with blue tits, however, the behavior seems innate, and only knowing the proper place to perform it needs to be conditioned.

Learning and Play

It may seem surprising that the ravens did not seem to learn from one another but instead appeared to solve the problem independently. In fact, there is very little evidence for observational learning outside of primates. Most (some would say all) of what researchers have initially assumed was observational acquisition of a technique has turned out to be "local enhancement": learning where other animals congregate, not how they harvest what they find there. Bottle opening in blue tits spread quickly because the birds learned from others *where* cream was to be found and had been born with the technique for peeling back the lid.

As longtime cat and dog enthusiasts, we were originally as dubious as many readers probably are of the idea that animals rarely, if ever, learn to copy behavior. A cat, for instance, that



FORMING A FUTURE PLAN, or a "cognitive map," was demonstrated in rats in the 1940s. On the first day, rats were allowed to explore a maze that terminated with food in a narrow, dark box and in a wide, light box (rats prefer dark boxes). On the next day, the rats were taken to a dark box and electroshocked. On the third day, the rats navigated to the light box, indicating that the rats used two unrelated experiences to form a plan for the third day.

PHOTOGRAPHS BY ROBERT F. SISSON *National Geographic Society*

NOVEL FORAGING TECHNIQUE can develop in animals. Green herons have been seen to toss food or twigs into the water as bait to attract fish to the surface (left). *In a con-*

reaches for a doorknob apparently to obtain help in getting out seems to be imitating part of the human behavior associated with door opening. In fact, however, vertical stretches are part of the innate solicitation behavior of felines. What the cat may have had the insight to do is perform the solicitation at the door when it wants to go out. This example, like so many others of ostensible copying, is a clever application of an innate or conditioned behavior in a novel location via local enhancement.

About the only possible exception to the local-enhancement theory outside of primates comes from work on octopuses. In one test done in 1992, an untrained octopus on one side of a glass partition was allowed to view a trained octopus on the other side choose between two objects that differed in color. Later, when provided with the same choice, the observing octopus selected the same-colored object as the "teacher" animal had about 10 times as often. In other, more demanding experiments, the observer octopus watched while a trained octopus in the adjoining compartment opened a container holding food. When tested, the "student" could open a similar container (using the same technique) much sooner than an untrained peer. These findings, however, are still preliminary; researchers have had difficulty in verifying them fully.

One behavior that intelligent animals appear to share is play, defined as performing seemingly pointless but energetic behaviors that human observers consider (introspectively) playful. Octopuses, for instance, jet at floating objects. Parrots will swim (they prefer the backstroke) and make snowballs. Dolphins and whales leap high in the air for no obvious reason and engage objects on the surface. Ravens will toss rocks to one another in midair—it looks to be a game of catch—and repeatedly slide down snowbanks. And primates are famous for their antics—hanging upside down from a limb over a stream to splash water noisily or covering their eyes with broad leaves to play blindman's buff high overhead in trees. Although we cannot know what is going on in the minds of these creatures, even the most hardened observer must wonder if these are not intelligent but bored animals injecting some excitement into their lives.

Evidence for Primate Thinking

One important aspect of logic is the ability to recognize and act on relations between objects and individuals. Perhaps the first well-documented example of how much animals know about one another came from the work of Robert M. Seyfarth and Dorothy L. Cheney, now at the University of Pennsylvania, on vervet monkeys in Africa [see "Meaning and Mind in Monkeys," by Robert M. Seyfarth and Dorothy L. Cheney; SCIENTIFIC AMERICAN, December 1992]. Dominance interactions had already suggested that each monkey understood the position of every other vervet in the troop hierarchy. Seyfarth and Cheney performed numerous ingenious experiments to investigate what individual vervets knew. They discovered that the monkeys also kept track of each infant's mother and her social status. When the researchers played recordings they had made of various infants' distress calls, the infant's mother would look in the direction of the hidden loudspeaker, while all the other females would look at the mother.

The logical operations that support the behavior specific to individual vervets are essential to the social calculus of the group. Studies by Frans B. M. de Waal of Yerkes Regional Primate Research Center and Emory University on the intricate social maneuvering that goes on in captive chimpanzee troops show how this kind of knowledge can be exploited. More dramatic, however, are his descriptions of the chimpanzees' use of deceit, which had been reported from the wild by the naturalist Jane Goodall.

The master of dissimulation in one of de Waal's troops was a (then) low-ranking male named Dandy. Usually alpha males do not permit other males to mate with females. Dandy and his special female friend would meet as if by chance behind rocks or brush. The simultaneous disappearance of a female and a low-ranking male usually provokes suspicion in alphas, but Dandy and his date would choose cover that hid only their lower bodies. They would mate while pretending to forage, and the female would suppress the shrieks that accompany typical chimpanzee intercourse.

Dandy also took advantage of distractions to mate or would even create them himself, as when he once rushed to the front of the enclosure and began screaming at the passing humans. The alphas hurried to see what was going on, and Dandy slipped away in the confusion. Another time Dandy observed a low-ranking male courting his own special female. Instead of throwing a tantrum—the usual response to this kind of affront—Dandy fetched the nearest alpha and allowed him to deal decisively with the transgressor.

BERND HEINRICH

trolled study, ravens had to figure out how to retrieve a piece of meat dangling on a string from the perch (right). *Most developed unique ways to pull up the string.*

These and many other instances of Dandy's expert use of social logic imply an ability to think and plan—even scheme—at an impressive level. Combined with other extensive observations of chimpanzees in both the wild and more controlled seminatural enclosures, these examples strongly implicate an evolutionary continuity in the ability to analyze situations and imagine solutions. Without words, the mental operations involved may be of necessity pictorial; language doubtless permits our species to contrive far more elaborate plans, not to mention fantasies and self-delusions.

Humans in Perspective

Language has played a dominant role in discussions about thinking and consciousness. Some philosophers go so far as to assert that language is uniquely and essentially human, a creation of a conscious intellect, a tool necessary to planning and thought. The discovery of symbolic languages in animals ranging from vervets to honeybees has been sobering; the almost overwhelming evidence for nonverbal planning has further blunted the authority of such sweeping generalizations. But nothing has been as deflating to the human self-image as the discovery that consonant recognition, language processing and even grammar are largely innate [see "The Perception of Speech in Early Infancy," by Peter D. Eimas; SCIENTIFIC AMERICAN, January 1985; "Creole Languages," by Derek Bickerton; SCIENTIFIC AMERICAN, July 1983; and "Specializations of the Human Brain," by Norman Geschwind; SCIENTIFIC AMERICAN, September 1979].

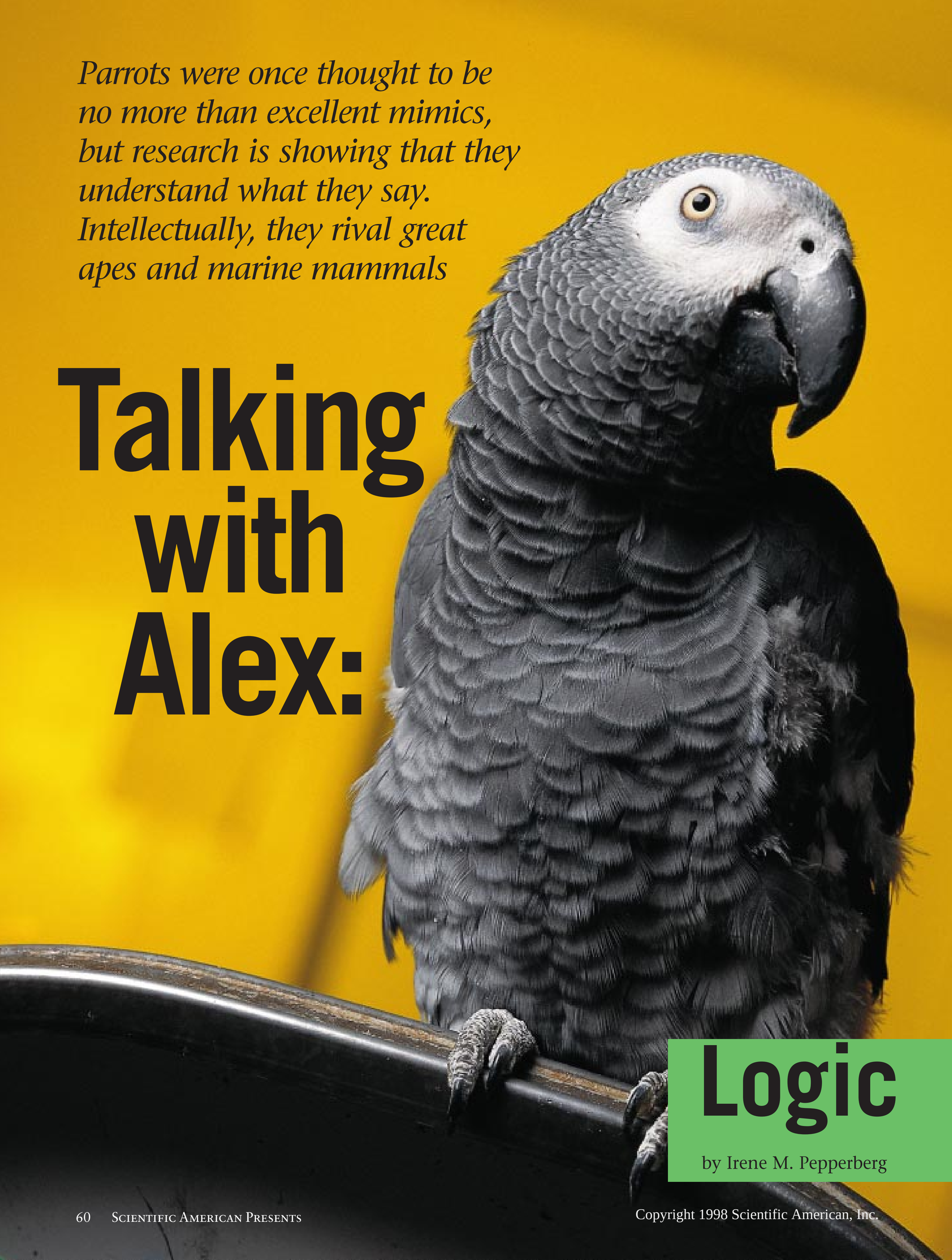
Our uniqueness as a species, it would seem, depends on a genetic specialization not obviously more elaborate than the one that confers the power of echolocation on bats. But language empowers what already appears to be a phylogenetically widespread ability to reason and plan with an evolutionarily new capacity for elaboration, communication and coordination that has catapulted our species into a position of astonishing intellectual potential. When we look at the fascinating fauna with which we share the planet, we should recall that but for the fickle logic of evolution, our species would be just another variety of conniving, inarticulate primates. SA

About the Authors

CLARE H. GOULD

JAMES L. GOULD and CAROL GRANT GOULD have co-authored many articles and books on animal behavior. James Gould became interested in animal behavior in the 1960s, when he was a young draftee at a U.S. military base in Germany. Spending his off-duty hours in the library, he one day picked up a copy of *King Solomon's Ring,* by Konrad Lorenz, the Austrian ethologist perhaps best known for his studies on imprinting in birds. When Gould returned to college at the California Institute of Technology, he signed up for a course in animal behavior. He went on to get his Ph.D., studying learning in honeybees with Donald R. Griffin at the Rockefeller University. Although he enjoys working on animal cognition, Gould doesn't recommend cutting one's academic teeth on such a controversial problem. "Studying animal intelligence is no longer tantamount to professional suicide, but it used to be," he says. As a professor of ecology and evolutionary biology at Princeton University, Gould is now studying how females choose their mates—particularly among guppies, mollies and other tropical fish.

Carol Grant Gould got her Ph.D. in Victorian literature from New York University and often joins Jim in the field, whether tracking birds in upstate New York or watching whales in Argentina. "When you're married to a field biologist, you have to become a biologist by association if you ever want to see your spouse," she says. "Fortunately, learning biology, like studying literature, opens fascinating new windows on life." Carol is a science writer by profession and teaches English at a private high school in Princeton, N.J. Besides writing projects, they have also collaborated to produce two kids and enjoy biking, canoeing and hanging out in Princeton.



Parrots were once thought to be no more than excellent mimics, but research is showing that they understand what they say. Intellectually, they rival great apes and marine mammals

Talking with Alex: Logic

by Irene M. Pepperberg

Bye. I'm gonna go eat dinner. I'll see you tomorrow," I hear Alex say as I leave the laboratory each night. What makes these comments remarkable is that Alex is not a graduate student but a 22-year-old Grey parrot.

Parrots are famous for their uncanny ability to mimic human speech. Every schoolchild knows "Polly wanna cracker," but the general belief is that such vocalizations lack meaning. Alex's evening good-byes are probably simple mimicry. Still, I wondered whether parrots were capable of more than mindless repetition. By working with Alex over the past two decades, I have discovered that parrots can be taught to use and understand human speech. And if communication skills provide a glimpse into an animal's intelligence, Alex has proved that parrots are about as smart as apes and dolphins.

When I began my research in 1977, the cognitive capacity of these birds was unknown. No parrot had gone beyond the level of simple mimicry in terms of language acquisition. At the time, researchers were training chimps to communicate with humans using sign language, computers and special boards decorated with magnet-backed plastic chips that represent words. I decided to take advantage of parrots' ability to produce human speech to probe avian intelligence.

My rationale was based on some similarities between parrots and primates. While he was at the University of Cambridge, Nicholas Humphrey proposed that primates had acquired advanced communication and cognitive skills because they live and interact in complex social groups. I thought the same might be true of Grey parrots (*Psittacus erithacus*). Greys inhabit dense forests and forest clearings across equatorial Africa, where vocal communication plays an important role. The birds use whistles and calls that they most likely learn by listening to adult members of the flock.

Further, in the laboratory parrots demonstrate an ability to learn symbolic and conceptual tasks often associated with complex cognitive and communication skills. During the 1940s and 1950s, European researchers such as Otto D. W. Koehler and Paul Lögler of the Zoological Institute of the University of Freiburg had found that when parrots are exposed to an array of stimuli, such as eight flashes of light, some of them could subsequently select a set containing the same number of a different type of object, such as eight blobs of clay. Because the birds could match light flashes with clay blobs on the basis of number alone means that they understood a representation of quantity—a demonstration of intelligence.

But other researchers, including Orval H. Mowrer, found that they were unable to teach these birds to engage in referential communication—that is, attaching a word "tag" to a particular object. In Mowrer's studies at the University of Illinois, a parrot might learn to say "hello" to receive a food reward when its trainer appeared. But the same bird would also say "hello" at inappropriate times in an attempt to receive another treat. Because the parrot was not rewarded for using the word incorrectly, eventually it would stop saying "hello" altogether. Some of Mowrer's parrots picked up a few mimicked phrases, but most learned nothing at all.

Because parrots communicate effectively in the wild, it occurred to me that the failure to teach birds referential speech might stem from inappropriate training techniques rather than from an inherent lack of ability in the psittacine subjects. For whatever reason, parrots were not responding vocally to the standard conditioning techniques used to train other species to perform nonverbal tasks. Interestingly, many of the chimpanzees that were being taught to communicate with humans were not being trained with the standard paradigms; perhaps parrots would also respond to nontraditional training. To test this premise, I designed a new method for teaching parrots to communicate.

Go Ask Alex

The technique we use most frequently involves two humans who teach each other about the objects at hand while the bird watches. This so-called model/rival (M/R) protocol is based, in part, on work done by Albert Bandura of Stanford University. In the early 1970s Bandura showed that children learned difficult tasks best when they were allowed to observe and then practice the relevant behavior. At about the same time, Dietmar Todt, then at the University of Freiburg, independently devised a similar technique for teaching parrots to replicate human speech.

In a typical training session, Alex watches the trainer pick up an object and ask the human student a question about it: for example, "What color?" If the student answers correctly, he or she receives praise and is allowed to play with the object as a reward. If the student answers incorrectly, however, the trainer scolds him or her and temporarily removes the object from sight. The second human thus acts as a model for Alex and a rival for the trainer's attention. The humans' interactions also demonstrate the consequences of an error: the model is told to try again or to talk more clearly.

We then repeat the training session with the roles of trainer and model reversed. As a result, Alex sees that communication is a two-way street and that each vocalization is not specific to an individual. In Todt's studies, birds were exposed only to pairs of individuals who maintained their respective roles. As a result, his birds did not respond to anyone other than the human who initially posed the questions. In contrast, Alex will respond to, interact with and learn from just about anyone.

TIMOTHY ARCHIBALD

and Speech in Parrots

ALEX CAN IDENTIFY ITEMS on a tray by shape, color, substance or quantity.

The fact that Alex works well with different trainers suggests that his responses are not being cued by any individual—one of the criticisms often raised about our studies. How could a naive trainer possibly cue Alex to call an almond a "cork nut"—his idiosyncratic label for that treat?

In addition to the basic M/R system, we also use supplemental procedures to enhance Alex's learning. For example, once Alex begins to produce a word describing a novel item, we talk to him about the object in full sentences: "Here's the paper" or "You're chewing paper." Framing "paper" within a sentence allows us to repeat the new word frequently and with consistent emphasis, without presenting it as a single, repetitive utterance. Parents and teachers often use such vocal repetition and physical presentation of objects when teaching young children new words. We find that this technique has two benefits. First, Alex hears the new word in the way that it is used in normal speech. Second, he learns to produce the term without associating verbatim imitation of his trainers with a reward.

We also use another technique, called referential mapping, to assign meaning to vocalizations that Alex produces spontaneously. For example, after learning the word "gray," Alex came up with the terms "grape," "grate," "grain," "chain" and "cane." Although he probably did not produce these specific new words intentionally, trainers took advantage of his wordplay to teach him about these new items using the modeling and sentence-framing procedures described earlier.

Finally, all our protocols differ from those used by Mowrer and Todt in that we reward correct responses with intrinsic reinforcers—the objects to which the targeted questions refer. So if Alex correctly identifies a piece of wood, he receives a piece of wood to chew. Such a system ensures that at every interaction, the subject associates the word or concept to be learned with the object or task to which it refers. In contrast, Mowrer's programs relied on extrinsic reinforcers. Every correct answer would be rewarded with a preferred food item—a nut, for example. We think that such extrinsic rewards may delay learning by causing the animal to confuse the food item with the concept being learned.

Of course, not every item is equally appealing to a parrot. To keep Alex from refusing to answer any question that doesn't involve a nut, we allow him to trade rewards once he has correctly answered a question. If Alex correctly identifies a key, he can receive a nut—a more desirable item—by asking for it directly, with a simple "I wanna nut." Such a protocol provides some flexibility but maintains referentiality of the reward.

What's Different, What's the Same

I began working with Alex when he was 13 months old—a baby in a species in which individuals live up to 60 years in captivity. Through his years of training Alex has mastered tasks once thought to be beyond the capacity of all but humans and certain nonhuman primates. Not only can he produce and understand labels describing 50 different objects and foods but he also can categorize objects by color (rose, blue, green, yellow, orange, gray or purple), material (wood, wool, paper, cork, chalk, hide or rock) and shape (objects having from two to six corners, where a two-cornered object is shaped like a football). Combining labels for attributes such as color, material and shape, Alex can identify, request

TARGET OBJECTS vary and include blocks, letters, numbers and small toys.

PHOTOGRAPHS BY WILLIAM MUÑOZ

DIALOGUE 1

Alex is shown two plant stakes and three keys on a tray.

Trainer: **How many key?**
Alex: **Wood**
Irene (*with back to tray, to trainer*): **Are there any wood?**
Trainer (*to Irene*): **Yes.**
Irene: **Try that.**
Trainer: **Okay, tell me, how many wood?**
Alex: **Two.**
Irene: **Two?**
Trainer: **Yes.**

Alex is given one stake, which he chews apart. It is replaced, and the tray is presented again.

Trainer: **Now, how many key?**
Alex: **Key.**
Trainer: **That's right, keys. How many?**
Alex: **Two wood.**
Trainer: **There are two wood, but you tell me, how many key?**
Alex: **Five.**
Trainer: **Okay, Alex, that's the number of toys; you tell me, how many key?**
Alex: **Three.**
Irene: **Three?**
Trainer: **Good boy! Here's a key.**

DIALOGUE 2

Irene: **Okay, Alex, here's your tray. Will you tell me how many blue block?**
Alex: **Block.**
Irene: **That's right, block...how many blue block?**
Alex: **Four.**
Irene: **That's right. Do you want the block?**
Alex: **Wanna nut.**
Irene: **Okay, here's a nut.** (*Waits while Alex eats the nut.*) **Now, can you tell me how many green wool?**
Alex: **Sisss...**
Irene: **Good boy!**

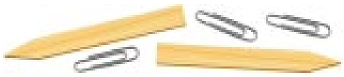
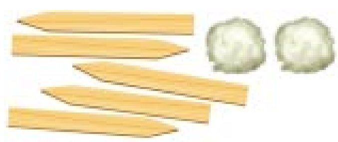
TRANSCRIPTS OF DIALOGUES indicate that Alex can count objects on a tray. Dialogue 1, recorded in 1986, shows that Alex can distinguish five objects of two different types—in this case, plant stakes and keys. Dialogue 2, from 1997, reveals that Alex has become more sophisticated in his ability: presented with a more complex set of objects (photograph), *Alex can count the number of blue blocks and green wool balls without being distracted by the other items on the tray.*

WILLIAM MUÑOZ

and describe more than 100 different objects with about 80 percent accuracy.

In addition to understanding that colors and shapes represent different types of categories and that items can be categorized accordingly, Alex also seems to realize that a single object can possess properties of more than one category—a green triangle, for example, is both green and three-cornered. When presented with such an object Alex can correctly characterize either attribute in response to the vocal queries "What color?" or "What shape?" Because the same object is the subject of both questions, Alex must change his basis for classification to answer each query appropriately. To researchers such as Keith J. Hayes and Catherine H. Nissen, who did related work with a chimpanzee at the Yerkes Regional Primate Research Center at Emory University, the ability to reclassify items indicates "abstract aptitude." On such tests, Alex's accuracy averages about 80 percent.

Alex has also learned the abstract concepts of "same" and "different." When shown two identical objects or two items that vary in color, material or shape, Alex can name which attributes are the same and which are different. If nothing

Object set	Target items	Alex's response	Correct
	Keys	Wood	
	Wood	2	✓
	Rocks	2	✓
	Keys	3	✓
	Wood	2	✓
	Jacks	4	✓
	Yellow wool	4	✓
	Corks	2	✓
	Rocks	Rock	
	Wood	Wool	

GEORGE RETSECK

ALEX'S ACCURACY in identifying the number of targeted items in 1986 was 70 percent (seven out of 10 questions); now Alex is correct more than 80 percent of the time.

about the objects is the same or different, he replies, "None." He responds accurately even if he has not previously encountered the objects, colors, materials or shapes.

Alex is indeed responding to specific questions and not just randomly chattering about the physical attributes of the objects. When presented with a green, wooden triangle and a blue, wooden triangle, his accuracy was above chance on questions such as "What's same?" If Alex were ignoring the question and responding based on his prior training, he might have responded with the label for the one anomalous attribute—"color"—rather than either of the correct answers—"matter" or "shape."

Alex's comprehension matches that of chimpanzees and dolphins. He can examine a tray holding seven different objects and respond accurately to questions such as "What color is object-X?" or "What object is color-Y and shape-Z?" A correct response indicates that Alex understood all parts of the question and used this understanding to guide his search for the one object in the collection that would provide the requested information. His accuracy on such tests exceeds 80 percent.

We also used a similar test to examine Alex's numerical skills. He currently uses the terms "two," "three," "four," "five" and "sih" (the final "x" in "six" is a difficult sound for a parrot to make) to describe quantities of objects, including groupings of novel or heterogeneous items. When we show Alex a "confounded number set"—a collection of blue and red keys and toy cars, for example—he can correctly answer questions about the number of items of a particular color and form, such as "How many blue key?" His accuracy in this test, 83.3 percent, equals that of adult humans who are given a very short time to quantify similarly a subset of items on a tray, according to work done by Lana Trick and Zenon Pylyshyn of the University of Western Ontario.

Alex also comprehends at least one relative concept: size. He responds accurately to questions asking which of two objects is the bigger or smaller by stating the color or material of the correct item. If the objects are of equal size, he responds, "None." Next, we will try to get Alex to tackle relative spatial relations, such as over and under. Such a proposition presents an added challenge because an object's position relative to a second object can change: what is "over" now could be "under" later.

One last bit of evidence reinforces our belief that Alex knows what he is talking about. If a trainer responds incorrectly to the parrot's requests—by substituting an unrequested item, for example—Alex generally responds like any dissatisfied child: he says, "Nuh" (his word for "no"), and repeats his initial request. Taken together, these results strongly suggest that Alex is not merely mimicking his trainers but has acquired an impressive understanding of some aspects of human speech.

Tricks of the Training

What is it about our technique that allows Alex to master these skills? To address that question, we enlisted a few years ago the help of Alo, Kyaaro and Griffin—three other juvenile Grey parrots. Of the many different variations on our technique we tried with these parrots, none worked as well as the two-trainer interactive system.

We attempted to train Alo and Kyaaro using audiotape recordings of Alex's training sessions. The birds also watched video versions of Alex's sessions while they were in isolation (with an automated system providing rewards) or in the presence of trainers who were slightly interactive. Griffin viewed the same videos in the presence of a highly interactive human trainer who rephrased material on the video and questioned the bird directly. Although all three parrots occasionally mimicked the targeted labels presented in the interactive video sessions, they failed to learn referential speech in any of these situations.

When we then trained these birds using the standard M/R protocol, their test scores improved dramatically. In the past two years Griffin, for example, has acquired labels for seven objects and is beginning to learn his colors. The parrots' failure to learn from the alternative techniques suggests that modeling and social interactions are important for maintaining the birds' attention during training and for highlighting which components of the environment should be noted, how new terms refer to novel objects and what happens when questions are answered correctly or incorrectly. All these concepts are critical in training birds to acquire some level of human-based communication.

The M/R technique and some variants have also proved valuable in teaching other species referential communication. Diane Sherman of New Found Therapies in Monterey, Calif., uses the M/R technique for teaching language skills to developmentally delayed children. Even Kanzi, the bonobo (pygmy chimpanzee) trained by Sue Savage-Rumbaugh and her colleagues at Georgia State University, initially learned to communicate with humans via computer by watching his mother being trained—a variant of our modeling technique. Kanzi's abilities are probably the most impressive of all primates' trained to date. Chimpanzees have been taught human-based codes through a variety of techniques; however, apes that were trained using protocols similar to those developed by Mowrer demonstrated communication skills that were far less flexible and less "languagelike" than those of apes trained using systems that had more in common with our techniques.

MODEL/RIVAL PROTOCOL used to teach Alex has the trainer ask the student about objects; a correct response by the student earns praise and possession of the object. In this way, the student acts as a model for Alex and a rival for the trainer's attention. Roles are often reversed to demonstrate that the same person is not always the questioner.

Bird Brains

Alex continues to perform as well as apes and dolphins in tests of intellectual acuity, even though the structure of the parrot brain differs considerably from that of terrestrial and aquatic mammals. Unlike primates, parrots have little gray matter and thus not much of a cerebral cortex, the brain region associated with cognitive processing in higher mammals. Other parts of Alex's brain must power his cognitive function.

The parrot brain also differs somewhat from that of songbirds, which are known for their vocal versatility. Yet Alex has surpassed songbirds in terms of the relative size of their "vocabularies." In addition, he has learned to communicate with members of a different species: humans. With each new utterance, Alex and his feathered friends strengthen the evidence indicating that parrots are capable of performing complex cognitive tasks. Their skills reflect the innate abilities of parrots and suggest that we should remain open to discovering advanced forms of intelligence in other animals. SA

About the Author

PHOTOGRAPHS BY WILLIAM MUÑOZ

IRENE M. PEPPERBERG's work is for the birds—or so the funding agencies first thought. "My early grants came back with pink sheets basically asking what I was smoking," she jokes. Pepperberg actually trained as a theoretical chemist: as a Ph.D. student at Harvard University, she generated mathematical models to describe boron compounds. But an episode of *Nova* featuring "signing" chimps, singing whales and squeaking dolphins drew her to her current work. "I was fascinated to see that people could study animal behavior as a career," she says. Now Pepperberg is an associate professor at the University of Arizona at Tucson, a city that brings tears to her eyes—literally. "I'm allergic to everything that grows in Tucson," Pepperberg says of the trees, grasses, molds and weeds. In 1997 she used the funds from a John Simon Guggenheim Memorial Foundation fellowship to write a book on parrot cognition and communication, *In Search of King Solomon's Ring: Studies on the Communicative and Cognitive Abilities of Grey Parrots* (currently in press).

Alex also has a life in publishing—he is the title character in *Alex and Friends,* a children's book about the animals that have learned to communicate with humans. Through the Internet, you can order a special copy—one that Pepperberg has signed and Alex has chewed. It is available at www.azstarnet.com/nonprofit/alexfoundation/ on the World Wide Web.

Can Animals

Yes

Animals that pass the mirror test are self-aware and thus can infer the states of mind of another individual

by Gordon Gallup, Jr.

I used to tell students that no one ever heard, saw, tasted or touched a mind. There is no way for me to experience your experience, let alone that of a species other than my own. So although minds may exist, they fall outside the realm of science.

I have since changed my mind. A number of years ago I began to study whether primates could recognize themselves in a mirror. Most animals react to their images as if confronted by another animal. But chimpanzees, orangutans and, of course, humans learn that the reflections are representations of themselves—these creatures are objects of their own attention and are aware of their own existence. In the past three decades, I and other researchers have used the mirror test in various ways to explore self-awareness in animals. I conclude that not only are some animals aware of themselves but that such self-awareness enables these animals to infer the mental states of others. In other words, species that pass the mirror test are also able to sympathize, empathize and attribute intent and emotions in others—abilities that some might consider the exclusive domain of humans.

I began exploring self-awareness with mirrors in 1969, when I was at Tulane University. I presented a full-length mirror to preadolescent chimpanzees at the university's Delta Regional Primate Research Center. Initially, they reacted as if they were seeing other chimpanzees, but after a few days they grew accustomed to the mirror and began to use it to make faces, look at the inside of their mouths, and groom and inspect other parts of their bodies that they had never seen before.

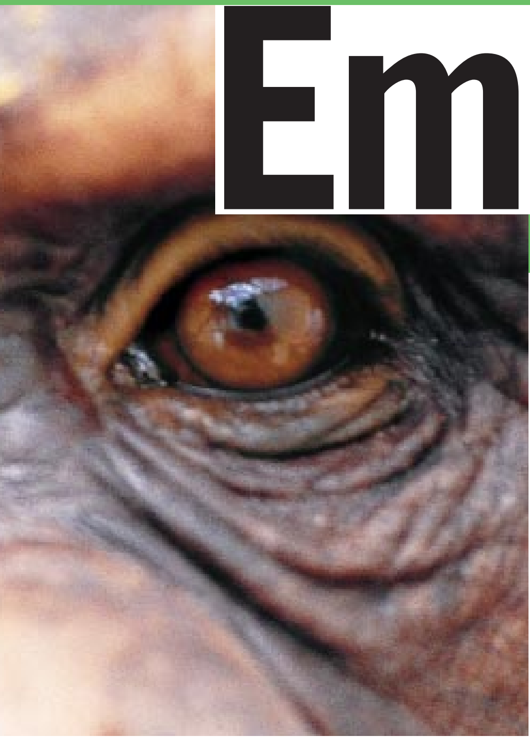
The Mirror Test

To determine whether they had learned to recognize their own reflections, I anesthetized each animal and applied red dye to an eyebrow ridge and to the top half of the opposite ear. Later, on awakening and seeing themselves in the mirror, the chimpanzees reached up and touched the red marks on their faces, following this in some instances with looking at and smelling their fingers. Chimpanzees that did not have the benefit of prior experience with mirrors acted as if confronted by another chimpanzee and failed to locate the marks on their faces. These findings of self-recognition have now been replicated with chimpanzees more than 20 times by scientists all over the world.

Many other animals, including a variety of primates, elephants, birds and even dolphins, have been tested for self-recognition. But only chimpanzees, orangutans and humans have consistently passed this test. (Marc D. Hauser of Harvard University reported that cotton-top tamarins pass the mirror test when their white tufts of hair are marked, but no one has been able to replicate these results.)

The failure to find self-recognition in other animals is not for want of trying. Susan D. Suarez of the Sage

Continued on page 68



DONNA BIERSCHWALE *USL New Iberia Research Center*

Empathize?

Maybe not

Even though chimpanzees pass the mirror test, they do not seem to conceive of others'—or even their own—mental states

by Daniel J. Povinelli

Let me begin with a point on which Gordon Gallup, Jr., and I agree: the reactions of chimpanzees when they see themselves in mirrors reveal that these animals possess a self-concept. Furthermore, we agree that this self-concept appears to be restricted to the great apes and humans. Beyond this point, however, our views diverge. Gallup speculates that the capacity for self-recognition may indicate that chimpanzees are aware of their own internal, psychological states and understand that other individuals possess such states as well. I have come to doubt this high-level interpretation of the chimpanzees' reactions to seeing themselves in mirrors. More generally, I question whether chimpanzees possess the deep psychological understanding of behavior that seems so characteristic of our species. In what follows, I describe why I have come to this conclusion, and I offer an explanation of how humans and chimpanzees can behave so similarly and yet understand this behavior in radically different ways.

Knowing That Others See

Consider the simple act of seeing. When we witness other people turning their eyes toward a particular object, we automatically interpret this behavior in terms of their underlying psychological states—what they are attending to, what they are thinking about, what they know or what they intend to do next. These inferences are often solely based on fairly subtle movements of their eyes and heads.

Do chimpanzees understand seeing in this manner? Gallup thinks they do, and at first glance it seems hard to deny it. For example, chimpanzees exhibit a strong interest in the eyes of their fellow apes. Frans B. M. de Waal of the Yerkes Regional Primate Research Center at Emory University has reported that chimpanzees do not appear to trust the reassurance gestures of their former opponents unless such gestures are accompanied by a mutual gaze—that is, unless they stare directly into one another's eyes. Research from our own laboratory has established that chimpanzees follow the gaze of other apes—and of humans as well. If you stand face-to-face with a chimp, lock your gaze with hers and then suddenly look over her shoulder, the ape will reliably turn around, as if trying to determine what you are looking at.

In short, the spontaneous behavior of chimpanzees seems to make a fairly persuasive case that they can reason about the visual perspectives of others. Does this behavior, then, provide confirmation of Gallup's model? Maybe, but maybe not. The problem is that there are other equally plausible interpretations that do not assume that chimpanzees are reasoning about one another's visual experiences. The case of gaze following illustrates the problem quite well. A chimpanzee who follows your gaze leads you to assume that the animal is trying to figure out what you are looking at. But what excludes

Continued on page 72

GALLUP **Yes**

SELF-RECOGNITION is evident when chimpanzees touch the red dot painted on their faces. Once familiar with the mirrors, they will inspect themselves and make faces.

Continued from page 66

Colleges and I gave a pair of rhesus monkeys, reared together in the same cage, continuous exposure to themselves in a full-length mirror for 17 years (more than 5,000 hours of mirror exposure a year). Despite this extended opportunity to learn about the mirror, neither monkey ever showed any evidence of self-recognition. On the other hand, when I would walk into the room where they were kept and they saw my reflection in the mirror, they would immediately turn to confront me directly. So it was not that they were incapable of learning to interpret mirrored information about other objects correctly.

Experiments have also failed to uncover compelling evidence of self-recognition in gorillas. After pondering those results, Suarez and I decided to give gorillas the benefit of the doubt, reasoning that maybe gorillas do not care about the superimposed marks. We tested this hypothesis at the Yerkes Regional Primate Research Center at Emory University by applying marks to gorillas' wrists as well as to their faces. We discovered that on recovery from anesthesia all the gorillas touched and inspected the marks on their wrists. But despite extensive prior experience with mirrors, none of the gorillas were able to locate comparable marks on their faces that could be seen only in the mirror.

Gorillas naturally avoid making eye contact with one another, so a possible reason for their mirror-test failure is that they avoid eye contact with their reflection and hence never learn to recognize themselves. Daniel J. Shillito and Benjamin B. Beck of the National Zoological Park in Washington, D.C., and I recently tested this hypothesis, relying on a technique developed by James R. Anderson of the University of Stirling in England. It calls for a pair of mirrors placed together at an angle that renders it impossible to make eye contact with the reflection. But none of the gorillas showed evidence of self-recognition, not even one that had more than four years of exposure to mirrors.

We ought to be able to identify animals that can or cannot recognize themselves in mirrors and their empathetic tendencies.

In other tests of learning, problem solving and cognitive functioning, differences in performance among species are typically a matter of degree, not kind. What is to be made of such decisive differences in self-recognition? Maybe the reason most species cannot process mirrored information about themselves stems from an inability to conceive of themselves. Correctly inferring the identity of the reflection presupposes an identity on the part of the organism making that inference.

That conclusion seems reasonable, considering the way members of *Homo sapiens* interpret mirror images. Humans do not begin to show compelling evidence of mirror-guided self-recognition until they reach 18 to 24 months of age—about the same time at which the prefrontal cortex begins to mature in structure and function. Younger infants react to themselves in mirrors as though they were seeing other children, just as most species do. At about the time that children learn to recognize themselves, they begin to show other evidence of self-conception, such as using personal pronouns, smiling after mastering a task and engaging in self-conscious play.

Before about two years of age, no one has experiences that can be consciously recalled in later life. Consistent with my interpretation, this period of "infant amnesia" stops at about the same time that children begin to show self-recognition. As would be expected, the onset of an autobiographical memory only begins with the emergence of self-conception.

That may terminate prematurely at the other end of the life span if dementia sets in. Disturbances in self-awareness and impaired structure and function of the prefrontal cortex often accompany this condition. Thus, for some, human development may be bounded at both ends by periods of unconsciousness.

Knowing Mental States

Some practical advantages are derived from being able to conceive of the self. I argue that self-awareness, consciousness and mind are an expression of the same underlying process, so that organisms aware of themselves are in a unique position to use their experience as a means of modeling the experience of others. When you see someone in a situation similar to one you have encountered, you automatically assume his or her experience will be similar to yours. Although it is probably true that no two people experience the same event in exactly the same way, as members of the same species we share the same sensory and neurological mechanisms. So there is bound to be considerable overlap between your experience and mine.

Moreover, given a knowledge of how external events influence my mental states (and vice versa), I have a means of modeling the mental states of others.

To see my point, imagine you have a dog that returns home one day in obvious distress: it has porcupine quills in its nose. You could either have a veterinarian remove the quills, or you could attempt to extract them yourself using a pair of pliers. If you were to opt for the latter, it would be an excruciating ordeal for you. Not that you would experience any pain in the process, but as you pulled the quills from the dog's nose and witnessed its reaction, it would prove virtually impossible not to empathize with the dog. That is, you would use your prior experience with pain to model your dog's ostensible experience.

But how do you think another unrelated dog witnessing this transaction would respond? Pet owners may be surprised to learn—and any veterinarian can tell you—that dogs are empathetically oblivious to pain and suffering in other, unrelated dogs. I suspect that dogs experience pain in much the same way that we do, but because they cannot conceive of themselves, dogs cannot use their experience with pain to model painful experiences in other creatures. (They might, of course, react to the yelping.)

Another way to illustrate this incapacity involves people who have a condition called blindsight experience. These patients have sustained extensive damage to the visual cortex and often act as if they were blind, even though their primary visual system remains intact. Lawrence Weiskrantz of the University of Oxford and his colleagues discovered that such patients can show a surprising ability to "guess" the identity of objects and their location. In other words, vision in such patients has been reduced to an unconscious sensation. Blindsight patients can still respond to visual information, but they are not aware of it. As a consequence, they have been rendered mindless when it comes to vision. I would predict that individuals born with blindsight can grow up using guessing strategies and hence act visually normal. Their condition would become apparent only if they were placed in a situation that required them to make inferences about the visual experiences in other people—understanding how high-beam headlights affect oncoming drivers on a dark country road, for instance.

So back to my main point: I maintain that knowledge of mental states in others presupposes knowledge of mental states in oneself and, therefore, that knowledge of self paves the way for an inferential knowledge of others. Most humans routinely make inferences and attributions about what other people may or may not know, want or plan to do. By the same token, species that fail to recognize themselves in mirrors should fail to use introspectively based social strategies such as sympathy, empathy, attribution, intentional deception, grudging, gratitude, pretense, role playing or sorrow.

Evidence for Empathy

We ought to be able to identify animals that can or cannot recognize themselves in mirrors and their empathetic tendencies in some fairly definitive ways. If you were to cover the eyes of an animal at some point, how would it later respond to a cagemate wearing a blindfold? An animal that is self-aware ought to be in a position to use its prior experience with blindfolds to take into account its cagemate's inability to see. If you were to teach an animal to vocalize for a food reward every time you entered the room and then blocked its hearing with earplugs or headphones, how would it respond the next day if you entered the room wearing headphones? If self-aware, it should vocalize more loudly to compensate for your impaired ability to hear.

In these kinds of tests, monkeys that fail to show evidence of self-recognition (as distinct from chimpanzees and orangutans, which are great apes) seem completely incapable of taking into account what other monkeys may or may not know. Dorothy L. Cheney and Robert M. Seyfarth of the University of Pennsylvania have found that vervet monkeys give alarm calls on seeing a predator even if other monkeys have already seen it, too. Likewise, they found that Japanese monkey mothers do not distinguish between offspring that know or do not know about food or danger when it comes to alerting their babies to the presence of one or the other.

Monkeys that cannot recognize themselves in mirrors approximate what psychologists call radical behaviorists. Their

have been too young; the onset of self-recognition in chimpanzees does not occur until adolescence. Still another possibility is that we humans categorize our experiences (for example, by sight, hearing or smell). Lacking language, chimpanzees may not distinguish between visual, auditory and tactile experiences. Therefore, inferences they make about attention may be more global.

Also, most studies have focused on whether chimpanzees can take various informational states of mind into account (that is, whether they can figure out what another individual knows). But the data on humans show that children attribute feelings and motivation before they have the ability to attribute informational states of mind. Beginning at about the time or shortly after (but never before) they learn to recognize

interactions with other monkeys seem to be based entirely on an analysis driven by the external features of the other monkey and not on what it might be thinking or what it might want to do. Chimpanzees, on the other hand, ought to represent primitive, albeit imperfect, cognitive psychologists—they should be able to respond empathetically and modify their behavior accordingly.

Initial experiments by Daniel J. Povinelli and Sarah T. Boysen of Ohio State University showed that chimpanzees appear to distinguish between what humans may or may not know. When two humans pointed toward different cups, the chimpanzees learned to pick the cup implicated by the human who had witnessed which cup had been baited with food. Although chimpanzees seemed to recognize ignorance on the part of human informants, rhesus monkeys did not.

Further evidence for cognitive empathy in chimpanzees comes from a mutual problem-solving experiment in which humans and chimpanzees had to perform different tasks. For instance, a chimpanzee had to pull a handle to bring food cups within reach but could not see which cup had been baited, whereas the human who could not reach the cups had to point to the baited cup. The chimpanzees were able to switch roles with the humans with no decrement in performance. Rhesus monkeys, however, failed to show any evidence of transfer when the roles were reversed.

Arguing against self-awareness and empathy of chimpanzees, Povinelli cites experiments that failed to find evidence in chimpanzees for an ability to take into account what another creature sees. He concludes that chimpanzees cannot even conceive of their own mental states, let alone those of others.

There are some explanations for the negative results, however. Povinelli's experiments relied on chimpanzees that might

themselves in mirrors, children start to make primitive inferences about emotional states of mind in others; the more sophisticated ability to infer informational states of mind does not happen until a year or two later. Autistic children, in contrast, have difficulty taking into account what other people may know, want or feel. As expected, self-recognition in autistic children is often delayed or even absent.

Because chimpanzees and orangutans pass the

mirror test, Povinelli hypothesizes that they possess a motor self-concept rather than a psychological one. That is, they do not really recognize themselves but simply learn an equivalence between their behavior and what they see in the mirror.

But matters of appearance have little to do with movement. So why should chimps and orangutans seem so intent on using mirrors to look at and inspect parts of their bodies they have never seen before? Why should they bother to respond to strange but motorically inconsequential red marks on their own faces? Suzanne Calhoun and Robert Thompson of Hunter College describe the reaction of a chimpanzee that, on being reintroduced to a mirror a year after learning to recognize herself, became very agitated when she opened her mouth and saw several missing teeth. It is hard to see how this reaction could be understood purely in motor terms.

Many species may have clever brains but blank minds.

Self-Awareness and the Brain

Other, more speculative clues about self-awareness lie in the physical makeup of the brain: certain areas seem to be responsible for it. Donald T. Stuss of the Rotman Research Institute in Toronto and I have been collaborating on a long-term project that focuses on human patients who have damage to the frontal cortex, the part of the brain responsible for some of the most complex activities of the mind. Preliminary data show that such patients seem unable to model mental states in others.

Self-awareness may correlate with activity in the right prefrontal cortex. Julian P. Keenan and Alvaro Pascual-Leone of Harvard Medical School, along with my colleagues N. Bruce McCutcheon and Glenn S. Sanders and me, tested how fast humans can recognize faces. When responding with the left hand (controlled by the right hemisphere), subjects identified their own faces faster than the faces of friends or co-workers. In addition, subjects viewing their own faces displayed significant changes in electrical potentials in the right prefrontal cortex. Moreover, when we altered the electrical activity in this brain area with magnetic fields, subjects changed their response rates to their own faces but not to the other faces.

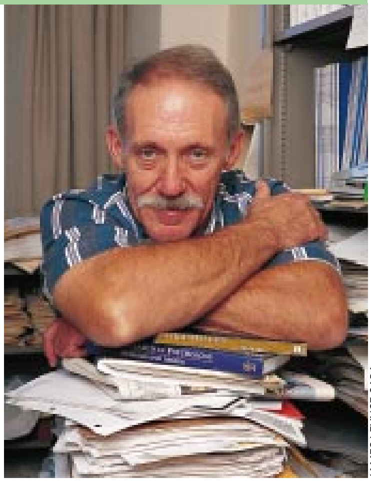
Given this evidence of functional lateralization of self-awareness in humans, it is interesting to note that compared with other great apes, gorilla brains are the least anatomically lateralized. The absence of a highly specialized right hemisphere might explain the gorilla's weak and inconsistent performance in the mirror tests. Povinelli claims that the gorilla's failure here is a "crucial test" of his theory of the motor self-concept. In particular, he speculates that it arose as an adaptation to life in the trees: unlike chimpanzees and orangutans, gorillas spend most of their time on the ground. But at night, gorillas still return to the trees to sleep, even though they are at a greater risk of falling because they are so large. In fact, humans are the ones that have much more completely emancipated themselves from the branches. Therefore, humans and not gorillas ought to fail to recognize themselves in mirrors.

PHOTOGRAPHS BY DONNA BIERSCHWALE

Povinelli's data notwithstanding, I think most people working in this area would agree that the jury is still out on whether great apes can attribute mental states to others. Much of the research in this topic is consistent with the conclusion reached by Nicholas Humphrey of the University of Cambridge that many species may have clever brains but blank minds: clever brains in the sense of learning, memory and problem solving, but blank minds in the sense of being unable to use their experience to take into account the experience of others. As evidenced by the behavior of people who sleepwalk and those who suffer from blindsight, you do not have to know what you are doing in order to do it in an appropriate way. Humans and possibly a few species of great apes appear to have entered a unique cognitive domain that sets us apart from other creatures.

This model of consciousness and mind based on self-awareness has brought me full circle. When I devised the initial test of self-recognition almost 30 years ago, it is apparent that I was using my experience and imagination about how I would respond to strange facial marks to anticipate how chimpanzees might respond to such marks if they could recognize themselves in mirrors. Moreover, if this model or some modified version of it eventually proves correct, it would mean that the ability to conceive of oneself in the first place is what makes consciousness and thinking possible. The famous quote from Descartes would have to be rewritten as "I am, therefore I think." SA

About the Author



JAMES LEYNSE *SABA*

GORDON GALLUP, JR.'s research interests run the gamut: he has hypnotized chickens to examine how their immobility serves as a defense against predation, worked on open-field behavior in rats, looked at depression and reproductive failure in people, theorized about the demise of the dinosaurs and monitored risk-taking behaviors in menstruating women. Each project—odd though it might sound—adds to our understanding of the evolutionary forces that underlie behavior, both animal and human. Gallup devised the mirror test while he was a graduate student at Washington State University. The idea came to him one day while he was shaving in front of the mirror.

After serving on the faculty at Tulane University, Gallup accepted a position as a professor and chair of psychology at the State University of New York at Albany. He lives on an old dairy farm, where he grows his own food—potatoes, tomatoes, beans and corn—and maintains a small herd of beef cattle. In the fall, Gallup bales hay and chops wood before heading off to teach class and grade exams. And he enjoys it. "I just love being outside and doing physical work," he says. "It helps me keep one foot firmly planted in reality."

Maybe Not

Continued from page 67

the possibility that evolution has simply produced "mind-blind" mechanisms that lead social primates to look where other animals look, without entertaining any ideas about their visual perspective?

To disentangle these issues, we need to study the behavior of these animals in more revealing experimental situations. One method occurred to us after watching our chimpanzees in their everyday play. They frequently covered their heads with blankets, toy buckets or even their palms and then frolicked around their compound until they bumped into something—or someone. Occasionally they would stop and lift the obstruction from their eyes—to peek, as it were—before continuing their blind strolls. On more than one occasion I made the mistake of imitating these behaviors while playing with the animals, a maneuver that left me vulnerable to a well-timed play attack!

Does this behavior mean that chimpanzees have a concept of seeing? For example, when they play with someone else who covers his or her head, do they know that this person cannot see them, or do they simply learn that this person is unable to respond effectively?

GAZE FOLLOWING is a common behavior among chimpanzees. When the experimenter looks over the chimpanzee's shoulder (left), *the ape looks in the same direction* (right).

To answer these questions, we examined one of our chimpanzees' most common communicative gestures: begging. First, we allowed them to beg for food from an experimenter who was sitting just out of their reach. When they did so, they were handed an apple or banana. Next, we confronted them with two familiar experimenters, one offering a piece of food and the other holding out an undesirable block of wood. As we expected, the chimps had no trouble: after glancing at the two experimenters, they immediately gestured to the one offering the food.

This set the stage for our real objective, which was to provide the apes with a choice between a person who could see them and a person who could not. If the high-level model of chimpanzee understanding were correct, the chimps would gesture only to the person who could see them. We achieved the "seeing/not-seeing" contrast by having the two experimenters adopt different postures. In one test, one experimenter wore a blindfold over her eyes while the other wore a blindfold over her mouth. In the other tests, one of the experimenters wore a bucket over her head, placed her hands over her eyes or sat with her back turned to the chimpanzee. All these postures were modeled after the behaviors we had observed during the chimpanzees' spontaneous play.

The results of this initial experiment were astonishing. In three of the four tests—the ones involving blindfolds, buckets and hands over the eyes—the apes entered the lab and paused but then were just as likely to gesture to the person who could not see them as to the person who could. In several cases, the apes gestured to the person who could not see them and then, when nothing happened, gestured again, as if puzzled by the fact that the experimenter did not respond.

PHOTOGRAPHS BY DONNA BIERSCHWALE

We were not prepared for such findings. Surely our apes understood that only one of the experimenters could see them. Indeed, the apes did perform excellently in one of the tests, where one experimenter sat with her back turned to the chimpanzees. But why only this one? At first we assumed that the back/front test was simply the most obvious or natural contrast between seeing and not seeing. In this test the apes might have been demonstrating their genuine understanding of seeing—an understanding that was obscured by the arguably less natural postures in the other tests.

Another idea, however, began to nag at us. Perhaps the apes' excellent performance on the back/front test had nothing to do with their reasoning about who could or could not see them. Maybe they were just doing what we had taught them to do in the first part of the study—gesture to the front of someone who was facing them. Or perhaps the act of gesturing to the front of a social partner is simply a hardwired social inclination among chimpanzees, unconnected to a psychological concept of seeing or attention.

As a first attempt to distinguish among these possibilities, we conducted another test in which both experimenters sat with their backs to the chimpanzees, but one looked over her shoulder at them. This posture was quite familiar to the apes—in their daily interactions, they frequently looked over their shoulders at one another. The high-level model of chimpanzee understanding predicted that the animals would gesture only to the experimenter who could see them. The low-level model predicted that the apes would choose at random because they could not see the front of either experimenter. Their performance turned out to be random—they were just as likely to gesture to either experimenter.

I should point out that what I am describing are the apes' initial reactions to these situations. As you might guess, with enough experience of not being handed a banana after gesturing to someone whose face was not visible, our chimpanzees quickly learned to choose the other option. But what exactly did the apes learn? Did they finally realize what we were asking them—"Oh, I get it! It's about seeing!"—or had they simply learned another rule that could work every time: "Gesture to the person whose face is visible."

We examined this question in an extended series of studies, the results of which were consistent with the low-level model. For example, after the chimpanzees learned not to gesture to an experimenter whose head was obscured by a cardboard disk, we retested the animals using the original conditions (buckets, blindfolds, hands over the eyes and looking over the shoulder). We realized that if the apes had genuinely understood the idea of seeing, they ought to gesture only to the experimenters who could see them in all the other tests as well. But if the chimpanzees had simply

CHIMPANZEE UNDERSTANDING of the concept of seeing was tested in a series of experiments. Confronted with pairs of "seeing" and "not-seeing" experimenters (above), *the chimps were equally likely to gesture to either one. The apes performed better in the back/front test* (right), *but their performance was random in the looking-over-the-shoulder test* (below).

learned to gesture to a person whose face was visible, they would still choose randomly in the blindfold test, because the faces of the experimenters were equally visible (one had the blindfold over her eyes; the other had it over her mouth). Just as the low-level model predicted, the chimpanzees were more likely to gesture to the experimenter who could see them in all the tests except one—the blindfold test.

These findings contrast sharply with the development of these abilities in human infants. John H. Flavell and his colleagues at Stanford University have shown that children as young as two or three years seem to understand the concept of seeing. And indeed, when we tested young children using our seeing/not-seeing method, we found that even two-and-a-half-year-old children performed at levels suggesting that they understood that only one of the experimenters could see them.

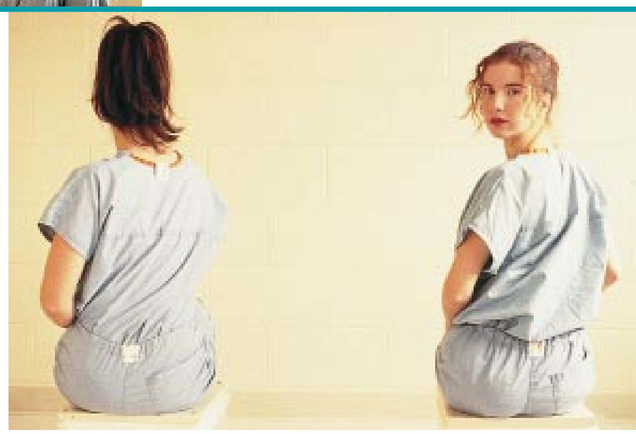
Growing Up Ape

Let me address one important criticism of our work raised by Gallup concerning the age of our animals. The initial tests were conducted in 1993 and 1994, when the chimpanzees were five to six years old. Although several of our apes were displaying all the traditional evidence of recognizing themselves in mirrors, some of them were still on the cusp of developing this ability. Could it be that older chimpanzees might fare better in the seeing/not-seeing tests?

One year after the initial research—and after our apes had been engaged in many other studies—we assessed their reactions to several of the original seeing/not-seeing tests. Much to our surprise, the chimpanzees initially responded at random, even to the test where one of the experimenters hid her head behind a cardboard disk—a test the apes had learned extremely well a year earlier. Our chimpanzees' performance improved only gradually, after considerable trial and error. Furthermore, after another year had passed and our apes had become young adults, additional tests revealed that they were still relying on rules about the frontal posture, faces and eye movements of the experimenters—not about who could see them. Thus, despite the fact that many of our chimpanzees had displayed evidence of self-recognition for more than four years, we had no evidence that they genuinely understood one of the most basic empathic aspects of human intelligence: the understanding that others *see*.

The Meaning of Self-Recognition

If we knew nothing more about chimpanzees, we might simply conclude that they understand visual perception in a very different manner than we do. Other studies in our laboratory, however, have suggested that chimpanzees may not understand any behavior in a psychological manner. For example, careful tests revealed that our apes do not comprehend pointing gestures as referential actions, nor do they understand the difference between accidental and intentional behavior. Furthermore, recent tests conducted with Daniela K. O'Neill of the University of Waterloo suggest that our original interpretations of our earlier studies on cooperation—which Gallup cites in support of his theory—may have been incorrect. Although



PHOTOGRAPHS BY DONNA BIERSCHWALE

our chimpanzees easily learn to cooperate with one another, our new results cast doubt on whether they truly appreciate the differing subjective mind-sets of their partners.

If chimpanzees do not genuinely reason about mental states in others, what can we say about their understanding of self? Exactly what is revealed by their antics in front of mirrors? And do such reactions to mirror images really indicate the onset of autobiographical memory—in both apes and humans—as Gallup suggests?

As a first attempt to answer these questions, we shifted our attention to humans—specifically, two-, three- and four-year-old children. In a series of studies, we individually videotaped the children as they played an unusual game with an experimenter.

Self-recognition in chimpanzees and human toddlers is based on a recognition of the self's behavior, not the self's psychological states.

During the game, the experimenter praised the child and used this opportunity to place a large, brightly colored sticker secretly on top of the child's head. Three minutes later the children were shown either a live video image of themselves or the recording we had made several minutes earlier, which clearly depicted the experimenter placing the sticker on the child's head.

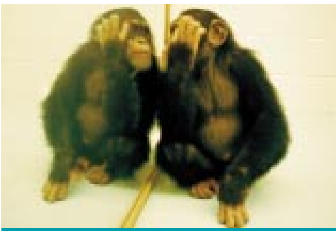
These tests revealed that the younger children—the two- and three-year-olds—responded very differently depending on whether they observed the live or delayed images. When confronted with a live image, the vast majority of the two- and three-year-olds reached up and removed the sticker from their heads. When confronted with three-minute-old images, however, only about one third of the younger children reached up for the sticker. Did the others simply not notice the sticker in the delayed video? Hardly. After experimenters drew their attention to the sticker in the video and asked them, "What is that?" the majority of the children responded, "It's a sticker." But this acknowledgment did not cause them to reach up and remove the sticker.

In one sense, of course, the children clearly "recognized themselves" in the delayed video. When they were asked, "Who is that?" even the youngest children confidently replied, "Me!" or stated their proper names. This reaction, however, did not seem to go beyond a recognition of facial and bodily features. When asked, "Where is that sticker?" the children frequently referred to the "other" child: "It's on her [or his] head." It was as if the children were trying to say, "Yes, that looks like me, but that's not *me*—she's not doing what I'm doing right now." One three-year-old girl summarized this psychological conflict quite succinctly: "It's Jennifer," she stated, only to hurriedly add, "but why is she wearing my shirt?"

So when do children come to think of themselves as having a past and a future? Our studies have revealed that by about four years of age, a significant majority of the children began to pass our delayed self-recognition test. Unlike their younger counterparts, most four- and five-year-olds confidently reached up to remove the sticker after they observed the delayed video images of themselves. They no longer referred to "him" or "her" or their proper names when talking about their images. This finding fits nicely with the view of Katherine Nelson of the City University of New York and others, who believe that genuine autobiographical memory appears to emerge in children between 3.5 and 4.5 years old—not at the two-year mark that Gallup favors. Of course, any parent knows that two-year-olds can recall past events, but this is very different from understanding that those memories constitute a genuine "past"—a history of the self leading up to the here and now.

Although it is still too early to rule out Gallup's model altogether, our research suggests that self-recognition in chimpanzees and human toddlers is based on a recognition of the self's behavior, not the self's psychological states. When chimpanzees and orangutans see themselves in a mirror, they form an equivalence relation between the actions they see in the mirror and their own behavior. Every time they move, the mirror image moves with them. They conclude that everything that is true for the mirror image is also true for their own bodies, and vice versa. Thus, these apes can pass the mirror test by correlating colored marks on the mirror image with marks on their own bodies. But the ape does not conclude, "That's me!" Rather the animal concludes, "That's the same as me!"

Thus, although Gallup and I agree that passing the mirror test reveals the presence of a kind of self-concept, we differ on the nature and scope of that concept. Gallup believes that chimpanzees possess a psychological understanding of themselves. In contrast, I believe these apes possess an explicit mental representation of the position and movement of their own bodies—what could be called a kinesthetic self-concept.



SELF-RECOGNITION TEST for chimpanzees (left) *was modified for human children with the help of video images* (below). *The experimenter secretly placed a sticker on each child's head. Young children reached for the sticker* (right) *only when the video image was live.*

Ironically, this may be close to what Gallup himself had in mind when he originally published his discovery nearly 30 years ago. He noted that self-recognition appears to require the ability to project "kinesthetic feedback onto the reflected visual image so as to coordinate the appropriate visually guided movements via the mirror."

But why do humans, chimpanzees and orangutans possess this kinesthetic self-concept, whereas other nonhuman primates—such as monkeys—do not? One clue may be the large difference in body size between the great apes and other primates. Consider orangutans, which may represent the closest living approximation to the common ancestor of the great apes and humans. Several years ago, John G. H. Cant of the University of Puerto Rico and I spent months in the Sumatran rain forest observing the orangutan's chaotic blend of slow, carefully planned movements and sudden, breathtaking acrobatics. We concluded that the problems encountered by these 40- to 80-kilogram (90- to 180-pound) animals in bridging the gaps between trees were qualitatively different from the problems faced by the much smaller monkeys and lesser apes. We hypothesized that as the ancestors of the great apes evolved, quadrupling in body size over 10 to 20 million years, they may have needed to evolve a high-level self-representational system dedicated to planning their movements in their arboreal environment. Ultimately, this unprecedented increase in body size for a tree-dwelling mammal may have left a psychological imprint on the great apes: an explicit kinesthetic self-concept. It was this self-concept that Gallup tapped millions of years later in his tests of chimpanzee self-recognition.

A crucial test for our theory is the gorilla, the largest nonhuman primate. Although gorillas share the same common ancestor as humans, chimpanzees and orangutans, they have readapted to spending most of their lives on the ground. The surprising absence of self-recognition in this species may reflect the fact that gorillas no longer needed to execute the complex movements that were necessary to transport their enormous body weight across the gaps between trees. Their evolution appears to have focused on aspects that were more relevant to their new terrestrial way of life, including a more rapid physical growth rate than is found in chimpanzees and orangutans. This process may have interfered with the development of a kinesthetic self-concept. Humans, in contrast, slowed down their growth rate, allowing more years for cognitive development.

If self-recognition depends on a kinesthetic rather than a psychological self-concept, it would help explain some puzzling facts. Several studies have found no connection between the ability of 18- to 24-month-old infants to pass the mirror test and their ability to understand that a mirror reflects any object placed in front of it. Our theory explains this result by postulating that the infants do not see their mirror images as representations of themselves. Rather they see their images as a special class of entities that share their behavior and appearance.

Our theory also explains why toddlers often fail the self-recognition test if there is even a minimal disruption of the visual feedback—for example, a two-second delay in the video images of themselves. Although the children continue to recognize their facial and bodily features, the two-second disjunction between their actions and the movements of their images leads them to conclude that the images are not equivalent to themselves. Finally, our theory explains why both toddlers and chimpanzees, after recognizing themselves in the mirror, may nonetheless persist in looking behind the mirror, as if searching for the "other" child or ape.

PHOTOGRAPHS BY DONNA BIERSCHWALE

Understanding Minds: A Human Specialization

At this point we are still left with a troubling question: How can humans and chimpanzees share such sophisticated social behaviors but understand them so differently? Why do humans interpret these behaviors in terms of psychological states, but apes do not?

My answer may become more obvious if we imagine our planet 60 million years ago, long before any of the modern primates had evolved. Alison Jolly of Princeton University has speculated that as the solitary lifestyle of the small, early primates gave way to existence in large groups, these animals were forced to cope with increasingly complex social interactions. As a result, Jolly argues, the primates became stunningly adept at reasoning about one another's actions, slowly evolving the rich array of social behaviors now observed among the modern primates: gaze following, deception, appeasement and so on.

But, in my view, none of these behaviors required the early primates to reason about one another's mental states. Our research suggests that only one primate lineage—the human one—evolved the unique cognitive specialization that enables us to represent explicitly our own psychological states and those of others. But in evolving this specialization, we did not discard our array of basic primate behaviors. Our new awareness of the mental dimension of behavior was woven into our existing neural circuitry, forever altering our understanding of our own behavior and the behavior of those around us. Other species, including chimpanzees, may simply be incapable of reasoning about mental states—no matter how much we insist on believing that they do. SA

About the Author

DANIEL J. POVINELLI first became interested in chimpanzee behavior in 1979, when he was 15 years old. While doing research for a high school debate, Povinelli came across an article by Gordon Gallup, Jr., in *American Scientist* describing his mirror tests on chimpanzees. "The elegance and ingenuity of Gallup's tests really struck me," he says. "I thought that here might be a species profoundly similar to our own." Inspired, Povinelli studied primate behavior as an undergraduate at the University of Massachusetts at Amherst and earned his Ph.D. in biological anthropology from Yale University in 1991. He then joined the University of Southwestern Louisiana's New Iberia Research Center, a 150-acre facility that is home to more than 300 chimpanzees. Now an associate professor, Povinelli directs the center's division of behavioral biology, which studies cognitive development in both chimpanzees and young children. Over the years Povinelli has become a friend and colleague of Gallup's, but his view of the chimpanzee's mental abilities has diverged from that of his mentor. "It took a lot of patience on the part of the chimpanzees," he says, "but they've finally taught me that they're not hairy human children."

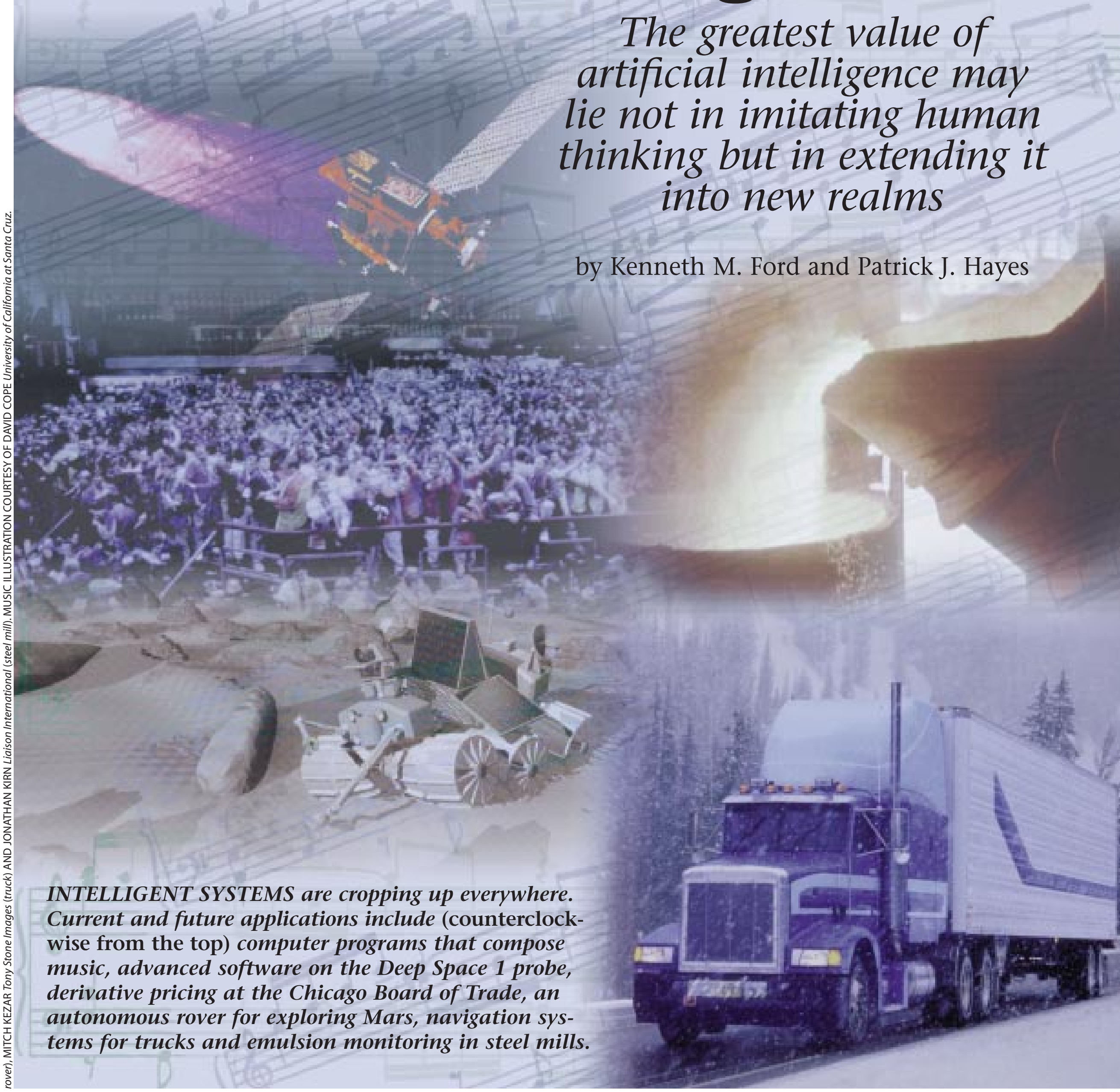
MACHINE

On Computational Wit

Rethinking the Goals of Artificial Intelligence

The greatest value of artificial intelligence may lie not in imitating human thinking but in extending it into new realms

by Kenneth M. Ford and Patrick J. Hayes



INTELLIGENT SYSTEMS are cropping up everywhere. Current and future applications include **(counterclockwise from the top)** ***computer programs that compose music, advanced software on the Deep Space 1 probe, derivative pricing at the Chicago Board of Trade, an autonomous rover for exploring Mars, navigation systems for trucks and emulsion monitoring in steel mills.***

ILLUSTRATION BY LAURIE GRACE. PHOTOGRAPHS COURTESY OF SPECTRUM ASTRO (*space probe*), JEFFERY TITCOMB *Liaison International* (*trading floor*), NASA AMES RESEARCH CENTER (*Mars rover*), MITCH KEZAR *Tony Stone Images* (*truck*) AND JONATHAN KIRN *Liaison International* (*steel mill*). MUSIC ILLUSTRATION COURTESY OF DAVID COPE *University of California at Santa Cruz.*

Wings:

Many philosophers and humanist thinkers are convinced that the quest for artificial intelligence (AI) has turned out to be a failure. Eminent critics have argued that a truly intelligent machine cannot be constructed and have even offered mathematical proofs of its impossibility. And yet the field of artificial intelligence is flourishing. "Smart" machinery is part of the information-processing fabric of society, and thinking of the brain as a "biological computer" has become the standard view in much of psychology and neuroscience.

While contemplating this mismatch between the critical opinions of some observers and the significant accomplishments in the field, we have noticed a parallel with an earlier endeavor that also sought an ambitious goal and for centuries was attacked as a symbol of humankind's excessive hubris: artificial flight. The analogy between artificial intelligence and artificial flight is illuminating. For one thing, it suggests that the traditional view of the goal of AI—to create a machine that can successfully imitate human behavior—is wrong.

For millennia, flying was one of humanity's fondest dreams. The prehistory of aeronautics, both popular and scholarly, dwelled on the idea of imitating bird flight, usually by somehow attaching flapping wings to a human body or to a framework worn by a single person. It was frustratingly clear that birds found flying easy, so it must have seemed natural to try to capture their secret. Some observers suggested that bird feathers simply possessed an inherent "lightness." Advocates of the possibility of flight argued that humans and birds were fundamentally similar, whereas opponents argued that such comparisons were demeaning, immoral or wrongheaded. But both groups generally assumed that flying meant imitating a bird. Even relatively sophisticated designs for flying machines often included some birdlike features, such as the beak on English artist Thomas Walker's 1810 design for a wooden glider.

This view of flying as bird imitation was persistent. An article in *English Mechanic* in 1900 insisted that "the true flying machine will be to all intents and purposes an artificial bird." A patent application for a "flying suit" covered with feathers was made late in the 19th century, and wing-flapping methods were discussed in technical surveys of aviation published early in this century.

The Turing Test

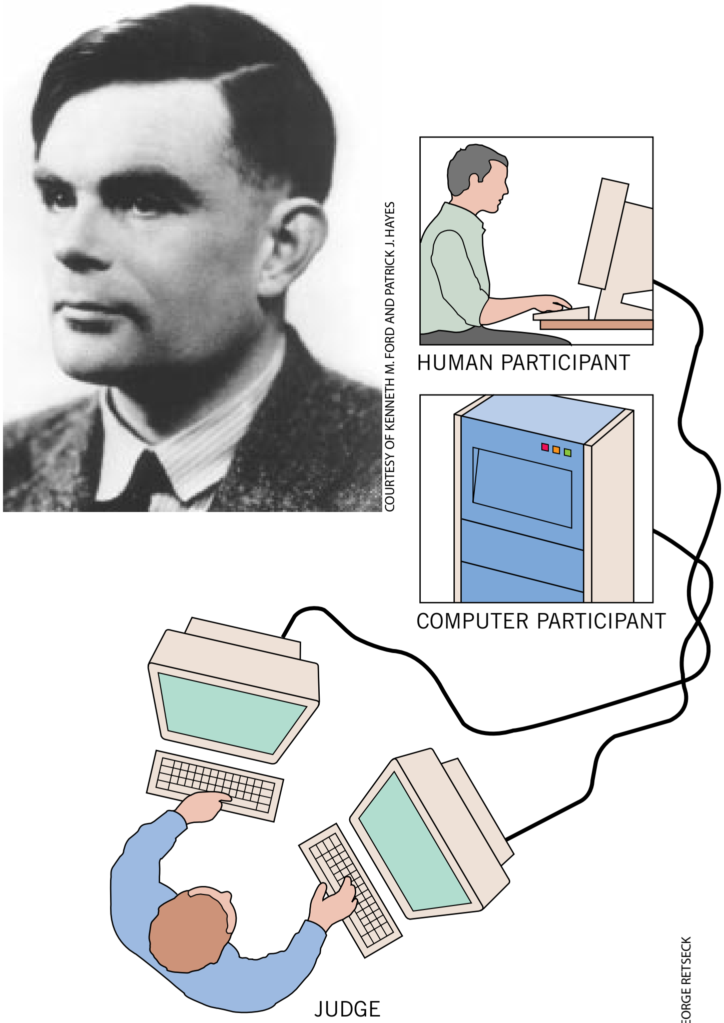
Intelligence is more abstract than flight, but the long-term ambition of AI has also traditionally been characterized as the imitation of a biological exemplar. When British mathematician Alan M. Turing first wrote of the possibility of artificial intelligence in 1950, he suggested that AI research might focus on what was probably the best test for human intelligence available at the time: a competitive interview. Turing suggested that a suitable test for success in AI would be an "imitation game" in which a human judge would hold a three-way conversation with a computer and another human and try to tell them apart. The judge would be free to turn the conversation to any topic, and the successful machine would be able to chat about it as convincingly as the human. This would require the machine participant in the game to understand language and conversational conventions and to have a general ability to reason. If the judge could not tell the difference after some reasonable amount of time, the machine would pass the test: it would be able to seem human to a human.

There is some debate about the exact rules of Turing's imitation game, and he may not have intended it to be taken so seriously. But some kind of "Turing test" has become widely perceived, both inside and outside the field, as the ultimate goal of artificial intelligence, and the test is still cited in most textbooks. Just as with early thinking about flight, success is defined as the imitation of a natural model: for flight, a bird; for intelligence, a human.

The Turing test has received much analysis and criticism, but we believe that it is worse than often realized. The test has led to a widespread misimpression of the proper ambitions of our field. It is a poorly designed experiment (depending too much on the subjectivity of the judge), has a questionable technological objective (we already have lots of human intelligence) and is hopelessly culture-bound (a conversation that is passable to a British judge might fail according to a Japanese or Mexican judge). As Turing himself noted, one could fail the test by being too intelligent—for example, by doing mental arithmetic extremely fast. According to media reports, some judges at the first Loebner competition in 1991—a kind of Turing test contest held at the Computer Museum in Boston—rated a human as a machine on the grounds that she produced extended, well-written paragraphs of informative text. (Apparently, this is now considered an inhuman ability in parts of our culture.) With the benefit of hindsight, it is now evident that the central defect of the test is its species-centeredness: it assumes that human thought is the final, highest pinnacle of thinking against which all others must be judged. The Turing test does not admit of weaker, different or even stronger forms of intelligence than those deemed human.

Most contemporary AI researchers explicitly reject the goal of the Turing test. Instead they are concerned with exploring the computational machinery of intelligence itself, whether in humans, dogs, computers or aliens. The scientific aim of AI research is to understand intelligence as computation, and its engineering aim is to build machines that surpass or extend human mental abilities in some useful way. Trying to imitate a human conversation (however "intellectual" it may be) contributes little to either ambition.

In fact, hardly any AI research is devoted to trying to pass the Turing test. It is more concerned with issues such as how machine learning and vision might be improved or how to design an autonomous spacecraft that can plan its own actions. Progress in AI is not measured by checking fidelity to a human conversationalist. And yet many critics complain of a lack of progress toward this old ambition. We think the Turing test should be relegated to the history of science, in the same way that the aim of imitating a bird was eventually abandoned by the pioneers of flight. Beginning a textbook on AI with the Turing test (as many still do) seems akin to starting a primer



COURTESY OF KENNETH M. FORD AND PATRICK J. HAYES

GEORGE RETSECK

TURING TEST for artificial intelligence was proposed in 1950 by British mathematician Alan M. Turing (photograph). *In the test, a human judge would hold a three-way conversation with a computer and another human. If the judge could not distinguish between the responses of the human and those of the computer, the machine would pass the test.*

on aeronautical engineering with an explanation that the goal of the field is to make machines that fly so exactly like pigeons that they can even fool other pigeons.

Imitation versus Understanding

Researchers in the field of artificial intelligence may take a useful cue from the history of artificial flight. The development of aircraft succeeded only when people stopped trying to imitate birds and instead approached the problem in new ways, thinking about airflow and pressure, for example. Watching hovering gulls inspired the Wright brothers to use wing warping—turning an aircraft by twisting its wings—but they did not set out to imitate the gull's wing. Starting with a box kite, they first worked on achieving sufficient lift, then on longitudinal and lateral stability, then on steering and finally on propulsion and engine design, carefully solving each problem in turn. After that, no airplane could be confused with a bird either in its overall shape or in its flying abilities. In some ways, aircraft may never match the elegant precision of birds, but in other ways, they outperform them dramatically. Aircraft do not land in trees, scoop fish from the ocean or use the natural breeze to hover motionless above the countryside. But no bird can fly at 45,000 feet or faster than sound.

Rather than limiting the scope of AI to the study of how to mimic human behavior, we can more usefully construe it as the study of how computational systems must be organized in order to behave intelligently. AI programs are often components of larger systems that are not themselves labeled "intelligent." There are hundreds of such applications in use today, including those that make investment recommendations, perform medical diagnoses, plan troop and supply movements in warfare, schedule the refurbishment of the space shuttle and detect fraudulent use of credit cards. These systems make expert decisions, find meaningful patterns in complex data and improve their performances by learning. All these actions, if done by a human, would be taken to display sound judgment, expertise or responsibility. Many of these tasks, however, could not be done by humans, who are too slow, too easily distracted or not sufficiently reliable. Our intelligent machines already surpass us in many ways. The most useful computer applications, including AI applications, are valuable exactly by virtue of their lack of humanity. A truly humanlike program would be just as useless as a truly pigeonlike aircraft.

Waiting for the Science

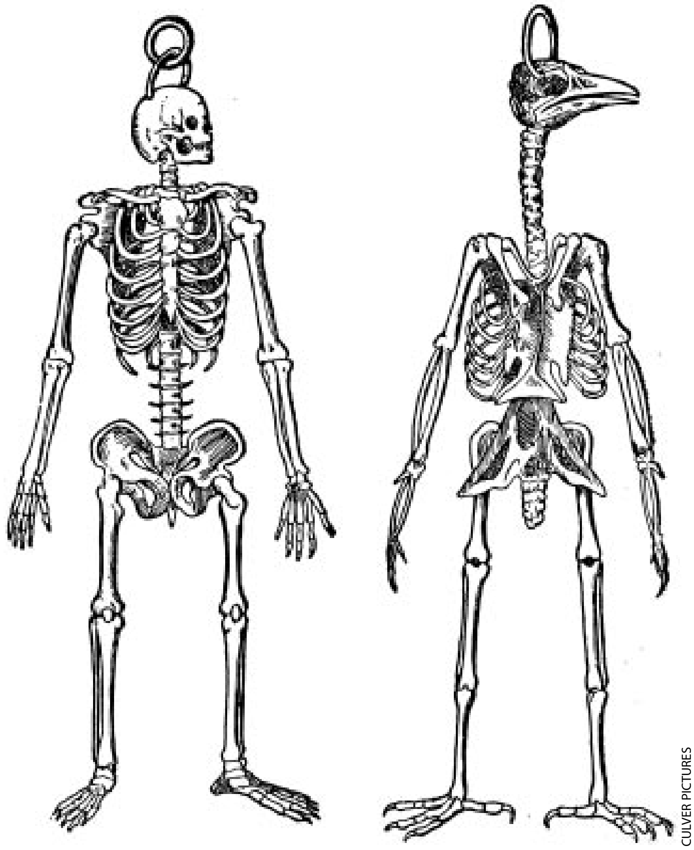
The analogy with flight provides another insight: technological advances often precede advances in scientific knowledge. The designers of early aircraft could not learn the principles of aerodynamics by studying the anatomy of birds. Evolution is a sloppy engineer, and living systems tend to be rich with ad hoc pieces of machinery with multiple uses or mechanisms jury-rigged from structures that evolved earlier for a different reason. As a result, it is often very difficult to discover basic principles by imitating natural mechanisms.

Experimental aerodynamics became possible only in the early part of this century, when artificial wings could be tested systematically in wind tunnels. It did not come from studying natural exemplars of flight. That a gull's wing is an airfoil is now strikingly obvious, yet the airfoil was not discovered by examining the anatomy of birds. Even the Wright brothers never really understood why their *Flyer* flew. The aerodynamic principles of the airfoil emerged from experiments done in 1909 by French engineer Alexandre-Gustave Eiffel, who used a wind tunnel and densely instrumented artificial wings. The first aircraft with "modern" airfoils—which were made thicker after engineers demonstrated that thicker airfoils improved lift without increasing drag—did not appear until late in World War I. As is true for many other disciplines, a firm theoretical understanding was possible only when controlled experiments could be done on isolated aspects of the system. Aerodynamics was discovered in the laboratory.

The same reasoning applies to the study of human intelligence. It may be impossible to discover the computational principles of intelligent thought by examining the intricacies of human thinking, just as it was impossible to discover the principles of aerodynamics by examining bird wings. The Wright brothers' success was largely attributed to their perception of flight in terms of lift, control and power; similarly, a science of intelligence must isolate particular aspects of thought, such as memory, search and adaptation, and allow us to experiment on these one at a time using artificial systems.

By systematically varying functional parameters of thought, we can determine the ways in which various kinds of mental processes can interact and support one another to produce intelligent behavior.

Several areas of AI research have been transformed in the past decade by an acceptance of the fact that progress must be measurable, so that different techniques can be objectively compared. For example, large-scale empirical investigations must be conducted to evaluate the efficiency of different search techniques or reasoning methods. In this kind of AI research, computers are providing the first wind tunnels for thought.



COMPARISON OF SKELETONS of a human and a bird—here taken from a 16th-century manuscript by French naturalist Pierre Belon—examined similarites in anatomy in an attempt to understand how birds can fly.

A Science of Intelligence

Rejecting the Turing test may seem like a retreat from the grand old ambition of creating a "humanlike" mechanical intelligence. But we believe that the proper aim of AI is much larger than simply mimicking human behavior. It is to create a computational science of intelligence itself, whether human, animal or machine. This is not a new claim; it has been made before by AI pioneers Allen Newell and Herbert A. Simon, cognitive psychologist Zenon Pylyshyn and philosopher Daniel C. Dennett, among others. But it was not until we noted the analogy with artificial flight that we appreciated the extent to which the Turing test, with its focus on imitating human performance, is so directly at odds with the proper objectives of AI. Some of our colleagues say their ultimate goal is indeed the imitation of human intelligence. Even with this limited aim, however, we believe that the perspective sketched here provides a more promising way to achieve that ambition than does the method outlined by Turing.

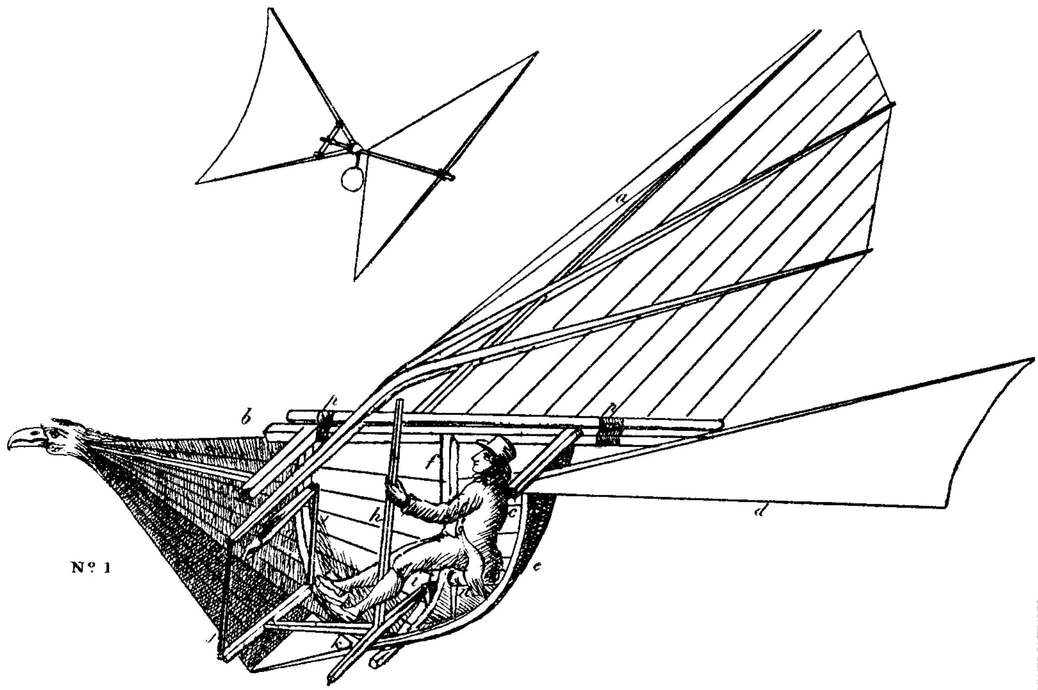
Consider again the analogy with flight. Just as the principles of aerodynamics apply equally to any wing, natural or artificial, the computational view of intelligence—or, more broadly, of mentality—applies just as well to natural thinkers as to artificial thinkers. If cognitive psychology and psycholinguistics are like the study of bird flight in all its complexity, then applied AI is like aeronautical engineering. Computer science supplies the principles that guide the engineering, and computation itself is the air that supports the wings of thought.

The study of artificial intelligence, like a large part of computer science, is essentially empirical. To run a program is often to perform an experiment on a large, complex apparatus (made partly of metal and silicon and partly of symbols) to discover the laws that relate its behavior to its structure. Like artificial wings, these AI systems can be designed and instrumented to isolate particular aspects of this relation. Unlike the research methodology of psychology, which employs careful statistical analysis to discern relevant aspects of behavior in the tangled complexity of nature, the workings of AI systems are open to direct inspection. Using computers, we can discover and experiment directly with what Newell and Simon have called the "laws of qualitative structure."

This picture of AI defines the field in a more useful and mature way than Turing could provide. In this view, AI is the engineering of cognitive artifacts based on the computational understanding that runs through and informs current cognitive science. Turing correctly insisted that his test was not meant to define intelligence. Nevertheless, in giving us this touchstone of success, he chose human intelligence—in fact, the arguing skill of an educated, English middle-class man playing a kind of party game—as our goal. But the very science that Turing directed us toward provides a perspective from which a much broader and more satisfying account of intelligence is emerging.

Scholastic Critics

Artificial intelligence and artificial flight are similar even in the criticisms they attract. The eminent American astronomer Simon Newcomb argued passionately in the early 1900s against the idea of heavier-than-air flight. Newcomb's fulminations seem amusing now, but his arguments were quite impressive and reflected the view of the informed intelligentsia of his day. Like British mathematical physicist Roger Penrose, who uses Gödel's theorem to "prove" that AI is impossible, Newcomb employed mathematical arguments. He pointed out that as birds get bigger, their wing area increases in proportion to the square of their size, but their body weight increases in proportion to the cube, so a bird the size of a man could not fly. He was still using this argument against the possibility of manned flight several years after the Wright brothers' success at Kitty Hawk, N.C., when aircraft were regularly making trips lasting several hours. It is, in fact, quite a good argument—aircraft takeoff weights are indeed roughly proportional to the cube of their wingspan—but Newcomb had no idea how sharply the lift from an airfoil increases in proportion to its airspeed. He thought of a wing as simply a flat, planar surface.

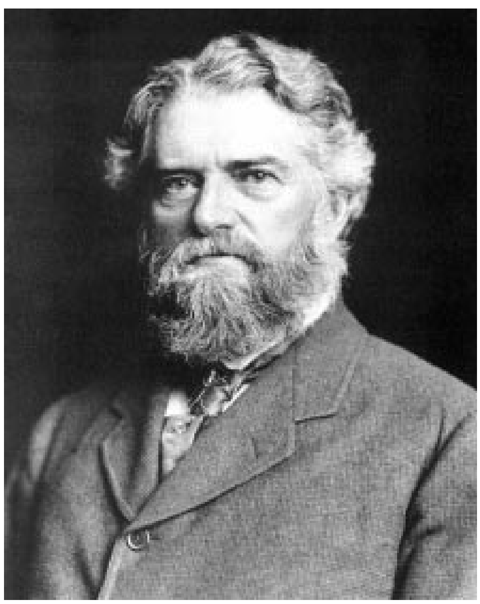


WOODEN GLIDER designed in 1810 by English artist Thomas Walker included a birdlike beak.

CULVER PICTURES

Newcomb also used a combination of thought experiment and rhetoric to make his point—the same tactic that philosopher John R. Searle has employed in his famous "Chinese Room" argument against AI [see "Is the Brain's Mind a Computer Program?" by John R. Searle; SCIENTIFIC AMERICAN, January 1990]. Newcomb stated scornfully, "Imagine the proud possessor of the aeroplane darting through the air at a speed of several hundred feet per second! It is the speed alone that sustains him. How is he ever going to stop?" Newcomb's arguments, with their wonderful combination of energy, passion, cogency and utter wrongheadedness, are so similar to contemporary arguments against artificial intelligence that for several years we have offered the annual Simon Newcomb Award for the silliest new argument attacking AI. We welcome nominations.

A common response to our analogy between artificial intelligence and artificial flight is to ask what will be the Kitty Hawk of AI and when will it happen. Our reply follows that of Herbert Simon: *it has already happened*. Computers regularly perform intelligent tasks and have done so for many years. Artificial intelligence is flying all around us, but many simply refuse to see it. Among the thousands of applications in use today, here are just a few examples: AI systems now play chess, checkers, bridge and backgammon at world-class levels, compose music, prove mathematical theorems, explore active volcanoes, synthesize stock-option and derivative prices on Wall Street, make decisions about credit applications, diagnose motor pumps, monitor emulsions in a steel mill, translate technical service manuals, and act as remedial reading tutors for elementary school children. In the near future, AI applications will guide deep-space missions, explore other planets and drive trucks along freeways.



MARY LEA SHANE ARCHIVES, LICK OBSERVATORY

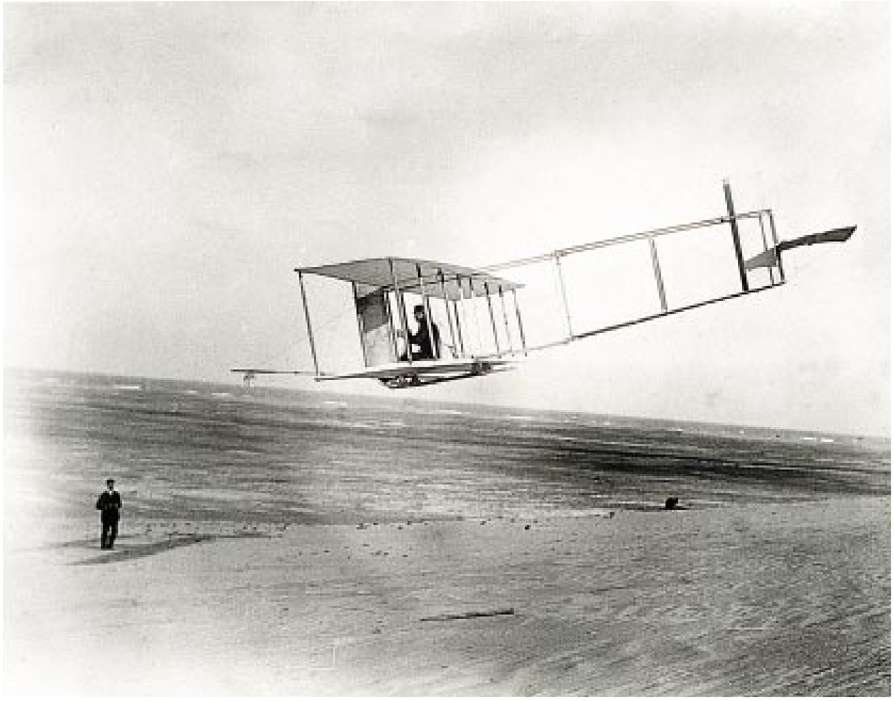
SIMON NEWCOMB, American astronomer and mathematician, argued passionately against the possibility of artificial flight—even after the Wright brothers' successful tests of their aircraft in 1903.

But should all this really count as "intelligent"? The performance of AI systems, like the speed or altitude of aircraft, is not open to dispute, but whether or not one chooses to call it "intelligent" is determined more by social attitude than by anything objective. When any particular ability is mechanized, it is often no longer considered to be a hallmark of mental prowess. It is easy now to forget that when Turing was writing, a "computer" was a human being who did arithmetic for a living, and it was obvious to everyone that computing required intelligence. The meaning of the word has now changed to mean a machine, and performing fast, accurate arithmetic is no longer considered a hallmark of mental ability, just as the meaning of "flying" has changed to cover the case, once inconceivable, of dozing quietly in an airplane seat while traveling at hundreds of miles an hour far above the clouds. Newcomb—who was famous as one of the finest computers of his time—went to his deathbed refusing to concede that what early aircraft did should be called "flying."

Turing suggested his test as a way to avoid useless disputes about whether a particular task counted as truly intelligent. With considerable prescience, he anticipated that many people would never accept that the action of a machine could ever be labeled as "intelligent," that most human of labels. But just as there was no doubt that the early flyers moved through the air at certain altitudes and speeds, there is no doubt that electronic computers actually get arithmetic done, make plans, produce explanations and play chess. The labels are less important than the reality.

The arbitrariness of the social labeling can be illustrated by a thought experiment in which the machine is replaced by something mysterious but natural. Whereas a dog will never pass the Turing test, no one but a philosopher would argue that a dog does not display some degree of intelligence—certainly no one who has owned a dog would make such an argument. It is often claimed that Deep Blue, the com-

THE WRIGHT FLYER, *shown at Kitty Hawk, N.C., with Orville Wright piloting, proved that aircraft need not imitate birds.*



ARCHIVE PHOTOS

puter that defeated chess champion Garry Kasparov, is not *really* intelligent, but imagine a dog that played chess. A chess-playing dog that could beat Kasparov would surely be acclaimed a remarkably smart dog.

The idea that natural intelligence is a complex form of computation can only be a hypothesis at present. We see no clear reason, however, why any mental phenomenon cannot be accounted for in this way. Some have argued that the computationalist view cannot account for the phenomenology of consciousness. If one surveys the current theories of the nature of consciousness, however, it seems to us that a computationalist account offers the most promise. Alternative views consider consciousness to be some mysterious physical property, perhaps arising from quantum effects influenced by the brain's gravity or even something so enigmatic as to be forever beyond the reach of science. None of these views seems likely to explain how a physical entity, such as a brain in a body, can come to be aware of the world and itself. But the AI view of mental life as the product of computation provides a detailed account of how internal symbols can have meaning for the machine and how this meaning can influence and be influenced by the causal relations between the machine and its surroundings.

The scientific goal of AI is to provide a computational account of intelligence or, more broadly, of mental ability itself—not merely an explanation of human mentality. This very understanding, if successful, must deny the uniqueness of human thought and thereby enable us to extend and amplify it. Turing's ultimate aim, which we can happily share, was not to describe the difference between thinking people and unthinking machines but to remove it. This is not to disparage or reduce humanity and still less to threaten it. If anything, understanding the intricacies of airflow increases our respect for how extraordinarily well birds fly. Perhaps it seems less magical, but its complexity and subtlety are awesome. We suspect that the same will be true for human intelligence. If our brains are indeed biological computers, what remarkable computers they are. SA

About the Authors

INSTITUTE FOR HUMAN AND MACHINE COGNITION

KENNETH M. FORD (*left*) is associate director at the National Aeronautics and Space Administration Ames Research Center and director of the NASA Center of Excellence for Information Technology. He is on leave from the Institute for Human and Machine Cognition at the University of West Florida, where he is the director. Ford entered computer science and artificial intelligence through the back door of philosophy. After studying epistemology as an undergraduate, he joined the navy and wound up fixing computers. "I had no interest in computers," he says. "I didn't even know how to program them." But Ford learned quickly—he received his Ph.D. in computer science from Tulane University in 1987. He still finds a compelling connection between computers and philosophy. "I'm convinced," he says, "that were they reborn into a modern university, Plato, Aristotle and Leibniz would most suitably take up appointments in the computer science department." Over the years he has developed a love of stalking wary redfish and speckled trout on the shallow flats of the Gulf of Mexico—quiet hours that are often the source of fresh ideas.

PATRICK J. HAYES is John C. Pace Eminent Scholar at the Institute for Human and Machine Cognition at the University of West Florida and is a past president of the American Association for Artificial Intelligence. His path toward AI started at age 12, when he constructed a robot that could wander around a tabletop without falling off. He went on to study mathematics at the University of Cambridge and machine intelligence at the University of Edinburgh. Visiting Stanford University to work with AI pioneer John McCarthy sparked his interest in the use of logic in artificial intelligence. Later, at the University of Rochester, Hayes headed one of the first multidisciplinary programs in cognitive science. His current research focuses on the representation of knowledge, the underpinnings for an artificial consciousness and the philosophical questions raised by AI. Hayes also has a more temporal interest: his wife, Jacqueline, and he collect and restore antique mechanical clocks.

More than just competing with people, game-playing machines complement human thinking by offering alternative methods to solving problems

Computers, Games and the Real World

by Matthew L. Ginsberg

The world watched with considerable amazement in May 1997 as IBM's chess computer, Deep Blue, beat Garry Kasparov, the world champion, in a six-game match. With a machine's victory in this most cerebral of games, it seemed that a line had been crossed, that our measurements of ourselves might need tailoring.

The truth of who ultimately won and who lost, of course, is not so black-and-white. Kasparov played poorly, resigning a game that would have led to a draw early in the match and making a completely uncharacteristic error in the last game. And while chess-playing computers have been gaining an edge on their human competitors for some time, in many other games, such as Go and bridge, computer players remain relatively weak. Still, in checkers and Othello, machines have been the world's strongest players for years. Backgammon, like chess, is currently too close to call, whereas machines have a slight but definite edge in Scrabble.

The board and card games that researchers build programs to play provide an environment with specific rules and objective outcomes, a closed system allowing theories to be tested and achievements to be tracked. As an element of artificial intelligence, game-playing software highlights the key differences between the brute-force calculation of machines and the often intuitive, pattern-matching abilities of humans.

Considering Moves

People have been designing machines and programs to play games almost as long as computer code has been written. In 1946 British mathematician Alan M. Turing began designing a chess player on a souped-up code-breaking machine used by Britain during World War II. The computer became the first machine to play a full game of chess, albeit at an extremely slow beginner level. Turing and his colleagues at the University of Manchester later went on to tackle the more basic programming challenges of tic-tac-toe and checkers.

Since then, many people have designed different types of programs and computers with varying degrees of success. The most recent and best game programs [*see box on pages 86 and 87*] are interesting because they generally play their games quite well. But perhaps more interesting is that they achieve this level of performance by using techniques very different from those used by their human counterparts. In games such as chess, a human player will consider some tens (or perhaps hundreds) of positions when selecting a move. A machine, on the other hand, will consider billions, searching through many possible lines of play in the process of selecting an action.

Considering the far greater computational capacity of computers, how is it that humans can win at all? The answer is that although we look at a relative handful of successor positions, we look at the right handful. Emanuel Lasker, world chess champion from 1894 to 1920, was once asked how many moves he considered when analyzing a chess position. "Only one," he replied. "But it's always the best move."

We identify the best positions to consider by a process known as pattern matching. It is how we immediately identify the four-legged platform in a room as a table or the images in a police mug shot as those of the same person despite the different orientations of the front and profile views. An expert chess player compares a given chess position to the tremendous number of such positions that he has seen over the course of his career, using lessons learned from analyzing those other posi-

LOUISE AND WALTER ANNENBERG COLLECTION, PHILADELPHIA MUSEUM OF ART

Portrait of Chess Players, **by Marcel Duchamp**

JONATHAN ELDERFIELD *Gamma Liaison*

MAN AGAINST MACHINE: Although the IBM computer Deep Blue officially beat world champion Garry Kasparov (two wins, one loss, three ties), it is not entirely clear whether the computer would have won had Kasparov played in his usual top form.

tions to identify good moves in the current game.

Pattern matching is a parallel process; if you had *n* computers, you could do it *n* times faster. For example, suppose you are trying to compare a particular chess position to the 100,000 positions that you have seen previously. Each comparison is in some sense independent: given 100,000 computers, you could do the overall comparison 100,000 times more quickly.

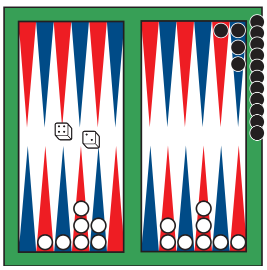
Searching is not an inherently parallel process; problems cannot be split up, because what you want to do next depends on what you just did. For Deep Blue, there is no preexisting list of positions that it evaluates. Rather it can examine a position only after it has constructed its predecessor.

It is important to note that when I say that pattern matching is parallel, whereas brute-force searching is not, I am referring not to the problem being solved but only to the method being used to solve it. I have not said that playing a good game of chess is a parallel problem or that it is not. In fact, the evidence in some sense is that chess is not inherently parallel or serial, because parallel techniques (human pattern matching) and serial ones (Deep Blue's brute-force searching) can be applied equally well to the game.

Function Follows Form

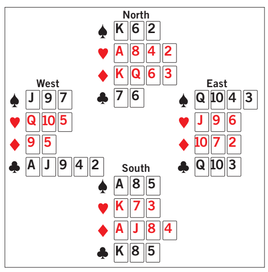
There is a good reason that Kasparov and other human players use a parallel technique to play chess: the human brain appears to be a parallel machine, consisting of about 100 billion neurons, each capable of operating 1,000 times a second.

Games Computers Play



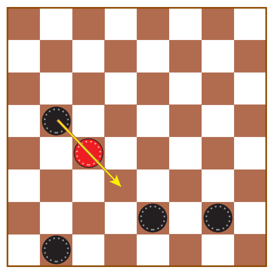
BACKGAMMON

- 2 players
- 15 pieces each
- Goal: Move all pieces off the board
- Rules:
  - Dice roll determines number of moves
  - Players move in opposite directions
  - Piece cannot land on a point occupied by 2 or more of opponent's pieces
  - Single piece can be "hit" if landed on by opponent; hit piece must start anew
- Program: TD-Gammon*
- Web site: www.research.ibm.com/massdist/tdl.html
- Advantage: Too close to call



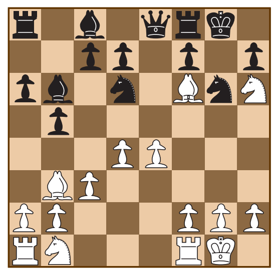
BRIDGE

- 4 players in 2 teams
- 13 cards dealt to each player
- Goal: Make 2 "game contracts," or a "rubber"
- Rules:
  - The bid: Each player predicts how many times his or her card will be the highest (a trick)
  - The play: Put down 1 card at a time and compare it with others; this occurs 13 times
  - The scoring: Points scored if bid is made or exceeded; otherwise points go to the opposing team
- Program: GIB*
- Web site: www.gibware.com
- Advantage: Human



CHECKERS

- 2 players
- 12 pieces each
- Goal: Avoid being the player who can no longer move (usually when a player has no pieces left)
- Rules:
  - Move forward on dark diagonal, 1 square at a time
  - Opponent's piece captured when jumped to empty square diagonally behind opponent's piece
  - Creation of a "king," a piece that can move backward and forward, occurs when piece is moved to opponent's last row
- Program: Chinook
- Web site: www.cs.ualberta.ca/~chinook
- Advantage: Machine



CHESS

- 2 players
- 16 pieces each (1 king, 1 queen, 2 rooks, 2 bishops, 2 knights, 8 pawns)
- Goal: Capture opponent's king (checkmate)
- Rules:
  - Pieces are captured when landed on by opponent's piece
  - Type of piece dictates movement options
- Program: Deep Blue
- Web site: www.chess.ibm.com/meet/html/d.3.html
- Advantage: Too close to call

*Indicates commercial software that runs on personal computers

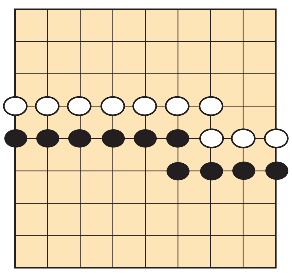
About 30 billion neurons are laid out in six layers of the cortex, the gray matter ("thinking" neurons) making up the outer folds of the human brain. An additional 70 billion constitute the white matter ("connecting" neurons). This massively parallel configuration is good at recognizing patterns but is challenged by serial calculations, such as searching.

In contrast, Deep Blue contains only 480 chess-specific processors, each of which is capable of examining about two million chess positions a second. This setup enables it to search many positions in very little time. Although this search-intensive approach provides a certain advantage, it has limitations. Even with the most powerful computer imaginable—say, one performing perhaps 10^{17} operations per second (one operation in the amount of time it takes light to traverse the space of a hydrogen atom)—you still would not be able to make a dent in solving a game such as Go, for which there are some 10^{170} possible positions.

When humans play a game that depends on a brute-force search through an enormous number of positions and strategies, such as Othello, we cannot use methods that depend on the possibility of executing a billion instructions a second; the neurons in our brain fire at a millionth of that rate. Because our brains operate so slowly, serial methods to solve problems are generally ineffective for us.

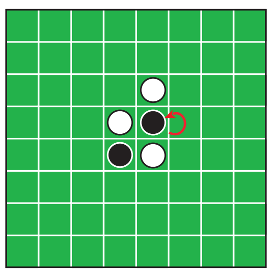
Of course, 1,000 operations per second may be relatively slow, but humans can still use the serial method in a pinch. We use serial methods when we multiply large numbers, for instance. We also commonly use them to solve puzzles, such as Rubik's cube, and brainteasers, such as the old problem of figuring out how to get three missionaries and three cannibals across a river using a single rowboat that can hold two people, subject to the condition that the cannibals cannot outnumber the missionaries on either bank because they will eat them. (In the more modern version of the problem, the missionaries cannot outnumber the cannibals because they will convert them.) Although we are capable of applying reasoning to solve brainteasers, the reasoning itself seems very unnatural because we typically give up on parallel methods and instead search through the possible combinations. For artificial intelligence, this method is referred to as "puzzle mode" reasoning. Machines are good at it, because their hardware is designed for it, but humans are not.

And unlike the human brain, which is stuck where it is, computers can improve their game-solving ability with faster hardware and more efficient programs. In most game-playing programs, a computer is programmed to analyze only those moves close to the current position, to avoid a massively deep search. Its move options can be assigned values using a procedure known as minimaxing. An additional technique, called alpha-beta pruning, allows the computer to compute these



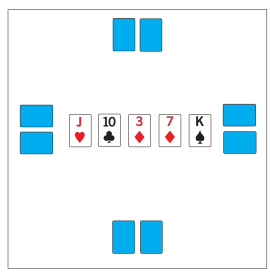
GO

- 2 players
- Black-and-white stones
- Grid size of board can vary: typical game is on 19-by-19 grid points
- Goal: Conquer a larger part of the board (conquered part encompasses stones placed on board plus stones that could be added safely—that is, within the player's walls)
- Rules:
  - Both sides alternate in placing stones on the board
  - Stones surrounded by an opponent's stones are captured and removed from the board
- Program: Handtalk*
- Web site: www.webwind.com/go
- Advantage: Human, by a huge margin



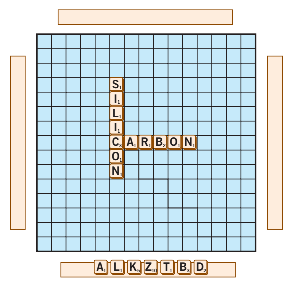
OTHELLO

- 2 players
- Black-and-white disks
- Goal: Have most disks on the board at the end of the game
- Rules:
  - Players alternate placing disks on unoccupied board spaces
  - If opponent's disks are trapped between other player's disks, opponent's disks are flipped to the other player's color
- Program: Logistello
- Web site: www.neci.nj.nec.com/homepages/mic/log.html
- Advantage: Machine



POKER (Texas Hold 'Em)

- 3 to 20 players
- 2 cards dealt to each player; 5 cards placed in center of table
- Goal: Obtain the best hand and win the "pot"
- Rules:
  - 5 center (community) cards start facedown
  - First round of betting ensues; 3 community cards are turned over
  - Subsequent rounds of betting ensue; 4th and 5th community cards turned over
  - Players select best 5 from the community cards and their hands to obtain identical kinds of cards (pairs, 3- and 4-of-a-kind), flushes (all same suit), straights (sequential) or their combinations
  - Final round of betting ensues
- Program: LOKI
- Web site: www.cs.ualberta.ca/~games/poker
- Advantage: Human, by a huge margin



SCRABBLE

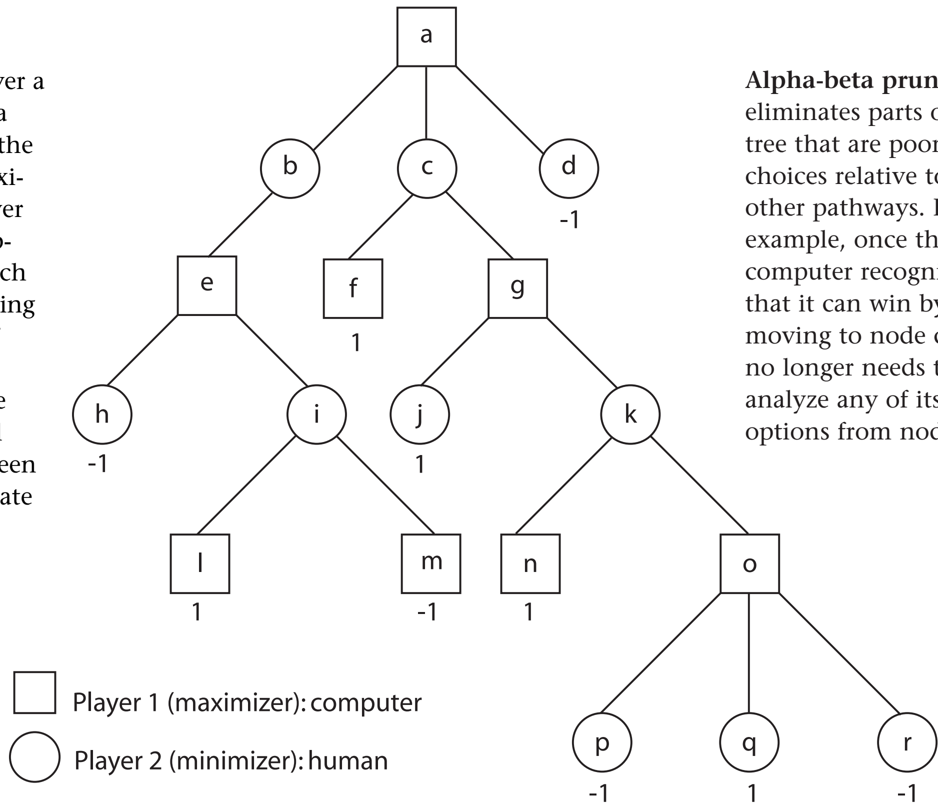
- 2 to 4 players
- 100 tiled letters
- Goal: Accumulate most points by creating high-scoring words
- Rules:
  - Each player draws 7 letters
  - Each letter has a value
  - Squares on the board have values
  - Words created must join an array
- Program: Maven* (used in Scrabble CD-ROM)
- Web site: www.hasbroscrabble.com/cd/cd.html
- Advantage: Machine, by a slight margin

*Indicates commercial software that runs on personal computers

JOHN MENGEL *Ponzi & Weill*

How Game-Playing Computers Think

Minimaxing assigns one player a positive value and the other a negative value. (In this case, the computer is player 1, the maximizer, and the human is player 2, the minimizer.) Once established, the values assigned each node can be judged as benefiting the maximizer (the "positive" player) or the minimizer (the "negative" player). Each node represents the positions of all the pieces after a move has been made—more generally, the state of the game at the moment.



Alpha-beta pruning eliminates parts of the tree that are poor path choices relative to other pathways. For example, once the computer recognizes that it can win by moving to node c, it no longer needs to analyze any of its other options from node a.

MEG CRANE

values without examining every imaginable possibility. This strategy enables the computer to perform a more effective search given its fixed computational resources [*see illustration above*].

There have been attempts to produce chess computers that play the game in a more humanlike way. But the performance of these systems has been modest at best. Nobel laureate Herbert A. Simon of Carnegie Mellon University believes that the basic differences in architecture may prevent efficient humanlike reasoning in computers: "It could be that because of the radical differences between electronic devices and brains, programs designed to be efficient [intelligent programs] would be totally different in architecture and process from systems designed to simulate human thinking." Thus, the hardware may make what we consider efficient reasoning not so efficient when run on a silicon-based system.

Prowess Follows Process

In summary, some problems are best solved using pattern matching, whereas others are best solved using serial search. Go seems to be a fundamentally parallel challenge; Othello seems to be serial. Other games, such as chess, seem equally amenable to both methods.

This division also exists for games of imperfect information, where the players do not know what cards or other assets are held by their opponents. (A game of perfect information provides all players with complete data about the state of the game; backgammon, chess, checkers and Othello are examples.) Imperfect-information games have historically eluded competent computer play. In these games, such as poker and bridge, humans often rely on experience and intuition to play well. Computers are at a disadvantage; there is just too much information to process. But recently massive computational resources have brought games of imperfect information closer to being solved. Daphne Koller and Avi Pfeffer of Stanford University suggest that it will be possible to "solve poker." They base this conclusion on successful algorithms they designed to play perfectly using an eight-card deck. The question now is if enough computational power will ever be available to apply the same approach to a 52-card deck.

In bridge, too, the power of exhaustive methods is beginning to be felt. Earlier programs modeled human thinking, but a modern approach works as follows. The opponents are repeatedly given specific random hands, and the result is then analyzed assuming that the locations of all the cards are known. This approach identifies the best play or plays in one particular situation, and the best play overall is the one that is best in as many of the random situations as possible. Once again, this style of analysis is possible primarily because of increasing hardware power. Although the best humans still outplay the best programs, the gap is narrowing. As in chess, programs that attempt to model human thinking are no match for their search-based competitors.

In all these cases, Simon's speculation on the innate importance of architecture has proved correct. The strongest machine players do indeed bear little resemblance to their human counterparts. The only game that seems to be an exception is backgammon. In this case, Gerald J. Tesauro of IBM created a program called TD-Gammon that appears, at least on the surface, to have a humanlike architecture. Specifically, it relies on an artificial neural network, which is software designed to mimic the function and structure of neurons.

Games People (and Computers) Play

The nature of the game and the type of solution processing most conducive to success often dictate whether human or machine plays better. Machines excel at checkers, a game that involves deep-search methods to evaluate possible combinations. Chinook, currently the best checkers program, knows immediately which player (if either) will win once there are eight or fewer checkers on the board. It determines the outcome by accessing its enormous database of endgames. This task is not a pattern-matching problem, because there are no reliable patterns that characterize all the positions; instead Chinook simply stores a huge table of the positions and values and looks in that table when a result is needed.

Machines also have a tremendous advantage in Othello because it is a difficult game for humans to get a feel for; it is almost impossible to tell at a glance who is winning at any particular point. The markers flip back and forth so frequently that having a preponderance of markers with your color in the middle of the game does not necessarily indicate that you are winning. In other words, Othello is a game that is difficult to play using pattern matching but is perfectly suited to a machine's brute-force search methods. Therefore, machines excel.

Go, however, is the computer's Achilles' heel. It is a pattern-matching game in which human experts can generally recognize large configurations of stones that are dead (surrounded and fated to eventual capture), alive (permanently safe from capture) or whose fate is currently undetermined. Playing Go using brute-force search, however, is extremely difficult, because at any given point there will be some 250 legal moves. (In comparison, there are only approximately 30 legal moves in chess and seven in Othello.) Building an endgame database such as Chinook's is completely out of the question because the number of possible ending positions in a Go game is beyond a computer's computational power.

And other games? The best in backgammon is a close call between human and computer and is very likely to remain so: because of the relative simplicity of the game, both people and machines play backgammon nearly perfectly. Scrabble is also close but not very likely to remain so, as machines become better at the strategic parts of the game. (Both humans and machines have no difficulty playing the highest scoring move at any point, but high-level Scrabble is also a matter of keeping a good balance of tiles in your rack and minimizing your opponent's opportunities.) Humans won a two-game match in 1997 but lost an 11-game match in 1998. Bridge is likely to become close in about five years, as hardware becomes faster and algorithms improve. Humans narrowly won a two-hour match this past July, and at the 1998 World Bridge Championships, held in August in Lille, France, the bridge program I wrote placed 12th in a field of 34 of the top human bridge players.

Playing Nicely Together

As artificial intelligence has developed, success has come most often through the application of good serial algorithms. These successes are not limited to game playing: serial algorithms are the most effective known solutions for selecting the order in which to assemble the component parts of a Boeing 747. These algorithms lead to production schedules some 10 to 20 percent shorter than the best schedules produced by humans. Pattern matching and other parallel techniques are not terribly well suited to scheduling complex tasks, because a schedule that looks good may in fact not be.

At least for the foreseeable future, humans will be better than machines at solving parallel problems, and machines will be better at solving serial ones. There should be nothing particularly surprising or threatening here; we have designed machines to achieve other results that we ourselves are not capable of achieving, such as airplanes to fly us or forklifts to raise objects our muscles cannot move. And we do not feel compelled to pit humans against forklifts in Olympic weight lifting.

The lesson is that intelligent machines are not our competitors but our collaborators. The complementary skills of humans and machines enable problems to be solved that neither could have figured out alone. And that is exceptionally good news for us all, carbon and silicon alike.

About the Author

ROBERT KAISER

MATTHEW L. GINSBERG is a senior research associate at the University of Oregon and founder of the university's Computational Intelligence Research Laboratory (CIRL). He received his doctorate in mathematics from the University of Oxford in 1980, where he also captained the bridge team. Although he currently plays little competitive bridge, he has remained in the game via his alter ego, an expert-level bridge-playing program called GIB (Ginsberg's Intelligent Bridge player). "On a personal level, GIB has been a blast," Ginsberg says. "I can interact with top players, but no one is angry when the computer beats them." Pending software adjustments, Ginsberg predicts that GIB will become the world's top bridge player in five years. When not conducting research, supervising graduate work at CIRL or tinkering with GIB, Ginsberg likes to relax with a few loops and rolls in his kit-built stunt plane. Lately he has cut down on that thrill to once a week, choosing instead to spend time with his wife, his infant daughter and his four-year-old son, who has just learned to play chess.

Miniature computers built into clothes, shoes and eyeglasses may become the "smartest" new fashion accessories

Wearable Intelligence

by Alex P. Pentland

SAM OGDEN

Research on intelligence is mostly about investigating how brains work or building intelligent machines or creating "smart" environments such as a house that can identify and track its occupants. But what about making people smarter? To accomplish this goal, one can consider biochemistry or bioimplants, but the easiest way to improve intelligence is by augmenting the items we wear all the time—glasses, wristwatches, clothes and shoes—with miniature computers, video displays, cameras and microphones. These high-tech "wearables," which are being developed at the Massachusetts Institute of Technology Media Laboratory, can extend one's senses, improve memory, aid the wearer's social life and even help him or her stay calm and collected.

The idea of increasing intelligence with wearable devices is very old. English physicist Robert Hooke wrote in 1665 (in the preface to *Micrographia*): "The next care to be taken, in respect of the Senses, is a supplying of their infirmities with Instruments, and as it were, the adding of artificial Organs to the natural.... And as Glasses have highly promoted our seeing ... there may be found many mechanical inventions to improve our other senses of hearing, smelling, tasting and touching."

One must draw a distinction between wearable devices and those that are merely

INTELLIGENT CLOTHES were recently displayed at a fashion show at the Massachusetts Institute of Technology Media Lab. At the left, a model wears a television reporter's outfit, equipped with a video camera in her glove and a heads-up display in her glasses.

portable, the classic example being the pocket watch and wristwatch. The difference is simple: you have to pull out the pocket watch and open it to see the time, whereas the wristwatch enables you to see the time instantly, even while working with both hands. Although this may seem like a minor difference, it greatly affects how you use the device and how completely it is integrated into your life. Watches, eyeglasses and radios have all evolved from handheld portable versions to wearable items, and many of today's portables are destined to become tomorrow's wearables.

Electronic devices are beginning to make the transition from portable to wearable. There are now wristwatches that contain medical monitors and pagers; eyeglasses with embedded computer displays that only the user can see; vests, belts and watches with computers inside them; and cell phones and pagers that come with Internet connections and tiny teleconferencing cameras.

Equipped with wearable computers and other devices, people can conveniently check messages or finish a presentation while sitting on the subway or waiting in line at a bank. Even more important, they can also ignore these machines while attending to other affairs. Operating portable devices, in contrast, often requires your full attention and both hands. You have to stop everything you are doing and concentrate on the device. To appreciate how inconvenient this situation is, imagine having human aides (instead of electronic aids) who grabbed your hands and shouted in your face every time they had something to say.

Wearable devices can be much less disruptive, and people relate to them differently than they do to other tools. Something that's with you all the time can change the sense of who you are and what you can do. As we adapt to wearable devices and shape our personal habits around them, over time the culture as a whole will shift to incorporate them.

Hardware That's Made to Wear

Psychological studies show the validity of the phrase "the clothes make the man." Our self-perception and self-confidence can indeed change with our clothes. The same is true for any constantly available device—and not always for the better. Those of us who are continually "on call" via a pager know how fundamentally these tools can alter one's life. The personal effects of many information and communications technologies recall Marshall McLuhan's dictum, "the medium is the message"—that is, the way in which a new technology changes our way of life can be more important than the information it conveys. But wearables are more personal than traditional communications tools because they are a constant part of one's physical presence: they are not only part of what you wear but also part of who you are.

In the near future, the trend-setting professional may wear several small devices, perhaps literally built into their clothes. A person "dressed for success" in this manner may appear to have a fantastic memory, to be amazingly knowledgeable and to have powers of detection and deduction second only to Sherlock Holmes. These wearable intelligence devices can enhance one's "memory" by providing instant access to books, digitized maps, calendars and various databases; providing wireless connections to the Internet and e-mail; and boosting one's awareness with various sensors.

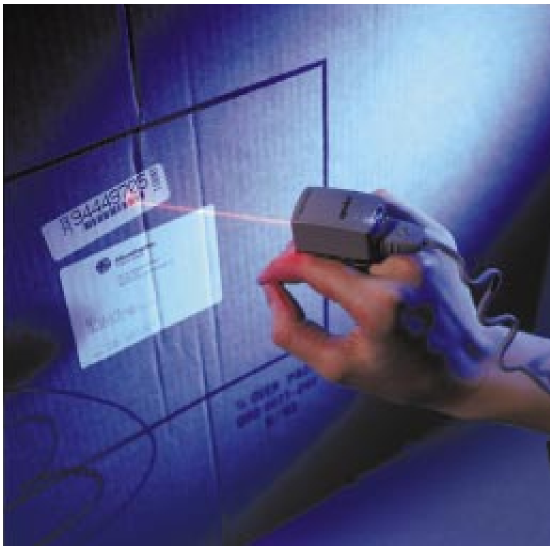
The hardware technology for this scenario has already been developed at research universities such as Carnegie Mellon, the Georgia Institute of Technology and the M.I.T. Media Laboratory, at large companies such as IBM, Toshiba and Motorola, and at start-up companies such as MicroOptical in Boston and the Flexible PC Company in Northfield, Minn. In my "wearables closet" I have glasses with a private, full-resolution computer display; a health monitor in a watch that records my temperature, heart rate and blood pressure; a computer-in-a-belt with a wireless Internet connection; a lapel pin that doubles as a camera and microphone; and a touchpad or keyboard literally sewn into a jacket. Soon there may be no need for batteries because sufficient power can be generated by harvesting the excess energy in normal walking (for example, by putting piezoelectric materials in shoes that generate electricity when compressed). Connecting wires might also become unnecessary by making use of conductive fibers woven into clothes or by transmitting small amounts of power via radio signals and skin conduction—all of which have been demonstrated at the Media Lab.

It is too early to tell which approaches to wearable design will prove popular. Some people, for example, may be comfortable with head-mounted video displays; others may find them unwieldy. Some may like the feel of headsets similar to those used by telephone operators; others may prefer less conspicuous audio and speech interfaces. The devices can be built in many ways, and it will take a fashion and style battle to determine what people really want to buy. The Media Lab, however, is not taking a passive attitude toward this issue. On the contrary, several years ago I initiated a collaboration with some of the world's most famous design schools to see what future wearable fashion would look like. Some tantalizing visions have already emerged from this effort.

As with most new technologies, wearables will probably make their biggest inroads in specialized tasks before becoming widely adopted by the gener-

SAM OGDEN

VEST WORN by a model is designed to translate a person's speech into another language. Microphones on the front of the vest record the voice, and speakers on the shoulders broadcast the translation.



SAM OGDEN

RING WITH BAR-CODE READER is already being sold for use in warehouses and loading docks. The device allows workers to identify the contents of a carton and to read shipping and handling instructions.

al public. Wall Street traders could rely on the devices for information needed to make quick decisions on the trading floor. Doctors could use them to store medical records and take pictures and notes. Industrial inspectors and scientists working in the field could jot down their observations while walking around. Repair workers could obtain assistance in the midst of a complicated job.

Thousands of Federal Express delivery people are now equipped with wearables so that the company can better coordinate its efforts around the world. Another company, Symbols Technologies in Holtsville, N.Y., makes a wearable device in the form of a ring with a built-in Universal Product Code (UPC) reader and computer display. When pointed at any product that has a UPC bar code, the ring can automatically pull up consumer reviews, instruction manuals and other information about the product.

Tailoring for a Better Fit

Although their potential is vast, many of these devices suffer from a common problem: they are mostly oblivious to you and your situation. They do not know what information is relevant to you personally or when it is socially appropriate to "chime in." The goal in solving this problem is to make electronic aids that behave like a well-trained butler. They should be aware of the user's situation and preferences, so they know what actions are appropriate and desirable—a task I call "situation awareness." They should also make relevant information available before the user asks for it and without forcing it on the user—a task I call "anticipation and availability."

To enhance situation awareness, the wearable device can employ sensors of various types to determine where the user is and what he or she is doing. The device can also monitor the user's choices and build a model of his or her preferences. A person can actively train the computer by saying, "Yes, that was a good choice; show me more," or "No, never suggest country music to me." The models can also work solely by statistical means, gradually compiling information about the user's likes and dislikes. (Firefly Network, a company started by my Media Lab colleagues, takes this approach, recommending books or movies to people depending on how their tastes match the profiles of millions of other users.)

For anticipation and availability, the wearable device can take a few key facts about the user's situation to prompt searches through a digital database or the World Wide Web. The information obtained in this manner is then presented in an accessible, secondary display outside the user's main focus of attention.

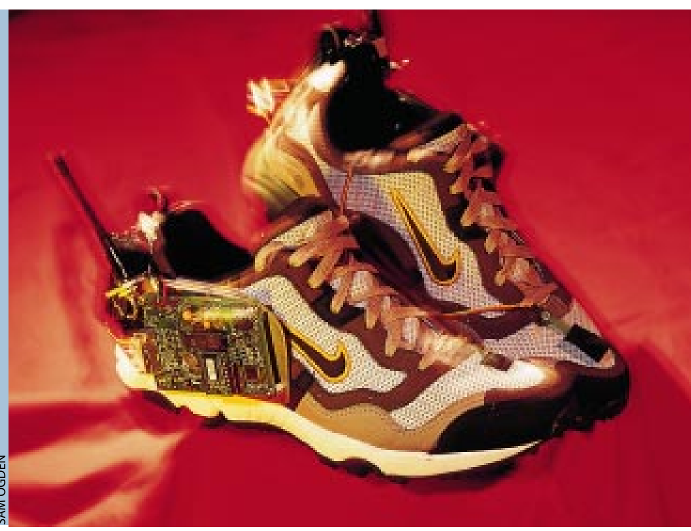
A good example of memory augmentation devices that use these design principles are electronic navigation aids relying on Global Positioning System (GPS) satellites. The typical navigation aid has a display that constantly shows one's current position on a map and indicates with an arrow how to reach the stated destination. There are handheld versions for hikers and plug-ins for laptops, but most are currently found in automobiles.

The promise of never being lost is a strong selling point for these aids, but they can do much more: for example, the devices can use your current location to call up information about nearby landmarks. You don't have to type in queries to find the local restaurants or gas stations; everything is retrieved on the basis of your present position. The ease and utility of such automatic indexing is making navigation aids a huge commercial success.

A wearable version of this device is now being manufactured by Motorola with advice from my students and me. The U.S. Army will soon be field-testing 50 of these GPS navigation and communications systems on its troops and plans to outfit tens of thousands of soldiers with the technology in the next few years. Of course, the same wearable aids can be used just as easily by tourists. The system would include a GPS sensor, a wireless connection to a digital database (such as the Web), a microphone and a digital camera. When you visit a tourist attraction, the device could show you the historical facts about the site and give you directions to the next stop on your itinerary. You could then wander around at your leisure with the wearable equivalent of a personalized tour guide.

DANCING SHOES developed by Joe Paradiso, a scientist at the M.I.T. Media Lab, convert dance steps into music. The shoes could also inform runners of a kink in their stride.

SAM OGDEN



This type of system relies on database "filters" and "agents" that use information about the wearer's situation—for example, his or her location and the time of day—to fetch pertinent data and to label the images, text and sounds that the wearer might find interesting. Although software agents will never be able to magically anticipate our desires, they can discern something about our patterns from statistical analyses. For instance, depending on the user's instructions, today's tools can bring to one's immediate attention e-mail from a spouse or boss and save the rest for future perusal.

SOCIAL WEARABLES can be used as icebreakers at parties. The devices flash infrared light to communicate the names of their users and any information they would like to share.

SAM OGDEN

Although it is impossible to say exactly where wearable intelligence technology is heading, I suspect the trend will be toward devices with greater situation awareness, achieved in part by using additional sensors such as cameras and microphones. My research, for instance, focuses on building wearables that attempt to see what the user sees and hear what the user hears. My idea is that you can't know what people might be interested in unless you know what they are hearing and seeing.

In essence, I want to give the software agents eyes and ears so that they can better understand—and thus better help—their human users. As the tools my students and I build become more reliable, and people become more comfortable with them, the agents could be allowed greater initiative. I expect that eventually many of the small tasks that complicate our lives will be delegated to such agents.

To this end, my research group has built wearables with small cameras mounted on the user's hat or glasses, which employ computer vision techniques to recognize what the person is looking at, without the need for bar codes or other tags. Once the computer knows what the person is looking at, it automatically gathers information about that object. When you meet someone, the computer can run a face-recognition program on the camera image to remind you of the person's name and other noteworthy facts. Alternatively, this computer-camera wearable can function as an expert adviser, analyzing the layout of balls on a pool table, for example, and identifying the best available shot.

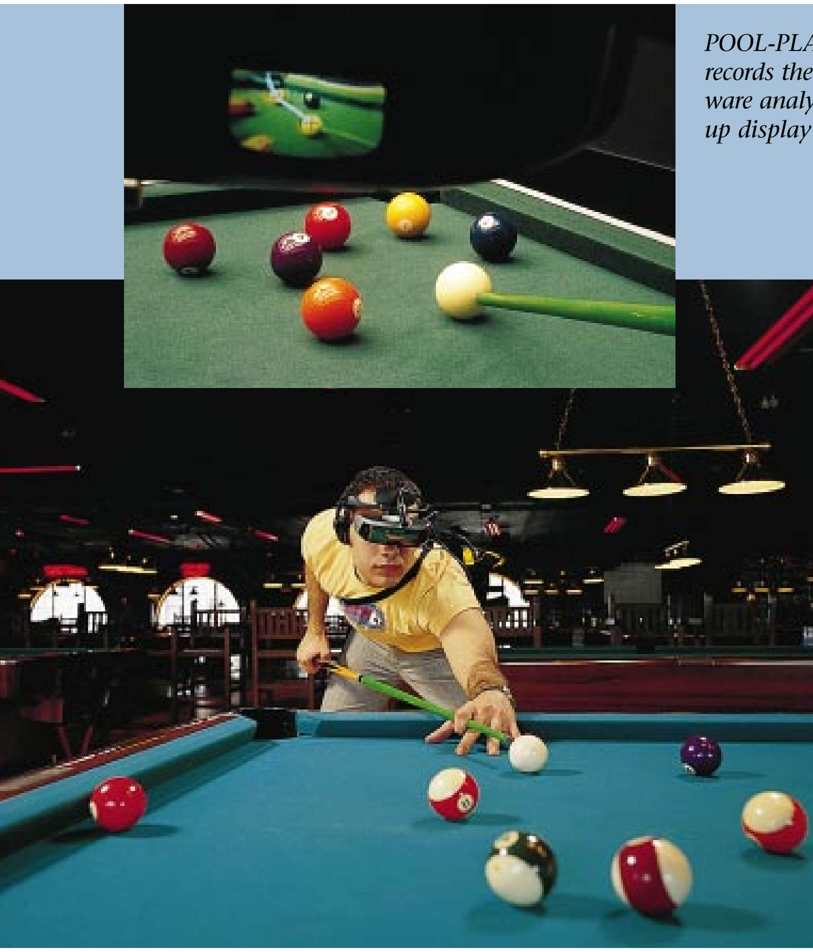
A wearable with a downward-looking camera provides another interesting source of situation awareness, because it can see what you're doing and observe your hand gestures. One version of this system reads American Sign Language and converts it into audible English. Another version can distinguish between activities such as handshakes, typing and driving, so that it can tailor its information retrieval to fit the current activity. (Technology similar to that used for speech recognition can be used to identify patterns of motion rather than patterns of sound.)

Other kinds of situation awareness can be achieved with audio input. We have built wearables that know when you and another person are talking, so that they don't interrupt. Although the system is not 100 percent accurate, we plan to make it better by using a camera that can determine whether sounds are coming from you or someone you're talking with, rather than from anybody in the vicinity.

We have also built devices that recognize what you are saying and then translate your phrases (albeit crudely) into another language. This system could be helpful for travelers and for people with serious speech impediments. Currently the technology works only for

SAM OGDEN

AFFECTIVE WEARABLE monitors the stress of Jennifer Healey, a graduate student at the M.I.T. Media Lab, by measuring skin conductivity and temperature. The data can be downloaded to a PalmPilot, which can display the user's vital signs.



POOL-PLAYING WEARABLE includes a head-mounted camera that records the position of the balls on the pool table. Specially designed software analyzes the possible shots and identifies the easiest one. A heads-up display (inset) *helps graduate student Tony Jebara line up the shot.*

SAM OGDEN

SAM OGDEN

SIGN-LANGUAGE TRANSLATOR is demonstrated by its developer, Thad Starner, one of the Media Lab's original "cyborgs." The video camera on his hat records his hand gestures, and motion-recognition software converts the signs into English. In the photograph Starner is signing the word "bicycle."

a user who has "trained" the system. Simultaneous translation of a two-way conversation, unfortunately, is still a distant dream.

Wearable items can offer important social benefits, helping us recognize people we might otherwise ignore or providing new ways for strangers to find common ground. In addition to assisting our memory, wearable intelligence aids can also augment our other talents and abilities in such areas as music, dance and athletics. One device (called "dancing shoes") converts dance steps into music; another can assist people with their baseball swings.

The Body Electric

Wearable medical monitors should become increasingly useful in the future. Today your doctor gets a "snapshot" of your physical condition about once a year, which is far too infrequent to catch incipient diseases. The failure to do more regular health monitoring is particularly problematic for the elderly, whose condition can change quite quickly. Even more troubling is the fact that current medical specialists cannot explain how most problems develop, because they only get to see people when something has gone wrong.

Yet it is now possible to build small devices that continuously monitor a wide range of vital signs. My students and I are working with the Center for Future Health at the University of Rochester to develop such medically oriented wearables, including early-warning systems for people with high-risk medical problems and "elder care" wearables that will help keep seniors out of nursing homes. Another simple but important application for medical wearables is to give people feedback about their alertness and stress level—an approach currently under study at the Media Lab by Rosalind W. Picard's "affective wearables" group.

A system that constantly tracks one's vital signs could yield helpful information, but it could also overwhelm the wearer with raw data, making it difficult to reach any decision. Similar concerns can be raised about wearable intelligence systems in general, which could potentially swamp users with too much data and leave them feeling burned out from the lack of "down time." The devices might also encourage people to retreat further into themselves and their machines, leading to greater social isolation.

I agree that poorly designed wearables could cause such problems. But information overload and social disruption are usually not caused by too much information or connectivity per se. After all, business and government leaders have always dealt with huge amounts of information and organizations with thousands of people. Instead it seems to me that most difficulties arise when information and communications are not properly integrated into our daily routine.

To avoid these problems, we need wearable devices that are organized around the pattern of our lives, rather than organizing our lives around them. I think we can accomplish this goal by making wearable devices that are sufficiently aware of their surroundings and the likes and dislikes of their users.

It should be noted that when books first became cheap and portable items, many feared that family life and popular culture would disintegrate, as people spent more time reading and less time talking. The impacts of eyeglasses and watches were also hotly debated in their time. But despite gloomy predictions, books, watches and glasses are now an accepted part of our lives. We've grown accustomed to them, and I think we are considerably better off, even though we are different people because of them. Wearable intelligence aids will cause similar adjustments.

The great advantage of wearable devices is that they can be with you constantly, serving as a mental aid that is part of your body and part of your everyday life. If we can endow these tools with sufficient situation awareness to make them a help rather than a hindrance, they offer the promise of enhancing human intelligence in a seamless and enjoyable way. SA

About the Author


SAM OGDEN

ALEX P. PENTLAND is the academic head of the M.I.T. Media Laboratory, Toshiba Professor of Media Arts and Sciences at M.I.T. and external director of the Center for Future Health at the University of Rochester. He is a founder of the IEEE Wearable Computing technical area and has published over 200 papers in the fields of wearable computing, machine and human vision, human-machine interface, computer graphics and artificial intelligence. *Newsweek* magazine recently named him one of the 100 Americans most likely to shape the next century. "I got into this field because I've always been unhappy with traditional theories of intelligence," he says. "There are different aspects of human intelligence, each of which can be augmented."

In addition to developing wearable devices, Pentland enjoys exploring their use in dance, fashion and other artistic endeavors. In recent years he has organized wearables dance performances in Hollywood, wearables fashion shows in Paris, Tokyo and Boston, and wearables performance pieces at various sites around the world. He would like to thank the Media Lab's former and current graduate students—particularly Thad Starner, Bradley Rhodes and Steve Mann—and colleagues Neil Gershenfeld, Mike Hawley, Pattie Maes, Joe Paradiso, Alice Pentland, Rosalind Picard and Mitch Resnick.

FURTHER READING

RETHINKING ARTIFICIAL INTELLIGENCE

THE ROMANCE OF AERONAUTICS: AN INTERESTING ACCOUNT OF THE GROWTH AND ACHIEVEMENTS OF ALL KINDS OF AERIAL CRAFT. Charles Cyril Turner. J. B. Lippincott Company, 1912.

THE PREHISTORY OF FLIGHT. Clive Hart. University of California Press, 1985.

THE EMPEROR'S NEW MIND. Roger Penrose. Oxford University Press, 1989.

TURING TEST CONSIDERED HARMFUL. P. J. Hayes and K. M. Ford in *14th International Joint Conference on Artificial Intelligence,* pages 972–977. Morgan Kaufmann Publishers, 1995.

WHY GÖDEL'S THEOREM CANNOT REFUTE COMPUTATIONALISM. G. LaForte, P. J. Hayes and K. M. Ford in *Artificial Intelligence,* Vol. 104, Nos. 1–2, pages 265–286; October 25, 1998.

GAME-PLAYING MACHINES

THE AGE OF INTELLIGENT MACHINES. Raymond Kurzweil. MIT Press, 1990.

ESSENTIALS OF ARTIFICIAL INTELLIGENCE. Matthew L. Ginsberg. Morgan Kaufmann Publishers, 1993.

DO COMPUTERS NEED COMMON SENSE? Matthew L. Ginsberg in *Proceedings of the 5th International Conference on Principles of Knowledge Representation and Reasoning* (Cambridge, Mass.). Morgan Kaufmann Publishers, 1996.

ONE JUMP AHEAD: CHALLENGING HUMAN SUPREMACY IN CHECKERS. Jonathan Schaeffer. Springer-Verlag, 1997.

DEEP BLUE VS. KASPAROV, ROUND TWO. On the *Scientific American* Web site at www.sciam.com/explorations/042197chess/

WEARABLE COMPUTING

SMART ROOMS. Alex P. Pentland in *Scientific American,* Vol. 274, No. 4, pages 68–76; April 1996.

AFFECTIVE COMPUTING. Rosalind W. Picard. MIT Press, 1997.

AUGMENTED REALITY THROUGH WEARABLE COMPUTING. Thad Starner et al. in *Presence: Teleoperators and Virtual Environments*, Vol. 6, No. 4, pages 386–398; August 1997.

FIRST INTERNATIONAL SYMPOSIUM ON WEARABLE COMPUTERS. Digest of papers. IEEE Computer Society Press, 1997.

WEARABLE COMPUTING: A FIRST STEP TOWARD PERSONAL IMAGING. Steve Mann in *Computer*, Vol. 30, No. 2, pages 25–32; 1997.

WEARING YOUR COMPUTER. Wendy M. Grossman in *Scientific American*, Vol. 278, No. 1, page 46; January 1998.

Information on wearable devices is available at www.media.mit.edu/wearables on the World Wide Web.

> **To consider Earth the only populated world in infinite space is as absurd as to assert that in an entire field sown with millet, only one grain will grow.**
>
> —*Metrodorus of Chios, 4th century B.C.*

Is There Intelligent

by Guillermo A. Lemarchand

Making first contact is equivalent to finding a needle in a haystack 35 times the size of Earth. Actively sending announcements to introduce ourselves may be the best way

Life Out There?

The land lies sleeping under the enveloping mantle of night. Bright stars gleam like jewels from the velvet darkness. Beyond, in depths frightening in their sheer immensity, the Milky Way trails its tenuous gown of stardust across the heavens, and well beyond that billions of stars, galaxies and planets dance in a cosmic symphony.

From our earliest days, humans have strongly sensed that this endless majesty is too huge to be contemplated by a single intelligent species, and one thread that links the ancient Greek philosophers to modern space scientists is the desire to know whether other inhabited worlds exist. Vast and old beyond understanding, the universe forces us to ponder the ultimate significance of our tiny but exquisite life-bearing planet and to long for the knowledge that somewhere out there, someone like us is gazing toward the heavens and having similar thoughts.

We have the means to test the possibility that advanced extraterrestrial civilizations exist. This is the search for extraterrestrial intelligence, known as SETI.

The Chances of Intelligent Life

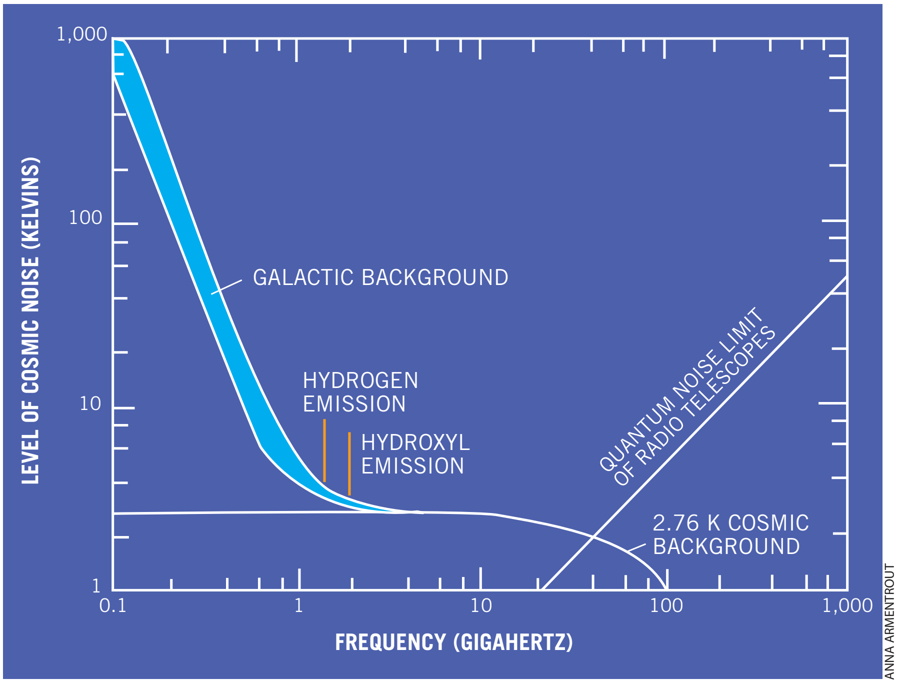
Despite its roots in some of our most profound questions, the goal of SETI is not to fulfill a spiritual longing. Instead it is a realistic, practical response to the statistical likelihood that the evolution of life is a natural occurrence everywhere across the universe.

SETI operates under a two-pronged hypothesis. The first assumption, known as the principle of mediocrity, is that the development of life is an unexceptional consequence of physical processes taking place in appropriate environments—in this case, on Earth-like planets. Because our galaxy has hundreds of billions of stars and the universe has billions of galaxies, many habitable Earth-like planets should exist, and life should be common.

The second assumption is that on some planets that shelter living creatures, at least one species will develop intelligence and a technological culture. They will have an interest in communicating with other sentient beings elsewhere in the cosmos and will beam signals into space with that goal. Assuming that these cultures would use electromagnetic signals to communicate and that their signals would have an artificial signature we could recognize, it should be possible to establish contact and exchange information.

Life as we know it could only exist on Earth-size planets because liquid water—apparently a prerequisite for organisms similar to terrestrial ones—seems to occur only on planetary bodies that size. Recent astronomical observations indicate that planetary systems are common. In just the past three years, researchers have detected 13 planetary systems orbiting sunlike stars. Current detection methods prevent us from knowing how sim-

MEG CRANE



RADIO SPECTRUM OF SPACE has a "quiet" area between one and 100 gigahertz, in which noise comes only from the cosmic background radiation. The "magic frequencies" in this area include the frequency at which hydrogen emits energy, at 1,420 megahertz, and that of the hydroxyl radical (oxygen and hydrogen), at 1,667 megahertz. The combination of both substances yields water—possibly a universal signature of life.

ilar these new systems are to our own solar system. At best, we know the new planets to be gas giants like Jupiter.

Based on these discoveries, SETI pioneer Philip Morrison of the Massachusetts Institute of Technology has estimated that the number of planetary systems just in our own galaxy could range from as few as 10 million to as many as 100 million. From this estimate, I believe we can realistically speculate about the number of Earth-like planets.

The most important determining factors are how frequently Earth-like planets are formed when a planetary system develops and how soon afterward life would appear. The best current estimates of the number of planets close in mass to Earth, combined with the best current estimates of the long-term stability of oceans, suggest that one or two possible worlds around every sunlike star have environments suitable for life—essentially the profile of our own solar system.

Based on Earth's history, life emerges relatively quickly. When Earth formed some 4.6 billion years ago, it was a lifeless, inhospitable place. Only one billion years later the whole planet was teeming with one-celled organisms resembling blue-green algae. The principle of mediocrity suggests a logical progression: the emergence of life will lead to the emergence of intelligence, which will give rise to interstellar communications technology. Viewed from one angle, it may be said that SETI is simply an attempt to test this theory.

There are no guarantees, though, that life everywhere will develop along the path followed on Earth and lead to intelligence. For example, Ernst Mayr of the Museum of Comparative Zoology at Harvard University notes that out of some 50 billion species that have arisen on Earth, only one achieved the kind of intelligence needed to establish a civilization. Intelligent life on Earth occupies less than 0.025 percent of the total history of life here. Mayr believes that such high intelligence may simply not be favored by natural selection: after all, every other species on Earth gets along fine without it.

Another possibility is that high intelligence is extraordinarily difficult or dangerous to acquire. For example, two or more competing intelligent species could destroy each other before either could give rise to a technological civilization. If this is so, we probably cannot expect more than one intelligent species to exist on any planet.

Technological civilizations must also survive long enough to be discovered. The late Carl Sagan referred to our period as "technological adolescence," when technology brings the civilization-ending threats of ecological catastrophe, exhaustion of natural resources and nuclear war. There may be 100 million suitable planets in our galaxy, and if even a small fraction of civilizations survive technological adolescence, then the possible number of galactic civilizations may still be very large. Sagan considered an estimate of one million of them in the galaxy to be conservative.

Making Conversation

SETI researchers also assume that the physical laws governing the universe are the same everywhere. If so, then we should be able to communicate through our common principles of mathematics, physics, chemistry and so on.

Not all researchers, however, agree. Nicholas Rescher, a philosopher at the University of Pittsburgh, argues that extraterrestrials would be organisms with different needs, senses and behaviors. So despite sharing universal laws with us, they are extremely unlikely to have any type of science we would recognize.

But artificial-intelligence pioneer Marvin Minsky of M.I.T. argues that intelligent extraterrestrials will think like us, in spite of different origins, because all intelligent problem solvers are subject to the same ultimate constraints: limitations on space, time and resources. According to Minsky, in order for intelligent life-forms to evolve powerful ways to deal with such constraints, they must be able to represent the situations they face and to manipulate those representations. To do this, every intelligence will inevitably discover the same basic principles. As a result, he says, aliens will have evolved thought processes and communications strategies that will match our own to a degree that will enable us to comprehend them. SETI proponents largely concur.

As a tool that cuts across cultural and linguistic boundaries, mathematics would seem to be a "cognitive universal" that could be used to communicate with extraterrestrial intelligences (ETIs). As early as 1896 Sir Francis Galton, a cousin of Charles Darwin, published an essay describing a mathematical language he developed for extraterrestrial communication.

In 1960 Dutch mathematician Hans Freudenthal created a language for a cosmic dialogue, known as Lincos (Lingua Cosmica), based on mathematical principles for exchanging concepts of time, space, mass and motion. Recently Louis E. Narens of the University of California at Irvine noted that many kinds of cognitive universals can be surmised by considering pragmatic requirements—for example, what the extraterrestrials must know to build sending and receiving equipment.

Efforts in First Contact

Since the first formal SETI efforts, researchers have used the microwave region of the electromagnetic spectrum for detecting interstellar communications, because microwave signals require little energy to exceed natural background radiation and are not deflected by galactic or stellar fields. Moreover, they are easy to generate, detect and beam and are not absorbed by the interstellar medium or by planetary atmospheres. A quiet cosmic frequency window exists in the microwave region, between one and 100 gigahertz.

In September 1959 Giuseppe Cocconi and Morrison, both then at Cornell University, proposed the first realistic strategy for searching for ETIs. It would use radio-astronomy telescopes to scan the nearest sunlike stars for artificial signals at or near the 21-centimeter wavelength (1,420 megahertz), which corresponds to the frequency of microwave energy that neutral hydrogen emits. (Hydrogen is the most abundant element in the universe, so presumably radio astronomers in any technological civilization would scan at this wavelength to study the substance.) Independently, Frank D. Drake, an astronomer then at the National Radio Astronomy Observatory (NRAO) in Green Bank, W.Va., was planning an actual search. On April 8, 1960, he turned the 26-meter-wide Howard Tatel radio telescope toward the nearby solar-type stars Tau Ceti and Epsilon Eridani. Drake dubbed the search Project Ozma, in reference to a princess who appeared in sequels to L. Frank Baum's book *The Wonderful Wizard of Oz.*

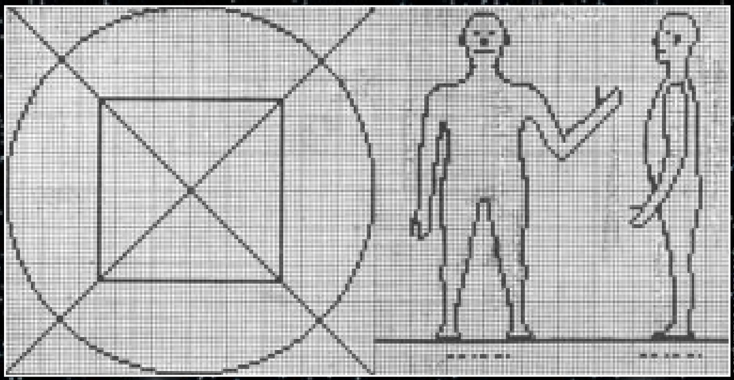
With $2,000 worth of parts, the low-profile, low-budget Ozma system had only one channel with a spectral resolution of 100 hertz and a sensitivity of one one-hundred septillionth (10^{-22}) of a watt per square meter: with current receiver technology, the same search would be thousands of times more sensitive. In the end, no signals were found after 150 hours of observation. Despite its failure, however, Project Ozma fired the imagination of the public.

In the Days before SETI

The first initiatives to communicate with extraterrestrial beings on the moon or on Mars began more than 150 years ago. German mathematician Carl F. Gauss (1777–1855) suggested that there be erected in Siberia a giant figure of the diagram used in Euclid's demonstration of the Pythagorean theorem. The hypothetical Selenites (moon dwellers), on seeing this figure through their telescopes, would recognize it as having been made by intelligent terrestrial beings and would respond accordingly. In 1869 French intellectual prodigy Charles Cros (1846–1888) suggested that rays from electric lights could be focused by parabolic mirrors so as to be visible to hypothetical inhabitants of Mars or Venus. He also presented a code using periodic flashes.

During the 1920s, an extensive debate about how to communicate with the hypothetical Martians began in the pages of *Scientific American*. In those days, radio pioneers Nikola Tesla (1856–1943), Guglielmo Marconi (1874–1937) and David Todd (1855–1939) began their speculations about the use of radio waves for interplanetary communication. On January 27, 1920, the *New York Times* reported that Marconi occasionally detected with his radio equipment "very queer sounds and indications, which might come from somewhere outside the Earth." No less a scientific authority than Albert Einstein was quoted as believing that Mars and other planets might be inhabited but that Marconi's strange signals stemmed either from atmospheric disturbances or experiments with other wireless systems.

In a 1920 *Scientific American* article, H. W. Nieman and C. Wells Nieman proposed a system to encode messages to other planets, arguing that the key to communication was the timing—in the duration of the signal to produce dots and dashes and in the lack of a signal to produce pauses. Their proposal was the basis for the encoding system used in 1974 by Frank D. Drake and his colleagues in the first interstellar message sent from the Arecibo Observatory in Puerto Rico toward the Great Cluster in the constellation Hercules. *—G.A.L.*



SCIENTIFIC AMERICAN

ENCODED MESSAGES can yield images for interstellar communications, as proposed in the March 20, 1920, Scientific American.

MAIN SETI PROJECTS NOW UNDER WAY

	BETA	META II	SERENDIP IV	SOUTHERN SERENDIP	ITALIAN SERENDIP	PROJECT PHOENIX		
Observatory	Oak Ridge	IAR	Arecibo	Parkes	Medicina	Parkes	NRAO	Arecibo
Starting observation date	1995	1990	1997	1998	1998	1995	1996–1998	1998
Site	Harvard, Mass.	Buenos Aires, Argentina	Puerto Rico	NSW, Australia	Bologna, Italy	NSW, Australia	Green Bank, W. Va.	Puerto Rico
Antenna diameter (meters)	26	30	305	64	32	22 and 64	30 and 43	305
Range of telescope motion (declination, in degrees)	–30 to +60	–90 to –10	–2 to +38	–90 to +26	–30 to +90	–90 to +26	–35 to +80	–2 to +38
Channels (in millions)	250 x 8	8.4	168	4.2 x 2	4.2 x 2		28.7 x 2	
Spectral resolution (hertz)	0.5	0.05	Down to 0.6	0.6	1.2		Down to 1	
Operation frequency (gigahertz)	1.4–1.7	1.4, 1.6, 3.3	1.4	1.4	0.4, 1.4, 1.6		1–3	
Instantaneous bandwidth (megahertz)	40	0.4–2	100	2.4	5		20	
Total bandwidth coverage (megahertz)	320	1.2–6	180	2.4	5		2,000	
Sensitivity (watts per square meter)	3×10^{-24}	8×10^{-24}	$\sim 10^{-24}$	2×10^{-25}	$\sim 10^{-25}$		$\sim 10^{-25}$	
Approximate sky coverage (percent)	70	50	30	75	75		Not applicable (targeted survey)	
Types of signals	C, Slow CH	C, CH	C, CH, P	C, CH, P	C, CH, P		C, CH, P	
Funding sources	Planetary Society, Bosack-Kruger and Shulsky Foundations	Planetary Society, CONICET	Planetary Society, Friends of SERENDIP, SETI Institute	University of New South Wales	Italian Research Council		SETI Institute	

IAR

COURTESY GUILLERMO A. LEMARCHAND

ARECIBO

SETH SHOSTACK *SETI Institute*

GREEN BANK

SETH SHOSTACK *SETI Institute*

PARKES

In the early 1970s the National Aeronautics and Space Administration began to show interest in SETI. The late Bernard Oliver, vice president for development at Hewlett-Packard, and John Billingham, a NASA scientist, headed Project Cyclops, a summer school convened to design an array of 1,000 100-meter-wide antennae to eavesdrop on the television, radar and other "domestic" transmissions of hypothetical galactic neighbors 1,000 light-years away. Project Cyclops, however, was too ambitious for NASA funding and was never built. Instead, during the 1970s and 1980s, NASA funding for SETI was limited to workshops and conferences. In 1992 NASA launched a 10-year, $100-million SETI project, but Congress canceled the program after a year.

Still, SETI researchers have managed without NASA funding. From 1973 to 1997 the Ohio State University Radio Observatory, led by John D. Kraus and

BETA, META and the three SERENDIPs make full-sky surveys for ultra-narrowband signals, limited only by the range of motion of each radio telescope (defined by its declination range). Project Phoenix searches for signals around nearby stars, using the Arecibo antenna and the 76-meter-wide antenna at Jodrell Bank in England as a means to confirm Arecibo signals. The number of channels, spectral resolution and instantaneous and total bandwidth are characteristics of each spectral analyzer. The sensitivity, which varies with frequency, is proportional to each antenna diameter and to the technical characteristics of the receivers and spectrometer. Carrier signals (C) are continuous, modulated waves (radio and television signals ride on carrier waves). Pulses (P) are brief, intermittent signals; chirps (CH) are pulses whose frequency changes.

OAK RIDGE

PLANETARY SOCIETY

MEDICINA

SETH SHOSTACK *SETI Institute*

STELIO MONTEBUGNOLI

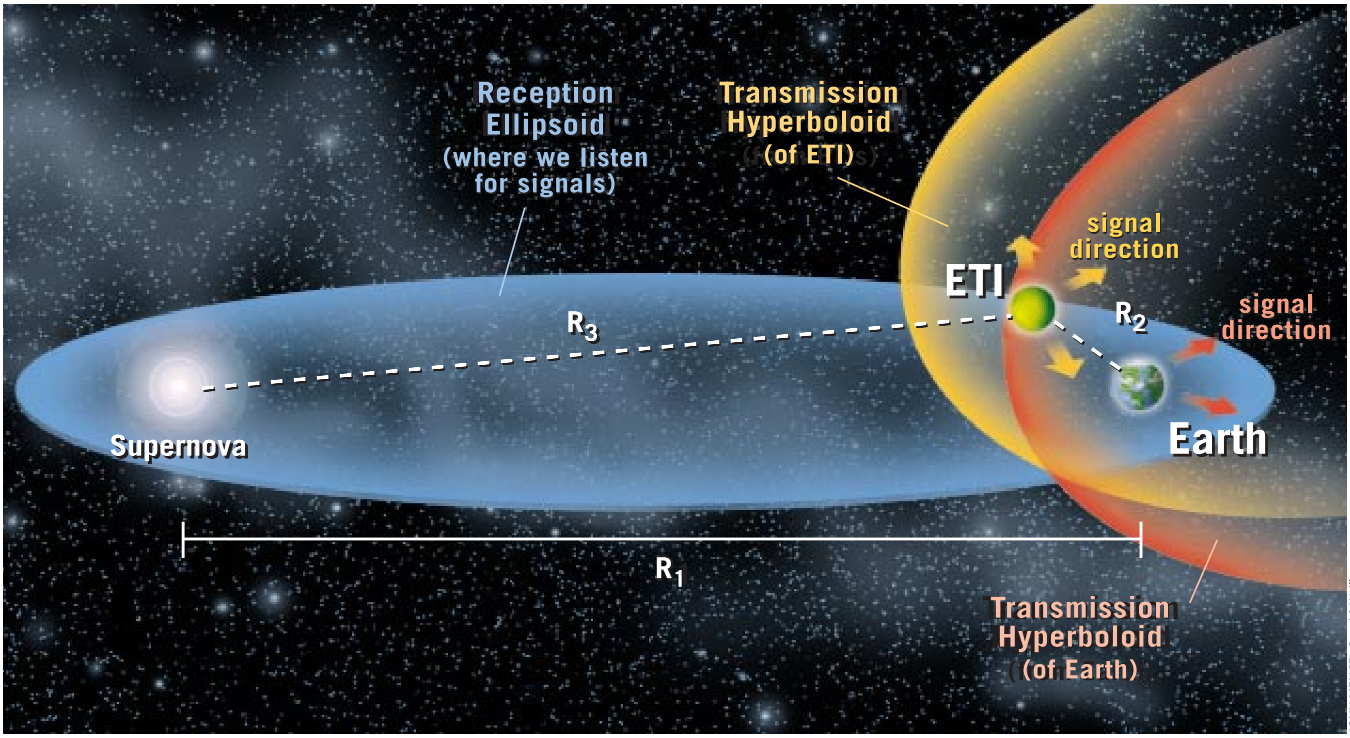
Robert Dixon, conducted the longest full-time, dedicated SETI search, entirely on a volunteer basis. In 1985 the Planetary Society, an organization based in Pasadena, Calif., with more than 100,000 members around the world, built an 8.4-million-channel analyzer known as META (Mega-channel Extraterrestrial Assay). The society installed the device, designed by Paul Horowitz of Harvard University, at the 26-meter antenna of Harvard's Oak Ridge Observatory. Five years later the society installed a similar spectral analyzer, META II, in one of the two 30-meter antennae of the Argentine Institute of Radio Astronomy near Buenos Aires. They were the first privately funded, dedicated, full-sky SETI surveys.

During the past 40 years, more than 90 different professional SETI projects have been carried out at observatories in Australia, Argentina, Canada, France, Germany, Italy, Russia, the Netherlands and the U.S. Together they have accumulated more than 320,000 observing hours, mostly in the so-called magic frequencies where we believe ETIs would broadcast. Unfortunately, none provided any conclusive evidence of the detection of an intelligent extraterrestrial signal.

Today private financial support for SETI comes from individual donations to nonprofit organizations, such as the SETI Institute, the Planetary Society and Friends of SERENDIP. Logistical support comes from institutions such as Harvard, the University of California at Berkeley, the National Astronomy and Ionospheric Center at Arecibo in Puerto Rico, NRAO, the University of New South Wales in Australia and the National Research Council of Argentina (CONICET). Thanks to the generosity of Hewlett-Packard's Oliver, the SETI Institute has a $20-million endowment that allows it to develop more ambitious projects. In particular, Project Phoenix is a mobile program that uses a 56-million-channel system; Berkeley's Project SERENDIP IV has 168 million channels; and the Planetary Society–Harvard's BETA has 250 million. These systems range in cost from several hundred thousand to several million dollars. The 64-meter antenna in Parkes, Australia, and the 43-meter antenna of the NRAO have already finished two observation campaigns and are now planning to extend their work using the observatories at Arecibo and Jodrell Bank in England.

Over the past few years, Paul Shuch of the SETI League, a nonprofit organization with members in more than 40 countries, has been trying to coordinate 5,000 small antenna dishes—built, maintained and operated by private individuals—in such a way that they will not miss any likely sky positions. Prototype stations went into operation in 1996, and many hundred enthusiasts worldwide are taking part in this project.

Another initiative, called SETI@home, is trying to use the Internet to organize 50,000 to 100,000 volunteers to perform massive parallel computation on desktop computers. Participants could download a screen-saver program that will not only provide the usual graphics but also perform sophisticated analyses of



JOHN MENGEL *Ponzi & Weill*

STRATEGY TO USE SUPERNOVA AS A BEACON can narrow the search for an extraterrestial intelligence (ETI), which is assumed to rely on the exploding star as a source of attention. Earth radio telescopes would look for signals among stars that fall within an ellipsoidal region of space defined by Earth's distance to the supernova (R_1) and to the possible ETI planet (R_2), and by the distance from the supernova to the ETI (R_3). (The relation is $R_2 + R_3 - R_1$ = a constant for each specific time after the supernova explosion. The ellipsoid enlarges over time, and R_1 and R_3 can be several hundred thousand light-years.) Moreover, we could transmit greetings to stars that fall within a particular region, which is a "hyperboloid of transmission"—a shape defined by time and the supernova's position in the sky. It basically corresponds to a zone that provides the best view of the supernova and Earth, so that an ETI studying the supernova would also see our signal coming to it from the same direction. Likewise, Earth would fall in the transmission hyperboloid of the ETI, if the ETI chose an identical strategy.

SETI data using the host computer. The data would be tapped from Project SERENDIP IV's receiver at Arecibo.

SETI Search Methods

The practical requirements of SETI make the notion of "searching for a needle in a haystack" pale in comparison, because an electromagnetic transmission channel always has several variables that must be set. These include a four-dimensional aspect: the location of the extraterrestrial civilization (three dimensions in space) and a temporal dimension that coordinates transmission and reception (you can be looking to the correct place but at a moment when nobody is transmitting, or vice versa). Other factors include the frequency, the signal intensity and the cryptographic variables, such as polarization, modulation, information rate, code and semantics (which all must be overcome to decode any message). All these variables make up our "cosmic haystack."

Leaving aside certain complicating factors, there are roughly 3×10^{29} places, or "cells," in the sky to explore. Each cell's dimensions are 0.1 hertz wide, multiplied by the number of beams that a 300-meter Arecibo-type radio telescope (the world's largest) would need to conduct a full-sky survey. The calculation assumes a receiver sensitivity of 10^{-20} to 10^{-30} watt per square meter—less than the energy we would receive from a 100-watt lightbulb shining on Pluto.

Assuming Sagan's estimate of one million technological civilizations, this search is comparable to looking for an actual five-centimeter-long sewing needle in a haystack 35 times the size of Earth. So far only a small fraction of the whole haystack has been explored, a mere 10^{-16} to 10^{-15} of the total possible number of cells.

The success of the search depends not only on the number of civilizations in our galaxy but also on their transmission strategies. Historically, researchers assumed that some "supercivilizations" can make omnidirectional transmissions strong enough to be detected by full-sky surveys. Yet even if many civilizations are communicating with one another across the galaxy, only a vanishingly small probability exists that we on Earth, randomly observing different directions in the sky, would be able to eavesdrop on narrow-beam ETI signals. Full-sky surveys made by the Harvard, Arecibo, Ohio and Buenos Aires SETI projects did not find any evidence of omnidirectional supercivilization transmissions at a distance of 22 megaparsecs (70 million light-years).

What kind of intentional signal might we expect? It will most likely be narrowband, approximately one hertz or less in width and ideally a single wavelength (and thus obviously artificially generated), because the senders would want their signal to stand out as artificial against similar natural signals and because such a signal travels farthest for a given transmitting power. Most SETI projects can distinguish only the presence of such a signal among the broad band of cosmic noises but cannot ascertain the content of a message that might be coded in some unknown form.

Current SETI detection devices simultaneously analyze several million or billion spectral channels, whereas computers check for any strong narrowband signals among the cacophony of cosmic noise. Other instrumentation eliminates all human-made terrestrial and space radio interference. After years of observation and the analyses of hundreds of billions of signals, fewer than 100 signals have looked like potential extraterrestrial signals. Unfortunately, none of them could be detected in follow-up observations.

To cull the false alarms, James M. Cordes, Joseph W. Lazio and Sagan of Cornell University derived tests to analyze the unexplained signals detected by the META and META II projects between 1986 and 1995. Their analyses found signals that originated near the galactic plane that could not be ruled out as alien.

To check the origin of these and other unexplained signals, SETI researchers instituted new observation strategies. Horowitz's Project BETA now uses a billion-channel analyzer and three different antenna beams in order to exclude any possible terrestrial interference. Project Phoenix uses what its members call a FUDD (Follow-Up Detection Device): a second antenna hundreds of kilometers away that simultaneously analyzes signals and can screen out false ones (as shown in the recent movie *Contact*). Using these improvements, SETI researchers identified the META and META II candidate signals and other unexplained blips as different kinds of terrestrial interference.

Is it possible that we have already received an intelligent contact signal and that we missed it? I believe we probably have. But our detectors were not sensitive enough to distinguish it from the cosmic noise. Or it could be that our antenna was not pointed to the correct place at the right moment, or that we are searching in the wrong frequency or using the wrong observation strategy. Perhaps the signal faded because it passed through charged plasma clouds that pervade interstellar space.

I believe that the first evidence of an intelligent signal will probably come accidentally, when a traditional astronomer, unable to explain some anomalous observation, will realize that his or her data can be explained only as a consequence of some technological extraterrestrial activity. He or she will be able to draw this conclusion by using what we have learned through SETI.

This prediction reflects the distinctly unglamorous character of the day-to-day work of SETI. There are very few full-time SETI researchers: much time is spent designing and testing computer programs, and computers automatically do most of the work related to observation. The typical SETI researcher is also involved with learning and designing new hardware and software, developing new observational strategies and, most important, interpreting observational data to discern in them any possible intelligent signal patterns among the waterfall of cosmic noise.

Supernova Beacons

The greatest difficulty in making the first contact stems from the requirement that the incoming signal must arrive at the same time that the target civilization has its receiver pointed toward the unknown transmitter. The need for this synchronization is one of the weakest parts of our search strategy. But an extraterrestrial civilization using this kind of "active" search method (broadcasting signals to be discovered, in contrast to "passive" listening only) might overcome this problem by using a natural astronomical phenomenon—probably a supernova—as a "beacon" that would attract the attention of other civilizations. The sending civilization would transmit its own message in the diametrically opposite, or antipodal, direction of the supernova as seen from the transmitting planet.

In 1976 and 1977 Tong B. Tang of the Cavendish Laboratory of the University of Cambridge and P. V. Makovetskii of the Leningrad Institute of Aeronautical Instrument Manufacture independently argued that we might improve the probability of contact if we assumed that ETIs transmitting signals might use supernova beacons. They calculated that we should observe only those stars within an ellipsoidal volume, with Earth at one of the foci of the ellipse and a supernova at the other [*see illustration on opposite page*].

In fact, my colleagues and I have suggested that SETI researchers use exactly this strategy to attempt to contact ETI civilizations, using as the beacon the supernova detected in the Large Magellanic Cloud on February 23, 1987. Given that there are on average only one to four supernova explosions in our galaxy every 100 years and that the supernova, dubbed SN1987A, was the brightest one in 383 years, we can assume that most of the possible galactic civilizations would be paying close attention to it.

We would transmit our message in the direction antipodal to the supernova, in a field defined by a hyperboloid (roughly speaking, it corresponds to an area around Earth that provides the best view of the supernova within the ellipsoid). There are only 33 nearby objects inside this hyperboloid, which would focus the effort even further: of these 33 objects, 16 are solar-type stars that could have planets with other civilizations.

Are We Lunch?

The idea of using this kind of active search strategy concerns people in many quarters of the SETI community about whether to send such signals at all. The heat surrounding this issue can be traced to the first—and to date the only—attempt to send such a signal. On November 16, 1974, the Arecibo Observatory transmitted an interstellar message describing some characteristics of life on Earth toward the Great Cluster in Hercules, M13, a group of about 300,000 stars 25,000 light-years distant.

The action provoked some major protests. Former U.S. diplomat Michael A. G. Michaud considered the attempt a political act. He suggested a public discussion of the potential benefits and risks of ETI contact and urged that a decision be made openly, "with the involvement of public authorities." Martin Ryle, a Nobel laureate and Astronomer Royal of England, wrote to leading astronomers saying that he felt it was very hazardous to reveal our existence and location to the galaxy. For all we know, he said, "any creatures out there are malevolent or hungry," and once they knew of us "they might come to attack or eat us." He strongly recommended that no such messages be sent again.

Frank Drake replied to Ryle in a letter stating: "It's too late to worry about giving ourselves away. The deed is done, and repeated daily with every television transmission, every military radar signal, every spacecraft command...." According to Drake, Ryle seemed satisfied with the rejoinder.

Ben R. Finney, an anthropologist at the University of Hawaii at Manoa, has described human responses to contact with ETIs as "paranoid" (assuming that extraterrestrials are malevolent) or "pronoid" (assuming that interaction with ETIs would be extremely beneficial to humanity). Ever since H. G. Wells introduced in 1898 the idea of the invasion of Earth by murderous aliens in *The War of the Worlds,* the paranoid idea has dominated not only science fiction but also the thinking of some scientists. For example, in the early 1960s the Brookings Institution in Washington, D.C., prepared a report for NASA that concluded that "the discovery of life on other worlds could cause the Earth's civilization to collapse."

Medical anthropologist Melvin Konner of Emory University has said, "Evolution predicts the existence of selfishness, arrogance and violence on other planets even more surely than it predicts intelligence. If they could get to Earth, extraterrestrials would do to us what we have done to lesser animals for centuries."

"Any creature we contact will be every bit as nasty as we are," echoes Michael Archer, a biologist at the University of New South Wales. He thinks the gold-coated copper phonograph records affixed to each Voyager spacecraft—which contain, among other indications of intelligent life, 118 photographs of our planet, ourselves and our civilizations—are giant dinner invitations to the cosmos.

The pronoid school of thought is reflected in the writings of William J. Newman and Sagan, who have suggested that there may be universal impediments against cosmic imperialism. They have gone so far as to suggest that a *Codex Galactica,* produced by more mature civilizations, might exist to educate younger societies on cosmic etiquette. They have further argued that advanced civilizations with long histories must have learned how to be benign and how to treat an adolescent society like ours "delicately."

"As our own species is in the process of proving, one cannot have superior science and inferior morals. The combination is unstable and self-destroying," the science-fiction writer Arthur C. Clarke has said. This position was shared by the late Isaac Asimov and by other SETI proponents, including myself. If other civilizations agree, we might expect advanced societies to make only limited information available to emerging societies. This view is opposite to the contact scenario usually advocated by SETI pioneers, such as Sagan, who expect vast amounts of information or some kind of *Encyclopedia Galactica*.

Going beyond Adolescence

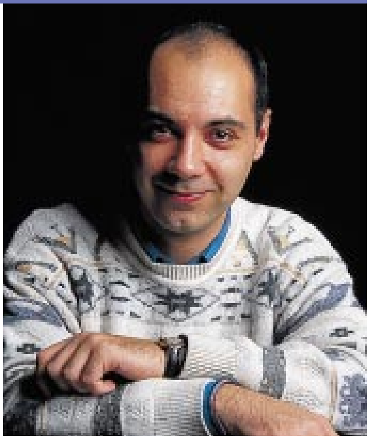
One final argument may be made in favor of active search strategies, which may imply strongly that they are essential if we are to have any hope at all of contacting extraterrestrial intelligence.

Communication is a two-way process. If all beings in the universe are trying to detect signals from other beings without sending out any of their own, then no one will receive a signal. This possibility conjures up the disturbing image of a galaxy filled with technological civilizations eager to make contact with one another but with all of them only listening and thus forever consigned to isolation.

Of course, such a "listeners-only" universe is unlikely, even if no intentional signals are being sent. As Drake noted, humanity has already made known its existence and location to a large part of our galaxy. Perhaps this announcement is typical for emerging adolescent civilizations, which may be no more cautious and quiet than adolescent humans.

Indeed, our position relative to the outcome of SETI is very much like that of an adolescent setting out on life's journey: the possibilities are infinite, the future is wide open, and we have grand plans, but much of the shape of that future hangs not only on what we do but also on luck—whether or not certain critical "ifs" actually come to pass. SETI may yield the greatest discovery in the history of humankind *if* life is ubiquitous across the cosmos; *if* life inevitably gives rise to intelligence and technology; *if* technological civilizations routinely survive long enough to broadcast and receive interstellar signals; *if* such civilizations want to be found; *if* we are using the correct search strategies and are tuned to the right frequencies; and *if* we recognize the signal when it arrives. Until then, we must do what most adolescents do very poorly: we must wait. SA

About the Author


COURTESY OF GUILLERMO A. LEMARCHAND

GUILLERMO A. LEMARCHAND was five years old when Neil Armstrong first set foot on the moon. "So I have always been interested in space," he says. "And I've always wondered whether life could have started on another planet in another place in the universe." But Lemarchand did more than wonder. As an undergraduate student in physics at the University of Buenos Aires, Lemarchand organized an international meeting on intelligent life in the universe. Some 500 students attended the meeting and listened to presentations by eminent biologists, astronomers and radio astronomers. A few months later Lemarchand made the first SETI observations at the Argentine Institute of Radio Astronomy—a project that he helped to establish and now coordinates.

When he's not scanning the sky for signs of intelligent life, Lemarchand works with mathematical models trying to understand long-term dynamics of social and economic systems and devotes his energies to promoting scientists' sense of social responsibility. He established the Argentine branch of Pugwash and organized an international symposium on scientists, peace and disarmament, where he proposed a Hippocratic oath for scientists, which is now used in graduation ceremonies at the University of Buenos Aires. Lemarchand's activism brought him to the attention of Carl Sagan of Cornell University, where he subsequently spent a year as a visiting fellow before returning to the University of Buenos Aires.

Further Reading

El Llamado de las Estrellas, G. A. Lemarchand. Ediciones Lugar, Buenos Aires, 1992.

We Are Not Alone. Walter Sullivan. Plume, 1994.

The Biological Universe. S. J. Dick. Cambridge University Press, 1996.

Astronomical and Biochemical Origins and the Search for Life in the Universe. Edited by C. B. Cosmovici, S. Bowyer and D. Werthimer in *Proceedings of the 5th International Conference on Bioastronomy,* IAU Colloquium No. 161, Editrice Compositori, Bologna, Italy, 1997.

Carl Sagan's Universe. Edited by Y. Terzian and E. Bilson. Cambridge University Press, 1997.

Origins of Planets and Life. Edited by H. J. Melosh. Annual Reviews, Inc., Palo Alto, Calif., 1997.