The Emergence of Intelligence

Language, foresight, musical skills and other hallmarks of intelligence are connected through an underlying facility that enhances rapid movements

by William H. Calvin

To most observers, the essence of intelligence is cleverness, a versatility in solving novel problems. Bertrand Russell once wryly noted: "Animals studied by Americans rush about frantically, with an incredible display of hustle and pep, and at last achieve the desired result by chance. Animals observed by Germans sit still and think, and at last evolve the solution out of their inner consciousness." Besides commenting on the scientific fashions of 1927, Russell's remark illustrates the false dichotomy usually made between random trial and error (which intuitively seems unrelated to intelligent behavior) and insight.

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. Psychologist Jean Piaget emphasized that intelligence was the sophisticated groping that we use when not knowing what to do. 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 a witty reply, or guessing what is likely to happen next. Indeed, we all routinely predict what comes next, even when passively listening to a narrative or a melody. That is 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 are surprised by the mismatch.

We will never agree on a universal definition of intelligence, because it is an open-ended word, like consciousness. 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 would use to recognize a friend or 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's an evolutionary question and a neurophysiological one as well. Both kinds of answers are needed if we are to understand our own intelligence. They might even help us appreciate 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, 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.

Yet 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. The specialization would allow a quantum leap in cleverness and foresight during the evolution of humans from apes. If, as I suspect, that specialization involves 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 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 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 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 novel combination of search image and movement during play and find a use for it later. Many animals are playful only as

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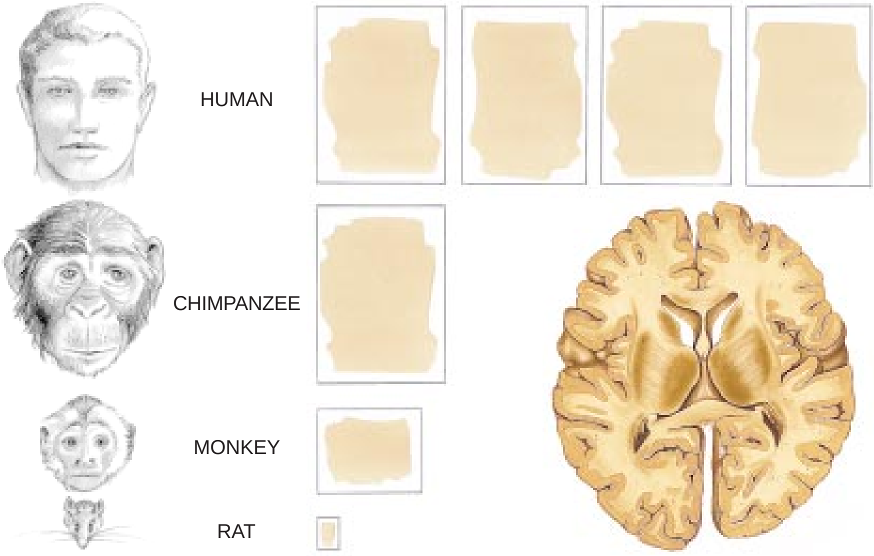
BONOBOS and other chimpanzees have a remarkable aptitude for simple language and certain tool-usage skills, such as hammering with stones. Yet compared with those of humans, the abilities of these animals are fairly rudimentary. Human intelligence may have evolved through the enhancement of a core facility that assists with the planning of rapid hand and mouth movements.



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

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 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. As frequent airline travelers know, passengers who have only carry-on bags can get all the available taxicabs while those burdened by three suitcases await their luggage. On the other hand, if the weather is so unpredictable that everyone has to travel with clothing ranging from swimsuits to Arctic parkas, the "jack of all trades" has an advantage over the "master" of one. And so it is with behavioral versatility and brain size.

When chimpanzees in 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'.

Whether versatility is advantageous depends on the timescales: for both the modern traveler and the evolving ape, it is how fast the weather changes and how long the trip lasts. Paleoclimatologists have discovered that many parts of the earth suffer sudden climate changes, as abrupt in onset as a decade-long drought but lasting for centuries. A climatic flip that eliminated fruit trees would be disastrous for many monkey species. It would hurt the more omnivorous animals, too, but they could make do with other foods, and eventually they would enjoy a population boom when the food crunch ended and few of their competitors remained.

Although Africa was cooling and drying as upright posture was becoming established four million years ago, brain size did not change much. The fourfold expansion of the hominid brain did not start until the ice ages began, 2.5 million years ago. Ice cores from Greenland show frequent abrupt cooling episodes superimposed on the more stately rhythms of ice advance and retreat. Entire forests disappeared within several decades because of drastic drops in temperature and rainfall. The warm rains returned with equal suddenness several centuries later.

The evolution of anatomical adaptations in the hominids could not have kept pace with these abrupt climate changes, which would have occurred within the lifetime of single individuals. Still, these environmental fluctuations could have promoted the incremental accumulation of mental abilities that conferred greater behavioral flexibility.

One of the additions 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, we can 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 chance to learn syntax during the critical years of early childhood.

As neurologist Oliver W. Sacks described him in *Seeing Voices:* "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.

We humans also use about three dozen vocalizations, called phonemes. Yet only their combinations have content: we string together meaningless sounds to make meaningful words. No one has yet explained how our ancestors got over the hump of replacing "one sound/one meaning" with a sequential combinatorial system of meaningless phonemes, but it is probably one of the most important advances that took place during ape-to-human evolution.

Furthermore, human language uses strings of strings, such as the word phrases that make up this sentence. The simplest ways of generating word collections, such as pidgin dialects (or my tourist German), are known as protolanguage. In a protolanguage, the association of the words carries the message, with perhaps some assistance from customary word order (such as the subject-verb-object order in English declarative sentences).

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 2.5-year-old child. Neither Kanzi nor the child constructs such sentences independently, but each can demonstrate understanding.

With a year’s experience in comprehension, the child starts constructing fancier sentences. 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 extreme case of nesting word phrases inside one another, yet even preschoolers understand how “that” changes its meaning.

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. Generating and speaking a unique sentence demonstrate whether you know the rules of syntax well enough to avoid ambiguities. Even children of low intelligence acquire syntax effortlessly by listening, although intelligent deaf children like Joseph may miss out.

Something close to verbal syntax also seems to contribute to another outstanding feature of human intelligence, the ability to plan. Aside from hormonally triggered preparations for winter and mating, animals exhibit surprisingly little evidence of planning more than a few minutes ahead. Some chimpanzees use long twigs to pull termites from their nests, yet as 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.”

Short-term planning does occur to an extent, and it seems to allow a crucial increment in social intelligence. Deception is seen in apes, but seldom in monkeys. A chimp may give a call signaling that she has found food at one location, then quietly circle back through the dense forest to where she actually found the food. While the other chimps beat the bushes at the site of the food cry, she eats without sharing.

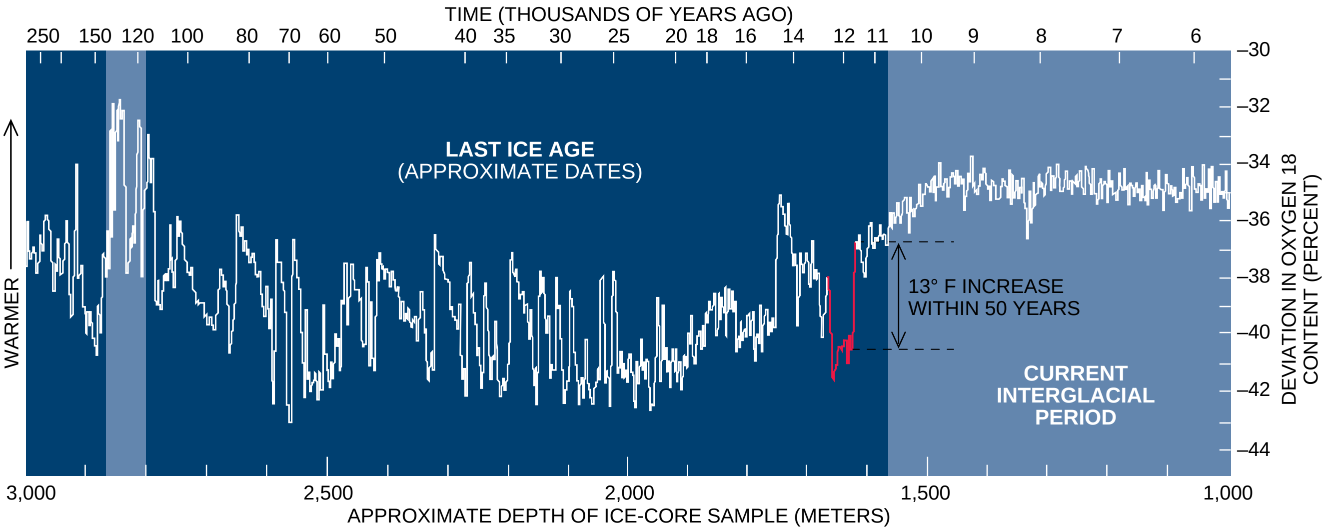
The most difficult responses to plan are those to unique situations. They require imagining multiple scenarios, as when a hunter plots various approaches to a deer or a futurist spins three scenarios bracketing what an industry will look like in another decade. Compared with apes, humans do a lot of that—we can heed the admonition sometimes attributed to British statesman Edmund Burke: “The public interest requires doing today those things that men of intelligence and goodwill would wish, five or 10 years hence, had been done.”

Human planning abilities may stem from our talent for building syntactical, string-based conceptual structures larger than sentences. As the writer Kathryn Morton observes about narrative:

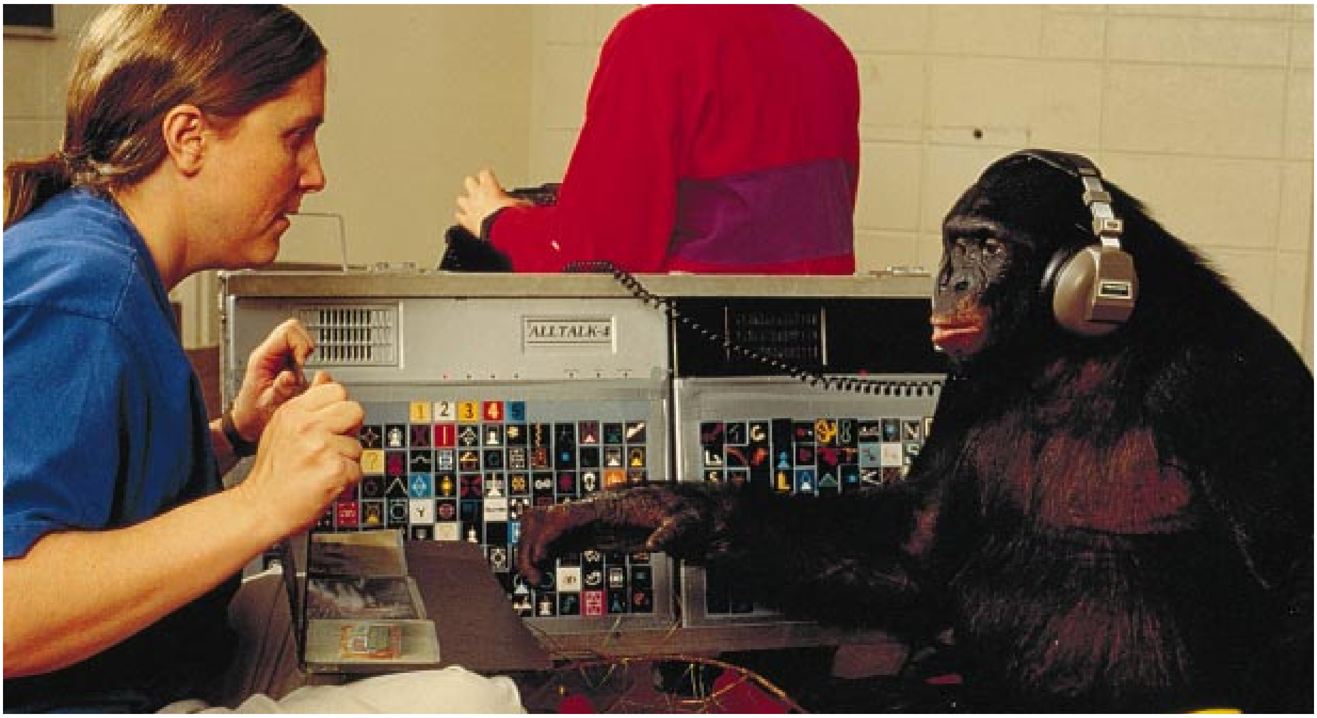
> The first sign that a baby is going to be a human being and not a noisy pet comes when he begins naming the world and demanding the stories that connect its parts. Once he knows the first of these he will instruct his teddy bear, enforce his worldview on victims in the sandlot, tell himself stories of what he is doing as he plays and forecast stories of what he will do when he grows up. He will keep track of the actions of others and relate deviations to the person in charge. He will want a story at bedtime.

Our abilities to plan gradually develop from childhood narratives and are a major foundation for ethical choices, as we imagine a course of action, imagine its effects on others and decide whether or not to do it.

In this way, syntax raises intelligence to a new level. By borrowing the mental structures for syntax to judge other combinations of possible actions, we can extend our planning abilities and our intelligence. 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 dangerous nonsense, mere nonsense, possible, likely or logical. But our thinking is not limited to language-like constructs. Indeed, we may shout, “Eureka!” when feeling a set of mental relationships click into place and yet



RAPID CLIMATE CHANGES may have promoted behavioral flexibility in the ancestors of modern humans. During the last ice age, the average temperature was much lower than it is today, but it was also subject to large, abrupt fluctuations that sometimes lasted for centuries. During one climatic oscillation, for example (*red line*), the temperature rose 13 degrees Fahrenheit, rainfall increased by 50 percent and the severity of dust storms fell, all in the space of a few decades. Cold periods began just as suddenly. Early humans may have needed greater intellectual resources to survive these changes. This graph is based on work by W. Dansgaard of the University of Copenhagen and his colleagues using Greenland ice cores.



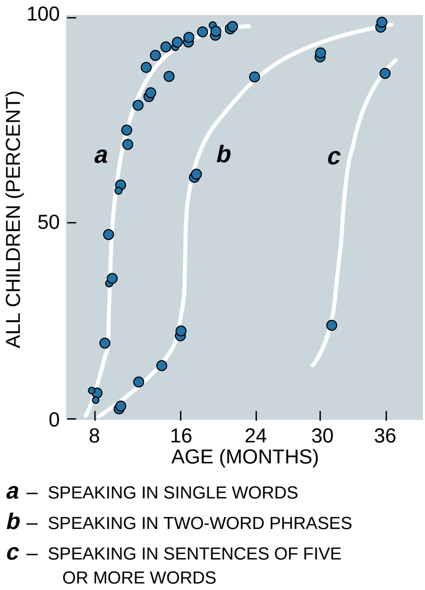
KANZI, a bonobo, has been reared at Georgia State University in a language-using environment. By pointing at symbols that represent various words, Kanzi can construct requests much like those of a two-year-old child. His comprehension is as good as that of a 2.5-year-old. Language experiments on bonobos ask how much of syntax is uniquely human.

have trouble expressing them verbally.

Language and intelligence are so powerful that we might think evolution would naturally favor their increase. As evolutionary theorists are fond of demonstrating, however, the fossil record is full of plateaus. Evolution often follows indirect routes rather than "progressing" through adaptations. To account for the breadth of our abilities, we need to look at improvements in common-core facilities. Environments that give the musically gifted an evolutionary advantage over the tone deaf are difficult to imagine, but there are multifunctional brain mechanisms whose improvement for one critical function might incidentally aid other functions.

We 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, one commonly useful to language, storytelling, planning, games and ethics? If so, natural selection for any of these talents might augment their shared neural machinery, so that an improved knack for syntactical sentences would automatically expand planning abilities, too. Such carryover is what Charles Darwin called functional change in anatomical continuity, distinguishing it from gradual adaptation. To some extent, music and dance are surely secondary uses of neural machinery shaped by sequential behaviors more exposed to natural selection, such as language.

As improbable as the idea initially seems, the brain's planning of ballistic movements may have once promoted language, music and intelligence. Ballistic 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. These movements are integral to the manufacture and use of tools and hunting weapons: in some settings, hunting and toolmaking were probably important additions to hominids' basic survival strategies.



ACQUISITION OF LANGUAGE by children occurs quickly and naturally through exposure to adults.

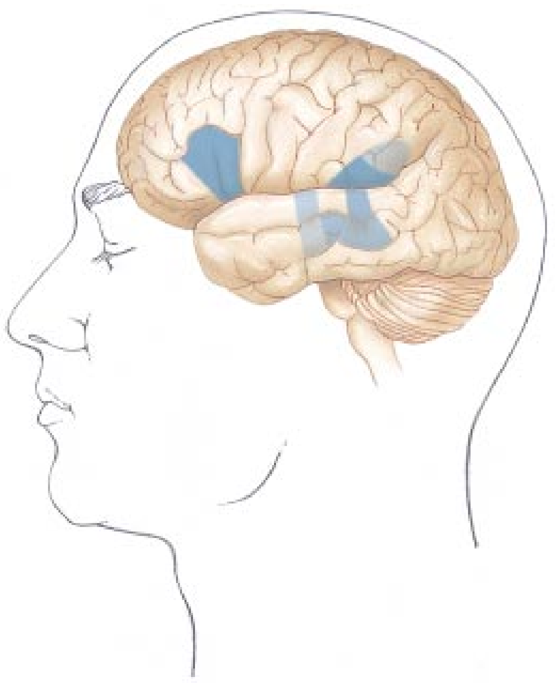
Ballistic movements require a surprising amount of planning. Slow movements leave time for improvisation: when raising a cup to your lips, if the cup is lighter than you remembered, you can correct its trajectory before it hits your nose. Thus, a complete plan is not needed. You start in the right general direction and then correct your path, just as a moon rocket does.

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 determine every detail of the movement in advance, as though it were silently punching a roll of music for a player piano.

Hammering requires scheduling the exact sequence of activation for dozens of muscles. The problem of throwing is further compounded by the launch window—the range of times in which a projectile can be released to hit a target. When the distance to a target doubles, the launch window becomes eight times narrower; statistical arguments indicate that programming a reliable throw would then require the activity of 64 times as many neurons.

If mouth movements rely on the same core facility for sequencing that ballistic hand movements do, then enhancements in language skills might improve dexterity, and vice versa. Accurate throwing abilities open up the possibility of eating meat regularly, 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.

Is there actually a sequencer common to movement and language? Much of the brain's coordination of movement occurs at a subcortical level in the basal ganglia or the cerebellum, but novel combinations of movements tend to depend on the premotor and prefrontal cortex. Two major lines of evidence point to cortical specialization for sequencing, and both suggest that the lateral language area has a lot to do with it.



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

Doreen Kimura of the University of Western Ontario [see "Sex Differences in the Brain," Scientific American, September 1992] has found that stroke patients with language problems (aphasia) resulting from damage to left lateral brain areas also have considerable difficulty executing unfamiliar 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 non-language ones.

These discoveries reveal that parts of the "language cortex," as people sometimes think of it, serve a far more generalized function than had been suspected. The language cortex is concerned with novel sequences of various kinds: both sensations and movements, for both the hands and the mouth.

The big problem with inventing 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. We 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 whole high end of intelligence and consciousness—involves playing mental games that shape up quality before acting. What kind of mental machinery might it take to do something like that?

By 1874, just 15 years after Darwin published *The Origin of Species,* the 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 an intermediate timescale of days governs the immune response following a vaccination. 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 patterns of brain activity associated with a thought might qualify. Second, copies are made of these patterns. (Indeed, that which is reliably copied defines a unit pattern.) Third, patterns must occasionally vary, whether through mutations, copying errors or a reshuffling of their parts.

A Meditation on Creative Thought

I believe the brain plays a game—some parts providing the stimuli, the others the reactions, and so on.... One is only consciously aware of something in the brain which acts as a summarizer or totalizer of the process going on and that probably consists of many parts acting simultaneously on each other. Clearly only the one-dimensional chain of syllogisms which constitutes thinking can be communicated verbally or written down.... If, on the other hand, I want to do something new or original, then it is no longer a question of syllogism chains. When I was a boy I felt that the role of rhyme in poetry was to compel one to find the unobvious because of the necessity of finding a word which rhymes. This forces novel associations and almost guarantees deviations from routine chains or trains of thought. It becomes paradoxically a sort of automatic mechanism of originality.... And what we call talent or perhaps genius itself depends to a large extent on the ability to use one's memory properly to find the analogies... [which] are essential to the development of new ideas.

—Stanislaw M. Ulam, *Adventures of a Mathematician,* 1976

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 is influenced by their environment; this result is what Darwin called natural selection. And, finally, the makeup of the next generation of patterns depends on which variants survive to be copied. The patterns of the next generation will be variations spread around the currently successful ones. Many of these new variants will be less successful than their parents, but some may be more so.

Sex and climatic change may not be numbered among the six essentials, but they add spice and speed to a Darwinian process, whether it operates in milliseconds or millennia. Note that an "essential" is not Darwinian by itself: for example, selective survival can be seen when flowing water carries away sand and leaves pebbles behind.

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 exist as patterns of spatiotemporal activity in the brain, each representing an object, action or abstraction. I estimate that a single cerebral code minimally involves a few hundred cortical neurons within a millimeter of one another either firing or keeping quiet.

Evoking a memory is simply a matter of reconstituting such an activity pattern, according to psychologist Donald O. Hebb's cell-assembly hypothesis [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; this "long-term potentiation" may fade in a matter of minutes. The transition from short- to long-term patterning is not well understood, but structural alterations may sometimes follow potentiation, such that 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. Perceptions of the thinker's current environment and memories of past environments may bias that competition and shape an emerging thought.

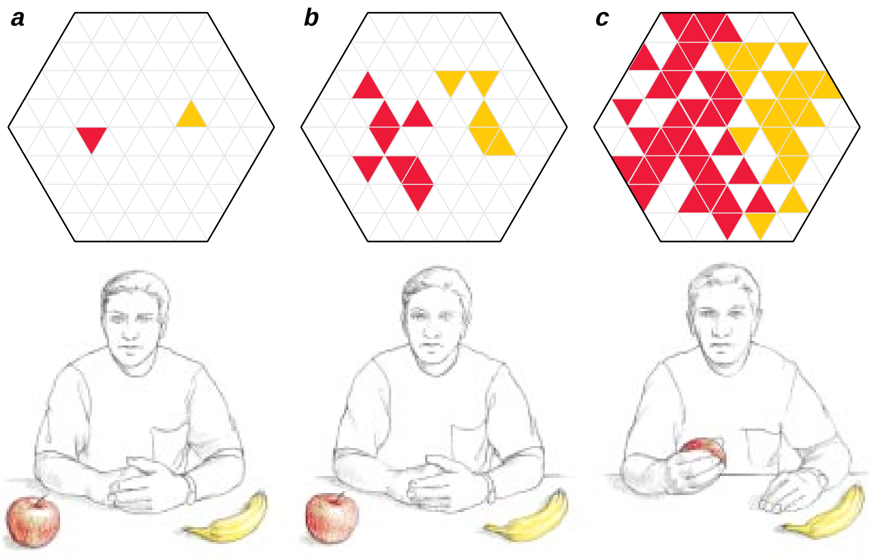
An active cerebral code moves from one part of the brain to another by making a copy of itself, much as a facsimile machine re-creates a copy of a pattern on a distant sheet of paper. The cerebral cortex also has circuitry for copying spatiotemporal patterns in an immediately adjacent region less than a millimeter away, although our present imaging techniques lack enough resolution to see the copying in progress. Repeated copying of the minimal pattern could colonize a region, rather the way 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 and undergo variations. When you try to remember someone's name, initially without success, the candidate codes might continue copying for the next half an hour until, suddenly, Jane Smith's name seems to "pop into your mind" because your variations on the spatiotemporal theme finally hit a resonance and create a critical mass of identical copies. 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 bound by rules. But we often deal with novel situations in creative ways, as when you decide what to fix for dinner tonight. You survey what is already in the refrigerator and on the kitchen shelves. You think about a few alternatives, keeping track of what else you might have to fetch from the grocery store. All this can flash through your mind within seconds—and that is probably a Darwinian process at work.

In phylogeny and its 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. There may be other ways in which high intelligence can be



DARWINIAN MODEL OF THINKING suggests that ideas compete for "workspace" within the brain. When a person is choosing between an apple and a banana (*a*), spatiotemporal patterns of neural activity representing these possibilities (*red for apple, yellow for banana*) may appear in the cortex (*hexagon*). Copies of each pattern proliferate at different rates, depending on the individual's experiences and sensory impressions (*b*). Eventually, the number of copies of one pattern passes a threshold, and the person makes that choice—in this case, to take the apple (*c*).

THROWING is a ballistic movement at which humans excel, despite the lack of effective feedback from the arm during most of the throw. Before a pitch starts, the brain must plan the sequence of muscle contractions that will launch the ball toward a target. Some of the neural mechanisms that plan such movements may also facilitate other types of planning.

achieved, but up-from-movement is the known paradigm.

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, compare the prospects of different species by asking how many elements of intelligence each has amassed.

Does the species have a wide repertoire of movements, concepts or other tools? Does it have tolerance for creative confusion that allows individuals to invent categories occasionally? (Primatologist Duane M. Rumbaugh of Georgia State University has noted that small monkeys and prosimians, such as lemurs, often get trapped into repeating the first set of discrimination rules they are taught, unlike the more advanced rhesus monkeys and apes.)

Does each individual have more than half a dozen mental workspaces for concurrently holding different concepts? Does it have so many that it loses our human tendency to "chunk" certain concepts, as when we create the word "ambivalence" to stand for a whole sentence's worth of description? Can individuals establish new relations between the concepts in their workspaces? These relations should be fancier than "is a" and "is larger than," which many animals can grasp. Treelike relations seem particularly important for linguistic structures; our ability to compare two relations (analogy) enables operations in a metaphorical space.

Can individuals mold and refine their ideas off-line, before acting in the real world? Does that process involve all six of the essential Darwinian features, as well as some accelerating factors—shortcuts that allow the process to start from something more than a primitive level? Can individuals make guesses about both long-term strategies and short-term tactics, so that they can make moves that will advantageously set the stage for future feats?

Chimps and bonobos may be missing a few of these elements, but they are doing better than the present generation of artificial-intelligence programs. Even in entities with all the elements, we would expect considerable variation in intelligence because of individual differences in processing speed, in perseverance, in implementing shortcuts and in finding the appropriate level of abstraction when using analogies.

Why are there not more species with such complex mental states? 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 University 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 for it, but here we are."

FURTHER READING

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