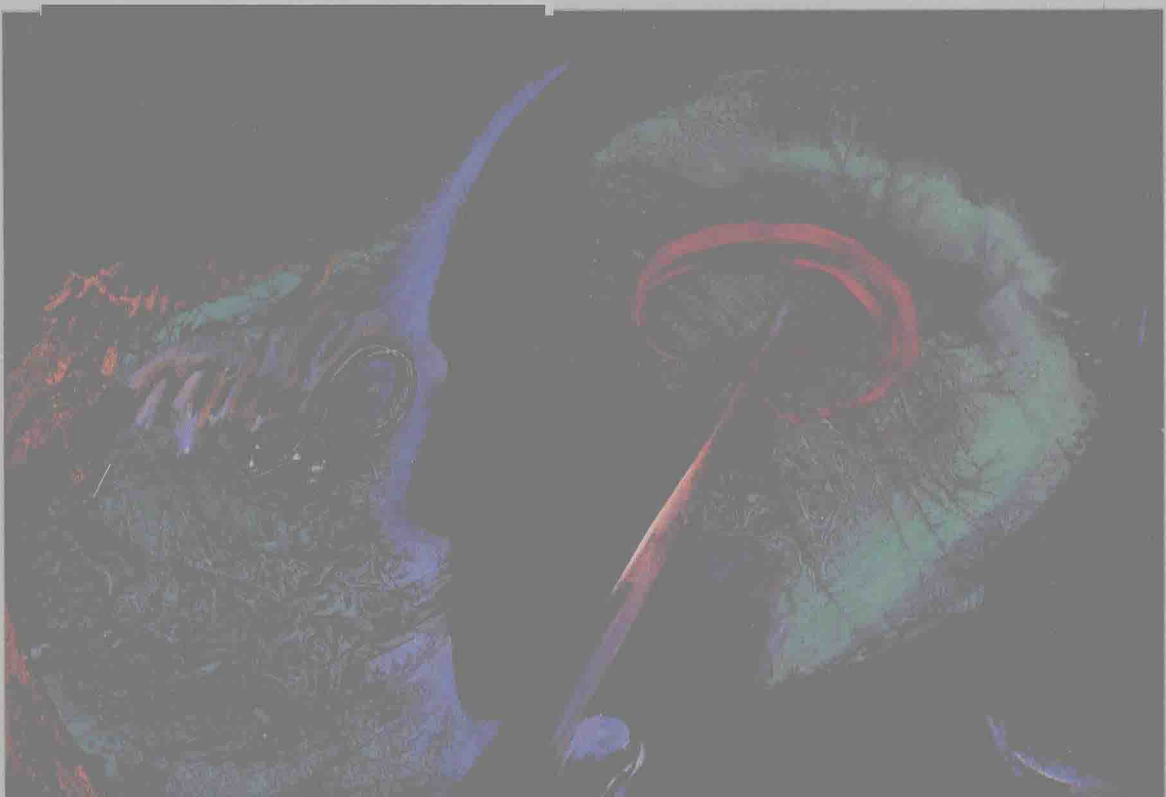
FOUNDATIONS OF COGNITIVE SCIENCE

edited by Michael I. Posner



Foundations of Cognitive Science

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Michael I. Posner

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Preface: Learning Cognitive Science

To learn a new field, according to the cognitive science approach, is to build appropriate cognitive structures (chapter 1) and to learn to perform computations (chapter 2) that will transform what is known into what is not yet known. Despite the presence of preliminary theories of scientific induction, no one knows how to teach this over any substantial domain (chapters 12, 13). Nonetheless this book is meant to convey to a new generation of researchers what is currently known about the basic structure of cognitive science.

In this volume cognitive science deals with the nature of intelligence from the perspective of computation (chapters 1, 2). Sometimes its focus is upon symbols, those representations that stand for something else (chapter 3). The ability to manipulate symbols has allowed inanimate physical systems to solve problems and perform functions previously performed only by human beings (chapter 14). The concept of the mind as a symbol processor implies an architecture of cognition (chapter 3) that has been and is currently of great influence in the field. This architecture is then applied to the development of language (chapter 9), the construction of meaningful discourse (chapter 11), and the understanding of problems (chapters 13, 14).

Inspiration for computational ideas may come from animate systems as well as from inanimate ones. The architecture of parallel distributed (connectionist) systems is inspired by the style of computation found in nervous systems. The impressive new results in this field are reviewed in chapter 4, and methods for bridging the distance between real neurons and more abstract computational levels are introduced in chapter 8. In one way or another the chapters on reading, vision, memory, and action all relate to the theory and methods of connectionism.

Grammar was the impetus for many important developments in cognitive science. Many of the ideas for rule-based systems as the basis of computation in language came originally from transformational grammar (see chapter 5 for a review). Language involves more than syntax; it has the character of being about something that stands outside itself.

The complex of issues that relate language to the outside world raises many logical questions of semantics (discussed in chapter 6).

Syntax and semantics are both very basic to the study of the acquisition of spoken (chapter 9) and written language (chapter 10) and to its use in communication (chapter 11). The effort to develop direct communication between humans and machines (chapter 11) makes clear the centrality of real world understanding that lies outside of the formal domain of language. The nonlinguistic functions so important to the understanding and use of language include the learning of categories (chapter 13), constructing models of real world activity (chapter 12), and studying the ability to develop and employ heuristics in the process of solving problems (chapter 14). A greal deal of this book can be seen as based on the foundations of the formal analysis of grammars and semantics.

Much of cognitive science rests on empirical studies that describe the performance of human subjects in cognitive tasks. These empirical studies may involve verbal protocols (chapter 1), eye movement protocols (chapters 7, 10), or other experimental methods using response speed (chapters 2, 7), accuracy, or memory performance (chapter 7). The results of these experimental methods form the basis for the domains of reading (chapter 10), attention (chapter 16), memory (chapter 17), and action (chapters 18, 19). What makes many of these domains exciting now is the ability to summarize and extend empirical findings by the use of a variety of formal mathematical or simulation methods. Some of these methods are introduced in the foundations section in chapters 2 and 3. These methods have led to the development of expert systems, computer-assisted tutors, and other simulations based on symbolic processing. They have had their greatest impact in the study of language acquisition, induction, and problem solving.

Connectionist models have been important in tieing the findings made with cognitive methods to underlying neural systems. The use of simulation based on neural style computation directs attention to methods that connect neural systems with cognition. These methods are reviewed in chapter 8. They are having important applications in the study of language processing (chapter 10), attention (chapter 16), memory (chapter 17), and motor control (chapters 18, 19), among other areas. In order for connectionist models to make additional contact with the underlying physiology, it will be necessary to employ empirical techniques that allow for the localization of cognitive operations within the brain. Fortunately, newer methods of neural imaging and recording of time-locked electrical and magnetic signals are providing methods for making such connections (chapter 8). In some areas (chapters 16, 17, 19) the combined cognitive and neuroscience methodology makes it difficult to separate brain and mind approaches to empirical issues. It appears likely that in some areas of cognition there will be very fruitful links between neuroscience and cognitive science. In other areas only cognitive methods and simulations will be available.

Achievements in many domains of cognitive science have been impressive. Nonetheless, if the goal is no less than a verified architecture of cognition that can illuminate the full range of human intelligence, the distance yet to go is staggering. Two areas in which these distances are most notable are in the study of cultural differences in cognition and subjective mental experience and the brain. In the former area cognitive psychologists and anthropologists have both pointed the way to methods for understanding the pervasive role of culture in directing the thought processes. Although it may be convenient to suppose that a cognitive theory of representation is complete without consideration of the different contents imposed by acculturation, it seems more likely that we will understand cognitive representations better when we can consider them in the context of the cultures in which they are found (chapter 20).

Similarly, it was once fashionable to say that cognition could be implemented in any electromechanical system, so that the details of mere hardware were of no basic importance to cognitive theory. The influence of connectionist ideas (chapter 4) and the increased understanding of localization of function (chapter 8) have both worked to erode this separation. While we can now begin to talk more confidently about the neural systems involved in word reading or selective attention, this is not sufficient to explain how the brain creates and contains subjective experience. This issue is discussed from the point of view of philosophy in chapter 21. The chapter raises paradoxes that may become more critical with progress in synthesizing mind and brain.

The organization of this volume is simple. Following an overview chapter, the foundations of the field are laid in seven review chapters. These foundations are then applied to a dozen areas prominent in the current literature. The final two chapters represent critiques of the field's current state from the point of view of cultural anthropology and philosophy.

The idea for this volume arose from members of the cognitive science community who contacted Harry Stanton of Bradford Books at The MIT Press. Harry and Betty Stanton have been instrumental in all phases of the development of this project from its initiation to the production of the volume. Charlotte Golar Richie helped with assembling the manuscript. A board of editors, which included many of the authors of this volume, assembled in St. Louis to outline the chapters needed to carry forth the project. In editing the volume, I had very substantial help from George Miller, Dan Dennett, Allen Newell, Tom Wasow, Steve Pinker, Ed Smith, Richard Ivry, Barbara Tversky, Scott DeLancey, Gordon Shulman, Adele Diamond, and Steven Petersen. A generous grant from the Sloan Foundation has been vital to the development of this project.

There is no pretense that this volume contains all of cognitive science as it currently exists and still less as it will be by the time you read these words. But we hope that in these pages you will find out enough about the field to get a feeling for its methods, suppositions, and results.

Foundations of Cognitive Science

Contents

1 Foundations of Cognitive Science

Herbert A. Simon and Craig A. Kaplan

This chapter treats rather concisely a range of topics that help define the scope of cognitive science and the numerous dimensions along which the field can be explored. It focuses more on identifying issues than on providing definite answers, a task more appropriately left for the contributors on specific topics.

Since many different methods are used in cognitive science research, since several different conceptual approaches have been taken to the field, and since a number of different architectures for intelligent systems are being explored, we take some pains to recognize this diversity. At the same time we do not hesitate to express opinions about which ideas seem most correct or promising and which lines of inquiry seem most worthy of pursuit. The authors of other chapters have ample opportunity to redress our imbalances.

1.1 The Goals of Cognitive Science

Cognitive science is the study of intelligence and intelligent systems, with particular reference to intelligent behavior as computation. Although no really satisfactory intentional definition of intelligence has been proposed, we are ordinarily willing to judge when intelligence is being exhibited by our fellow human beings. We say that people are behaving intelligently when they choose courses of action that are relevant to achieving their goals, when they reply coherently and appropriately to questions that are put to them, when they solve problems of lesser or greater difficulty, or when they create or design something useful or beautiful or novel. We apply a single term, "intelligence," to this diverse set of activities because we expect that a common set of underlying processes is implicated in performing all of them.

When we wish to compare different people on a scale of intelligence, we construct batteries of tests presenting a variety of tasks that require them to solve problems or to use language appropriately. There are innumerable kinds of tests that exercise the intellectual capabilities of the test takers. Some of them call upon knowledge of very specific subject matter, but those we specifically label "intelligence tests" are usually designed to be as independent of subject-matter knowledge as possible—or at least only to draw upon subject matter that is presumed to be familiar to most members of the culture (general vocabulary, arithmetic, and the like). In this chapter we discuss both knowledge-based and (almost) knowledge-free intelligence.

Today it is quite common to attribute intelligence to both human and nonhuman systems and, in particular, to programmed computers. Not everyone accepts this usage, but we call programs intelligent if they exhibit behaviors that would be regarded as intelligent if they were exhibited by human beings. Intelligence is to be judged by the ability to perform intellectual tasks, independent of the nature of the physical system that exhibits this ability.

Cognitive science, defined as the study of intelligence and its computational processes, can be approached in several ways. We can undertake to construct an abstract theory of intelligent processes, divorced from specific physical or biological implementations. We can study human (or animal) intelligence, seeking to abstract a theory of intelligent processes from the behavior of intelligent organisms. Or we can study computer intelligence, trying to learn the computational principles that underlie the organization and behavior of intelligent programs.

In fact, cognitive science follows all of these paths. Several venerable examples of the study of intelligence in the abstract predate the computer. Formal logic is one such example; the theory of maximization of expected utility is another. For a century or more, experimental psychology has been studying organismic intelligence, especially as exhibited by people, rats, and pigeons in the laboratory. Since at least 1950 (we might take Turing's (1950) essay "Computing Machinery and Intelligence" as a convenient starting point) that branch of computer science called "artificial intelligence" has been studying the intelligence exhibited by machines. (Watt's governor or Pascal's calculating machines might be regarded as even earlier examples of machine intelligence.)

For the purposes of this chapter, then, we define cognitive science as the study of intelligence and its computational processes in humans (and animals), in computers, and in the abstract. It will be instructive to see how the communality among these three topics came to be recognized and how that recognition led to the birth of the discipline of cognitive science.

1.2 The Principal Contributing Disciplines

From a sociological standpoint, disciplines are defined less by their intellectual structure and content than by the scientists who identify with them. But more accurately, over time the intellectual content of a discipline gradually defines its boundaries and membership, whereas its membership gradually redefines its content. Therefore, if we are to understand cognitive science, we must know what disciplines have contributed to its formation (Norman 1981). Among these we must certainly count experimental and cognitive psychology, artificial intelligence (within computer science), linguistics, philosophy (especially logic and epistemology), neuroscience, and some others (anthropology, economics, and social psychology will also come in for comment).

Psychology

From its beginnings the discipline of psychology has been concerned with intelligence. The Binet–Simon intelligence test (the IQ test par excellence) dates from the turn of the century. The dominance of behaviorism during the first half of the century prevented experimental psychologists from being much interested in what was going on inside the organism, however; hence there was limited speculation and research about process. Brain research contributed to our knowledge of the location of functions witin the brain but had relatively little to say about cognitive processes. Even the precise physiological basis of memory was not (and has not yet been) unambiguously determined.

During the high tide of behaviorism, experimental psychology focused on relatively simple cognitive performance, with emphasis on sensory and motor processes such as rote verbal learning, tracking tasks requiring hand-eye coordination, memory tasks involving relatively short-term retention, and the attainment of simple concepts. The intelligence of rats and pigeons received as much attention as the intelligence of people. It was left primarily to the Gestalt psychologists to develop theories of human cognitive processes, especially for complex cognitive performances like concept formation and problem solving.

Psychology was no more monolithic than chemistry or physics: various specializations were (and are) visible, each of which has brought its particular contribution to cognitive science. Psychometrics brought its measures of intelligence and the components of intelligence. Neurophysiology brought knowledge of the biological structures that support thought. Experimental psychology brought a host of information about the speed and limitations of simple sensory, perceptual, motor, and memory processes. Gestalt psychology brought hypotheses about the processes that occur in complex thinking. Although there was some communication among these specialities, each tended to go its own way, guided by its own paradigm. A new paradigm was required to make a convincing case for their mutual relevance.

The shift came with the so-called information-processing revolution of the fifties and sixties, which viewed thinking as a symbol-manipulating process and used computer simulation as a way to build theories of thinking (Simon 1979a). A relatively new specialization, psycholinguistics, found the information-processing view congenial and opened up a line of communication between psychology and linguistics.

Mainline experimental psychology also began to adopt the information-processing point of view without necessarily embracing computer simulation, and a rough division of labor began to develop between those scientists (often computer simulators) who studied the so-called higher mental functions, such as concept formation, problem solving, and use of language, and those (less often computer simulators) who studied simpler, and more traditional, memory and perceptual tasks. The chapters by Simon (1979b) and Posner and McLeod (1982) in the *Annual Reviews of Psychology* provide a good overview of these two parts of the cognitive psychology scene in the late seventies and early eighties.

Artificial Intelligence

The very term "artificial intelligence," coined about 1956, incorporated the belief that the concept of intelligence now had to be extended beyond human and animal performance to include artificial systems—computers. Because it is by no means evident just what the intelligence of people and the intelligence of computers have in common beyond their ability to perform certain tasks, the close relation that has been maintained between research in AI and research in cognitive psychology was not preordained or even predictable.

The earliest artificial intelligence programs (for example, the Logic Theorist (Newell and Simon 1956)) are perhaps best viewed as models of abstract intelligence; but nonetheless their design was informed by psychological research on memory and problem solving—note, for example, the use of associative structures in list-processing programming languages and subsequently the frequent use of means–ends analysis for inference.

In turn AI research has made numerous contributions to cognitive psychology. For example, AI provided list-processing languages that permit the modeling of elaborate associative structures—schemas, scripts, frames—to simulate important properties of human semantic memory (Newell and Simon 1963). AI research also adapted programming languages built up from so-called productions as a sophisticated interpretation and augmentation of classical stimulus–response relations and stimulus-recognition processes (Rich 1983). Research on robotics has often turned to sensory and perceptual psychology for ideas about processing schemes, and the psychology of vision and speech recognition has borrowed many ideas from AI.

In fact, then, there has been a close continuing relation between AI and cognitive simulation during the whole thirty-odd years of the history of both subjects, and their mutual relevance and synergy was a major motivation for creating a common meeting ground in cognitive science.