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SIXTEEN

The Cognitivists

Revolution

In 1960, George A. Miller, though youthful and somewhat pixieish in appearance at forty, was a professor of psychology at Harvard and assured of his prestigious post and comfortable style of living for the rest of his career. Yet that year he felt compelled, despite deep misgivings, to reveal his true colors even if it meant giving up his place at Harvard.

His revelation would not be about radical politics or radical sex, both on the rise at that time, but about his interest in the mind.

The *mind*? What could be subversive or disreputable about that? Wasn't it the core concern of psychology?

No, not then, nor had it been since the beginning of the behaviorist dominion over American psychology four decades earlier. To behaviorists, the mind, invisible, nonmaterial, and conjectural, was an obsolete metaphysical concept that no experimental psychologist concerned about his career and reputation would talk about, much less devote himself to.

But Miller had become a covert mentalist over the years. Born and raised in Charleston, West Virginia, as a freshman in college he had been uninterested in and even a trifle hostile toward psychology; in a memoir he says, tongue in cheek (a frequent mode of his), that he saw drawings of the brain and other organs in a psychology textbook and, "raised by Christian Scientists, I had been trained to avoid *materia medica*, and I could recognize the devil when I saw him."[1]

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Either education or infatuation changed his outlook. In his junior year at the University of Alabama, Miller, smitten with a girl (whom he later married), went to the informal seminars in psychology she was attending, given by Professor Donald Ramsdell at his home. Miller made such an impression on Ramsdell that a couple of years later, when he completed a master's in speech and communication, Ramsdell offered him a job teaching psychology to undergraduates, although Miller had never had a formal course in the subject. By then married and a father, Miller needed the job and took it; a year of teaching psychology made a convert of him.

He went to Harvard for graduate studies, received a solid grounding in behaviorist psychology, and so distinguished himself that after earning his doctorate he was made an instructor. For the next fourteen years, first at Harvard and then at the Massachusetts Institute of Technology, he conducted experimental studies in speech and communication. Despite his behaviorist training, this work, unlike rat-based research, forced him willy-nilly to think about human memory and other higher mental processes. He drifted still closer to mentalism after attending a summer seminar at Stanford, where he worked closely with the psycholinguist Noam Chomsky, and a sabbatical year at the Center for Advanced Study in the Behavioral Sciences at Palo Alto, where he was exposed to new ways of doing research on thinking, especially the simulation of thought processes by computer programs.

In the fall of 1960 Miller returned to Harvard a changed man. As he tells it in his memoir:

> I realized I was acutely unhappy with the narrow conception of psychology that defined the Harvard department. I had just spent a year romping wildly in the sunshine. The prospect of going back to a world bounded at one end by psychophysics and at the other by operant conditioning was simply intolerable. I decided that either Harvard would have to let me create something resembling the interactive excitement of the Stanford Center or else I was going to leave.

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Miller confided in his friend and colleague, the social psychologist Jerome Bruner, about his discontent and the dream of a new center devoted to the study of mental processes. Bruner shared both his feelings and his vision. Together they approached McGeorge Bundy, provost of the university, won his approval, and with funding from the Carnegie Corporation established the Harvard Center for Cognitive Studies. Naming it that made Miller feel like a declared apostate:

> To me, even as late as 1960, using "cognitive" was an act of defiance. It was less outrageous for Jerry [Bruner], of course; social psychologists were never swept away by behaviorism the way experimental psychologists had been. But for someone raised to respect reductionistic science, "cognitive psychology" made a definite statement. It meant that I was interested in the mind—I came out of the closet.

And became a leader of the movement that radically changed the focus and methods of psychology and has guided it ever since.

George Miller's coming-out typifies what was happening to experimental psychologists in the 1960s. At first a few, then many, and soon a majority abandoned rats, mazes, electric grids, and food-dispensing levers in favor of research on the higher mental processes of human beings. Within the decade, the movement had assumed such proportions as to earn the name "the cognitive revolution."

Many forces had been building toward it. During the two previous decades, Gestaltists, personality researchers, developmentalists, and social psychologists were all, in their different ways, exploring mental processes. Coincidentally, a series of developments in several other scientific fields (some of which we have already heard about, some of which we will hear about shortly) were producing knowledge of other kinds about how the mind works. Specifically:

> —Neuroscientists, using microelectrode probes and other new techniques, were observing the neural events and cellular interconnections involved in mental processes.

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—Logicians and mathematicians were developing information theory and using it to account for both the capabilities and limitations of human communication.
—Anthropologists, analyzing the thought patterns of people in other cultures, were discovering which mental processes vary among cultures, and which are universal and therefore possibly innate.
—Psycholinguists, studying language acquisition and use, were learning how the mind acquires and manipulates the intricate symbol system we call language.
—Computer scientists, a new hybrid (part mathematician, part logician, part engineer), were contributing a brand-new theoretical model of thinking, and designing machinery that seemed to think.

By the late 1970s, cognitive psychology and these related fields came to be known as the cognitive sciences; a number of enthusiasts called them collectively, "cognitive science" and regarded it as a new and distinctive field.[2] In the 1980s and early 1990s they expected it to replace the field of psychology; instead, standard psychology morphed, absorbing the new ideas of cognitive science. Today, most departments of psychology include many cognitive science topics, and the relatively few separate departments of cognitive science that exist include many or most classical psychology topics.[3] The bottom line: The cognitive revolution was more than a remarkable broadening and deepening of psychology; it was the extraordinary—indeed, wholly improbable—simultaneous development in six sciences of new knowledge bearing on mental processes.

Computer science had by far the greatest impact on psychology. This new field was the product of intense research during World War II, when Allied forces urgently needed calculating machines that could rapidly handle large sets of numbers to direct antiaircraft guns, operate navigation equipment, and the like. But even very high-speed calculating machines needed to be told by a human operator, after each calculation, what to do next, which severely limited their speed and introduced inaccuracies. By the late 1940s, mathematicians and engineers were

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starting to provide the machines with sets of instructions (programs) stored in their electronic memories. Now the machines could swiftly and accurately guide their own operations, carry out lengthy sequences of operations, and make decisions about what needed to be done next. The calculating machines had become computers.

At first, computers dealt only with numerical problems. But as the mathematicians John von Neumann and Claude Shannon and other computer experts soon pointed out, any symbol can represent another kind of symbol. A number can stand for a letter and a series of numbers for a word, and mathematical computations can represent relationships expressed by language. For instance, [H11005] can stand for "is the same as," [HS11005] for "is not the same as," > for "more than" or "too much." Given a set of rules by which to turn words into numbers and algebraic relationships and then back into words, a computer can perform operations analogous to some kinds of human reasoning.[4]

In 1948 the idea that the computer might in some ways function like a mind—at the time this seemed more like science fiction than science—was first broached by von Neumann and the neurophysiologist Warren McCulloch at a California Institute of Technology conference, "Cerebral Mechanisms in Behavior."

That notion captivated Herbert Simon, then a young professor of political science at the Carnegie Institute (now Carnegie-Mellon University).[5]"Professor of political science" hardly describes him, however. Simon, the son of an electrical engineer, was so bright that he was skipped in school and was considerably younger than his friends and classmates. Add to that his being unathletic and growing up in Wisconsin keenly aware of his Jewishness, and it is not surprising that he solaced himself by becoming an exceptional student. In college he liked to think of himself as an intellectual, but in fact his interests were freakishly wide-ranging; although he became a political scientist, he was interested and self-taught in mathematics, economics (for which he was awarded a Nobel Prize in 1978), administration, logic, psychology, and computer science.

In 1954, Simon and a brilliant young graduate student of his, Allen Newell, discovered that they shared

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passionate interests in computers and thinking (both men later earned degrees in psychology), and in creating a computer program that would think. For a first attempt, they chose a very limited kind of thinking, namely, proving theorems in formal logic, an entirely symbolic and almost algebraic process. Simon's task was to work out proofs of theorems while "dissecting as minutely as possible, not only the proof steps, but the cues that led me to each one." Then the two men together tried to incorporate this information in a flow diagram that they could turn into a computer program.

After a year and a half of work, Simon and Newell electrified the audience at a 1956 symposium on information theory at MIT with a description of their intellectual offspring, Logic Theorist. Running on JOHNNIAC, a gigantic, primitive, vacuum-tube computer, it was able to prove a number of theorems in formal logic in anywhere from under a minute to fifteen minutes per proof.[6] (On a modern computer it would do the same thing in virtually the blink of an eye.) Logic Theorist, the first artificial intelligence program, wasn't very intelligent; it could prove only logic theorems—at about the same speed as an average college student—and only if they were presented in algebra-like symbols. Still, as the first computer program that did something like thinking, it was a breathtaking achievement. (George Miller was at the presentation; he regards that day as the birthday of cognitive science, even though it took him another four years to declare his apostasy from behaviorism.[7])

By the end of the following year, 1957, Newell, Simon, and a colleague, Clifford Shaw, had created a much cleverer program, General Problem Solver (GPS), which incorporated a number of broad principles common to many intellectual tasks, including proving theorems in geometry, solving cryptarithmetic problems, and playing chess. GPS would make a first move or probe to begin determining the "problem space" (the area containing all possible moves between its initial state and the desired goal), look at the result to see whether the move had brought it closer to the goal, concoct possible next moves and test them to see which one would advance it toward the goal, back up to the last decision point if the train of

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reasoning veered off course, and start again in another direction. A simple problem that GPS solved easily early in its career went as follows (the problem was presented not in these words, which GPS could not understand, but in mathematical symbols):

> A heavy father and two young sons have to cross a swift river in a deep wood. They find an abandoned boat that can be rowed across, but will sink if overloaded. Each young son weighs 100 pounds. Two sons weigh as much as the father, and more than 200 pounds is too much for the boat. How do the father and the sons cross the river?[8]

The solution, though simple, requires a seeming retreat in order to advance. The two sons get in and row across; one debarks and the other rows back and lands; the father rows across and gets out; the son on that side rows back, picks up his brother, and returns to the far shore. GPS, in devising and testing this solution, was doing something akin to human problem solving. By means of the same heuristic—a broad stratagem of exploration and evaluation—it was able to solve similar but far more difficult problems.

Two basic features of GPS and later artificial intelligence (AI) programs brought about a metamorphosis in cognitive psychology by giving psychologists a more detailed and workable conception of mental processes than any they had previously had, plus a practical way to investigate them.[9]

The first of those features is *representation:* the use of symbols to stand for other symbols or events. In GPS, numbers stand for words or relationships, and in the hardware (the actual computer) operated by GPS, groups of transistors, acting as binary switches that are either on or off, stand for those numbers. By analogy, cognitive psychologists could conceive of the images, words, and other symbols stored in the mind as representations of external events, and of the brain's neural responses as representations of those images, symbols, and thoughts. A representation, in other words, corresponds to the thing it represents without being at all similar to it. But this was

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actually an old discovery in new form; Descartes and Fermat discovered long ago that algebraic equations can be represented by lines drawn on a graph.

The second feature is *information processing:* the transforming and manipulating of data by the program in order to achieve a goal. In the case of GPS, incoming information—the feedback of each step—was evaluated as to where it had led, used to determine the next step, stored in memory, retrieved if needed again, and so on. By analogy, cognitive psychologists could conceive of the mind as an information-processing program that transforms perceptions and other incoming data into mental representations and, step by step, evaluates them, uses them to determine what to do next in the attempt to reach its goal, adds them to memory, and retrieves them for use again as needed.

The information-processing (IP) or "computational" model of thinking has been the guiding metaphor of cognitive psychology ever since the 1960s, and has enabled researchers and theorists to explore the inner universe of the mind as never before.

One specimen of such an exploration will exemplify how the IP model enables cognitive psychologists to ascertain what takes place in the mind. In a 1967 experiment, a research team headed by Michael Posner asked its subjects to say aloud, as fast as possible, whether two letters projected on a screen had the same or different names. When the subjects saw this

AA

they almost instantly said "Same," and when they saw this

Aa

they again almost instantly said "Same." But the researchers, using a highly accurate timer, measured a minuscule difference. On average, subjects replied to AA in 549 milliseconds and to Aa in 623 milliseconds. A tiny difference, to be sure—but a statistically significant one.[10] What could account for it?

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The IP model envisions any simple cognitive process as a series of step-by-step actions performed on the data. The following simple flow diagram, typical of many drawn by cognitive psychologists, symbolizes what goes on when we see and recognize something:

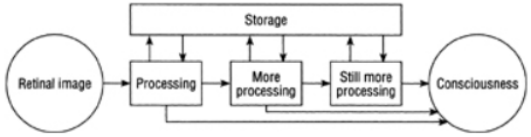


FIGURE 39
A typical information-processing diagram

That accounts for the reaction-time difference in the experiment. If an image proceeds directly from the first "processing" box to "consciousness," it does so in less time than when it must pass through two or three boxes. In order to identify the letters in AA as having the same name, subjects had to perform only visual pattern recognition on the visual image; to identify those in Aa as having the same name, they had to locate the name of each letter in memory and then see whether they were the same —additional processing that took 74 milliseconds more, a tiny but consequential difference, and strong evidence of how the mind performed this little task. In a follow-up experiment subjects had to say whether AU were both vowels, and in another whether SC were both consonants; the AU response took somewhat longer than AA or Aa had, and SC much longer (nearly a second). Again, these longer reaction times indicated that more steps of mental processing were required.[11] Thus even trifling experiments based on the IP model can reveal something of what goes on in the mind.

To be sure, the finding is an inference from results, not a direct observation of the process. But contrary to behaviorist dogma, inference of an unseen process from results is considered legitimate in the "hard" sciences. Geologists infer the events of the past from sediment layers, cosmologists the formation and development of the universe from the ancient light of distant galaxies, physicists the characteristics of short-lived atomic particles

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from tracks they leave in a cloud chamber or emulsion, and biologists the evolutionary path that led to *Homo sapiens* from fossils. So, too, with the interior universe of the mind: psychologists cannot voyage into it, but they can deduce how it works from the track, so to speak, made by an invisible thought process.

Revolution No. 2

What, another revolution so soon?

Well, not on the heels of the cognitive revolution, but not far behind it. This one, though long gathering force, would not burst forth until the 1980s, but we must look ahead to its emergence because much of what we will see happening in cognitive psychology will be affected by it. It was the cognitive neuroscience revolution.

That's a relatively new name for an old school of thought about the mind, the biological approach to mental processes that sought to explain them in terms of neuronal processes and events. We saw a notable example of it in Hubel and Wiesel's discoveries of retinal cells that respond only to specific shapes or directions of motion. That was recent, but the neuroscientific approach has antecedents going back at least to Descartes. Although he believed in the immateriality of mind, he conjectured, as we saw, that reflexes were caused by the flow of "animal spirits" through the nervous system, much as the movements of automata in the royal gardens were caused by the flow of water in pipes, and that memory was the result of the widening of the particular "pores of the brain" through which animal spirits had passed during learning.[12] Similarly, a century ago the young Freud confidently asserted that all psychological processes could be understood as "quantitatively determined states" of the neurons, though he soon admitted with chagrin that the time was not ripe for such understanding.

The same hope, though, had continued to inspire many researchers. And during the past sixty years, and especially the past twenty-five, extraordinary advances in cognitive neuroscience have led some enthusiasts to assert that it

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will soon replace the psychological approach to the mind and that concepts such as needs, emotions, and thoughts will be replaced by physiological data. When such data are available, Paul Churchland, a philosopher of neuroscience, asserted in 1984,

> we will set about reconceiving our internal states and activities, within a truly adequate framework at last. Our explanations of one another's behavior will appeal to such things as our neuropharmacological states, the neural activity in specialized anatomical areas, and whatever other states are deemed relevant by the new theory.[13]

Most research in behavioral neuroscience in the decades immediately preceding its 1980s breakout as cognitive neuroscience was focused not on thought processes but on the physical events taking place (as thought occurs) in the "wetware"—the hundred billion or more neurons that make up the human brain. Cognitive neuroscientists—some were neurobiologists who had studied psychology, others were psychologists who had studied neurobiology—were interested in such phenomena as the flow of sodium and other ions into and out of the axon (main stem) of a neuron as electrical impulses pass along it; the molecular structure of the neurotransmitters (the chemicals produced in the synapses, the junctions at which the impulses are passed to other neurons); the bursts of neurotransmitter molecules that leap across the microscopic synaptic gaps from neuron to neuron carrying messages of excitation or inhibition; and the neuronal routes and networks activated by different kinds of stimuli and mental activities.

Behavioral neuroscientists (as they were then known), often white-coated, spent much of their time in operating rooms and laboratories, where, among other things, they surgically destroyed specific portions of animals' brains to learn what aspects of behavior those parts control; they interviewed and tested people who had suffered brain damage; they measured and recorded the spikes of activity of single neurons and the overall patterns of brain excitation ("brain waves") during various mental activities; they administered drugs that increase or

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decrease the production of particular neurotransmitters to determine what functions these perform; and they did chemical analyses of the brain tissue of laboratory animals and human cadavers to see what neurotransmitters were in either short supply or excess in individuals whose behavior is abnormal in some respect.

A good deal of their work, as we have already seen, involved testing patients with cerebral damage (most often strokes), pinpointing the affected brain area and identifying it as the cause of the patient's diminished or lost perceptual and mental abilities. But much other neuroscientific research, though arguably valuable, had its comical overtones. One investigator implanted sixteen microelectrodes into the muscles of a male grasshopper in order to record the electrical impulses of its neurons during courtship. Others inserted microelectrodes into the left front leg of a cockroach and the foot of a snail to measure the neural impulses that produce movement toward some goal; the investigators regarded this as research on "motivated behavior."[14]

Of all cognitive processes, especially in more advanced species, memory is the most basic, and for decades cognitive neuroscientists sought to identify how and where memory exists at the cellular level. A few examples of the ways in which they did so:

> —As long ago as 1949, Donald Hebb, a Canadian psychologist, hypothesized that memories are stored by the modification of the synapses connecting neurons (an idea not unlike Descartes's). The repeated activation of a synapse in a learning experience, he said, somehow strengthens the synapse and links the two neurons into a circuit or "memory trace."[15] Hebb's hypothesis was more or less confirmed in 1973 when a British neurophysiologist, Timothy Bliss, and a colleague, Terje Lømo, measured the voltage in one neural pathway in the brain of a rabbit, then sent repeated bursts of electricity down the path, and afterward found that the pathway carried a higher voltage than before. The synapses had been strengthened by the electrical impulses. The implication was that that is what

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happens in learning.[16] (Later research, as we will see, has added many details and complexities to the explanation.) —Also in the early 1970s, an American psychologist, William Greenough, raised rats in two environments, one containing toys, mazes, and other stimulating devices, the other without any. The rats in the stimulating environment developed heavier areas of cerebral cortex; the neurons in those areas had grown more dendrites and thus more synapses than those of rats in the dull environment. Later, by means of electron microscopy, Greenough and a colleague actually counted 20 to 25 percent more synapses in the affected cortical areas of the enriched-environment rats than those of the deprived ones. Learning had generated the extra connections; memory traces must somehow be recorded in them.[17]

—In the late 1980s Daniel L. Alkon and his colleagues at the

National Institute of Neurological and Communicative Disorders and Stroke trained a sea snail, *Hermissenda crassicornis*, to respond to light in a way it does not normally do. *Hermissenda* instinctively swims toward light; also, when the water is turbulent it instinctively clenches its foot muscle in order to cling to a surface. Alkon combined these reactions. By flashing a light and simultaneously whirling the chamber in which he housed the snail, he conditioned it—taught it—to clench its foot muscle whenever it saw a flash of light. He then found that in certain of the snail's photoreceptor neurons, molecules of PKC, a calcium-sensitive enzyme, had moved from the interior of the neuron toward its membrane, where they reduced potassium-ion flow—a partial explanation of memory in molecular terms.[18]

—Over several decades, James L. McGaugh and other researchers did a number of studies in which they injected epinephrine (a hormone produced by the adrenal gland) and other catecholamine neurotransmitters into rats after training them to run a maze. Epinephrine, in particular, causes the rats to remember longer what they learned than rats not so dosed. The explanation, deduced from

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other studies, seems to be that a byproduct of the epinephrine combats opioids, a group of neurotransmitters that serve useful purposes but plug up receptors on the receiving side of synapses. The result: more receptors remain open, the synapses function more efficiently, and memory is strengthened.[19]

These and many other research studies made cognitive neuroscientists feel sure that they were on the right track to explaining the many mysteries of psychology. Their approach promised to end, once and for all, the ancient debate about body and mind by explaining all mental processes in terms of material substances and events. All high-level mental processes such as memory, language, and reasoning were only ions and molecules flowing hither and thither in the labyrinthine and infinitesimal plumbing of the brain.

But the great majority of cognitive psychologists, proud of their new dominance and excited by the amazing capacity of computers to mimic—and perhaps explain—human reasoning, were dismissive of cognitive neuroscience. In the 1950s, after Newell and Simon's dramatic presentation of Logic Theorist, whatever connection had existed between cognitive psychology and neuroscience fell apart; Simon, in fact, authoritatively declared that to "understand cognition, one needn't pay much if any attention to the underlying biology."[20]

For the next twenty-five or so years, most cognitive psychologists agreed with him, insisting that neural events do not provide an adequate or useful explanation of cognitive phenomena. Few were dualists in the sense of believing in immaterial mind, but they asserted that psychological processes, though constructed of neural events, were properties of the organization or metastructure of those components, not of the components themselves, even as shelter is not a property of bricks, beams, and shingles but of a house built of them.

Nobel Laureate Roger Sperry, though himself a brain scientist, offered another analogy: a higher-order mental process is like a wheel rolling downhill—the rolling is determined by the "overall system properties" of the

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wheel, not by the atoms and molecules of which it is made.

The developmentalist Jerome Kagan used a different analogy: the elegant laws of planetary motion illustrate phenomena that are not expressible in terms of the atoms of which the planets are made.

Another analogy, this from the cognitive scientist Earl Hunt: "We can tell from physical measures that the left temporal region of the brain is active when we read, but we cannot discriminate the activity induced by reading Shakespeare from that induced by reading Agatha Christie."

And a word from the cognitive psychologist George Mandler: "The mind has functions that are different from those of the central nervous system, just as societies function in ways that cannot be reduced to the function of individual minds."[21]

Most cognitive psychologists thus believed that a word retrieved from memory could not be equated with the firing of millions of neurons and the resultant millions or billions of synaptic transmissions, but was the product of the pattern or structure of those firings and transmissions. The neurobiological study of memory, valuable as it was, did not tell us how we learn anything, recognize things we have earlier experienced, or retrieve items from memory as needed—the words we use in speech, to give one example. Such phenomena, they insisted, were governed not by the laws of cognitive neuroscience but by those of cognitive psychology.

Martha Farah, a distinguished neuroscientist and director of the Center for Cognitive Neuroscience at the University of Pennsylvania, recalls that in 1980, when she was a graduate student of psychology at Harvard, "I asked to take a course in neuroanatomy—and got lectured. I was 'supposed to be studying how the mind worked, and looking at how the brain works was simply not relevant.' That was the received wisdom in those days. The '70s and '80s were the last hurrah of brain-free psychology."[22]

What ended the reign of brain-free psychology? Many things, including:

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—the growing mass of data on neuronal transmission, on the functions of brain substructures, and on the molecular and other factors that strengthen synaptic connections in learning;
—the shortcomings of the computer model of cognition (it was becoming apparent that although computers could simulate some aspects of cognition, the mind processes information in vastly more complex ways than the linear step-by-step fashion of computer programs);
—the weakening resistance of some leading cognitive psychologists to valuable neuroscientific findings about brain processes; and
—the growing sense among neuroscientists by the late 1970s that they were doing far more than exploring brain biology and that their domain should be called "cognitive neuroscience."

But as has been the case in various other sciences, it was a new tool (actually a set of tools) that transformed the domain of neuroscience and produced a second revolution in the cognitive sciences. The tools were an array of brain scan devices—machines that could produce various kinds of images of the working brain and, most importantly, of the physical changes or events taking place in it when mental processes were in progress.

Prior to the 1980s, physiologists had been able to use EEG (electroencephalography) to show the form of brain waves; this was useful in studying the differences in brain wave activity during various wakeful and sleep states and the distortions of the waves during epileptic seizures. The method, however, was poor at localizing the brain activity of specific cognitive processes because it reflected overall electrical activity, not that of specific regions or structures of the brain.[23]

But in the 1980s several dramatic advances were made. One was the development of PET (positive emission tomography) scanning after many years of experiments in measuring blood flow in the brain. In a PET scan the subject lies supine on a narrow table which rolls into a large tubular machine. A nearby cyclotron generates a weakly radioactive isotope with a half-life of only two minutes which is then injected into the patient. The

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scanner, sensitive to the isotope, records blood flow in a "slice" (narrow cross-section) of the brain, the isotope showing where the brain is active. From a number of slices, a computer assembles three-dimensional images of the brain. The PET scan can be used clinically to study physical damage to, and abnormalities in, the brain, but cognitive psychologists and neuroscientists soon began using PET scans to see what areas of the brain had increased blood flow during—and thus were involved in—various kinds of mental activity.[24]

In 1983 another important tool was introduced—CT (computed tomography) scanning, also known as CAT scanning (computerized axial tomography). It proved to be a valuable medical tool for assessing many kinds of physiological problems, but also for studying brain structure and identifying brain lesions. In the CT scan, the subject is, as in a PET scan, supine, and eased into the scanner, which has an X-ray source and a set of radiation detectors. The scanner sends radiation through the target part of the subject from various angles. The density of biological materials varies; accordingly, the data gathered by the detectors reveal the hidden structure, and are assembled by a computer program to yield X-ray pictures of the entire scanned target. CT scans were and are used primarily for clinical medical analyses, but the method also had some value for cognitive research on brain structure, although the results are not very distinct and lack fine resolution.[25]

By far the most important and latest new tool is the MRI (magnetic resonance imaging) scan. Again the subject is supine inside a scanning machine, which is about the size of a small SUV, and which, while making a horrendous racket, generates a powerful magnetic field that permeates the subject's head. The magnetism, unlike the radiation of the CT scan, is harmless—and capable of revealing brain structure and activity far better than the CT scan.

It can do so because the protons of hydrogen, a major component of the water and fat in the brain, behave like tiny magnets and line up under the influence of the magnetic field (normally, their orientation, unaffected by earth's weak magnetism, is randomly distributed). Then, radio waves, passed through the subject's head, change the

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protons' orientation, but the instant the radio waves stop, the protons bounce back to the orientation created by the magnetic field and, in so doing, emit energy signals. These, picked up by detectors, yield scans much clearer, and with far finer resolution (a spatial resolution of one millimeter and a temporal resolution of about one second) than any other scanning method.

Best of all, from the cognitive researcher's viewpoint, if the subject performs some prescribed mental task while being scanned, the resulting fMRI (functional MRI) scan gives an intimate look at exactly which brain areas and substructures are active, and how active, during that kind of mental activity. Accordingly, the fMRI quickly became the workhorse of cognitive neuroscience. A dozen years ago, a mere handful of studies based on fMRI scans appeared in a year's worth of research literature; today, the annual output is several thousand.[26]

What has all this done to psychology, the science of the human mind? That depends on who is assessing the situation.

Most psychologists, focused on mental processes rather than wetware, continue to use research methods that were available before the advent of scanning, but many of them also rely on the help of scanning. They no longer see cognitive psychology and cognitive neuroscience as distinct and unrelated fields. As Robert J. Sternberg, a notable cognitive psychologist, says, "Biology and behavior work together. They are not in any way mutually exclusive."[27] Some use stronger terms to appraise the impact of cognitive neuroscience: Psychologists Stephen Kosslyn and Robin Rosenberg write, "It is fair to say that neuroimaging techniques have transformed psychology, allowing researchers to answer questions that were hopelessly out of reach before the mid-1980s."[28]

Does that suggest that cognitive neuroscience will become the psychology of the future? Not according to cognitivist Michael Posner, who has worked in both camps and whose work has been admired by researchers in both: "An impressive aspect of the anatomical methods such as PET and fMRI is how much they have supported the view that cognitive measures can be used to suggest separate

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neural structures," and he stresses the importance of the contributions of both fields to understanding brain function.[29]

But some cognitive neuroscientists think it possible, even likely, that their field will come to dominate mental science. Martha Farah, when asked if cognitive neuroscience would eventually become the overarching theory of psychology, said, "Yes, because it's a broader and more heterogeneous approach to studying the mind which encompasses cognitive psychology. It's a molecular-cellular-systems explanation of how the brain acts during all the classical processes of cognitive psychology—how we learn, think, behave, why we differ from each other, the sources of personality. All these things are in principle explainable by various levels of brain activity at various levels of description."[30]
We seem to be at the top of the ninth, score tied, and will have to see how the game plays out.

Now let us return to the story of cognitive psychology and look more closely at several of its major themes of recent decades.

Memory

In the 1960s, the cognitive revolution rapidly won the allegiance, at least in academia, of some senior psychologists, most junior ones, and most graduate students of psychology. At first, they concentrated on perception, the first step of cognition, but fairly soon they shifted their attention to the uses the mind makes of perceptions—its higher-level mental processes. By 1980, John Anderson, a theorist of those processes, defined cognitive psychology as the attempt "to understand the nature of human intelligence and how people think."[31]

In information-processing theory, the essential first step is the storing of incoming data in memory, whether for part of a second or for a lifetime. As James McGaugh said in a 1987 lecture:

> Memory is essential for our behavior. There is nothing of significance that is not based fundamentally on memory. Our consciousness and our actions are shaped by our experiences. And,

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> our experiences shape us only because of their lingering consequences.[32]

How crucial memory is to thought is painfully apparent to anyone who has known a person suffering from advanced Alzheimer's disease. He may frequently forget what he wants to say partway through a sentence, get lost walking down the driveway to his mailbox, fail to recognize his children, and become upset by the unfamiliarity of his own living room.

In 1955—before the start of the cognitive revolution—George Miller had given an address at a meeting of the Eastern Psychological Association that has been called a landmark for cognitive theorists working on memory. In his typically breezy manner, Miller called the talk "The Magical Number Seven, Plus or Minus Two," and began by saying, "My problem is that I have been persecuted by an integer." The integer was 7, and what seemed to Miller both magical and persecutory about it was, as many experiments had shown, that it is the number of digits that one can usually hold in immediate memory.[33] (It is easy to remember briefly, after a moment's study, a number like 9237314 but not one like 5741179263.)

It is both noteworthy and mysterious that immediate memory, the limiting factor in what we can pay attention to, is so tiny. The limitation serves a vital purpose: it drastically prunes the incoming data to what the mind, at any moment, urgently needs to attend to and make decisions about, a function that undoubtedly helped our primitive ancestors survive life in the jungle or the desert.[34] But it raises perplexing questions. How can so small a field of attention handle the flood of perceptions we must attend to when driving a car or skiing? Or the welter of sounds and meanings when someone is talking to us—or when we are trying to say something to them?

One answer, Miller said, making good use of an idea that had lain fallow in psychology for a century, is that immediate memory is not limited to seven digits but to seven—more or less —*items:* seven words or names, for instance, or "chunks" such as FBI, IBM, NATO, telephone area codes, or familiar sayings, all of which contain far

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more information than single digits but are as easily remembered.

But even with chunking, the capacity of immediate memory is insignificant compared with the enormous amount of material—everyday experiences, language, and general information of all sorts—that we learn and store away in long-lasting memory and call up again as needed.

To explain this disparity and determine how memory works, cognitive psychologists conducted a great many experiments during the 1960s, 1970s, and 1980s; the findings, pieced together, gave shape to an information-processing picture of human memory. In it, memory consists of three forms of storage, ranging from a fraction of a second to a lifetime. Experiences or items of information needed only for an instant fade away as soon as used, but those needed longer are transformed and held for longer, or even worked into the semipermanent or permanent register of long-term memory. Researchers and theorists portrayed the three types and the transfer of information among them in flow charts something like the one on p. 608.

The briefest form of memory consists of sensory "buffers" in which incoming sensations are first received and held. By means of the tachistoscope, researchers verified that buffers exist and also measured how long memories endure in them before disappearing. In a classic experiment in 1960, the psychologist George Sperling flashed on a screen, before attentively watching volunteers, patterns of letters like this:



The letters appeared for a twentieth of a second, too brief a time for the volunteers to have seen all of them, although immediately afterward they could write down the letters of any one line. (A tone, right after the flash, told them which line to record.) They could still "see" all three lines when they heard the tone, but by the time they had written down one line, they could no longer remember the others; the memory had vanished in less than a second. (Experiments by others yielded comparable results with sounds.) Evidently, incoming perceptions are stored in buffers, from

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which they vanish almost at once—fortunately, for if they lasted longer, we would see the world as a continuous blur.[35]

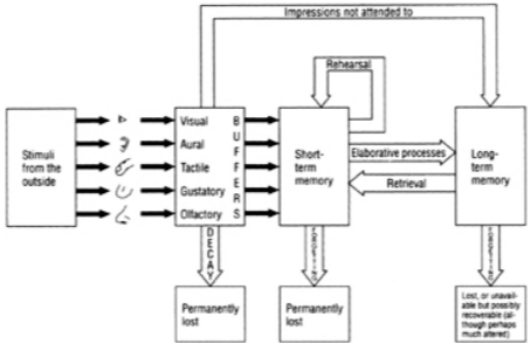


FIGURE 40

An information-processing model of human memory

Since, however, we need to retain somewhat longer the things we are currently concerned with, there must be another and longer-lasting form of temporary storage. When we pay attention to material in a sensory buffer, we process it in any of several ways. A digit becomes not just a perceived shape but a symbol—a 4 gets a name (four) and a meaning (the quantity it stands for); similarly, words we read or hear get meanings. This processing transfers whatever we are attending to from the buffers to the immediate or short-term memory that Miller was talking about.

In lay usage, short-term memory refers to the retention of events of recent hours or days, but in technical usage it denotes whatever is part of current mental activity but is not retained after use. This form of memory is brief. We have all looked up a phone number, dialed it, gotten a busy signal, and had to look up the number again to redial it. Yet we can retain it for many seconds or even minutes by continuously repeating it to ourselves—psychologists call this activity "rehearsal"—until we have used it.

To measure the normal duration of short-term memory, therefore, researchers had to prevent rehearsal. A team at Indiana University did so by telling their subjects that they were to try to remember a set of three consonants, a very easy task, but that as soon as they had seen them, they

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were to count backward by threes in time with a metronome; this preempted their attention and made rehearsal impossible. The researchers cut the volunteers' backward counting short at different times to see how long they would retain the three consonants; none did so longer than eighteen seconds. Many later experiments confirmed that the decay rate of short-term memory is between fifteen and thirty seconds.[36]

Later, other studies distinguished between two kinds of short-term memory (not shown in the above diagram). One is verbal: the immediate memory for numbers, words, and so on that we have been discussing. The second is conceptual: the memory of an idea or meaning conveyed in a sentence or other expression of several parts (an algebraic equation, for instance). In a 1982 experiment, subjects were shown sentences, a word at a time, at a tenth of a second per word; they could easily remember plausible (though not necessarily true) sentences like this:

> Tardy students annoy inexperienced teachers.

But they fared badly with nonsensical sentences of the same length, like:

> Purple concrete trained imaginative alleys.[37]

A number of studies showed that we easily retain the message of a sentence in short-term memory but swiftly forget its exact words. Similarly, we retain in long-term memory for months, years, or a lifetime the content or meaning of some conversations we have had and books we have read, the gist of courses we have taken, and innumerable facts we have learned, but none, or at most a few, of the exact words in which any of these were couched. The mass of material stored away in this fashion is far larger than most of us can imagine: John Griffith, a mathematician, calculated that the lifetime capacity of the average human memory is up to 10^{11} (one hundred trillion) bits,* or five hundred times as much information as is contained in the *Encyclopaedia Britannica.* [38]

New information in short-term memory is forgotten after we use it, unless we make it part of long-term

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memory by subjecting it to further processing. One form of processing is rote memorizing, as schoolchildren memorize multiplication tables. Another is the linking of new information to some easily remembered structure or mnemonic device, like a singsong jingle (the preschool alphabet song) or a rhyming rule ("When the letter C you spy, / Put the E before the I").

But a far more important kind, as became clear in the research performed in the 1960s and 1970s, is "elaborative processing," in which the new information is connected to parts of our existing organized mass of long-term memories. We splice it into our semantic network, so to speak. If the new item is a mango and we have never seen one before, we link the word and concept to the appropriate part of long-term memory (not a physical location—ideas and images are now thought to be scattered throughout the brain—but a conceptual one: the category "fruit"), along with the mango's visual image, feel, taste, and smell (each of which we also link to the categories of images, tactile qualities, and so on), plus what we learn about where it grows, what it costs, how to serve it, and more. In the future, when we try to think of a mango, we retrieve the memory in any one of many ways: by recalling its name, or thinking about fruit, or about fruit with a green skin, or about yellow sweet slices, or any other category or trait with which it is linked.

Much of what was learned about how all these kinds of information are organized was the product of reaction-time experiments such as asking subjects to name, in a brief period of time, as many things as they can that are red, or that are fruit, or that start with a given letter. Using that technique, Elizabeth Loftus found that in one minute volunteers could, on average, name twelve instances of "bird" but only nine of "yellow." Her conclusion was that we cannot readily look directly in memory for examples of a property but instead locate categories of objects (birds, fruit, vegetables), and scan each for that property.[39]

Similarly, as Loftus and a colleague, Allan Collins, found, it takes people longer to answer "true" or "false" to the statement "An ostrich is a bird" than to the statement "A canary is a bird." The implication: A canary is a more typical bird than an ostrich, is closer to the center of the

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category, so it requires less time to identify. Collins and Loftus, on the basis of such data, symbolically portrayed long-term semantic memory as an intricate network that is hierarchical (a general category is surrounded by specific instances) and associative (each instance is linked to a number of traits). They envisioned it as shown on p. 611.[40]

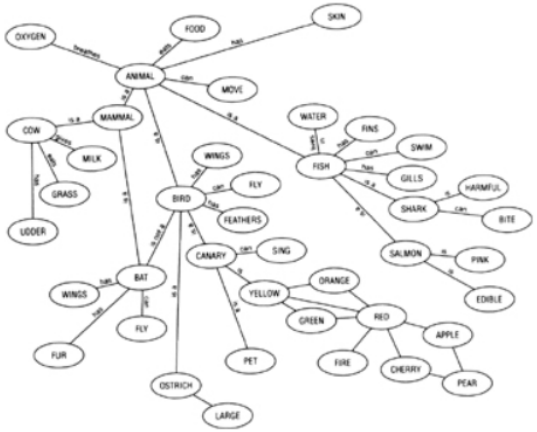


FIGURE 41

One portrayal of the long-term semantic memory network

This is only a minuscule sample of the semantic memory network. Every node shown here is connected to many other chains of nodes not shown: "Swim" might be linked to "cetaceans," "human swimmers," "sports," "healthful exercises," and each of those to other instances, characteristics, traits, and so on, and on.

A much later and much more detailed representation of the memory network relating to birds is bewilderingly complex; it is on page 612, as FIGURE 42, for those who care to puzzle it out.

Memory research has been so far-ranging and multifaceted over the last several decades that we must limit ourselves now to a handful of brief reports of major research findings and theories, and then move on.

Memory systems: The memory system portrayed in FIGURE 40, on p. 608, is now seen as too simple. According to the results of many studies, there are a number of interacting memory systems that encode and store different kinds of information in different ways. The memories stored about how to swim, drive a car, or sail a boat are very different from those concerning the names and identities of people

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you know, how to perform arithmetical procedures, or what a collie looks like. Each of these kinds of memory, and many others, require their own forms of processing and storage, and differ in the amount and kinds of effort required to enter and retain it in long term memory.

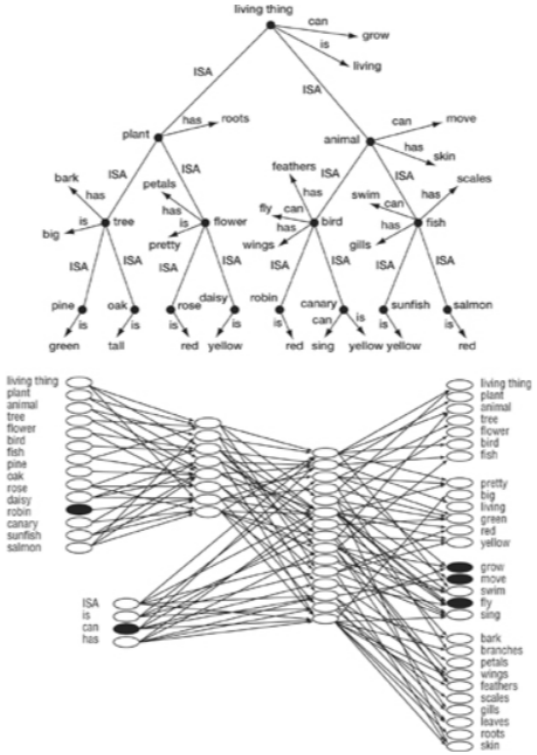


FIGURE 42

Network and connectionist representations of concepts

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Moreover, memory researchers distinguish among types of memory in other ways: Explicit memory refers to information or knowledge that we can bring to mind and to personal experiences, and implicit memory to information that is available without conscious effort, including motor skills and automatic responses (such as avoiding bumping into others on the sidewalk), built-in attitudes and reactions to people, objects, and situations—all of these requiring different memory systems.[41]

Other studies have investigated the differing process of recognition and recall—a distinction familiar enough in everyday experience (we all recognize a great many words that we cannot easily or at all summon up voluntarily). In a socially valuable application of the difference, a series of studies tested whether witnesses to a crime (a staged one before groups of students who were not told what was going on until later) would be more likely to identify the actual culprit in a lineup or by seeing a number of suspects one at a time. The latter method proved so much the better that many police departments are now changing their standard lineup procedures.[42]

Cognitive neuroscientists have lately done brain scans during different kinds of memory activity and come up with an answer to an old question: Where are memories stored? The answer, in the past, has vacillated between "locally" and "widely distributed." Brain scans now show that "widely distributed" is the answer—and that different kinds of memories are differently distributed.[43]

Categorization: Much research indicates that the human mind has a tendency to spontaneously group similar objects in memory and, from their similarities, develop general concepts or categories. Even infants only a few months old seem to do simple categorizing. One research team showed four-month-old babies patches of varied blues, greens, yellows, and reds. After seeing a number of patches of one color group, the babies showed a preference for a patch of any other color. The conclusion: Hue

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categorization is either innate or develops soon after birth.[44]

Many other studies have documented how, as children acquire language, they gradually develop such categories as "animal" after experiences of dogs, cats, squirrels, and others. Parents, to be sure, teach these concepts to their children, but in part the tendency seems to be built in. It is so general among all people as to be presumed an innate human trait. The anthropologist Brent Berlin found that people in a dozen different primitive societies group plants and animals in remarkably similar fashion, namely, hierarchically, starting with subgroups similar to biological species, combining these in larger headings similar to biological genera, and lumping these together in categories similar to biological plant and animal kingdoms.[45]

The ability to categorize was probably selected by evolution. It has survival value, since from such groupings we can make valid inferences about things that are new to us. Rochel Gelman and a colleague showed subjects pictures of a flamingo, a bat, and a blackbird. The blackbird was portrayed so that it looked much like the bat. Subjects were told about the flamingo, "This bird's heart has a right aortic arch only," and about the bat, "This bat's heart has a left aortic arch only." Then they were asked about the blackbird, "What does this bird's heart have?" Almost 90 percent answered "right aortic arch only," correctly basing their answer not on the visual similarity of bat and blackbird but the common membership in the bird category of flamingo and blackbird. Even four-year-old children, when given a similar but simpler test, based their answers almost 70 percent of the time on category membership.[46]

Representation: Researchers were long at odds about the form in which the material is stored in long-term memory. Some believed it is represented both in images and words and that there is communication between the two data banks. Others, drawing on information theory and the computer model, argued that information is recorded in memory only in the form of "propositions." A proposition is a simple "idea unit" or bit of knowledge embodied in a conceptual relationship like that between bat and wings (a bat has them) or bat and mammal (a bat is one).

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In the first view, a bat would be recorded in memory as an image, along with verbal statements about it; in the second view it would be recorded in the form of relationships (as in the bits of semantic networks in the figures above) which, though not verbal, are equivalent to "bat has wings," "salmon is red," and so forth. Another example of the propositional view is seen in these sentences:

The princess kissed the frog,

and its passive version,

The frog was kissed by the princess,

which mean the same thing; they are verbal expressions, differently focused, of the same proposition or unit of relationship knowledge.[47]

The proponents of each view have good evidence to back them up. The "mental rotation" experiments of Roger Shepard that we saw earlier indicate that we see objects "in the mind's eye" and deal with those images as if they were three-dimensional objects. Later studies by others confirmed and extended this finding. Several years ago, Stephen Kosslyn, who has long explored mental imagery, took a different tack: He had subjects memorize a map of a small roughly pear-shaped island with various things located here and there, among them a hut at one end, a lake nearby, a cliff somewhat farther off, a large rocklike object at the farthest end, and so on. Later, his subjects were asked to close their eyes, summon up the remembered image, focus on one location such as the site of the hut, and then find another named site and push a button as soon as they found it. The times of each mental search were recorded; most remarkably, the farther the second location was from the first, the longer it took them to find it. Obviously, they were scanning across the mental image.[48]

But the advocates of propositional representation have equally good grounds for their view. They contend that images cannot convey such relationships as "has," "causes," and "rhymes with," or represent categories and abstract concepts. Herbert Simon and William Chase found that chess masters could reproduce an entire board position after viewing it for just a few seconds—but only if it was a true board position in an actual game. If it was a

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random arrangement of the pieces, they could not. The implication: The masters' memory was not visual but was based on the geometrical relations—the attack and defense move potentials—of the pieces. Finally, information in computer programs is stored in propositional form, and if computability is a good model of cognition, it stands to reason that the mind stores information similarly.[49]

Quite reasonably, a third position has been taken for some time by many theorists: There are several types of representation—propositions, mental models, and images, each encoding information at a different level of abstraction. Finally, a fourth position is that different types of mental imagery use different brain networks: imagery involving spatial relations (as in imaginary rotation of an object) relies on a network in the parietal lobes, while imagery involving high-resolution shapes relies on a network in the occipital lobes.[50] (Even if true, that position doesn't help us understand how the masses of neuronal impulses arriving by either network get to be "seen" by us as mental images.)

Schemas: In 1932 the English psychologist Frederic Bartlett told subjects folk tales from non-Western sources and then asked them to recall the tales. They remembered the stories inaccurately, inadvertently filling in gaps, modifying events so as to provide reasons for what happened, and omitting details that made no sense to Western minds. Bartlett concluded that "remembering is not the re-excitation of innumerable fixed, lifeless, and fragmentary traces" but "an imaginative reconstruction, or construction" based on our own organized mass of experiences. He called that organized mass "schemata"; others prefer the anglicized version "schemas."[51]

Bartlett's idea has been revived and elaborated in recent years. Schemas—also known as "frames" and "scripts"—are now thought of as packages of integrated information on various topics, retained in memory, on which we rely to interpret the allusive and fragmentary information that ordinary conversation—and even most narrative writing—consists of. In 1978, David Rumelhart, then of the University of California in San Diego, reported on experiments in which he read stories, sentence by

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sentence, to his subjects to see how and when they formed a clear idea of what the stories were about. When, for instance, they heard this: "I was brought into a large white room, and my eyes began to blink because the bright light hurt them," some 80 percent at once assumed they were hearing either a hospital or interrogation scene, and supplied a wealth of information to the few words they had heard. If the next sentence or two contradicted this supposition, they changed it and filled out the story anew from a different schema.[52]

Much other recent work on schemas and a related type of information package known as a "script" has firmly established that it is by drawing on our expectations and organized knowledge structures that we understand and interpret—or often misinterpret—what we hear, read, and experience. Memory, in sum, is not only an information register to be consulted as needed but a program that directs our thinking.[53]

Forgetting: Many studies have explored why we forget some things and not others, and what can be done to improve memory, particularly in the elderly, most of whom undergo some degree of nonpathological memory impairment. (Normal age-related memory problems can often be ameliorated by mnemonic and other training. There is also the possibility that not far down the road a pharmacological treatment, rebalancing altered neurotransmitter output, will be found.)[54]

Much interesting research has concerned not the total loss of particular memories but the forgetting of important details and their replacement by new material. Our legal system relies heavily on the assumption that if we remember an event at all, we remember it as it was. The courts and many psychotherapists also believe that forgotten material retrieved through hypnosis is a true record of what happened. But psychotherapists have also long had evidence that we alter memories to make them more acceptable to the ego, and for many years Elizabeth Loftus has been amassing experimental evidence showing that the memory of a startling or traumatic event can be distorted by the trauma itself, that the memory of an event can be slanted by a skillful attorney's loaded questions, that we graft new information on to the memory of an

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event as time goes by and have no way of retrieving the original version, and that hypnosis sometimes retrieves deeply buried memories—and sometimes manufactured ones.[55] (In 2005, Loftus won a $200,000 Gravemeyer Award for her research on false recollections.)

Nearly all of us, however, feel sure that certain events are indelibly and accurately burned into our memories. Recollections of such experiences as first hearing about the assassination of President Kennedy or the explosion of the Challenger space shuttle are known to psychologists as "flashbulb memories," because they are vivid tableaus that seem utterly unforgettable. Ulric Neisser and an associate, Nicole Harsch, seized an extraordinary opportunity to study the phenomenon. The day after the Challenger disaster (which occurred on January 28, 1986), they asked a large sample of undergraduates to record, in detail, how they had heard the news of the explosion. Two and a half years later, those respondents who could still be reached were asked to answer a questionnaire about the event and six months later were interviewed.

Over a third of the students' recollections about time, place, who told them, and so on were dead wrong, as judged by their 1986 reports, and nearly another quarter were partly wrong. When the subjects were shown their original statements, Harsch and Neisser reported, "Many were quite upset by the discrepancies with their present memories… Interestingly, many continued to prefer their current 1989 recall to the version in the original 1986 record." Where did the errors come from? Harsch and Neisser call them "narrative reconstructions" of the type described by Bartlett in 1932.[56]

Sometimes, even in the fast-developing cognitive revolution, *plus ça change…*

Language

Scientists infer natural laws from specimens, events, natural phenomena, and experimental findings of one sort or another. The comparable raw materials for cognitive

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scientists are thoughts, but the neural discharges, or brainwaves, that indicate thought, though they can be seen by EEG (electroencephalography), reveal nothing of the content. Gestures, facial expressions, mathematical or artistic symbols, and demonstrations (as in sports training) convey thoughts, but within a very narrow range. The principal form in which thinking can be observed is language, which has accordingly been called "the window to the mind."

Or, one might also say, the spoor of thought, since language not only conveys thoughts but in its structure bears traces of how our minds work. The study of thought processes as revealed by these traces is the province of psycholinguistics. (Linguistics, an older discipline, deals with the characteristics of language itself.)

An example of such a trace: Small children tend to treat irregular verbs and nouns as if they were regular ("Doggy runned away," "Dat baby has two toofs"). But they have not heard adults make such mistakes, and therefore are not imitating them. The errors, psycholinguists say, show that children recognize such regularities in adult speech as adding "ed" to make a simple past tense, "s" or "es" to make a plural noun, and take these to be applicable to all verbs and nouns (the tendency is called "overregularization")—evidence that the human mind spontaneously generalizes from examples, then applies the generalization to new cases. Cognitive psychologists long had two different hypotheses about how this takes place: one, that regular past tense forms are generated by a rule and irregular ones retrieved from memory; and two, that both forms are generated by a single system and differ only in their reliance on sound and semantics. An fMRI-based study has just settled the issue: Brain area activation is the same for both regular and irregular verbs, thus confirming the single-system hypothesis.[57]

The acquisition of verb tenses is only one of a number of marks left by the thinking process that psycholinguists have found in language. They are not peculiar to English; analogous phenomena can be found in every language and seem to be characteristic of human thought. Human languages appear to be governed by the same universal principles and constraints.

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The universality does not, of course, involve grammar and vocabulary; in those respects English, Swahili, and Basque, for instance, have nothing in common. Yet children who grow up hearing each of those languages recognize, without being taught, the difference between singular and plural forms of a noun, the verb forms that denote present and past, and so on, and construct for themselves the rules governing their language. Similarly, they intuit the basic rules governing word order and are able to construct simple declarative sentences made up of words in the proper sequence. No child of English-speaking parents ever says, "Milk more some want I," nor does a child of parents who speak any other language get its basic word order wrong.

Psychology had little relationship to linguistics before midcentury, but in the dawn of the cognitive revolution some cognitive psychologists and linguists dimly saw that new developments in each of their disciplines called for explanations by the other one. For instance, certain new theories of the linguists about how grammar works implied that the mind, when dealing with concepts, performs complex manipulations that are not accounted for by behaviorist psychology. In 1953, a number of psychologists and linguists held a conference at Cornell University, discussed their areas of common interest, and adopted the term "psycholinguistics" to designate the study of the psychology of language.

Psycholinguistics was still a little-known discipline when, four years later, a twenty-nine-year-old member of the Harvard Society of Fellows published a monograph that thrust the subject into the limelight. The theory proposed in that monograph has been called one of the two most important developments in psychology in that era (the other being artificial intelligence).[58] Its author was Noam Chomsky, some of whose ideas we heard about earlier.

Chomsky, a shaggy-haired, bespectacled, rumpled genius—the Central Casting stereotype of an intellectual—very nearly did not become a psycholinguist.[59] He grew up during the Depression years in the radical Jewish community of New York; his father, however, was a distinguished Hebrew scholar, and even as a youth

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Chomsky picked up some knowledge of the structure of the Semitic languages and some idea of what linguistics was about. These two themes, radical politics and language, have dominated his life ever since. His work in linguistics, the basis of his renown in cognitive psychology, came about when he met Zellig Harris, a professor of linguistics at the University of Pennsylvania.

Harris, who got him excited about linguistics, was trying to develop a system based on behaviorist principles—a system that could account for language patterns without reference to meaning. But his scheme was flawed, and for some years Chomsky labored diligently in the effort to make it work. When he could not, he abandoned Harris's theory and within two years had developed his own. It is ironic that Chomsky is a leftist; the central thesis of his theory, advanced in his monograph *Syntactic Structures*, is that certain aspects of linguistic knowledge and ability are innate, not learned, a doctrine that leftists, liberals, and behaviorist-trained psychologists considered mentalistic and reactionary.

The child, Chomsky maintained, makes sense of heard speech and acquires language not by means of the grammar of the language ("surface grammar," in his terminology) but by an inherent ability to recognize deep-lying syntactical relationships among the component phrases of the heard sentence—what he calls the "deep structure" of the underlying connections. As evidence he points to the ease with which children understand what is meant when one form of sentence is transformed into another—when, for example, a declarative statement is reworded as a question—and make such transformations themselves. If surface grammar were what children relied on, they would extract incorrect rules for transforming sentences. From instances like these:

The man is tall.
Is the man tall?

they would derive the rule: Start at the beginning, move on to the first appearance of "is" or another verb, and shift that verb to the front. But the rule is too simple; it fails as soon as one confronts a sentence like:

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The man who is tall is in the room—

where the rule would lead them to say

Is the man who tall is in the room?

But children never make that mistake. They make trivial ones like "toofs" but not substantive ones; they sense the relationships among the elements of the thought—its syntactic constituents or "phrase structures." It is by means of this knowledge of "universal grammar" that children make sense of what they hear and effortlessly construct correct sentences they have never heard.

When and how do they come by a knowledge of universal grammar and deep structure? Chomsky's answer perfectly expresses the revolution against the behaviorist doctrine that the newborn's mind is a *tabula rasa.* Somewhere in the brain, he maintains, is a specialized neural structure—he calls it the Language Acquisition Device, or L.A.D.—that is genetically wired to recognize the ways in which the things and actions represented by noun phrases and verb phrases are related to one another as agent, action, and object.

Chomsky and the many psycholinguists who adopted his view or developed their own versions of it set out in new form the ancient question, banned during the behaviorist era, of whether knowledge exists in the mind before experience. Their answer: While language itself is learned, the brain is so constructed that children spontaneously extract the rules of speech from what they hear without being taught those rules and, making only minor errors, use them when constructing sentences.

Though usually serious and intense, Chomsky is certainly capable of wit. To illustrate the deep relationships among the components of a sentence, he concocted a completely absurd one that has become famous: "Colorless green ideas sleep furiously." Although totally nonsensical, it feels very different to the reader from an equally nonsensical rearrangement of the words: "Ideas furiously green colorless sleep." Anyone familiar with English finds the first version somehow comfortable—it almost seems to mean something—while the second is

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uncomfortable gibberish. The reason is that the first version obeys the rules of both surface grammar and deep structure; the second does not.

Chomsky's theory touched off fierce controversy, largely because of its innatism, although he did not posit inborn ideas but only the inborn capacity to experience language in useful ways. Some critics, rejecting the hypothesis of an L.A.D., agreed that the ability to acquire language is innate but said that it is a byproduct of general intellectual abilities. Others to whom the theory of an innate L.A.D. is unacceptable keep finding grounds on which to reject it. One such ground, for instance, is that genetically transmitted organs are subject to variations. If so, some children should have abnormal L.A.D.'s and be deficient in some areas of language comprehension, but there seems to be no evidence of that.[60]

Aside from the controversy, for half a century psycholinguists and cognitive psychologists have been gathering evidence that shows how language relates to thought and reveals thought processes. Some patiently observe the errors and self-corrections children make in learning language, some analyze language games, some study developmental language disorders like dyslexia and acquired language disorders produced by brain injuries, and some conduct reaction-time experiments. An instance of the last: Herbert Clark and others have found that when subjects are shown a simple pattern, such as a star above a plus sign, and alongside it either a true affirmation ("Star is above plus") or a true denial ("Star is not below plus"), it takes them two tenths of a second longer to say the denial is true than to say the affirmation is true. We seem to be programmed to think more easily about what is than about what is not, and we have to turn negative sentences into positive ones in order to deal with them.[61]

Today, many psycholinguists, as a result of their research, give more credit to environmental influences in language acquisition than Chomsky does. They stress, for instance, the informal language training provided by "motherese," the special way mothers (and some fathers) talk to small children. Nevertheless, while many psycholinguists question details of Chomsky's L.A.D. theory (which he himself has much qualified and modified

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over the years), most agree that human beings have a genetically determined ability to understand and acquire any language.

Psycholinguists have also explored other important questions about the relation of language to thought. Do we always or only sometimes think in words? Is thought possible without words? Do the words of our native language shape or limit our thinking? The issues have been much debated and much studied. A few highlights:

—The linguist Benjamin Whorf theorized in 1957 that thought is molded by the syntax and vocabulary of one's native language, and offered cross-cultural evidence to prove his point. One of his examples was that the Hopi Indian language does not distinguish, at least not as we do, between past, present, and future (a rare exception to a nearly universal rule). Instead, a Hopi speaker indicates through inflections whether he or she is talking about an event that actually happened, one that is expected to happen, or about such events in general. Whorf and his followers accordingly maintained that the language we use shapes or influences what we see and think.[62]

—On the other hand, anthropologists have found that in many other cultures people have fewer color terms than English-speaking people but experience the world no differently. The Dani of New Guinea have only two color terms: *mili* (dark) and *mola* (light), but tests of speakers of Dani and other languages that lack many explicit color names have shown that their memory for colors and their ability to judge differences between color samples are much the same as our own. At least when it comes to color, they can think without words.[63]

—The studies of children's thinking, carried out by Piaget and other developmental psychologists, show strong interactions between language and thought. Hierarchical categorization, for one thing, is a powerful cognitive mechanism that enables us to organize and make use of our knowledge; if we are told that an unfamiliar item in an ethnic grocery store is a fruit, says Philip Lieberman, we know at once that it is a plant,

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> edible, and is probably sweet.[64] This inferential capacity is built into the structure of language and acquired in the normal course of development. Studies show that children begin verbal categorization at about eighteen months, and that one of the results is the "naming explosion," a phenomenon every parent has observed. Thus, says Lieberman, "particular languages do not inherently constrain human thought, because both capacities [language and thought] appear to involve closely related brain mechanisms."[65]

The physical locations of some of those brain mechanisms were pinpointed through the study of aphasia, a speech disorder caused by an injury to or lesion in a specific part of the brain. A lesion in Wernicke's Area, as we saw earlier, results in speech that is relatively fluent and syntactical but often nonsensical; victims either mangle or cannot find the nouns, verbs, and adjectives they want. Howard Gardner, a Harvard cognitive psychologist who has explored aphasia, has given this example, taken from a conversation he had with a patient:

> "What kind of work have you done, Mr. Johnson?" I asked.
>
> "We, the kids, all of us, and I, we were working for a long time in the… you know…it's the kind of space, I mean place rear to the spedwan…"
>
> At this point I interjected, "Excuse me, but I wanted to know what work you have been doing."
>
> "If you had said that, we had said that, poomer, near the fortunate, forpunate, tamppoo, all around the fourth of martz. Oh, I get all confused," he replied, looking somewhat puzzled that the stream of language did not appear to satisfy me.[66]

In contrast, a person with damage to Broca's area, though able to understand language, has great difficulty producing any; the speech is fragmented, lacking in grammatical structure, and deficient in modifiers of nouns and verbs.

This much is known at the macro level. Nothing, however, is known about how the neuronal networks within Wernicke's and Broca's areas carry out language functions in normal persons; those areas are still "black boxes" to psychologists—mechanisms whose input and

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output are known but whose internal machinery is a mystery.

But neuroscientists have found a few clues. Analyses of brain function in speech-impaired persons by means of electrode probes during surgery, PET and fMRI scanning, and other methods have shown that linguistic knowledge is located not only in Wernicke's and Broca's Areas but in many parts of the brain and is assembled when needed. Dr. Antonio Damasio of the University of Iowa College of Medicine is one of many researchers who have concluded that information about any object is widely distributed. If the object is, say, a polystyrene cup (Damasio's example), its shape will be stored in one place, crushability in another, texture in another, and so on. These connect, by neural networks, to a "convergence zone" and thence to a verbal area where the noun "cup" is stored.[67] This is strikingly similar to the abstract portraits of the semantic memory network we saw earlier in this chapter.

In the past several years, PET and fMRI scans of normal people have identified areas in the brain that are active when specific linguistic processes are going on. But despite a wealth of such information, the data do not tell us how the firing of myriad neurons in those locations becomes a word, a thought, a sentence, or a concept in the mind of the individual. The data provide a more detailed model than was formerly available of where language processes take place in the brain, but cognitive neuroscience has not yet yielded a theory as to how the neural events become language. As Michael Gazanniga and his co-authors say in *Cognitive Neuroscience*, "The human language system is complex, and much remains to be learned about how the biology of the brain enables the rich speech and language comprehension that characterize our daily lives."[68]*

"Much remains"? A memorable understatement.

Reasoning

Some years ago I asked Gordon Bower, a prominent memory researcher, a question about thinking and was

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taken aback by his testy reply: "I don't work on 'thinking' at all. I don't know what 'thinking' is." How could the head of Stanford University's psychology department not work on thinking at all—and not even know what it is? Then, rather grudgingly, Bower added, "I presume it's the study of reasoning."

Thinking was traditionally a central theme in psychology, but by the 1970s the proliferation of knowledge in cognitive psychology had made the term unhandy, since it included processes as disparate as momentary short-term memory and protracted problem solving. Psychologists preferred to speak of thought processes in more specific terms: "chunking," "reasoning," "retrieval," "categorization," "formal operations," "problem solving," and scores of others. "Thinking" came to have a narrower and more precise meaning than before: the manipulation of knowledge to achieve a goal. To avoid any misunderstanding, however, many psychologists preferred, like Bower, to use the term "reasoning."

Although human beings have always viewed reasoning ability as the essence of their humanity, research on it was long a psychological backwater.[69] From the 1930s to the 1950s little work was done on reasoning except for the problem-solving experiments of Karl Duncker and other Gestaltists and the studies by Piaget and his followers of the kinds of thought processes characteristic of children at different stages of intellectual development.

But with the advent of the cognitive revolution, research on reasoning became an active field. The IP (information processing) model enabled psychologists to formulate hypotheses that portrayed, in flow-chart fashion, what went on in various kinds of reasoning, and the computer was a piece of apparatus—the first ever—with which such hypotheses could be tested.

IP theory and the computer were synergistic. A hypothesis about any form of reasoning could be described, in IP terms, as a sequence of specific steps of information processing; the computer could then be programmed to perform an analogous sequence of steps. If the hypothesis was correct, the machine would reach the same conclusion as the reasoning human mind. By the same token, if a reasoning program written for the

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computer produced the same answer as a human being to a given problem, one could suppose that the program was operating in the same way as, or at least in a similar fashion to, that of the human mind.

How does a computer do such reasoning? Its program contains a routine, or set of instructions, plus a series of subroutines, each of which is used or not used, depending on the results of the previous operations and the information in the program's memory. A common form of routine is a series of if-then steps: "If the input meets condition 1, then take action 1; if not, take action 2. Compare the result with condition 2 and if the result is [larger, smaller, or whatever], take action 3. Otherwise take action 4… Store resulting conditions 2, 3… and, depending on further results, use these stored items in such-and-such ways."[70]

But when computers carry out such programs, whether in mathematical computing or problem solving, are they actually reasoning? Are they not acting as automata that unthinkingly execute prescribed actions? The question is one for the philosopher. If a computer can, like a knowledgeable human being, prove a theorem, navigate a spacecraft, or determine whether a poem was written by Shakespeare, who is to say that it is a mindless automaton —or that a human being is not one?

In 1950, when only a few primitive computers existed but the theory of computation was being much discussed by mathematicians, information theorists, and others, Alan Turing, a gifted English mathematician, proposed a test, more philosophic than scientific, to determine whether a computer could or could not think. In the test, a computer programmed to solve a certain kind of problem is stationed in one room, a person skilled in that kind of problem is in another room, and in a third room is a judge in telegraphic communication with each. If the judge cannot tell from the dialogue which is the computer and which the person, the computer will pass the test: it thinks.[71] No computer program has yet won hands down, in publicly conducted contests, although some have fooled some of the judges. The validity of the Turing test has been debated, but at the very least it must mean that if a computer seems to think, what it does is as good as thinking.

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By the 1960s, most cognitive psychologists, whether or not they agreed that computers really think, regarded computation theory as a conceptual breakthrough; it enabled them for the first time to describe any aspect of cognition, and of reasoning in particular, in detailed and precise IP terms. Moreover, having hypothesized the steps of any such program, they could translate them from words into computer language and try the result on a computer. If it ran successfully, it meant that the mind did indeed reason by means of something like that program. No wonder Herbert Simon said the computer was as important for psychology as the microscope had been for biology; no wonder other enthusiasts said the human mind and the computer were two species of the genus "information-processing system."[72]

The ability to solve problems is one of the most important applications of human reasoning. Most animals solve such problems as finding food, escaping enemies, and making a nest or lair largely by means of innate or partly innate patterns of behavior; human beings solve or attempt to solve most of their problems by means of either learned or original reasoning.

In the mid-1950s, when Simon and Newell undertook to create Logic Theorist, the first program that simulated thinking, they posed a problem to themselves: How do human beings solve problems? Logic Theorist took them a year and a half, but the question occupied them for more than fifteen. The resulting theory, published in 1972, has been the foundation of work in that field ever since.

Their chief method of working on it, according to Simon's autobiography, was two-man brainstorming. This involved deductive and inductive reasoning, analogical and metaphoric thinking, and flights of fancy—in short, any kind of reasoning, orderly or disorderly:

> From 1955 to the early 1960s, when we met almost daily… [we] worked mostly by conversations together, with the explicit rule that one could talk nonsensically and vaguely, but without criticism unless you intended to talk accurately and sensibly. We could try out ideas that were half-baked or quarter-baked or not

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baked at all, and just talk and listen and try them again.[73]

They also did a good deal of laboratory work. Singly and together they recorded and analyzed the steps by which they and others solved puzzles and then wrote out the steps as programs. A favorite puzzle, of which they made extensive use for some years, is a child's toy known as the Tower of Hanoi. In its simplest form, it consists of three disks of different sizes (with holes in their centers) piled on one of three vertical rods mounted on flat bases. At the outset, the largest disk is on the bottom, the middle-sized one in the middle, the smallest one on top. The problem is to move them one at a time in the fewest possible moves, never putting any disk on top of one smaller than itself, until they are piled in the same order on another rod.

The perfect solution takes seven steps, although with errors leading to dead ends and backtracking to correct them, it can take several times that many. In more advanced versions, the solution requires complex strategies and many moves. A perfect five-disk game takes thirty-one moves, a perfect seven-disk game 127 moves, and so on.* Simon has said, quite seriously, that "the Tower of Hanoi was to cognitive science what fruit flies were to modern genetics—an invaluable standard research setting."[74] (Sometimes, however, he ascribes this honor to chess.)

Another laboratory tool used by the team was cryptarithmetic, a type of puzzle in which a simple addition problem is presented in letters instead of numbers. The goal is to figure out what digits the letters stand for. This is one of Simon and Newell's simpler examples:

```
  S E N D
  M O R E
---------
M O N E Y
```

The obvious first step: M must be 1, since no two digits—S + M in this case—can add up to more than 19, even with a carry.† Simon and Newell had volunteers talk out loud as they worked on such a puzzle, recorded everything they

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said, and afterward diagrammed the steps of their thought process in the form of a search track of moves, decisions at forks with more than one option, wrong choices pursued to dead ends, reversals to try another route from the last fork, and so on.

Simon and Newell made particular use of chess, a vastly more complex problem than either the Tower or cryptarithmetic. In a typical chess game of sixty moves, at each step there are on average thirty possible moves; to "look ahead" only three moves would mean visualizing twenty-seven thousand possibilities. A key question for Simon and Newell was how chess players deal with such impossibly large sets of contingencies. The answer: A skilled chess player does not consider all the possible moves he might make next and all the moves his opponent might make in response but only those few moves that make good sense and that follow elementary guidelines like "Guard the King" and "Don't give away a piece for one of lesser value." In short, the chess player makes a heuristic search—one guided by broad strategic principles of good sense—rather than a thorough but uninformed one.

The Newell and Simon theory of problem solving—for alphabetical reasons Newell's name is first on their joint publications—on which they worked for another fifteen years is that problem solving is a search for a route from an *initial state* to a *goal*. To get there, the problem solver has to find a *path* through a *problem space* made up of all possible states he might arrive at by making all the moves that obey the *path constraints* (rules or conditions of the domain).

In most such searches, the possibilities multiply geometrically, since each decision point offers two or more possibilities, each of which leads to another decision point offering another set of possibilities. In the sixty moves of an average chess game, each move, as already mentioned, has an average of thirty alternatives; the total number of paths in a game is 30^{60}—30 million trillion trillion trillion trillion trillion trillion—a number totally beyond human comprehension. Accordingly, as Simon and Newell's research demonstrated, problem solvers, in finding their

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way through such problem spaces, make no effort to look at every possibility.

In the massive tome they published in 1972 and straightforwardly called *Human Problem Solving*, Newell and Simon presented what they considered its general characteristics. Among them:[75]

> —Because of the limits of short-term memory, we work our way through a problem space in serial fashion, taking one thing at a time.
> —But we do not perform a serial search of every possibility, one after another. We use that method only when there are very few possibilities. (If, for instance, you don't know which one of a small bunch of keys opens a friend's front door, you try them one at a time.)
> —In many problem situations trial and error is not practicable; if so, we search heuristically. Knowledge makes this very effective. As simple a problem as solving an eight-letter anagram like SPLOMBER would take fifty-six working hours if you wrote out all 40,320 permutations at a rate of one every five seconds, but most people can solve it in seconds or minutes by ignoring invalid beginnings (PB or PM, for instance) and considering only valid ones (SL, PR, etc.).*
> —One important heuristic commonly used to simplify the task is what Newell and Simon call "best-first search." At any fork in the search path, or "decision tree," we first try the move that appears to carry us closest to the goal. It is efficient to move toward the goal with every step (although sometimes we have to move away from it to circumvent an obstacle).
> —A complementary and even more important heuristic is "means-end analysis," which Simon has called "the workhorse of GPS [General Problem Solver]." Means-end analysis is a mixture of forward and backward search. Unlike chess, which uses forward searching, in many cases the problem solver sees that he cannot proceed directly toward the goal but must first reach a subgoal from which the goal is attainable, or perhaps has to get first to an even earlier subgoal or one still earlier than that.

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In a relatively recent review of problem-solving theory, Keith Holyoak offers a homely example of means-end analysis. Your goal is to have your living room freshly painted. The subgoal nearest that goal is the condition in which you can paint it, but that requires you to have paint and a brush, so you must first reach the earlier subgoal of buying them. To do so requires reaching the even earlier subgoal of being at a hardware store. So it goes, backward chaining until you have a complete strategy by which to move from your present state to the state of having a painted living room.[76]

As major an achievement as Newell and Simon's theory of problem solving was, it dealt only with deductive reasoning. Moreover, it considered only "knowledge-poor" problem solving—the kind applicable to puzzles, games, and abstract problems. To what extent the method described problem solving in knowledge-rich domains—the sciences, business, or law, for instance—was unclear.

For the past several decades, therefore, a number of researchers have been expanding the investigation of reasoning. Some have studied the psychological tendencies on which deductive and inductive reasoning are based; some whether either form, or some other, is what we use in everyday reasoning; some the differences in the kinds of reasoning used by experts and by novices in knowledge-rich situations. These investigations have produced a wealth of insights into the formerly invisible workings of the reasoning human mind. Here are a few of the highlights:

Deductive reasoning: The traditional idea, going back to Aristotle, is that there are two kinds of reasoning, deduction and induction. Deduction extracts a further belief from one that is given; that is, if the premise or premises are true, so is the conclusion, since it is necessarily included in them. From the premises of Aristotle's classic syllogism

All men are mortal.
Socrates is a man.

it follows that

Socrates is mortal.

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This kind of reasoning is tight, strong, easy to follow, and fully convincing. It is exemplified by proofs of logic and geometry theorems.

Yet many other syllogisms that have only two premises and contain only three terms are not so transparent; some are so difficult that most people cannot draw a valid conclusion from them. Philip Johnson-Laird, who has done research on the psychology of deduction, gives an example that he has used in the laboratory. Imagine that in a room there are some archaeologists, biologists, and chess players, and that these two statements are true:

> *None of the archaeologists is a biologist.*
> *All the biologists are chess players.*

What, if anything, follows from those premises? Johnson-Laird has found that few people can give the right answer.[77]* Why not? He believes that the ease of drawing the valid conclusion in the Socrates syllogism and the difficulty of doing so in the archaeologist syllogism are due to the way the arguments are represented in the mind —the "mental models" we create of them, a theory he has been developing and testing ever since.[78]

People with formal training in logic usually visualize such arguments in the form of geometrical diagrams, the two premises being represented by circles, one inside the other, or overlapping it, or separate. But Johnson-Laird's theory, based on his research and validated by a computer simulation, is that people without such training use a more homespun model. In the Socrates syllogism, they unconsciously imagine a number of people, all mortal, imagine Socrates as related to that group, and then cast about for any other possibility (anyone outside the set—possibly Socrates). There being no such possibility, they correctly conclude that Socrates is mortal.

In the archaeologist syllogism, however, they imagine and try out first one, then another, and finally a third model, of increasing difficulty (we will spare ourselves the details). Some people rely on the first, unable to see that the second invalidates it, and others the second, not seeing that it, too, is discredited by the third and most difficult—which leads to the only valid conclusion.[79]

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Mental modeling is not the only source of erroneous deductions. Experiments have shown that even where the form of a syllogism is simple and its mental model easy to create, people are apt to be misled by their beliefs and information. One research team asked a group of subjects whether these two syllogisms were logically correct:

All things that have a motor need oil.
Automobiles need oil.
Therefore, automobiles have motors.
All things that have a motor need oil.
Opprobines need oil.
Therefore, opprobines have motors.

More people thought the first one logically correct than did the second, although the two are identical in structure, differing only in the substitution of the nonsense word "opprobines" for "automobiles." They were misled by their knowledge of automobiles; knowing the conclusion of the first syllogism to be true, they thought the argument logically correct. But it is not, as they could see in the case of opprobines, about which they knew nothing and where they could recognize that there is no necessary overlap between opprobines and things with a motor.[80]

Inductive reasoning: By contrast, inductive reasoning is loose and inexact. It moves from specific beliefs to broader ones, that is, from limited cases to generalizations. From "Socrates is mortal," "Aristotle is mortal," and other instances, one infers, with a degree of confidence based on the number of cases, that "all men are mortal," although even a single case to the contrary would invalidate that conclusion.

A good deal of important human reasoning is of this type. Categorization and concept formation, crucial to thinking, are the products of induction, as seen in studies of how children arrive at categories and concepts. All the higher knowledge humankind possesses about the world—everything from the inevitability of death to the laws of planetary motion and galactic formation—is the product of the derivation of generalizations from a mass of particulars.

Induction is also the reasoning used where pattern recognition is the key to solving a problem. A simple

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example:

What number comes next?

2 3 5 6 9 10 14 15 ——

A ten-year-old can answer correctly after a while; an adult can see the pattern and the answer (20) in a minute or less. It is the very reasoning process employed by economists, public health officials, telephone system planners, and many others whose recognition of patterns is critically important to the survival of modern society.

(Disconcertingly, researchers have found that many people frequently fail to reason inductively from incoming information. All too often, we notice and add to our memory store only what supports a strongly held belief, ignoring any that does not. Psychologists call this "confirmation bias." Dan Russell and Warren Jones gave subjects materials to read, some confirming and some disproving the existence of ESP. Afterward, believers in ESP remembered the confirming materials 100 percent of the time but the negative materials only 39 percent of the time, while skeptics remembered both kinds about 90 percent of the time.[81])

Much of our reasoning combines deduction and induction, each of which serves its own purposes. How we came by both kinds of reasoning ability has been explained, at least hypothetically, by evolutionary psychology: Both methods are assets in the struggle to survive and were the products of natural selection.[82] The hypothesis seems validated by a recent study using PET scans: When subjects were asked to solve problems requiring deduction, two small areas on the right side of the brain showed increased activity; when the problems required inductive thinking, two brain structures on the left side showed it.[83] Natural selection, in short, developed brain structures capable of both kinds of reasoning.

Probabilistic reasoning: The human mind's abilities are the product of evolutionary selection, but we have lived in advanced civilized societies too short a time to have developed an inherited ability for sound reasoning about statistical likelihoods, though it is often called for in modern life.

Daniel Kahneman and Amos Tversky, who did much of the basic work in this area, asked a group of subjects

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which they would prefer: a sure gain of $80, or an 85 percent chance of winning $100 along with a 15 percent chance of winning nothing. Most people preferred the sure gain of $80, although statistically the average yield of the risky choice is $85. Kahneman and Tversky concluded that people are "risk-averse": They prefer a sure thing even when a risky thing is the better bet.

Turning to the obverse situation, Kahneman and Tversky asked another group of subjects whether they would prefer a sure loss of $80 or an 85 percent chance of losing $100 along with a 15 percent chance of losing nothing. This time a large majority preferred the gamble to the sure thing even though, on average, the gamble is costlier. Kahneman and Tversky's conclusion: When choosing between gains, people are risk-averse; when choosing between losses, they are risk-seeking—and in both cases are likely to make poor judgments.[84]

An even more disquieting finding came from a later experiment in which they posed two versions of a public-health problem to groups of college students. The versions are mathematically identical but different in wording. The first version:

> Imagine that the U.S. is preparing for the outbreak of a rare Asian disease, which is expected to kill 600 people. Two alternative programs to combat the disease have been proposed. Assume that the exact scientific estimates of the consequences of the programs are as follows:
>
> If Program A is adopted, 200 people will be saved.
>
> If Program B is adopted, there is a ⅓ probability that 600 people will be saved, and a ⅔ probability that no people will be saved. Which of the two programs would you favor?

The second version gave the same story but worded the alternatives as follows:

If Program C is adopted, 400 people will die.

If Program D is adopted, there is a ⅓ probability that nobody will die, and a ⅔ probability that 600 people will die.

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Subjects responded quite differently to the two versions: 72 percent chose Program A over Program B, but 78 percent (of a different group) chose Program D over Program C. Kahneman and Tversky's explanation: In the first version, the outcomes are portrayed in terms of gains (lives saved), in the second version in terms of losses (lives lost). The same biases as shown by the experiments where money was at stake distorted subjects' judgment in this case, where lives were at stake.[85] (In 2002, Kahneman won the Nobel prize in economics for his work on probabilistic reasoning; Tversky, who would have shared it, unfortunately was dead by then.)

We reason poorly in these cases because the factors involved are "nonintuitive"; our minds do not readily grasp the reality involved in probabilities. This shortcoming affects us both individually and as a society; the electorate and its leaders often make costly decisions because of poor probabilistic reasoning. As Richard Nisbett and Lee Ross point out in their book *Human Inference*, many governmental practices and policies adopted during crises are deemed beneficial because of what happens afterward, even though the programs are often useless or worse. The misjudgment is caused by the human tendency to attribute a result to the action meant to produce it, although often the result stems from the normal tendency of events to revert from the unusual to the usual.[86]

It is reassuring, therefore, that a number of studies have found that unconscious mental processing often yields good evaluations and decisions—sometimes better than the results of conscious deliberation. In a series of studies reported in 2004, a Dutch psychologist asked subjects to make choices about complex real-world matters that had many positive and negative features such as choosing an apartment. One group was told to make an immediate (no thought) choice, another group to think for three minutes and then choose (conscious thought), and a third group to work for three minutes on a difficult distracting task and then choose (unconscious thought). In all three studies, the subjects in the unconscious thought condition made the best choices.[87]

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Analogical reasoning: By the 1970s, cognitive psychologists had begun to recognize that much of what logicians regard as faulty reasoning is, in fact, "natural" or "plausible" reasoning—inexact, loose, intuitive, and technically invalid, but often competent and effective.

One such form of thinking is the analogical. Whenever we recognize that a problem is analogous to a different problem, one we are familiar with and know the answer to, we make a leap of thought to a solution. Many people, for instance, when they have to assemble a piece of knocked-down furniture or machinery, ignore the instruction manual and work by "feel"—looking for relationships among the parts that are analogous to the relationships among the parts of different kinds of furniture or machinery they assembled earlier.

Analogical reasoning is acquired in the later stages of childhood mental development. Dedre Gentner, a cognitive psychologist, asked five-year-olds and adults in what way a cloud is like a sponge. The children replied in terms of similar attributes ("They're both round and fluffy"), adults in terms of relational similarities ("They both store water and give it back to you").[88]

Gentner interprets analogical reasoning as a "mapping" of high-level relations from one domain to another; she and two colleagues even wrote a computer program, the "Structure-Mapping Engine," that simulates the process. When it was run on a computer and provided with limited data about both the atom and the solar system, the program, like the great physicist Lord Rutherford, recognized that they are analogous and drew appropriate conclusions.[89]

With difficult or unfamiliar problems, people generally do not use analogical reasoning because they only rarely spot a distant analogy, even when it would provide the solution to their problem. But if they consciously make the effort to look for an analogy, they are far more apt to see one that is not at all obvious. M. L. Gick and Keith Holyoak used Duncker's classic problem, of which we read earlier, about how one can use X-rays to destroy a stomach tumor without harming the surrounding healthy tissue. Most of their subjects did not spontaneously

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discover the solution; Gick and Holyoak then provided them with a story that, they hinted, might prove helpful. It told of an army unable to capture a fortress by a single frontal attack but successful when its general divided it into separate bands that attacked from all sides. Having read this and consciously sought an analogy to the X-ray problem, most subjects saw that many sources of weak X-rays placed all around the body and converging on the tumor would solve the problem.[90]

Expert reasoning: Many cognitive psychologists, intrigued by Newell and Simon's work, assumed that their theory would apply to problem solving by experts in fields of special knowledge, but found, to their surprise, that it did not. In a knowledge-rich domain, experts do more forward searching than backward searching or means-end analysis, and their thinking often proceeds not step by step but in leaps. Rather than starting with details, they perceive overall relationships; they know which category or principle is involved and work top-down. Novices, in contrast, lack perspective and work bottom-up, starting with details and trying to gather enough data to gain an overview.[91]

Since the 1980s, a number of cognitive psychologists have been exploring the characteristics of expert reasoning in different fields. They have asked experts in cardiology, commodity trading, law, and many other areas to solve problems; again and again they have found that experts, rather than pursuing a logical, step-by-step search (as a newly trained novice or an artificial intelligence program would do), often leap from a few facts to a correct assessment of the nature of the problem and the probable solution. A cardiologist, for instance, might from only two or three fragments of information correctly diagnose a specific heart disorder, while a newly graduated doctor, presented with the same case, would ask a great many questions and slowly narrow down the range of possibilities. The explanation: Unlike novices, experts have their knowledge organized and arranged in schemas that are full of special shortcuts based on experience.[92]

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Even in the first flush of enthusiasm for IP theory and computer simulations of reasoning, some psychologists, of a more humanistic than computer-technical bent, had reservations about the comparability of mind and machine. There are, indeed, major dissimilarities. For one, the computer searches for and retrieves items as needed—at blinding speed, nowadays—but human beings retrieve many items of information without any search: our own name, for instance, and most of the words we utter. For another, as the cognitive scientist Donald Norman has pointed out, if you are asked "What's Charles Dickens's telephone number?" you know right away that it's a silly question, but a computer would not, and would go looking for the number.[93]

For a third, the mind knows the meaning of words and other symbols, but the computer does not; to it they're only labels. Nor does anything about the computer resemble the unconscious or all that goes on in it.

These are only a few of the differences that have been obvious since the first experiments in computer reasoning. Yet, no less an authority than Herbert Simon categorically asserted that mind and machine were kin. In 1969, in a series of lectures published as *The Sciences of the Artificial*, he argued that the computer and the human mind are both "symbol systems"—physical entities that process, transform, elaborate, and generally manipulate symbols of various kinds.

Throughout the 1970s, small cadres of dedicated psychologists and computer scientists at MIT, Carnegie-Mellon, Stanford, and a handful of other universities, possessed of a zealotlike belief that they were on the verge of a great breakthrough, developed programs that were both theories of how the mind works and machine versions of human thinking. By the 1980s the work had spread to scores of universities and to the laboratories of a number of major companies. The programs carried out such varied activities as playing chess, parsing sentences, deducing the laws of planetary motion from a mass of raw data, translating elementary sentences from one language to

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another, and inferring the structure of molecules from mass spectrographic data.[94]

The enthusiasts saw no limit to the ability of IP theory to explain how the mind works and of AI to verify those explanations by carrying out the same processes—and eventually doing so far better than human beings. In 1981 Robert Jastrow, director of the Goddard Institute for Space Studies, predicted that "around 1995, according to current trends, we will see the silicon brain as an emergent form of life, competitive with man."[95]

But some psychologists felt that the computer was only a mechanical simulation of certain aspects of the mind and that the computational model of mental processing was a poor fit. The eminent cognitivist Ulric Neisser had become "disillusioned" with information-processing models by 1976, when he published *Cognition and Reality.* Here, much influenced by James Gibson and his "ecological" psychology, Neisser made the case that IP models were narrow and far removed from real-life perception, cognition, and purposeful activity, and fail to take into account the richness of experience and information we continually receive from the world around us.[96]

A number of other psychologists, though not saying they were disillusioned, sought to broaden the IP view to include the mind's use of schemas, shortcuts, and intuitions, and its ability to function simultaneously on both the conscious and unconscious levels to conduct simultaneous processes in parallel (a critical issue we shall hear more of in a moment).

Still others challenged the notion that computors programmed to think like humans actually think. AI, they maintained, isn't anything like human intelligence, and though it may vastly outperform the human mind at calculations, it would never do easily, or at all, many things the human mind does routinely and effortlessly.

The most important difference is the computer's inability to understand what it is thinking about. John Searle and Hubert Dreyfus, both philosophy professors at Berkeley, the computer scientist Joseph Weizenbaum at MIT, and others argued that computers, even when programmed to reason, merely manipulate symbols

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without having any idea what they mean and imply. General Problem Solver, for instance, may have figured out how the father and two sons could get across the river, but only in terms of algebraic symbols; it did not know what a father, son, or boat were, what "sink" meant, what would happen if they sank, or anything else about the real world.

But many programs written in the 1970s and 1980s did seem to deal with real-world phenomena. This was especially true of "expert systems," computer programs written to simulate the reasoning, and make use of the special knowledge, of experts in fields ranging from oncology to investment and from locating veins of ore to potato farming.

Typically, such programs, designed to aid problem solving, ask the person operating them questions in English, use the answers and their own stored knowledge to move through a decision-tree pattern of reasoning, close off dead ends, narrow down the search, and finally reach a conclusion to which they assign a certainty ratio ("Diagnosis: systemic lupus erythematosus, certainty .8"). By the mid-1980s, scores of such programs were in routine use in scientific laboratories, government, and industry, and before the end of the decade many hundreds were.[97]

Probably the oldest and best-known expert system is MYCIN, created in 1976 and improved in 1984, which can be used to detect and identify (and potentially even treat) about a hundred different kinds of bacterial infections, and announce what degree of certainty it puts on its findings. In tests against human experts, "MYCIN's performance compared favorably with that of faculty members in the Stanford School of Medicine… [and] outperformed medical students and residents in the same school," notes the distinguished cognitivist Robert J. Sternberg in *Cognitive Psychology* (2006), "[and]… had been shown to be quite effective in prescribing medication for meningitis." internist, another expert system, diagnoses a broader range of diseases, although in doing so, it loses some precision, resulting in diagnostic powers less than that of an experienced internist.

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But although these and other expert systems are intelligent in a way that banking computers, airline reservation computers, and others are not, in reality they do not know the meaning of the real-world information they deal with, not in the sense that we know. caduceus, an internal medicine consultation system, can diagnose five hundred diseases nearly as well as highly qualified clinicians, but an authoritative textbook, *Building Expert Systems*, long ago pointed out that it "has no understanding of the basic pathophysiological processes involved" and cannot think about medical problems outside or at the periphery of its area of expertise, even when plain common sense is all that is needed.[98] One medical diagnostic program failed to object when a human user asked whether amniocentesis might be useful; the patient was male and the system simply wasn't "aware" that the question was absurd. As John Anderson has said, "The major difficulty which human experts handle well is that of understanding the context in which knowledge is to be used. A logical engine will only yield appropriate results if that context has been carefully defined."[99] But to define contexts as broadly and richly as the human mind does would require an unimaginable amount of data and programming.

The most impressive demonstrations of computer reasoning have been the chess matches in which AI programs have defeated human chess champions. In 1997 a program called Deep Blue defeated the world's best chess player, Garry Kasparov. In large part, it did so by brute force— searching about 200 million possible moves each second (a human being does well to manage one move per second). Since then, other programs, using far less hardware and running far more slowly, but using more strategy—particularly the kinds of creative and original strategies that chess masters can make—have defeated most of their top-level human opponents. Some of the newer programs make some counterintuitive, even ridiculous-looking, moves that can prove to be highly creative.[100]

Among other arguments against the assertion that AI programs think, made by many psychologists and other scientists, are these:[101]

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—AI programs of the expert system type or with broader reasoning abilities lack intuition, a crucial characteristic of human intelligence. Although computers can be excellent manipulators of symbols and can carry out complex prepackaged algorithms, they cannot act on the kinds of hunches that genuine experts can but people with only book knowledge cannot.

—AI programs have no sense of self or of their place in the world around them. This severely limits their ability to do much real-world thinking.

—They are not *conscious.* Even though consciousness is still proving extremely difficult to define, we experience it and they do not. They cannot, therefore, examine their own thoughts and change their minds as a result. They make choices, but these are determined by their built-in data and their programming. Computers thus have nothing that resembles free will (or, if you prefer, free choice).

—They cannot—at least not yet—think creatively except within the purely abstract realm of chess. Some programs do generate new solutions to technical problems, but these are recombinations of existing data. Others have written poetry and music and created paintings, but their products have made little dent in artistic worlds; as in Doctor Johnson's classic remark, they are "like a dog's walking on his hinder legs. It is not done well; but you are surprised to find it done at all."

—Finally, they have no emotions or bodily sensations, although in human beings these profoundly influence, guide, and not infrequently misguide, thinking and deciding.

Nonetheless, both the IP metaphor and the computer have been of immense value in the investigation of human reasoning. The IP model has spawned a profusion of experiments, discoveries, and insights about those cognitive processes which take place in serial fashion. And the computer, on which IP theories can be modeled and either validated or invalidated, has been an invaluable laboratory tool.

But the shortcomings of the IP model and the limitations of AI simulations led, by the 1980s, to a second stage of

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the cognitive revolution: the emergence of a radically revised IP paradigm. Its central concept is that while the serial model of information processing fits some aspects of cognition, most—especially the more complex mental processes—are the result of a very different model, parallel processing.

By astonishing coincidence—or perhaps through a cross-fertilization of ideas—this accorded with then-new findings of brain research showing that in mental activities, nerve impulses do not travel a single route from one neuron to another; they proceed by the simultaneous activation of multitudes of intercommunicating circuits. The brain is not a serial processor but a massively parallel processor.

Matching these developments, computer scientists got busy devising a new kind of computer architecture in which interlocking and intercommunicating processors work in parallel, affecting one another's operations in immensely complex ways that are more nearly analogous to those of the brain and mind than are serial computers.[102] The new computer architecture is not patterned on the neuron networks of the brain, most of which are still unmapped and too complex by an astronomical degree to be copied, but it does, in its own way, perform parallel processing.

The technical details of these three developments lie beyond the scope of this book. But their meaning and significance do not; let us see what we can make of them.

New Model

In 1908, Henri Poincaré, a French mathematician, labored for fifteen days to develop a theory of Fuchsian functions but without success. He then left to go on a geological expedition. Just as he boarded a bus, talking to a fellow traveler, the solution popped into his mind so clearly and unequivocally that he did not even interrupt his conversation to check it out. When he did so later, it proved correct.

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The annals of creativity are full of such stories; they suggest that two (or possibly more) thoughts can be pursued simultaneously by the mind, one consciously, the other or others unconsciously. Anecdotes are not scientific evidence, but in the early years of the cognitive revolution several experiments on attention did suggest that the mind is not a single serial computer.

In one of the best known, conducted in 1973, subjects put on headphones after being told by the experimenters, James Lackner and Merrill Garrett, to pay attention only to what they heard with the left ear and to ignore what they heard with the right one. With the left ear they heard ambiguous sentences, such as "The officer put out the lantern to signal the attack"; simultaneously, with the right ear some heard a sentence that would clarify the ambiguous one if they were paying attention to it ("He extinguished the lantern"), while others heard an irrelevant sentence ("The Red Sox are playing a doubleheader tonight").

Neither group could say, afterward, what they had heard with the right ear. But when asked the meaning of the ambiguous sentence, those who had heard the irrelevant sentence with the right ear were divided as to whether the ambiguous one had meant that the officer *snuffed out* or *set out* the lantern, but nearly all of those who had heard the clarifying sentence chose the *snuffed out* interpretation. Apparently, the clarifying sentence had been processed simultaneously and unconsciously along with the ambiguous one.[103]

This was one of several reasons why, during the 1970s, a number of psychologists began to hypothesize that thinking does not proceed serially. Another reason was that serial processing could not account for most of human cognitive processes; the neuron is too slow. It operates in milliseconds, so human cognitive processes that take place in a second or less would have to comprise no more than a hundred serial steps. Very few processes are that simple, and many, including perception, recall, speech production, sentence comprehension, and "matching" (pattern or face recognition), require vastly greater numbers.

By 1980 or so, a number of psychologists, information theorists, physicists, and others began developing detailed

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theories of how a parallel-processing system might work. The theories are extremely technical and involve high-level mathematics, symbolic logic, computer science, schema theory, and other arcana. But David Rumelhart, one of the leaders of the movement, summed up in simple language the thinking that inspired him and fifteen colleagues to develop their version, "Parallel Distributed Processing" (PDP):

> Although the brain has *slow* components, it has *very many* of them. The human brain contains billions of such processing elements. Rather than organize computation with many, many serial steps, as we do with systems whose steps are very fast, the brain must deploy many, many processing elements cooperatively and in parallel to carry out its activities. These design characteristics, among others, lead, I believe, to a general organization of computing that is fundamentally different from what we are used to.[104]

PDP also departed radically from the computer metaphor used until then in its explanation of how information is stored. In a computer, information is retained by the *states* of its transistors. Each is either switched on or off (representing a 0 or a 1), and strings of 0's and 1's stand for numbers symbolizing information of all sorts. When the computer is running, electric current maintains these states and the information; when you turn it off, everything is lost. (Permanent storage on a disk is another matter altogether; the disk is outside the operating system, much as a written memo is outside the mind.) This cannot be the mind's way of storing information. For one thing, a neuron is not either on or off; it adds up inputs from thousands of other neurons and, reaching a certain level of excitation, transmits an impulse to still other neurons. But it does not remain in an active state for more than a fraction of a second, so only very short-term memory is stored in the mind by neuronal states. And since memories are not lost when the brain is turned off in sleep or in the unconsciousness caused by anesthesia, it

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must be that longer-term storage in the brain is achieved in some other fashion.

The new view, inspired by brain research, is that knowledge is stored not in an "on or off" state of the neurons but in the *connections* among them formed by experience.* In the case of a machine, the connections exist among the "units" of a parallel distributed processor. As Rumelhart said,

> Almost all knowledge is *implicit* in the structure of the device that carries out the task…It is built into the processor itself and directly determines the course of processing. It is acquired through the tuning of connections as these are used in processing, rather than formulated and stored as declarative facts.[105]

The new theory, accordingly, came to be known as "connectionism," and has remained the number one buzz word of current cognitive theory.[106] In an interesting reversal, cognitive psychologists no longer think of mental processes as taking place in computer-like serial fashion and their connectionist model of mental processes—based on neurological evidence—has become the guiding standard for computer design.

Rumelhart and his collaborators were not the only psychologists to imagine how connectionism in the human mind might work; a number of other connectionist models have been drawn up in recent years. But the basic concept underlies them all, namely, that the brain functions by means of exceedingly intricate and complex networks of multiple interconnections among its neurons, enabling the mind, among other things, to work both consciously and unconsciously at the same time, make decisions involving multiple variables, recognize meanings of spoken or written words, and on and on.

For our purposes, the Rumelhart et al. model can serve to exemplify the whole genre. A diagram that Rumelhart and two of his collaborators drew up for their book on PDP will make the PDP idea clear if you are willing to take a minute or two to trace it through. It is a portrait not of a bit of brain tissue but of a bit of a theoretical connectionist network:

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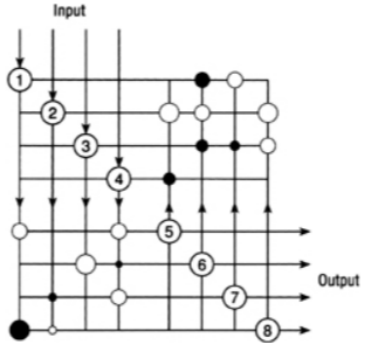


FIGURE 43
The mind's wiring? A hypothetical example of a connectionist network

Units 1 to 4 receive inputs from the outside world (or some other part of the network), plus feedback from the output units, 5 to 8. The connections among the units are indicated symbolically by the unnumbered disks: The bigger an open disk, the stronger the connection, the bigger a filled disk, the stronger the inhibition or interference with transmission. Thus, unit 1 does not influence unit 8, but does influence 5, 6, and 7 to varying degrees. Units 2, 3, and 4 all influence 8 in widely varying degrees, and 8 in turn feeds back to the input units, affecting 1 almost not at all, 3 and 4 rather little, and 2 strongly. All this goes on at the same time and results in an array of outputs, in contrast to the single process and single output of serial design.

Although Rumelhart and his collaborators said that "the appeal of PDP models is definitely enhanced by their physiological plausibility and neural inspiration," the units in the diagram are not neurons and the connections are not synapses.[107] The diagram represents not a physical entity but what *happens;* the brain's synapses and the model's connections operate in different ways to inhibit some connections and strengthen others. In both cases, the connections are what the system knows and how it will respond to any input.[108]

A simple demonstration: What word is partly obscured by inkblots in this diagram?

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FIGURE 44
How can you tell what the partly obscured word is?

You probably recognized instantly that the word is pen. But how did you know that? Each partly obscured letter could have been other than the one you took it to be.

The explanation (based on a similar example by Rumelhart and Jay McClelland): The vertical line in the first letter is an input into your recognition system that strongly connects to units in which P, R, and B are stored; the curved line connects to all three. On the other hand, the sight of the straight line does not connect—or, one can say, is strongly inhibited from connecting—to any unit representing rounded letters like C or O. Simultaneously, what you can see of the second letter is strongly connected to units registering F and E, but crossfeed from the first letter connects strongly to E not F, because experience has established PE, RE, and BE but not PF, RF, or BF as the beginning of an English word. And so on. Many connections, all operating at the same time and in parallel, enable you to see the word instantly as pen and not as anything else.[109]

On a larger scale, the connectionist model of information processing is in striking accord with other seminal findings of cognitive psychological research. Consider, for instance, what is now known about the semantic memory network in Figure 41. Each node in that network— "bird," "canary," and "sing," for instance— corresponds to a connectionist module something like the entire array in the last diagram but perhaps consisting of thousands of units rather than eight.[110] Imagine, if you can, enough such multithousand-unit modules to register all the knowledge stored in your mind, each with millions of connections to related modules, and… But the task is too great for imagination. The connectionist architecture of the mind is no more possible to visualize in its entirety

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than the structure of the universe; only theory and mathematical symbols can encompass it.

The connectionist model is strongly analogous to actual brain structure and function. The late Francis Crick, who shared a Nobel Prize for discovering the structure of DNA and then did neuroscience research at the Salk Institute, said that the concept of the brain as a complex hierarchy of largely parallel processors "is almost certainly along the right lines."[111] Paul Churchland and Patricia Churchland —each a philosopher of cognitive science—have said that the brain is indeed a parallel machine "in the sense that signals are processed in millions of different pathways simultaneously." Each aggregation of neurons sends millions of signals to other aggregations and receives return signals from them that modify its output in one way or another. It is these recurrent patterns of connection that "make the brain a genuine dynamical system whose continuing behavior is both highly complex and to some degree independent of its peripheral stimuli."[112] Thus could Descartes, lying abed all morning, think about his own thoughts, as has many a psychologist since.

Possibly the most remarkable development of all is, as noted above, the change in the relationship between computer and mind. A generation ago, it seemed that the computer was the model by which the reasoning mind could be understood. Now the order has been reversed: The reasoning mind is the model by which a more intelligent computer can be built. Artificial intelligence researchers have been writing programs that simulate the parallel processing of small neural networks, their aim being to create AI programs that are more nearly intelligent than those based on serial processing, and to create programs that simulate hypothesized mental processes so that they can be tested on a computer.

A wonderful irony: The brain that makes mind possible turns out to be the best model for the machine that had been thought vastly superior to it, a model so complex and intricate that it is all the computer can do, for now, to replicate a few of its multitude of functions and make only symbolic simulations of a handful of others.

As David, the greatest of psalmists, sang twenty-five centuries before the cognitive revolution and the computer

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age, “I will praise thee; for I am fearfully and wonderfully made.”

And the Winner Is—

We have followed the revolutionary development of cognitive psychology and the later but equally revolutionary development of cognitive neuroscience, which currently coexist, overlapping and infiltrating each other. But will they continue to do so or is one likely to dominate and absorb the other, becoming the psychology of the future? The answer would seem to depend on which discipline offers the better scientific explanation of mental processes and behavior.

Cognitive psychology, as we have seen, has compiled a remarkable record over the past six decades. Escaping from the severe limitations of behaviorist theory, it rediscovered the mind and found innumerable ways to investigate the unseen processes, among them perception, learning, memory, emotion, personality development, and social behavior, that take place in it. Cognitive psychologists were free to ask, once again, the great questions the Greek philosophers asked so long ago, summed up in the megaquestions “How do we know what we know, and why do we behave as we do?”

As is the case with other sciences, the proliferation of hypotheses and collecting of empirical evidence by cognitive psychologists has often produced corrections and drastic revisions of theories, minitheories, and data, but seen in perspective, cognitive psychology has been a cumulative, self-correcting, self-transforming science.

Its one great shortcoming has always been its lack of an adequate explanation of how the activity of billions of neurons in the brain can result in thoughts, emotions, and voluntary actions. As the neuropsychologist V. S. Ramachandran and science writer Sandra Blakeslee wrote a few years ago, “Many people find it disturbing that all the richness of our mental life—all our thoughts, feelings, emotions, even what we regard as our intimate selves—arise entirely from the activity of little wisps of protoplasm

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in the brain. How is this possible? How could something as deeply mysterious as consciousness emerge from a chunk of meat inside the skull?"[113]

In an effort to answer this question, ever since the early days of the cognitive revolution many psychologists have reached beyond the classic boundaries of their field to explain what they were studying in terms of hormonal, genetic, and other physiological factors. And for the past two and a half decades, as we have seen throughout this chapter, many psychologists have turned to the methods of cognitive neuroscience, especially brain scanning, to help validate their psychological hypotheses. But valuable as all this is, it still does not tell us how a blizzard of neural impulses becomes thought or other mental processes.

Cognitive neuroscience, especially since the advent of brain scans, has been compiling a record of advances in knowledge as impressive as that of cognitive psychology. The neuroscientists have traced neuronal pathways from sense receptors to various loci in the brain, located the areas where emotions are generated, shown that memories are stored in distributed network fashion, and in general extended their research deep into the territory of cognitive psychology, amassing a great deal of information about what areas of the brain are active in mental imagery, attention, speech, learning, voluntary and involuntary action, and other areas of classic psychological interest.

All of which is impressive and almost certainly will be the foundation on which some day a fuller explanation of how the brain becomes mind may be forthcoming. But not yet. The authors of one impressive tome of neuroscience write, "In this book, we explore how the brain actually does enable mind"[114]—but by "enable" they seem to mean something less than explain how the synaptic events become mental events. I asked Martha Farah, director of the Center for Cognitive Neuroscience at the University of Pennsylvania, if the problem were not akin to that of trying to account for the movement of a wave in terms of the movements of individual molecules of water; she laughed and said, "Fluid mechanics is independent of molecular physics. But cognition may not be describable without some details of neuronal function being in the picture."

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Thus, a mental process as simple as a word retrieved from memory cannot be equated with the firing of millions of neurons and the resultant billions of synaptic transmissions but is the product of the pattern or structure of those firings and transmissions. Mental phenomena such as speech, memory retrieval, and reasoning are governed not by the laws of neural activity but by those of cognitive psychology. The former logo of the journal *Cognition* is a striking example of this distinction:



FIGURE 45
Levels of reality: molecules, letters, words, impossible objects

The design is made up of molecules of ink on paper, a reality that has nothing to do with its meaning. At a higher level of organization, the molecules make up letters, which individually are symbols without meaning but as here organized make up the word "cognition." But we are not done. The design, though it looks real and three-dimensional, is an object that cannot exist in the real world; the paradoxical illusion is a mental epiphenomenon. Explain that, if you can, in terms of molecules of ink, letters, or bursts of energy in the neurons of the visual cortex.

Whether or not there is ever a full and satisfying explanation of mental events in neural terms, the revolutions of cognitive psychology and cognitive neuroscience have been successful side by side, overlapping, and in concert with each other.

As for the title of this section, "And the Winner Is—," we now seem to be at the top of the tenth (or eleventh? or twelfth?)—and still tied.

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* A bit, in information theory, is the smallest unit of information: it is equal to a simple yes or no. A digit or a letter of the alphabet is equal to several bits.
* The comment, made in 2002, still holds true.
* Lacking the toy, you can play the game with three or more coins of different sizes. Draw three squares on a sheet of paper, pile the coins in one of them, decide which square the pile is to end up in, and start. The three-coin game is easy, the four-coin game not so easy, and the five-coin game quite hard.
* The answer: PROBLEMS
* The only correct deduction is that some of the chess players are not archaeologists.
* Storage of information in the brain has long been thought to be the result of some kind of unexplained strengthening of the synapses involved in any learning experience. Recent neurophysiological research, too arcane to be fully spelled out here, has established that in any form of learning, a series of at least 15 steps involving 100 or more different molecules takes place, switching on certain genes. These make the post-synaptic neuron more easily activated by the presynaptic neuron's release of various neurotransmitters (Marcus, 2004:100). In addition, the process induces the growth of additional synaptic connections on the presynaptic side (Kandel, 2006, chaps. 14, 17, 19). These changes, in effect, record information, although any elementary item in memory—a shape, say, or a sound—may require that a vast number of strengthened synapses, linked in a network, fire together.

† The solution continues as follows:

S must be either 8 or 9, depending on whether or not there is a carry. Substituting 1 for M, where S + 1 = O, we see that O can be only 0 or 1. But M is 1, so O must be 0; therefore S must be 9 and there is no carry.

In the second column from the left, E + 0 would be E unless there is a carry; hence there must be a carry. So E + 1 = N.

If E is odd, N is even, and vice versa. If E is odd, it can only be 3, 5, or 7 (1 and 9 are already assigned). Try 3. And so on.

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