Most likely, however, neither the theoretical scope nor the empirical methods of the field are going to change dramatically. If there will be disagreement among scientists, it will concern the nature of the mental system intervening between environmental input and behavior. The most desirable future scenario is perhaps one in which the three main metaphors (i.e., computer, brain, ecological) will be integrated into a coherent one. Because the three metaphors deal with distinct levels of the human mind, this scenario is perhaps not an unlikely, remote theoretical possibility.

See also: Brain Development, Ontogenetic Neurobiology of; Cognitive Neuroscience; Cognitive Psychology: History; Cognitive Science: History; Cognitive Science: Overview; Cognitive Science: Philosophical Aspects; Experimentation in Psychology, History of; Human Cognition, Evolution of; Information Processing Architectures: Fundamental Issues; Intelligence, Evolution of; Intelligence: Historical and Conceptual Perspectives; Mathematical Psychology; Problem Solving and Reasoning, Psychology of; Psychology: Historical and Cultural Perspectives; Psychology: Overview

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Cognitive Science: History

The roots of cognitive science extend back far in intellectual history, but its genesis as a collaborative endeavor of psychology, computer science, neuroscience, linguistics, and related fields lies in the 1950s. Its first major institutions (a journal and society) were established in the late 1970s. This history describes relevant developments within each field and traces collaboration between the fields in the last half of the twentieth century.

A key contributor to the emergence of cognitive science, psychologist George Miller, dates its birth to September 11, 1956, the second day of a Symposium on Information Theory at MIT. Computer scientists Allen Newell and Herbert Simon, linguist Noam Chomsky, and Miller himself presented work that would turn each of their fields in a more cognitive direction. Miller left the symposium 'with a strong conviction, more intuitive than rational, that human experimental psychology, theoretical linguistics, and the computer simulation of cognitive processes were all pieces from a larger whole, and that the future would see a progressive elaboration and coordination of their shared concerns' (Miller 1979).

This early conference illustrates an enduring feature of cognitive science—it is not a discipline in its own right, but a multidisciplinary endeavor. Although a few departments of cognitive science have been created at universities in subsequent decades, most of its practitioners are educated and spend their careers in departments of the contributing disciplines. The relative prominence of these disciplines has varied over the years. Computer science and psychology have played a strong role throughout. Neuroscience initially was strong, but in the years immediately following the 1956 conference its role declined as that of linguistics dramatically increased. By the 1970s, such disciplines as philosophy, sociology, and anthropology were making distinctive contributions. Recently, with the emergence of cognitive neuroscience, neuroscience has once again become a central contributor.

1. *Intellectual Ancestors of Cognitive Science*

1.1 *Artificial Intelligence*

One of the central inspirations for cognitive science was the development of computational models of cognitive performance, which bring together two ideas. First, conceiving of thought as computation was an offshoot of the development of modern logic. In his 1854 book, *The Laws of Thought*, the British mathematician George Boole demonstrated that formal operations performed on sets corresponded to logical operators (and, or, not) applied to propositions; Boole proposed that these could serve as laws of thought. Second, conceiving of computers as devices for computation can be traced back to Charles Babbage's plans in the 1840s for an 'analytical engine' and his collaboration with Lady Lovelace (Ada Augusta Byron) in developing ideas for programming the device. These ideas gained new life in the 1930s and 1940s with the development of automata theory (especially the Turing machine), cybernetics (centered on Norbert Weiner's feedback loops), designs for implementing Boolean operations via electric on/off switches (Claude Shannon), and information theory (also Shannon). Implementation became possible with the invention of electrical circuits, vacuum tubes, and transistors and was put on a fast track by World War II (ENIAC was completed at the University of Pennsylvania in 1946). By the mid-1950s, Newell and Simon (at RAND and then Carnegie-Mellon) produced the first functioning program for reasoning, a theorem-prover called Logic Theorist, and the first list-processing language, IPL. Meanwhile, John McCarthy and Marvin Minsky at MIT were developing a broad based agenda for the field they named artificial intelligence (AI) and more specialized endeavors also got underway (e.g., machine translation of languages and chess-playing programs, neither truly successful until the 1990s).

1.2 *Psychology*

During the same period psychology began emerging from a long domination by behaviorism, especially in North America. Behaviorism had the lasting impact of focusing experimental psychology on explaining behavior and relying on behavior as its primary source of evidence. Radical behaviorists, such as B. F. Skinner, actively opposed positing internal processes and focused on what was observable: describing how behavioral responses changed with contingencies of reinforcement. Other behaviorists, such as Clark Hull, were willing to posit variables intervening between stimulus and response, such as drive, but emphasized doing so in the context of developing a mathematico-deductive theory accounting for behavior. Edward Tolman, an atypical behaviorist, went so far as to propose that rats navigate their environments by constructing cognitive maps. Most psychologists, however, took learning rather than cognition as their domain of concern. The sentiment was well captured by George Mandler, looking back on his graduate student days at Yale: '… cognition was a dirty word for us … because cognitive psychologists were seen as fuzzy, hand-waving, imprecise people who never really did anything that was testable' (quoted in Baars 1986).

Although behaviorism cast a broad shadow in the US, alternatives which later influenced cognitive science thrived elsewhere: Continental Europe (especially Jean Piaget's genetic epistemology), the UK (e.g., Sir Frederic Bartlett's appeal to schemas to explain memory distortions and Donald Broadbent's analyses of memory and attention), Germany and Austria (Gestalt psychology), and the Soviet Union (Lev Vygotsky and Alexander Luria). Within the US, psychophysics (and to some extent developmental, social, and clinical psychology) functioned largely outside behaviorism's influence. Several psychologists who later pioneered a more cognitive approach, including Miller, Ulric Neisser, and Donald Norman, received their training in S. S. Stevens's Psycho-acoustic Laboratory at Harvard. Miller earned his Ph.D. in 1946 for research on optimal signals for spot jamming of speech. Just 10 years later, he was talking about the structure of internal information processing systems, such as the 'seven plus or minus two' limitation in such domains as short-term memory. In 1960, Miller, Eugene Galanter, and Karl Pribram broke new ground in their *Plans and the Structure of Behavior*. In the same time frame, Miller's Harvard colleague Jerome Bruner was pioneering several strands of cognitive research: he showed that internal mental states influence perception and, arguing that categories are central to thought, Bruner, Goodnow, and Austin traced how people acquire them in their 1956 book, *A Study of Thinking*.

1.3 *Neuroscience*

Research into the brain was long thought to be relevant to understanding mental processes. One line of research focused on deficits stemming from brain lesions, such as Broca's classic nineteenth century work lining articulate speech to what is now called Broca's area. Although a holistic tradition in early twentieth century brain research temporarily turned investigators away from localization studies, Norman Geschwind and others gave new life to this approach in the 1950s. As well, improvements in electrophysiological techniques, including brain stimulation, single cell recording, and EEG recording, provided additional clues. As evidenced by a 1948 conference, 'Cerebral Mechanisms in Behavior,' there was eager engagement at the time between neurophysiologists, biologically oriented psychologists, and computer scientists.

One of the fruitful products of this engagement in the 1940s to 1960s was the development of neural networks, a kind of computational modeling pioneered by neurophysiologist Warren McCulloch and logician Walter Pitts. Donald Hebb proposed to build cell-assemblies by strengthening connections between neurons that fired simultaneously, a technique still in use. Oliver Selfridge had layers of units competing in parallel to recognize patterns in his *Pandemonium* simulation. Frank Rosenblatt built layered networks that learned through error correction (*Perceptrons*). Neural networks lost influence due to a devastating critique of Perceptrons by Minsky and Seymour Papert in 1969, but were revived when more effective techniques became available in the 'new connectionism' of the 1980s and beyond.

1.4 Linguistics

Linguistics began to move towards a central role in the emerging interdisciplinary discussion of mind and brain around the time of the 1956 MIT conference. In the early decades of the twentieth century, linguistics had changed its emphasis from reconstructing the history of languages to studying the structure of languages. Structuralist linguists such as Franz Boas, Edward Sapir, and the positivist Leonard Bloomfield focused on lower-level structural units (phonemes and morphemes). In the 1950s, post-Bloomfieldian Zellig Harris turned his attention to syntax and introduced the idea of transformations that normalized complex sentences by relating them to simpler kernel sentences. This idea launched a revolution in linguistics when it was further developed by Harris's student Noam Chomsky at the University of Pennsylvania and then MIT. In his 1957 *Syntactic Structures*, Chomsky proposed the idea of a grammar as a generative system—a set of rules that would generate all and only members of the infinite set of grammatically well-formed sentences of a human language—and argued that finite state and phrase structure grammars, though generative, were inadequate. A series of transformations was needed to obtain an appropriate surface structure from an initial deep structure created by means of phrase structure rules.

2. The Maturation of Cognitive Science

If the 1956 symposium represented the birth of cognitive science, it had a lot of maturing to do before it solidified into a major recognizable area of scientific inquiry. It did not even obtain its name and institutional identity until the mid- to late 1970s. But in the intervening two decades, interaction and collaboration between computer science, psychology, and linguistics developed and began to bear fruit.

2.1 Artificial Intelligence

Though based in computer science, much artificial intelligence (AI) research was directed towards accounting for the kinds of behavior studied by psychologists. Newell and Simon soon went beyond their initial Logic Theorist program to a General Problem Solver they used in less formal domains, such as solving Tower of Hanoi problems. They developed such concepts as subgoals, heuristics, and satisficing and introduced the production system framework, which employs rules that operate on the contents of working memory when their antecedent conditions are satisfied. Their collaborative work culminated in their 1972 book *Human Problem Solving*, but each went on to develop further systems, such as SOAR and extensions of EPAM. At MIT McCarthy developed a list processing language (LISP), which became a standard tool of AI. Students working with him and Minsky wrote LISP programs to perform such tasks as retrieving semantic information (Raphael's SIR) and solving algebra word problems (Bobrow's STUDENT) and geometric analogies (Evans's ANALOGY). A 1968 book reporting this work also included a seminal chapter by Ross Quillian introducing semantic networks. At Stanford, a team headed by Charles Rosen built a computer-controlled robot named Shakey that could reason backwards from goals and take appropriate actions with boxes that were found in its environment. Working with a simulated box world rather than a physical one, Terry Winograd's SHRDLU at MIT offered innovations in data structures and planning and had the most successful natural language interface of the early 1970s. Around the same time William Woods developed Augmented Transition Network (ATN) grammars at Harvard and BBN. As the 1970s progressed, AI researchers recognized the limitations of reasoning with only atomized information. Some proposed larger-scale knowledge structures, such as Roger Schank's scripts and MOPs and Minsky's frames. Also, considerable progress was made in such specialized areas as expert systems, speech understanding programs, and computational linguistics.

2.2 Psycholinguistics

One of the most fruitful collaborations was between psychology and linguistics. Modern psycholinguistics had already begun to emerge in the early 1950s, especially in the context of a summer seminar sponsored by the Social Science Research Council in 1953. One of the aims of this interaction between post-Hullians and post-Bloomfieldians was to investigate the psychological reality of linguistic constructs such as phoneme. Though many of their empirical strategies still thrive in some form, the field was impacted by the echos of Chomsky's revolution in linguistics. In his 1959 review of B. F. Skinner's *Verbal Behavior*, Chomsky emphasized not only that linguistic behavior does not consist in reproduction of acquired responses but is creative in the sense that there is no bound to the novel but grammatically well-formed sentences one might produce or hear. Focusing on the poverty of the stimulus argument (that the input to children is inadequate to induce a language), Chomsky also later argued for an innate language capacity (Universal Grammar). A long-standing conflict developed between Chomskian developmental psycholinguists and those taking a cognitive interactionist perceptive (e.g., Elizabeth Bates). Meanwhile, Chomkian inspired psychologists showed that sentences with more transformations in their derivation were more difficult to process. Later, changes in linguistic theory led to a more nuanced psycholinguistics, including some Chomskian approaches.

2.3 Psychology

Information processing psychology drew explicitly or implicitly on computational ideas from information theory and AI. Some of the first glimmers of an information processing approach to psychology appeared in the work of Miller and Bruner, who established a Center for Cognitive Studies at Harvard in 1960. Research in the center focused on a host of topics including conceptual organization, language processing and development, visual imagery, memory, and attention. Eleanor Rosch, a Bruner student, began work that led in the 1970s to a view of categories that emphasized prototypes, fuzzy boundaries, and the primacy of basic-level categories. And in 1967 Ulric Neisser, one of the Center's many research fellows and visitors, published *Cognitive Psychology*. This book introduced and synthesized the newly burgeoning work on information processing, particularly emphasizing attention and pattern recognition, and it quickly became the bible for a new generation of students.

Although the Center closed in 1970, information-processing approaches to psychology had already begun to spread to other universities. Stanford University, for example, built from its existing strength in mathematical psychology (including the work of William K. Estes) quickly to emerge as a premier center for information processing. In 1968 Richard Atkinson and Richard Shiffrin developed a model that integrated previous work on control processes, sensory memory (Sperling), short-term memory (Peterson and Peterson), and the distinction between short-term and long-term memory (William James; Waugh and Norman). Roger Shepard did elegant work in mathematical psychology (e.g., he pioneered nonparametric multidimensional scaling), but is best known for his research on mental imagery and mental rotation with such students as Lynn Cooper and Jacqueline Metzler. For example, they demonstrated that when subjects had to decide whether a comparison stimulus was a rotation or a mirror image of a geometrical form, their reaction times increased linearly with the degree of rotation. This suggested that subjects mentally rotated the comparison stimulus—an attention-grabbing claim at a time when mentalism was still suspect in many quarters. A third researcher, Gordon Bower, moved from mathematical models of learning towards more cognitively oriented work on the nature of mental representations. One of his students, John Anderson, worked with Bower on a very influential semantic network model (HAM), that was described in their 1973 book, *Human Associative Memory*. Later Anderson combined it with a production system component in ACT* and its predecessors.

Another exemplar is University of California, San Diego, where the trio of Peter Lindsay, Donald Norman, and David Rumelhart created a collaborative research group (LNR) in a new department and institution. In 1975 they published *Explorations in Cognition*, which ended with what may have been the first published use of the term cognitive science: 'The concerted efforts of a number of people from … linguistics, artificial intelligence, and psychology may be creating a new field: cognitive science' (Norman et al. 1975). (A second candidate for first use is a 1975 book by Bobrow and Collins, *Representation and Understanding: Studies in Cognitive Science*.) In addition to work on varied topics including memory, word recognition, problem solving, imagery, and analogy, the group implemented an ambitious memory model, MEMOD. It featured active structural networks, which used a common semantic network format to represent both data and process (e.g., declarative and procedural knowledge). A decade later yet another collaborative group coalesced at UCSD around Rumelhart and James McClelland; known as the PDP (parallel distributed processing) group, it helped bring neural networks (connectionist models) back to center stage.

Sensing the potential to catalyze cognitive science programs at these and other universities, the Alfred P. Sloan Foundation launched an initiative that eventually provided \$17.4 million over 10 years to such institutions as MIT and the University of California, Berkeley. During 1982–84 another foundation, The System Development Foundation, contributed \$26 million for computational linguistics and speech, with its largest support going to the Center for the Study of Language and Information at Stanford.

During the same period, linguist-turned-computer-scientist Roger Schank, psychologist Allan Collins, and computer scientist Eugene Charniak began a new journal called *Cognitive Science*. Describing a converging view of natural and artificial intelligence in his introduction to the first issue in 1977, Collins wrote: 'This view has recently begun to produce a spate of books and conferences, which are the first trappings of an emerging discipline. This discipline might have been called applied epistemology or intelligence theory, but someone on high declared it should be cognitive science and so it shall. In starting the journal we are just adding another trapping in the formation of a new discipline.' Drawing upon some of the early Sloan money, Donald Norman and his colleagues at UCSD organized the La Jolla Conference on Cognitive Science. But as planning proceeded the idea of a new society germinated, and the conference (held August 13–16, 1979) became the first annual meeting of the Cognitive Science Society.

3. Developing New Identities

By 1980 cognitive science had developed an institutional profile and was the focus of serious funding initiatives. It also had an identity, one that emphasized computational modeling of cognitive and linguistic processes, but also incorporated linguistics and psycholinguistics. The subsequent two decades have seen major efforts to revise this initial identity. Three contributing factors, each involving perspectives from disciplines not central to the cognitive science of the 1970s, deserve brief mention. First, the development of cognitive science gave philosophers, long interested in issues surrounding the mind, a chance to address such issues in the context of ongoing empirical research. Jerry Fodor argued that cognitive processes are autonomous from the neural substrate and capable of being realized in multiple ways; this view, congenial to the cognitive science of the 1970s and 1980s, was subsequently challenged by Patricia and Paul Churchland, who have emphasized the co-evolution of cognitive science and neuroscience.

Second, mavericks in a variety of disciplines found cognitive science's nearly exclusive focus on processes within the head a limitation. Philosopher Hubert Dreyfus challenged the attempt to analyze cognition as formal computational processes. Neisser integrated information processing with the ecological psychology of James J. and Eleanor J. Gibson. Edward Hutchens and many others began to focus on how embodiment and the situatedness of agents contribute to their cognitive performance.

Finally, although study of the brain largely disappeared from cognitive science in the 1960s and 1970s, partly because research on brain processes seemed too remote to contribute to understanding cognitive operations, the late 1980s and 1990s saw the emergence of cognitive neuroscience. Michael Posner, Marcus Raichle, and Steven Petersen collaborated at Washington University to show how images from PET could be used to link brain processes to cognitive processes. More recently greater spatial resolution has been gained using fMRI and greater temporal resolution using EEG-based methods such as ERP. Whether cognitive science can successfully incorporate these pilgrimages out into the world and down into the brain, or whether it will ultimately fractionate, is a question still unanswered.

See also: Artificial Intelligence in Cognitive Science; Behaviorism, History of; Cognitive Neuroscience; Cognitive Psychology: History; Cognitive Science: Overview; Cognitive Science: Philosophical Aspects; Psychology: Historical and Cultural Perspectives; Neuroscience, Philosophy of

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Cognitive Science: Overview

Cognitive science (CS) is a young discipline that emerged from a research program started in 1975. It partially overlaps with its mother disciplines: psychology, artificial intelligence, linguistics, philosophy, anthropology, and the neurosciences. By no means the only discipline dedicated to the study of cognition, cognitive science is unique in its basic tenet that cognitive processes are computations, a perspective which allows for direct comparison of natural and artificial intelligence, and emphasizes a methodology that integrates formal and empirical analyses with computational synthesis. Computer simulations as generative theories of cognition (see *Cognitive Modeling: Research Logic in Cognitive Science*) have therefore become the hallmark of CS methodology.

Today, CS is an internationally established field. The dominant tradition of the early years, close to artificial intelligence and its symbol-processing architectures, has been enriched by alternative computational architectures (e.g., artificial neural networks) and by the recognition that natural, especially human cognition, rests on biological as well as on social and cultural foundations. CS studies cognitive systems, which may be organisms, machines, or any combination of these acting in an environment that may be open and dynamically changing. Cognition in CS denotes a class of advanced control mechanisms that allow for sophisticated adaptation to changing

International Encyclopedia of the Social & Behavioral Sciences ISBN: 0-08-043076-7