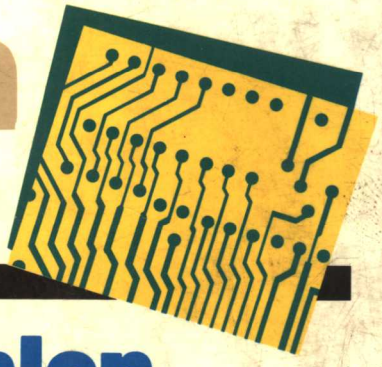
Intelligence

The Eye, the Brain, and the Computer



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Preface

This book is intended to be an intellectual journey into the domain of human and machine intelligence. The subject matter has been approached from a conceptual and sometimes even philosophical point of view, one biased by our experience in that branch of computer and cognitive science called artificial intelligence (AI). On this journey we will often be dealing with topics, such as the operation of the brain, where knowledge is lacking, and where there are only vague conjectures as to possible mechanisms. In our review of machine intelligence, we will discuss both the present-day and ultimate limits of machine performance.

We intend the book to provide the *Scientific American* level reader with an understanding of the concept of intelligence, the nature of the cognitive and perceptual capabilities of people and machines, and the representations and algorithms used to attain intelligent behavior. While we have attempted to make the material understandable by an educated layman, we are equally concerned with having something important to say to our professional colleagues and peers.

"Boxes" have been used to augment the text. These boxes, and longer appendices, present material of interest that expand on the topics being discussed, and sometimes they may contain technical material of more interest to the specialist. It is intended that the text should stand on its own; the reader can usually omit the boxes until a later reading.

A unifying theme in our exposition is the critically important concept of representation. Issues related to this and other important concepts may be raised in an earlier chapter, our position stated, and then elaborated and supported in later chapters. If our initial discussion on some important point appears to be brief or unsupported, have faith, since we will probably return to this topic many times before your journey through the book is completed.

Our primary purpose in the first part of this book is to provide a basis for understanding the nature of intelligence and intelligent behavior: (a) as it exists in man and higher animals, (b) as it could exist in a machine, and (c) as a scientific discipline concerned with the mechanisms and limits involved in acquiring, representing, and applying knowledge.

The last part of the book deals with perception and primarily vision, the means by which knowledge about our physical environment is acquired. We will see that perceptual behavior, far from being passive or mechanical, requires a reasoning ability at least equal to that needed for the most difficult problem-solving tasks.

The flavor of this book can be gleaned from the following brief description of chapter topics.

Intelligence

This chapter discusses the nature of intelligence, indicating its characteristics or components. We examine the issue of whether intelligence is primarily associated with functional behavior (performance) or with the structures and machinery that give rise to behavior (competence). The role of language in intelligence is explored and we speculate about the role of emotion (pain,pleasure), aesthetic appreciation, and physical interaction with the external world, in achieving intelligent behavior. The subject of artificial (machine) intelligence is introduced and something of its history, goals, and approach is indicated. Finally, the problem of measuring or evaluating intelligence is treated.

The Brain and the Computer

We examine the ultimate capacity of the computer as an *intelligence engine* and whether man can create a machine more intelligent than himself. Are there components of man's intelligence which cannot be found in any animal or duplicated in a machine? Are there essential differences between the architecture of the human brain and the digital computer which imply a difference in capacity or competence? Are there problems that cannot in theory be solved by a machine?

The Representation of Knowledge

We explore the concept of *knowledge*, and note that the nature of the physical encoding of knowledge is an important consideration in achieving intelligent behavior. We describe how knowledge can be represented in the memory of a computer and raise the question as to whether there are elements of knowledge that cannot be described or discussed.

Reasoning

This chapter discusses the role of reasoning in intelligent behavior. We describe how a reasoning system can use a formal language to represent things in the world and their relationships, and how it can solve problems using such a representation. The limits of formal representations in their ability to solve problems and to deal with vaguely formulated problems are indicated. The crucial difficulty arises of how a reasoning system might select the best representation for a given problem, since how can a reasoning system know which facts in its database are relevant to the problem at hand?

Learning

While a primary attribute of learning is the formulation of concepts and representations to deal effectively with new situations, an important aspect of the learning process is the identification of a particular situation as being an instance of an already-learned concept. We will find that the noting of such similarities is far from trivial, and that *analogy* lies at the heart of much of the learning process. This chapter examines the different modes of learning, and indicates the extent of present-day machine learning.

Language and Communication

This chapter examines the purpose of language and methods of communicating, and explores the role of language in intelligent behavior. The question arises as to whether man is the only organism with a true capacity for language. Finally, we discuss the approaches used for machine "understanding" of natural language.

Expert Systems

We describe *expert systems*, programs that duplicate human expertise in a specialized field such as medicine or engineering. These systems are of interest because they can act at a high level of competence by relying on a detailed *knowledge base* of information, despite a rather limited reasoning ability.

Biological Vision

Visual perception is one of the most difficult tasks yet faced in attempting to design machines that can duplicate human behavior. The relationship between the evolutionary development of vision in organisms and their needs and limitations is explored. We examine the universal mechanisms that nature has devised and which offer a solution to the problem of visual understanding of the world.

Computational Vision

This chapter describes the representations and algorithms that are used in computer analysis of images. We indicate how sensor information is converted to an array of numbers and the problems involved in deducing a model of the three-dimensional world

by means of operations carried out on such image arrays. The major problems and paradigms underlying current attempts to achieve machine vision are discussed.

Epilogue

In this concluding chapter we restate and summarize the most important views and arguments relevant to the modeling of intelligence as an information processing activity that can be carried out by a machine. We discuss whether it is possible to construct an intelligent machine that can function in the world.

Acknowledgments

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The Addison-Wesley reviewers, Anthony Pasera and Werner Feibel, were masterful in their criticisms, not only pointing out deficiencies, but also providing the references that broadened our thinking on a number of topics. Chris Varley, our original editor at Addison-Wesley, was very enthusiastic about the project, and we greatly appreciate the continuing support of Peter Gordon, our current editor.

Various chapters of the book were reviewed by the following people, but we take full blame for any remaining errors in the text: James Dolby, Martin Billik, and Jon Pearce, San Jose State University; Gordon Uber, Lockheed Palo Alto Research Laboratory; Peter Cheeseman, NASA Ames; Hugh Crane, Don Kelly, Michael Georgeff, Ray Perrault, Jerry Hobbs, Phil Cohen, and Enrique Ruspini, all of SRI. SRI colleagues who helped in other ways include Ken Laws, Grahame Smith, Lynn Quam, Helen Wolf, Steve Barnard, Bob Bolles, Alex (Sandy) Pentland, and Andrew Hanson.

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Our families served as intelligent lay reviewers: Beverly, Sharon, and Ron Fischler; and Ben, Joseph, and Theda Firschein. Sharon Fischler also contributed some of the ideas for the final artwork.

Menlo Park, CA

M.A.F.
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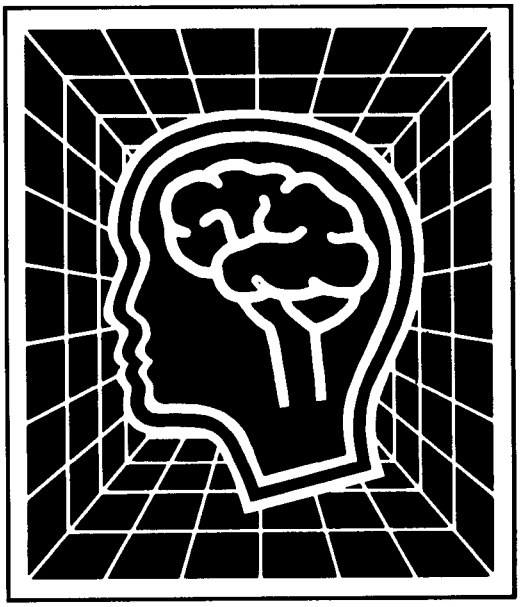
Contents

Part One

Foundations



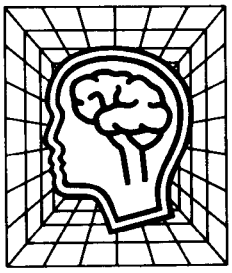
1. Intelligence
2. The Brain and the Computer
3. The Representation of Knowledge

In the first portion of this book we examine, in a very general way, the nature of intelligence and the principal mechanisms by which it is achieved.

Our subject matter includes the attributes of intelligent behavior, the structure of the "reasoning engines" devised by both nature and man, and the critical role played by the way in which knowledge is encoded. These topics provide a foundation for our discussion, in Parts II and III, of cognition and perception, the two major faculties by which intelligence is exhibited.

1

Intelligence



In this book we will explore some of the central aspects of intelligent behavior, and the approaches employed in creating machines that can exhibit such behavior. Our purpose in this chapter is to address three broad questions about the nature of intelligence:

- What is intelligence, and to what extent is it a unique attribute of the human species?
- How can intelligence be measured or evaluated?
- What is the nature of the mechanisms that are capable of intelligent behavior? In particular, can a machine be designed to display intelligent behavior?

WHAT IS INTELLIGENCE?

Intelligence is easier to recognize than to define or measure. While the word "intelligence" is used in ordinary conversation, and has a dictionary definition, it has no agreed-upon scientific meaning, and no quantitative natural laws relating to intelligence have as yet been discovered. In view of this situation, the concept of intelligence is subject to change as our understanding of human intelligence increases. Further, without a scientific definition, much of the social debate over matters relating to intelligence (e.g., contentions about racial differences with respect to intelligence) cannot be rationally resolved.

A dictionary definition of intelligence

includes statements such as *(1) the ability to meet (novel) situations successfully by proper behavior adjustments*; or *(2) the ability to perceive the interrelationships of presented facts in such a way as to guide action toward a desired goal.* We can associate the word "learning" with the first statement, and goal-oriented behavior, problem solving, and understanding with the second. Some additional attributes of intelligence (see Tables 1-1 and 1-2) include reasoning, common sense, planning, perception, creativity, and memory retention and recall.

Theories of Intelligence

Theories of intelligence are primarily concerned with identifying the major independent components of intelligent behavior, and determining the importance of, and interactions between mechanism, process, knowledge, representation, and goals. In particular, such theories address the following issues:

- *Performance theories*: How can one test for the presence or degree of intelligence? What are the essential func-

TABLE 1-1 ■ Attributes of an Intelligent Agent

We expect an intelligent agent to be able to:

- Have mental attitudes (beliefs, desires, and intentions)
- Learn (ability to acquire new knowledge)
- Solve problems, including the ability to break complex problems into simpler parts
- Understand, including the ability to make sense out of ambiguous or contradictory information
- Plan and predict the consequences of contemplated actions, including the ability to compare and evaluate alternatives
- Know the limits of its knowledge and abilities
- Draw distinctions between situations despite similarities
- Be original, synthesize new concepts and ideas, and acquire and employ analogies
- Generalize (find a common underlying pattern in superficially distinct situations)
- Perceive and model the external world (see Box 1-1)
- Understand and use language and related symbolic tools

TABLE 1-2 ■ Attributes Related to, but Distinct from, Intelligence

There are a number of human attributes that are related to the concept of intelligence, but are normally considered distinct from it:

- Awareness (consciousness)
- Aesthetic appreciation (art, music)
- Emotion (anger, sorrow, pain, pleasure, love, hate)
- Sensory acuteness
- Muscular coordination (motor skills)

tional components of a system capable of exhibiting intelligent behavior?

- *Structural/function theories*: What are the mechanisms by which intelligence is achieved?
- *Contextual theories*: What is the relationship between intelligent behavior and the environment with which an organism must contend?
- *Existence theories*: What are the necessary and/or sufficient conditions for intelligent behavior to be possible?

(A separate set of issues is associated with the question of how theories of intelligence can be validated.)

Theories are statements, circumscribed by definitions, about objects and their relationships that are implicit in a body of knowledge. Thus, definitions and theories of intelligence cannot be separated. Quantitative definitions of intelligence range from implicitly defining intelligence as that human attribute which is measured by IQ tests, to assuming that the total information processing capacity of the brain is measured by its size.[1] However, the dimension along which definitions of intelligence differ most is the structural (internal) versus the contextual (external). At the structural extreme, intelligence is viewed as the competence of the human (or animal) nervous system to reason, while at the contextual extreme, intelligence is viewed as the ability of an organism to adapt to its physical and social environment. In the latter case, goals, expectations, stored knowledge,

[1]Beyond that needed to support normal body functions.

BOX 1-1 Visual Thinking

The idea that "visual thinking" and artistic creation are part of intelligent behavior has been discussed by Arnheim as follows [Arnheim 69]:

> My contention is that the cognitive operations called thinking are not the privilege of mental processes above and beyond perception but the esssential ingredients of perception itself. I am referring to such operations as active exploration, selection, grasping of essentials, simplification, abstraction, analysis and synthesis, completion, correction, comparison, problem solving, as well as combining, separating, putting into context. These operations are not the prerogative of any one mental function; they are the manner in which the minds of both man and animal treat cognitive material at any level. There is no basic difference in this respect between what happens when a person looks at the world directly, and when he sits with his eyes closed and "thinks."

Another aspect of visual thinking is the concept that the artist constructs his drawings by a reasoning process. Gombrich [Gombrich 61] describes the task of setting down a pictorial likeness on a flat surface as resembling the method used by scientists in arriving at a theoretical description of the natural world. The artist does not simply trace an outline of their visual contours to represent the appearance of things, but instead prepares a hypothetical construction to be matched and then modified in the light of further evaluation. Through an iterative process, the artist gradually eliminates the discrepancies between what is seen and what is drawn, until the image on the flat surface begins to resemble a view of the world as it might be seen through a pane of glass. The iterative process of the artist corresponds to the conjectures and refutations of the scientist in creating a theory of nature.