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A History of Thinking

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By ratiocination, I mean computation.
Hobbes, 1656

Questions concerning the nature of thought are as old as history itself. I do not pretend to present a complete history of this richly debated topic. Instead, I offer a brief history[1] that focuses on a particular question: Is thought a material process? This fundamental question has been hotly debated for centuries. René Descartes (1641/1951) held that the mind was a metaphysical entity that interacted with the material body and that thinking was a property of the mind, not the body. Thomas Hobbes (1656/1839), in contrast, held a mechanistic view of the nature of thought, believing it to be a wholly materialistic process. Thinking to Hobbes was like computing sums; rather than trafficking in numbers, however, thinking required trafficking in *ideas*. To Hobbes, thinking meant adding ideas together to form new ideas, subtracting ideas from each other, comparing ideas, and so on. He believed that thinking could be mechanized; in short, he believed that matter could think and that, in principle, machines could be built that were capable of thought.

It is this belief that thinking is a material process that fuels scientific investigation into the nature of thought. The rest of this chapter is devoted to describing the ways in which philosophers, mathematicians, psychologists, and computer scientists have attempted to investigate and explain the nature of thought since the early 1800s. In a sense, this work can be viewed as a serious attempt to make good on Hobbes's claim that thinking is a material, computational process.

Cummins, D. D., "A History of Thinking," from R. J. Sternberg and E. E. Smith (eds), *The Psychology of Human Thought* (Cambridge University Press, Cambridge, 1988).

Logical Systems of Thought

In 1854, George Boole, a mathematician, sought to determine the laws governing thinking and to describe them within a system of logic. According to Boole, thoughts were propositions or statements about the world that could be represented symbolically. These symbols could be combined in certain ways to form other statements about the world. Thinking in Boole's system, then, was symbol manipulation.

To see how this system works, let us consider two propositions: "George is tall" and "Mary is tall." An important property of these and all propositions is their truth values. The proposition "George is tall" is true if George is in fact tall, and false otherwise. Boole proposed a number of connectives for combining single propositions like these into complex expressions, such as "George is tall AND Mary is tall." He also proposed truth tables, or rules, for determining the truth values of complex expressions. For example, the truth function for the connective "AND" states that the whole expression is true if and only if both propositions are true. So "George is tall AND Mary is tall" is true if both George and Mary are in fact tall; if either is short, the whole expression is false. More important, Boole proposed that propositions and complex expressions could be represented simply as binary truth values, a suggestion that would have great significance (as we shall see).

Following this syntactic approach to thinking, Gottlob Frege combined Boole's logic of truth functions with Aristotle's categorical logic. Under Frege's system, units smaller than propositions could be represented and combined in the same way as whole propositions in Boole's system. This move vastly increased the number and types of expressions and arguments that could be represented and evaluated. The system was formalized, axiomatized, and given a proof system by philosophers Bertrand Russell and Alfred North Whitehead. They called their compendium of human reasoning the "Principia Mathematica."

Physiological Systems of Thought

Whereas philosophers and mathematicians proposed logical systems of thought based on abstract propositions, scientists in other fields were concerned with deriving systems based on sensation and neural impulses. As intuitively obvious as this seems, there was some question at the time whether mental events such as thinking could be measured at all. Undaunted by such doubts, physiologist Ernst Weber and physicist Gustav Fechner began to study the relationship between external stimulation (e.g., light, sound) and internal sensations (brightness, loudness). They discovered that there existed lawlike relationships between changes in external stimulation and internal sensation. They then derived laws that captured these relationships and expressed them quantitatively.

Other scientists were interested in measuring the time it took to respond to stimuli and to carry out mental operations. Hermann von Helmholtz, a physicist and physiologist, measured the speed of neural transmission by requiring subjects to push a button whenever a stimulus was applied to their legs. E. C. Donders expanded this methodology to measure the time required to discriminate among stimuli (Gardner, 1985: 101). He did this by subtracting the time it took subjects to respond to a single event from the time it took them to respond to that same stimulus in the context of another, similar stimulus. The difference in time was attributed to the time required to perform the mental operation of discrimination. Together, this work on response latencies and sensation demonstrated that mental events could be scientifically studied. Thought was becoming a viable object of scientific investigation.

Structuralism and Thought

While the nature of cognition was being studied in a variety of disciplines, scientists began to feel the need for a discipline devoted exclusively to its investigation. With this goal in mind, Wilhelm Wundt established the first laboratory of *experimental psychology* in Leipzig in 1879. A similar laboratory was later established in the United States at Cornell University by E. B. Titchener, an American who had studied in Wundt's laboratory.

The primary objective of this new discipline, as envisioned by Wundt and Titchener, was the scientific study of the *structure* of mind and its processes. In keeping with this objective, the *structuralists* (as they came to be known) were eager to explain consciousness in physical terms, employing the same types of explanatory models used in the natural sciences. The model they chose to guide their research was that of physical chemistry. Just as chemists had identified the fundamental elements of matter, the structuralists hoped to identify the fundamental elements of thought and the laws governing their combination. The idea was that by combining these simple elements in law-governed ways, the more complex forms of thought typically experienced by humans could be derived.

The structuralists were heavily influenced by British empiricists (e.g., Locke, Hume, and Berkeley) in defining their search for the elements of cognition. Like the empiricists, they believed that sensations were the foundation of all knowledge about the world and all mental activity. They rejected Cartesian mind–body dualism, adhering strictly to the doctrine that thinking is fundamentally a physical process, not a metaphysical phenomenon. As a result, most of their research focused on the identification of the physical sensations that underlie or accompany our everyday experiences. As Titchener (1910) put it:

> When I am thinking about anything, my consciousness consists of a number of ideas. . . . But

> every idea can be resolved into elements . . . and these elements are sensations. (p. 33)

For Titchener, all mental events could be categorized as one of three types: images, affections (emotional responses), or pure sensations. Images and affections were themselves complex units that could be broken down into clusters of sensations. For example:

> Thus the "taste" of lemonade is made up of a sweet taste, an acid taste, a scent (the fragrance of lemon), a sensation of temperature, and a pricking (cutaneous) sensation. (Titchener, 1910: 62)

Notice that a complex experience (the taste of lemonade) is decomposed into a conglomeration of several more elementary sensations. More complex reasoning processes were described in the same way. Chess playing, for example, was described in purely sensual terms:

> The mental complexes involved in the game [of blindfold chess] consist of visual images, kinaesthetic images, and sensations . . . visual images predominate. From them arise the vertical board, and the pictures of past games. The kinaesthetic sensations and images . . . are centered in the heavy muscles and tendons of the shoulders. (Dallenbach, 1917: 227–8)

For Titchener and his colleagues, then, thoughts were images – there was no such thing as "imageless thought." And since images were constructed from elementary sensations, all complex reasoning and thought processes could be broken down eventually into elementary sensations.

The method used to obtain reports like these was called *introspection*, a technique that required an observer to describe his or her own internal sensations while performing some task or attending to some stimulus. This was not as easy as it sounds, since the observer was required to describe his or her experiences in terms of elementary sensations. Novices often committed what Titchener termed the "stimulus error"; that is, they reported, for example, "seeing a book" rather than "experiencing the sensations of a certain color, intensity," and other qualities. To ensure the veridicality of introspective reports, therefore, observers were required to be well-trained in the discipline. Wundt required his observers to have no less than 10,000 supervised practice trials before they could participate in any experiment (Boring, 1953), leading William James to comment that Wundt's program "could hardly have arisen in a country whose natives could be bored" (James, 1890: 193). Using this methodology, the structuralists reported identifying more than 44,000 elementary sensations, sensations that, according to them, were the "atoms" of thought. They did not fare as well in detailing laws for combining these "atoms," relying exclusively on the principle of simple association: "Atoms" became associated, or linked together, not through any similarity of structure or content, but rather through the accident of temporal co-occurrence.

What brought about the downfall of the structuralist school was the use of introspection as an analytic technique. The procedure was doomed from the start, because it was based on the assumption that one could discern the elements in compounds just by reflecting on them. This is rather like attempting to discern the elements of water by looking at a drop of water. The perceived qualities of water are not anything like the (indirectly) perceived qualities of its components (i.e., hydrogen and oxygen). However, a more pragmatic difficulty presented itself: Despite the careful training that observers received, agreement among introspective reports was the exception rather than the rule. It was not unusual to obtain markedly different reports from two observers who were exposed to the same stimulus. Such disagreements could not be settled in any scientific fashion owing to the inherently private nature of internal events. In more technical terms, introspection failed as a bona fide scientific method because it violated a fundamental rule concerning scientific investigation: that of independent access to both causes and effects. Although the cause (i.e., stimulus) was open to public observation, the effect (i.e., internal sensation) was not. Without such independent observation of the internal sensation, it was impossible to tell which of two conflicting introspective reports was the correct one. The conflicting reports could have arisen because (a) Subject A was truly experiencing a different sensation than Subject B, or (b) Subject A was experiencing the same sensation as Subject B but was misreporting it, or (c) Subject A was simply lying (Cummins, 1983: 123). There was no scientific way to determine which of these three conditions was true.

While structuralism was beginning to topple under the weight of these rather fundamental difficulties, three other events occurred that hurried its journey downward. The first was Hermann Ebbinghaus's work on the mechanisms underlying learning and memory. Ebbinghaus (1913) proposed that learning consisted of simple associations among stimuli. He chose memorization of lists of nonsense syllables as a paradigm of simple learning, reasoning that the principles that govern the learning of novel, simple stimuli are the same ones that govern the learning of more complex stimuli, such as meaningful text. Using this methodology, Ebbinghaus carefully documented the quantitative relations between such variables as list length and study time, and repetitions and retention. His approach to questions about mental phenomena therefore differed dramatically from that of the structuralists, emphasizing the discovery of quantitative laws governing the forming of associations among stimuli rather than the discovery of the structure of the stimuli themselves.

The second and more dramatic event that changed the nature of psychology at this time was Pavlov's discovery of *stimulus substitution*: that pairing an arbitrary stimulus with a stimulus that naturally elicits some response will empower the arbitrary stimulus to elicit the same response.[2] This was a startling discovery, because it suggested that "reflexes" could be learned. More important for our discussion, however, it suggested that learning could be described without reference to associations among ideas, thoughts, or other mental constructs. Instead, learning could be described solely in terms of associations among stimuli and responses. Here was an answer to the independent access problem, since this methodology made it possible to observe publicly both cause and effect.

The third event that brought about structuralism's demise was the rise of pragmatism in academics and social policy (Cummins, 1983). Pragmatists stressed the relation between mental events and action. John Dewey, a leading pragmatist at the time, argued that thought could not be understood independently of its role as the antecedent to action. From this perspective, the structuralists appeared to be overemphasizing internal responses to stimuli (which could not be observed anyway) and ignoring action or external responses (which could). There was a revolution in the making, and a student of Dewey's, John B. Watson, brought it about.

Behaviorism and Thought

Believing that the structuralists had swung the pendulum of psychological investigation too far in the direction of mental states and unobserved responses, J. B. Watson and his school of *behaviorism* gave it a vigorous shove in the other direction. It was a shove that would determine the nature of psychological investigation for the next 40 years, and it was based on the denial of the legitimacy of mental concepts, such as thinking.

The behaviorists overthrew the structuralist program by asserting that observable behavior was the true object of psychological study. They strove to eradicate such terms as *thought, belief*, and other intentional idioms from the whole of psychological theorizing, arguing that such mentalistic terms represented nothing more than fictitious constructs that clouded rather than clarified our understanding of human behavior. No reference to internal states was allowed, neither as effects of stimulation nor as causes of external behavior. Some behaviorists, such as Watson, went so far as to deny the existence of consciousness; others considered mental phenomena, such as thinking, to be epiphenomena, that is, side effects of external stimulation that could not themselves cause or explain behavior.

Behaviorists believed environmental influences to be the sole determinants of behavior and overt behavior to be the only legitimate object of scientific study. Within the behaviorist school, psychological investigation was devoted exclusively to the discovery of laws and principles governing the prediction and control of observable behavior. These laws and principles took the form of generalizations of observed relationships between environmental stimulation and organismic responses. An example of such a law is stimulus generalization. An organism exhibits stimulus generalization when it spontaneously responds to a stimulus in the same way it learned to respond to another stimulus without any pairing of the two stimuli.[3]

The phenomenon that most interested the behaviorists was that of learning, that is, how an organism's behavioral repertoire changed as a result of experience. They postulated two primary mechanisms for enacting these changes. The first was the simple associative learning discovered by Pavlov. This type of learning consisted of associating new stimuli with old responses through stimulus substitution. Moreover, the responses were primarily reflexive or visceral in nature, such as salivation in response to food, eye-blinking in response to sudden puffs of air, or emotional reactions to emotion-arousing stimuli. This type of learning is termed *respondent conditioning*.

The second mechanism of environmental shaping of behavior was reinforcement. The principle behind this mechanism is that, whenever a response terminates a noxious stimulus (negative reinforcement) or is followed by a "reward" (positive reinforcement), its probability of occurrence is increased.[4] The principle of positive reinforcement was proposed by Thorndike (1913), who called it the "Law of Effect." The notion of reinforcement in general was perfected by Skinner and his associates, who formulated various types and schedules of reinforcement and described their effects on behavior (Ferster and Skinner, 1957). Together, reinforcement and stimulus substitution constituted powerful mechanisms for shaping behavior.

If thinking was considered at all by the behaviorists, it was conceived as "laryngeal habits," that is, subvocal speech (Chaplin and Krawiec, 1974: 376). Such habits developed in early childhood out of spontaneous vocalizations. Through conditioning, these vocalizations become words; for example, *Da-da* becomes *Daddy* through reinforcement (response shaping). Social pressures inhibit spontaneous vocalizations, and they become subvocal. Now when seeing Daddy, the child can think *Daddy*. Thinking according to the behaviorists was quite simply talking to oneself.

Gestalt Psychology and Thought

Although behaviorism dominated most psychological circles following the demise of structuralism, it was by no means the only school bent on explaining psychological phenomena. In fact, just as behaviorism arose as a reaction against structuralism, a new school, called *Gestalt psychology*, grew out of a reaction against both structuralist and behaviorist doctrines. Unlike the behaviorists, however, the Gestaltists did not succeed in overthrowing their contemporaries' hold on psychological investigation. This lack of success was due largely to two factors. First, Gestalt psychology produced no cohesive, testable theory of behavior or cognition, nor was its work guided by any vision of what such a theory should be. Gestalt psychology tended instead to define itself in terms of objections to behaviorist and structuralist doctrines. As a result, the body of work the Gestaltists produced, though important and impressive, consists primarily of descriptions of phenomena that could not be explained through reductionist methods such as introspective analysis or by the simple associative principles of stimulus substitution and reinforcement. These phenomena were not taken as data upon which to build a model or theory of human psychology, but were presented simply as evidence of the inadequacy of the behaviorist and structuralist models. In contrast, both the behaviorists and the structuralists possessed very clear ideas of what a science of psychology should be and modeled their work after the physical sciences (i.e., physical chemistry and something akin to simple mechanics, respectively). When the behaviorists overthrew structuralism, they replaced one cohesive research program with another.

The second reason the Gestaltists did not succeed in overthrowing behaviorism is related to their failure to construct a comprehensive theory. They simply did not possess the tools and techniques for building models of the level of complexity they required. Unlike the behaviorists, who focused primarily on the prediction and control of simple response sequences, the Gestaltists attempted to explain complex behaviors, such as thinking, problem solving, and perception. The tools and techniques required to investigate these areas properly would be developed only much later, in the fields of cybernetics, information theory, and computer science. In a sense, the Gestalt school foreshadowed the cognitive revolution (see the next section), carving out the domains that would be explored later.

At the heart of the Gestaltists' investigations was the belief that higher-order psychological phenomena could not be *decomposed* into simple mental elements (structuralism) or simple stimulus–response chains (behaviorism). They argued that an adequate explanation of intelligent behavior required reference to internal states and highly integrated cognitive structures. Evidence for this belief came primarily from their work in the areas of perception, problem solving, and thinking.

Appreciating their arguments on the nature of perception requires a cognitive shift, which the following "thought experiment" might help us to achieve. Consider the difference between the way a human perceives the world and, for example, the way a frog does (to choose an organism sufficiently far down the phylogenetic scale). A frog's visual system (eyes and brain) responds only to very rudimentary stimulation, such as shadows and moving specks. In essence, this is all a frog can "see." The human visual system, of course, is capable of responding to a multitude of stimuli, including color, shape, and depth. The world we perceive bears very little resemblance to the world perceived by a frog because of the immense differences in the capacities of our visual systems. To put it another way, the nature of our internal states and architecture shapes our perceptual experience.

The Gestaltists presented even stronger evidence that our perceptual capacities shape our knowledge about the world. They showed that our visual system is capable of *augmenting and organizing* stimulation in reliable ways. A classic example is that of the phi phenomenon, an illusion produced by the sort of light display one sees around a movie marquee. If light bulbs are lined up in a row, and each one in succession is quickly turned on and off, one sees an illusion of movement down the line of bulbs. In fact, nothing in the physical environment is moving, but the pattern of light stimulation is "interpreted" by our visual system as movement. More important, the Gestaltists pointed out that the qualitative aspect of this illusion could not be decomposed or reduced to its components. The illusion was problematic for structuralists because it persists no matter how one tries to introspect the individual pieces separately. It was also problematic for behaviorists because they could not even talk about the illusion except in terms of differential responses. The question from this point of view is why the organism responds to the light display *as if it were movement*. Since this perception is spontaneous, there is no conditioning history to explain how successive light displays could become a substitution for genuine movement. Another example is that of melody transposition. If a melody is transposed into another key, it is still recognized as the same melody even though all of its elements are different.

Psychological phenomena such as these seemed to indicate that "the whole is greater than the sum of its parts," that is, that the wholeness of a perception cannot be found by analyzing any of its parts. The wholeness instead was probably a function of the internal organization of our perceptual–cognitive systems. The Gestaltists therefore believed perception to be an active, constructive process, not a passive, "reflexive" one (as envisioned by behaviorists). Essentially, this means that a type of organization is imposed on incoming stimulation by our internal states. (Bartlett, 1932, proposed the same thing about memory processes; that they were constructive.)

The Gestaltists believed thinking, like the process of perception, to be an active, constructive process. In fact, more than their predecessors or contemporaries, the Gestaltists concerned themselves with the nature of thinking and reasoning. Wertheimer (1945/1982) proposed a distinction between productive and reproductive thinking. Productive thinking involves a grasp of the structural relations in a problem or situation, followed by a grouping of those parts into a dynamic whole. Reproductive thinking is characterized by a failure to see relations among subparts. It instead involves blind repetition of learned responses to individual subparts. This type of thinking lacks insight, a phenomenon that Köhler (1925) characterized as a closure of the thinker's psychological field, where all elements come together into a whole structure.

Perhaps the most pragmatic and systematic approach to thinking among the Gestaltists was taken by Duncker (1945) in his work on problem solving:

> A problem arises when a living creature has a goal but does not know how this goal is to be reached. Whenever one cannot go from the given situation to the desired situation simply by action, then there has to be recourse to thinking. (By action we here understand the performance of obvious operations.) Such thinking has the task of devising some action which may mediate between the existing and the desired situations. (p. 1)

Duncker studied human problem-solving behavior by requiring subjects to "think aloud" as they attempted to solve a problem. He used these "think-aloud" protocols to trace the reasoning processes, or cognitive states, that subjects generated on their way toward a solution. These verbal protocols differed from the structuralists' introspection reports in two important ways. First, they relied on the subject's existing skills rather than on any special training that could influence or bias the subject's reports. Second, the focus of the protocols was the task itself, not the observer.

Subjects simply verbalized their plans and strategies, not the qualities of their sensations.

What these protocols revealed was that problem solving was better characterized as a top-down, goal-oriented process than as a bottom-up, stimulus-driven process of trial and error. Subjects typically recoded high-level goals into subgoals and searched for means to satisfy them. The steps generated by the subject while solving a problem, therefore, typically were not random or "blind," but highly purposive. In addition, there was a reliable relationship between the way subjects represented the problems to themselves (as evidenced by their protocols) and the accuracy of their solutions.

On the basis of these data, Duncker concluded that problem-solving behavior could be formalized as a search for means to resolve conflicts between current situations and desired goal situations. The process itself required an analysis of the differences, or conflicts, between the goal and current situations and an analysis of the means to reduce those differences. The outcome of this process was a collection of highly integrated internal representations that detailed the conflicting parts and subparts of the problem situation. Understanding and "insight" were characterized as internal states achieved by the problem solver, states that depended on the quality of the representation constructed by the subject (as evidenced in the concomitant verbal protocol).

This characterization of problem-solving behavior, with its reliance on internal representations and cognitive states, contrasted sharply with that of behaviorists. Since behaviorist doctrine would suffer no reference to internal states and processes (believing these to be "explanatory fictions"), its characterization of problem-solving behavior relied solely on trial-and-error learning. According to this view, responses were randomly emitted, or cued, by some aspect of the stimulus situation, and correct responses were reinforced through success. This model was simply not powerful enough to account for the observed data, particularly the goal-oriented purposiveness, or forward planning, of the problem solver. However, its attractiveness to the behaviorist is understandable because the goal of that school was the *prediction* and control of behavior. Conditioning histories, when they are observed, allow one to predict *which* response/strategy a subject will choose when solving a problem; that is, he or she is likely to choose one that met with success (reinforcement) in the past. However, the Gestaltists were not so much interested in the prediction as in the explanation of the phenomenon. At their level of analysis, it was much less important to predict which strategy a subject would choose than it was to derive an accurate characterization of the process itself. Verbal and written protocols clearly showed that, when solving a problem, subjects formed *plans*, generated *goals*, and developed *strategies* based on acquired *knowledge*. Removing these concepts from one's description of problem-solving behavior was tantamount to not describing the phenomenon at all.

However, such terms as *plans, goals, strategies*, and *thoughts* were troublesome to describe in any rigorous, non-question-begging manner. As a result, an uneasy tension arose in psychology between the behaviorists, who could see no way to characterize scientifically the existence of internal states, and the Gestaltists, who saw clearly the necessity of postulating them in order to explain cognition.

The Cognitive Revolution

What finally loosened behaviorism's grip on psychological investigation was a revolution that restored talk of internal states and processes to psychology, but in a scientifically rigorous manner. The discoveries that would form the bases of the revolution were made in a variety of disciplines during the 1940s and 1950s. It was not until the mid-1960s, however, that they came together (in rather scattershot fashion) to form a new psychology, one that Ulric Neisser dubbed *cognitive psychology*. The nature of these discoveries changed the way researchers in numerous other fields conceptualized the human mind. As a result, cognitive psychology became part of a larger discipline called *cognitive science*, which now includes researchers from such fields as philosophy, linguistics, psycholinguistics, computer science, and neuroscience. The common goal of these researchers is the explanation of higher mental processes.

One of the major foundations of cognitive science was mathematician Allen Turing's (1936, 1963) work on finite-state automata. Turing proposed a theoretical "machine" (mathematical abstraction) that could in principle carry out any recursive function. The "Turing machine," as it came to be called, is a very simple system. It consists of (a) a tape containing symbols, usually blanks and slashes; (b) a scanner to read the tape; and (c) four operations: move right, move left, write a slash, and erase a slash. What the scanner does at any given moment is fully determined by two factors: the symbol it reads on the tape (input) and its current internal state. This simple architecture comprises a machine of enormous computational power. It formed the theoretical basis on which the modern digital computer is built. And it was not long before researchers began wondering whether it represented a way to test Boole's (1854/1951) and Hobbes's (1656/1839) contention that thinking is *computation*.

One of the first researchers to test this idea was mathematician Claude Shannon (1948). Shannon's work was based on two major insights. The first was that information could be represented as binary choices among alternatives. The amount of information transmitted through a channel (e.g., a telephone wire) could be measured in bits, or binary digits, where one bit represents a choice between two equally probable alternatives. This perspective made it possible to quantify the concept of information. It also provided a means of representing information that was independent of its particular content or the nature of the device that carried it.

To appreciate the usefulness of this conceptualization of information, consider Shannon's second major insight: that electronic circuits could carry out Boole's operations of thought. Recall that, in Boole's system, propositions can be represented as binary truth values (true–false). Electromechanical relays also allow only two states: A circuit is either closed or open, on or off. Shannon demonstrated that, because of the binary nature of the two systems, electronic circuits could be used to simulate the logical operations of the propositional calculus. He had designed a machine that carried out the functions of thought in electronic circuitry.

This was a rather startling insight, for three reasons. First, it suggested that thinking (at least as proposed by Boole) could be automated. Machines could carry out reasoning processes. Second, it offered for the first time a means of describing the states and processes of mechanical systems in *information-processing* terms, that is, in terms of *what* information is represented and how it is processed. Third, it could be applied to the brain as well. In 1948, Warren McCulloch and Walter Pitts proposed that, since neurons also operate as binary units (either they fire or they do not), they could be thought of as logical units carrying information.[5] They further demonstrated how communication among networks of neurons could simulate the logical operations of the propositional calculus, just as electromechanical circuitry can. Essentially, McCulloch and Pitts had succeeded in "treating the brain as a Turing machine" (McCulloch, as cited in Jeffress, 1951: 32).

An implication of this neuronal model was that patterns of neuronal firing could be seen as statements about the world. This was a far cry from contemporary views of the human central nervous system, which was depicted as a predominantly quiescent, largely passive system that became active only in response to external stimulation – a view, incidentally, that fit well with behaviorist stimulus–response theories of organismic behavior. This view, however, was beginning to be questioned. Neurophysiologist Karl Lashley (1951), for example, pointed out that stimulus–response chains, even at the neuronal level, did not account for serially ordered behavior. He pointed out that the finger strokes of a pianist may reach 16 per second during complex passages. Sensory control of such rapid movements was impossible because there simply was not enough time for feedback from one finger movement to reach the brain in order to trigger the next movement. In fact, this speed exceeded visual recognition time. Complex piano skills, therefore, could not be made up of simple stimulus–response units. Lashley went on to argue that complex serial movements were products not of simple reflex arcs, but of an interaction among complex patterns of organization within the central nervous system. He proposed that complex movements were represented and activated as cohesive units. Control of such movements was therefore central rather than peripheral.

On the basis of observations and interpretations such as these, Lashley (1951) proposed a view of the central nervous system that closely resembles the characterization accepted today. He believed it to be "a dynamic, constantly active system, or rather, a composite of many interacting systems" (p. 135). This characterization was a far cry from the simple switching network conceptualization upon which behaviorist theory was built but entirely in line with the active, constructive processor proposed by the Gestaltists.

While neurophysiologists grappled with issues of feedback within the central nervous system, mathematician Norbert Wiener pursued similar questions concerning the use of feedback in mechanical systems. Wiener and his colleagues were concerned with servomechanisms, devices that kept airplanes and missiles on course. In order to perform this function, these devices had to correct themselves given feedback from the environment. Wiener argued that it was legitimate to describe the behavior of these machines as purposive, goal-directed activity (Rosenblueth, Wiener, and Bigelow, 1943). Wiener's servomechanisms worked by computing the difference between their goals and current states and employing operations to reduce those differences. This description of goal-directed, mechanized behavior is strikingly similar to Karl Duncker's description of problem-solving behavior in human subjects. Wiener's work clearly demonstrated that such terms as *plans* and *goals* could be precisely specified and instantiated in mechanical systems, contrary to behaviorist warnings.

Work in cybernetics, information theory, and automata theory had spawned a variety of rich concepts for researchers interested in explaining human cognitive capacities, and it was not long before the effects of these new resources were seen.[6] In the late 1950s and early 1960s, several models of cognition were put forth that capitalized on these concepts. In 1956, George Miller pointed out that performance on a variety of cognitive tasks declined dramatically when they required maintaining more than seven items in memory at a time. This invariance in performance suggested that humans contained a processer with limits and that these limits shaped the nature of mental processes. For example, Bruner, Goodnow, and Austin (1956) observed that, when learning to classify objects, humans tend to employ *strategies* that, among other things, minimize storage requirements. A common strategy they observed was *successive scanning*: choosing a single hypothesis about a category description and choosing only those instances that directly test that hypothesis. Thus, the way we go about acquiring knowledge and thinking about the world is strongly influenced by the limitations of our "cognitive architecture."

Once it was demonstrated that rigorous answers could be obtained, more and more psychologists began to ask questions about our cognitive architecture. In 1958, Donald Broadbent proposed a model of the mind that consisted of a flow chart containing structures as well as processes. After Shannon, Broadbent conceived of the various sense organs as "channels" of information. These channels fed into a short-term memory, then through a filter, and finally into a limited-capacity channel. From there the information was stored in long-term memory and/or outputted as an external response. In retrospect, Broadbent's model was a curious blend of the past and the present. His limited-capacity channel was analogous to the structuralist's "unitary attention," or consciousness (p. 300); the probability of a stimulus getting through the processing filter was determined by behaviorist reinforcement (p. 301). Yet it was a fresh look at human cognition because it was one of the first models that described the flow of information *through* the organism.

In 1960, Miller, Galanter, and Pribram published a book in which they called for a cybernetic approach to behavior. The idea was that humans should be viewed as active *information processers*, not as passive recipients that respond "reflexively" to the pushes and pulls of the environment. (This shift was similar to the one proposed by Lashley about the central nervous system.) Miller et al. described cognitive architecture as a hierarchical organization of test–operate–test–exit (TOTE) units. A TOTE unit operated on some input, testing the outcome at each step, until some goal was met; then it stopped, or exited. Implicit in this idea was the notion of feedback, not as simple reinforcement, but as information to be used by the system to achieve some goal, as in Wiener's servomechanisms.

By the late 1960s, investigation into the nature of human cognition had become more the rule than the exception in psychology. Like the Gestaltists, researchers were interested in detailing *how* stimuli were "turned into" responses by the organism. Phenomena such as stimulus generalization were taken as capacities to be explained, not as explanations themselves. As Neisser (1967) put it:

> The basic reason for studying cognitive processes has become as clear as the reason for studying anything else: because they are there. Our knowledge of the world must be somehow developed from stimulus input. . . . Cognitive processes surely exist, so it can hardly be unscientific to study them. (p. 5)

The influence of theories of computation on psychological theorizing was also apparent:

> The task of a psychologist in trying to understand human cognition is analogous to that of a man trying to discover how a computer has been programmed. In particular, if the program seems to store and re-use information, he would like to know by what "routines" or "procedures" this is done. Given this purpose, he will not care much whether his particular computer stores information in magnetic cores or in thin films; he wants to understand the program, not the "hardware". By the same token, it would not help the psychologist to know that memory is carried by RNA as opposed to some other medium. He wants to understand its utilization, not its incarnation. (Neisser, 1967: 6)

While psychologists such as Broadbent and Neisser viewed the digital computer as a useful metaphor for conceptualizing issues about cognition, other researchers began to build actual computer models of cognition. One of the first was a program called Logic Theorist (Newell, Shaw, and Simon, 1958). Logic Theorist proved theorems from the Principia Mathematica. Moreover, it did so in ways that were similar to those employed by humans. Building on Logic Theorist's general architecture, Newell and Simon (1972) produced another program, General Problem Solver (GPS). GPS was constructed as a model, or theory, of human problem solving, and its performance paralleled quantitative and qualitative aspects of the performance of human novices. It is of some importance, then, to note that GPS analyzes and solves problems in the way described by Karl Duncker. GPS analyzes a problem into a list of differences, or conflicts, between a current state description and a goal state description. A table of connections is used to resolve these differences, working backward from the goal. The table of connections is essentially a production system (body of rules) containing descriptions of possible differences between states and actions that will reduce those differences. This procedure for solving problems is called *means–ends analysis*, and it is a procedure often employed by human novices. Duncker's model of problem-solving behavior had been scientifically instantiated and tested.

Subsequent work on computer modeling has fallen into two general categories. The first contains programs that, like GPS, are intended to be viable models of human cognition. These models contain aspects of human processing, such as a limited-capacity working memory, and are based on and tested using data on human subjects. (Included in this category is John Anderson's (1983) ACT* system, a system that includes operations for producing the behaviorist processes of discrimination, generalization, and strengthening, or reinforcement.) The second category contains programs called *expert systems*, programs that generate expert levels of performance in circumscribed domains. The focus of these programs is to perform a task as efficiently and error free as possible. No human-like constraints are placed on their execution. Nonetheless, these systems carry out the processes of thought when performing their assigned tasks.

It would be misleading to give the impression that all current work on thinking is done by computer simulation. In fact, many investigators complain that computer models suffer from a certain rigidity that is uncharacteristic of human performance. Some argue that the face of psychological investigation is being shaped too closely to fit the limitations and characteristics of digital computers:

> Unlike men, "artificially intelligent" programs tend to be single-minded, undistractable, and unemotional. . . . In my opinion, none of [these programs] does even remote justice to the complexity of human mental processes. (Neisser, 1967: 9)

Ironically, Gestalt psychologists are among the strongest critics. They hold that the most important aspects of human reasoning have not been explained or even exhibited by computer simulation models:

> Missing in such work is the crucial step of *understanding*, that is, grasping both what is crucial in any given problem and why it is crucial. (Wertheimer, 1985)

Nonetheless, the influence of theories of computation can be found in the majority of psychological investigation. Computational concepts, such as memory buffers, encoding, search, and retrieval, are standard components of modern theories of cognition. The fundamental idea underlying most psychological theories today is that the human brain *processes* information in order to produce our percepts, memories, and other experiences. This idea has spawned such diverse psychological theories as Marr's (1982) computational theory of perception, Kintsch and van Dijk's (1978) process model of text comprehension, and Raaijmakers and Shiffrin's (1981) computational model of associative memory search. From the perspective of these theories, a percept or memory is the *outcome* of a (computational) process.

Many of the chapters in this book describe work on various aspects of cognition that are not embodied in computer models. However, the influence of the computer revolution on the cognitive revolution will still be found in these approaches. Theories and models that contain references to internal states, processes and structures are the intellectual progeny of theories of computation.

Notes

1 Although the information reported here was gathered from a variety of sources, my choice of historical perspective was influenced by Gardner's (1985) *The Mind's New Science*, Cummins's (1983) *The Nature of Psychological Explanation*, and Haugeland's (1985) *Artificial Intelligence: The Very Idea*. These three volumes are recommended to the reader who wishes more information.

2 For example, dogs normally salivate when food is placed in their mouths; if a bell is paired with food placement several times in a row, the dogs will come to salivate in response to the bell alone.

3 In our earlier example, dogs came to salivate in response to a bell if the bell were paired with food. If the dogs then spontaneously salivated in response to a musical tone (without any pairing of stimuli), this would be an instance of stimulus generalization. The same response generalized to the new stimulus.

4 An example of negative reinforcement is stopping a television from flickering by turning a knob. One's "knob-turning behavior" has been reinforced by the cessation of the flicker. An example of positive reinforcement is arriving at home by following a certain route. One's "route-following behavior" has been reinforced by arriving home.

5 This should not be taken to mean that the brain is necessarily a digital machine. Although neurons fire in an all-or-none manner, neural coding occurs through continuous changes in the *rate* of firing. Moreover, there is good evidence that the brain operates in a massively parallel fashion, with numerous interactions among its neurons. The point of this early neuronal model was to show how thinking could be automated in a process that was simple enough for neuronal networks in principle to execute.

6 In fact, automata theory did more than this. It revealed the inadequacy of the behaviorist model for explaining behavior. Briefly, it showed that predictions of a system's behavior – behaviorism's goal – were not possible without information concerning its internal states. A rather crude approximation of this proof follows. The interested reader should consult Nelson (1969, 1975) for a more complete exposition of the following proof:

A system's response is a function of its input and its internal state,

$$r_i = f(s_i, \sigma_i)$$

The internal state is in turn a function of past inputs and past internal states,

$$\sigma_i = g(s_{i-1}, \sigma_{i-1})$$

Since we are trying to compute *r*, we need information about at least one internal state somewhere along the way (or some way to reduce it to zero), or else we will continue to have one more unknown than we have equations, making *r* uncomputable.

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