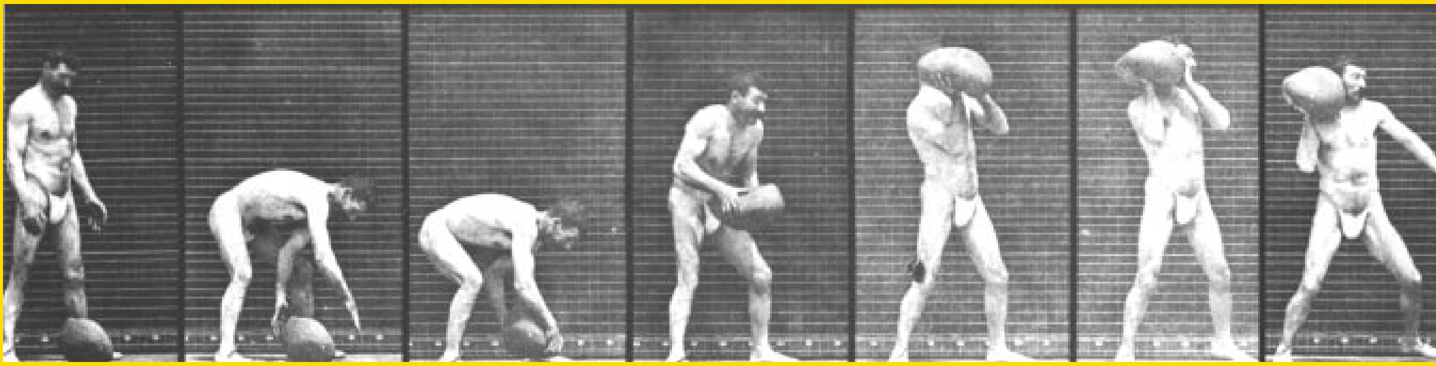


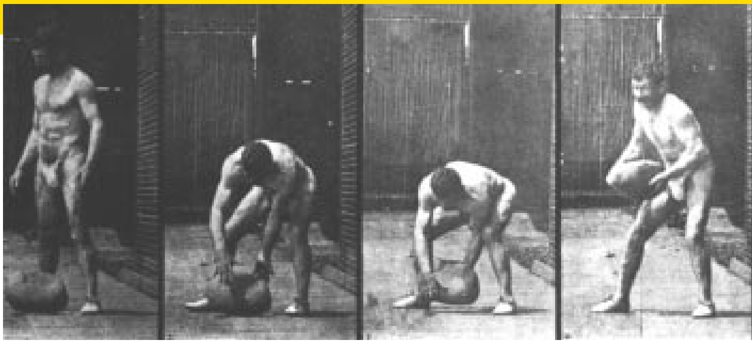
The Emergence of Intelligence

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.

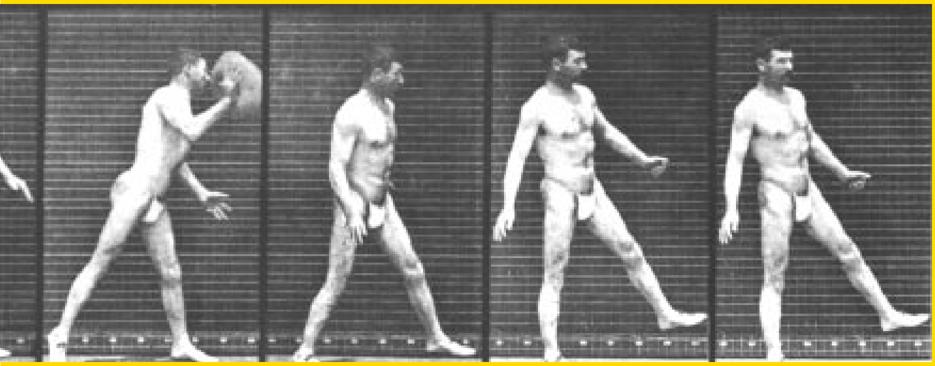


A particularly intelligent person often seems "quick" and capable of juggling many ideas at once. Indeed, the two strongest influences on your IQ score are how many novel questions you can answer in a fixed length of time and how good you are at simultaneously manipulating half a dozen mental images—as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

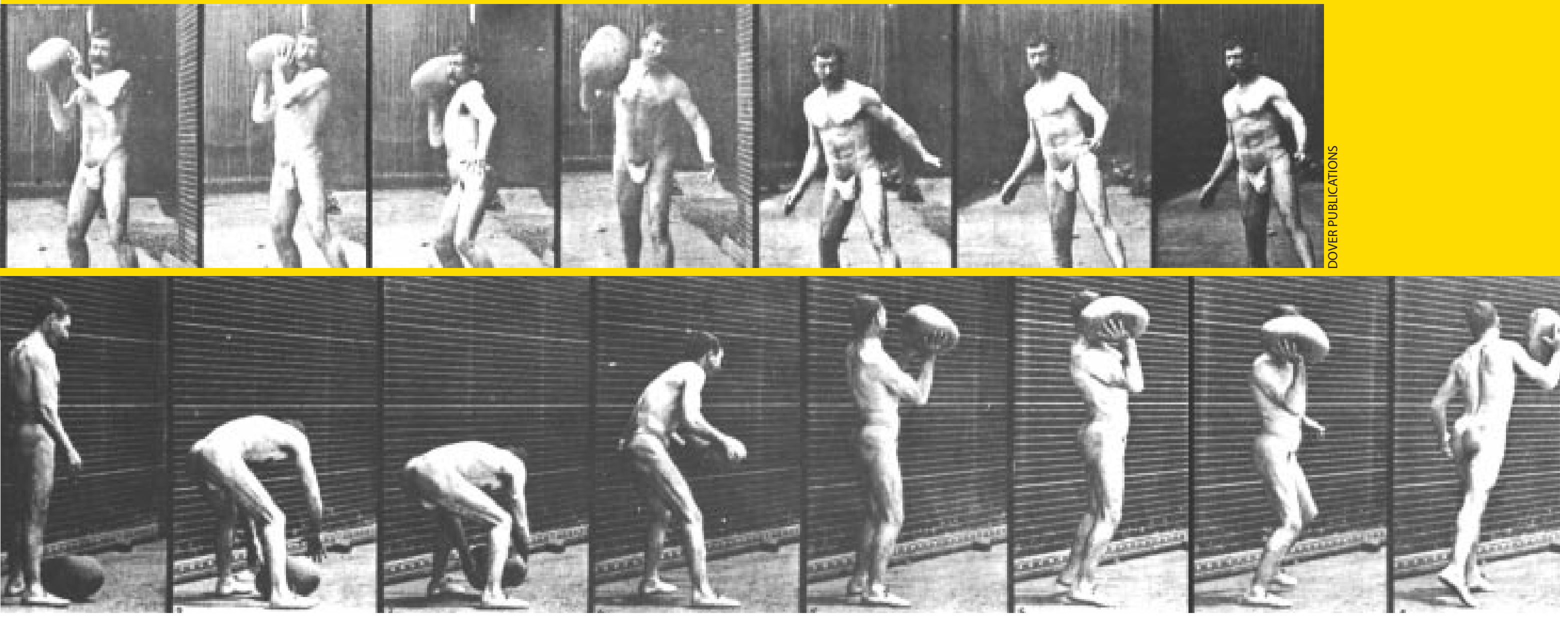
Versatility is another characteristic of intelligence. Most animals are narrow specialists, especially in matters of diet: the mountain gorilla consumes 23 kilograms (50 pounds) of green leaves each and every day. In comparison, a chimpanzee switches around a lot—it will eat fruit, termites, leaves and 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.

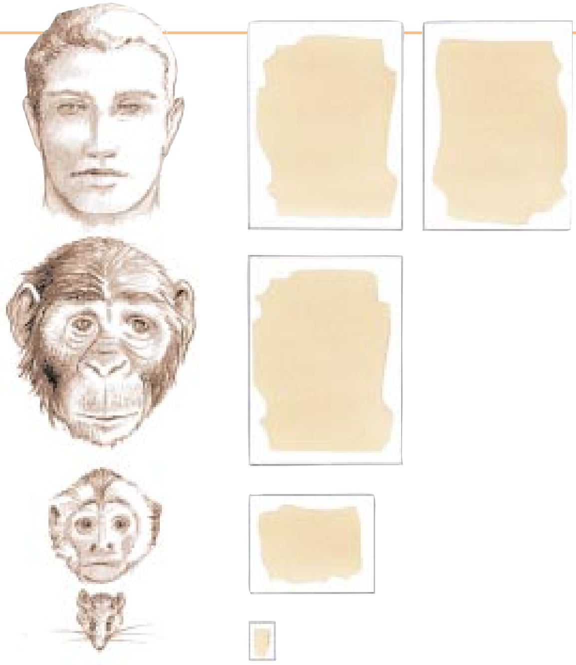
Yet versatility is not always a virtue, and more of it is not always better. When the chimpanzees of Uganda arrive at a grove of fruit trees, they often discover that the efficient local monkeys are already speedily stripping the trees of edible fruit. The chimps can turn to termite fishing, or perhaps 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

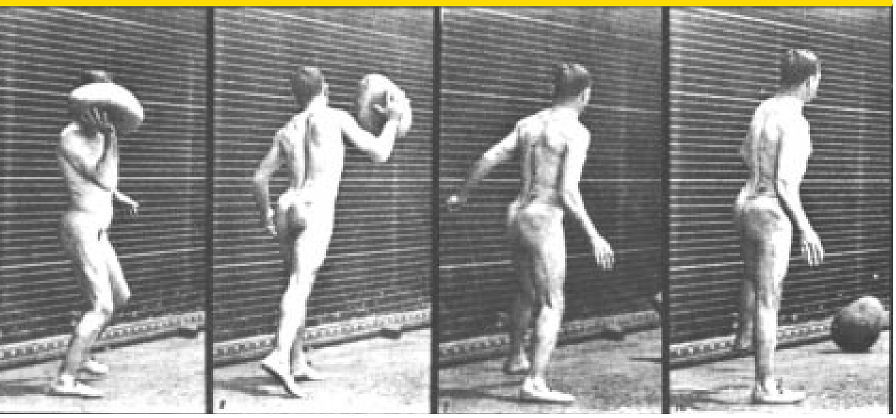


Relative Size of Cerebral Cortex

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?



Syntax and Structured Thought

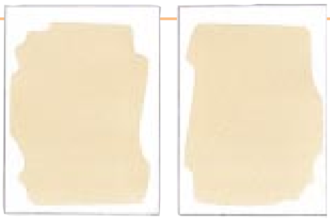
One of the improvements that occurred during the ice ages was the capacity for human language. In most of us, the brain area critical to language is located just above our left ear. Monkeys lack this left lateral language area: their vocalizations (and simple emotional utterances in humans) employ a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

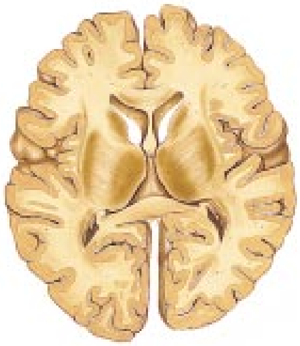
To understand why humans are so intelligent, we need to understand how our ancestors remodeled the apes' symbolic repertoire and enhanced it by inventing syntax. Wild chimpanzees use about three dozen different vocalizations to convey about three dozen different meanings. They may repeat a sound to intensify 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.

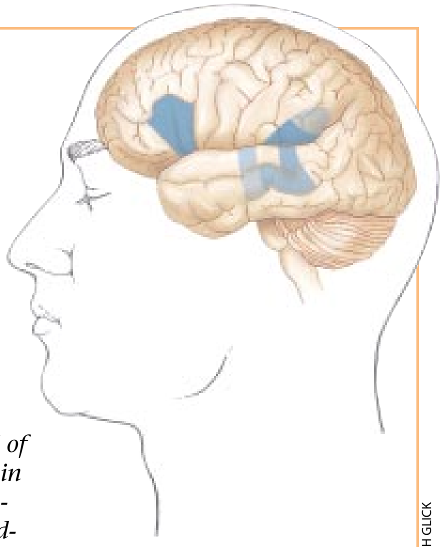
Our closest animal cousins, the common chimpanzee and the bonobo (pygmy chimpanzee), can achieve surprising levels of language comprehension when motivated by skilled teachers. Kanzi, the most accomplished bonobo, can interpret sentences he has never heard before, such as "Go to the office and bring 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

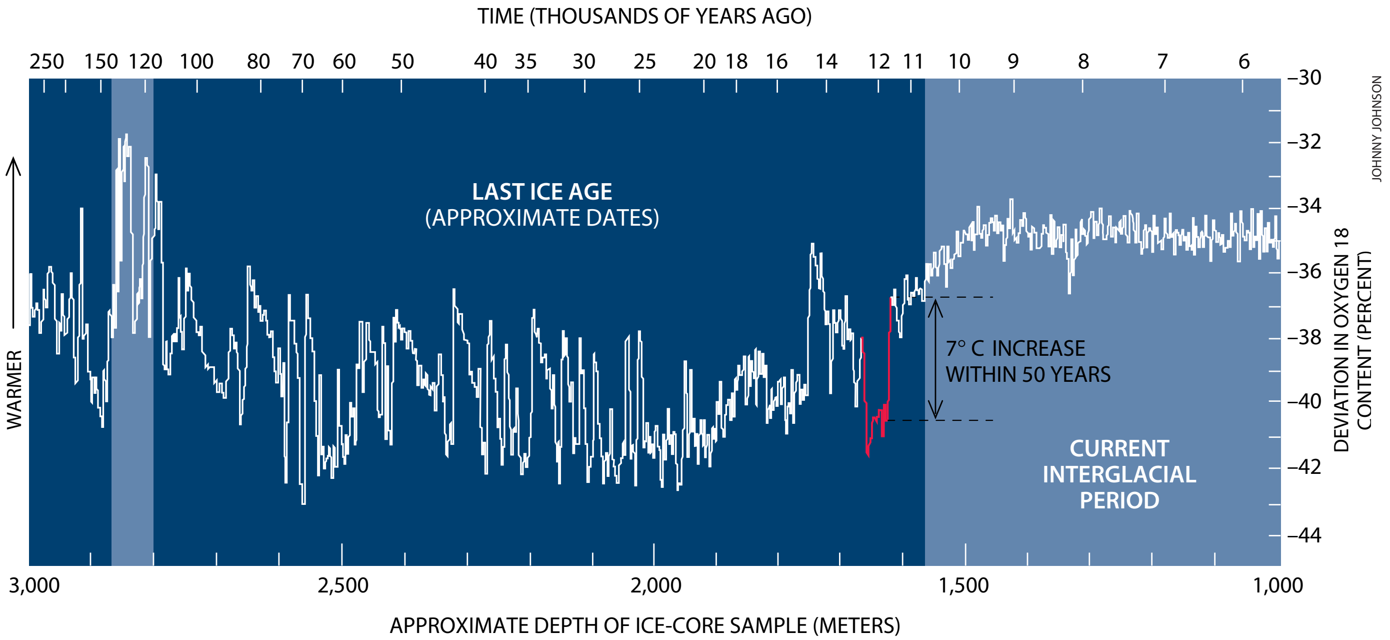
Language and intelligence are so powerful that we might think evolution would naturally favor their increase. But as Harvard University evolutionary biologist Ernst Mayr once said, most species are not intelligent, which suggests "that high intelligence is not at all favored by natural selection"—or 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, *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.*


DUOMO

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.

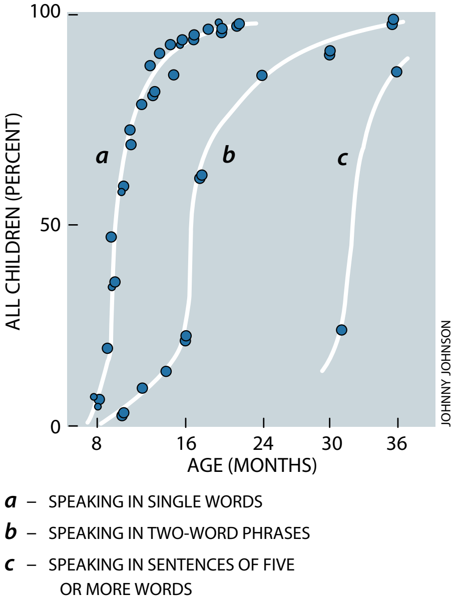
A Darwinian model of mind suggests that an activated memory can compete with others for "workspace" in the cortex. Both the perceptions of the thinker's current environment and the memories of past environments may bias that competition and shape an emerging thought. An active cerebral code moves from 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.

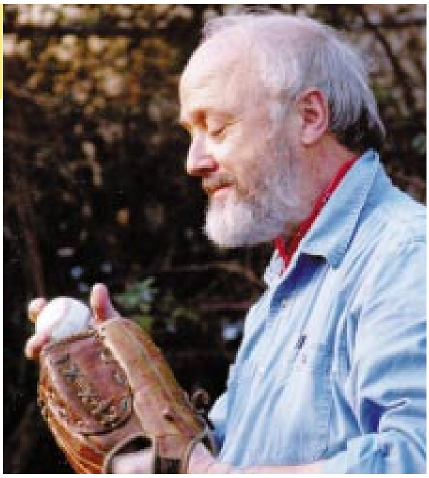
Bootstrapping Intelligence

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."

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*