

Intelligence

The Eye,
the Brain,
and the
Computer



Intelligence

The Eye, the Brain, and the Computer

Martin A. Fischler

SRI International

Oscar Firschein

SRI International



ADDISON-WESLEY PUBLISHING COMPANY

Reading, Massachusetts • Menlo Park, California • Don Mills, Ontario
Wokingham, England • Amsterdam • Sydney • Singapore • Tokyo
Madrid • Bogotá • Santiago • San Juan

Sponsoring Editor • Peter S. Gordon
Production Supervisor • Bette J. Aaronson
Copy Editor • G. W. Helfrich
Text Designer and Art Coordinator • Geri Davis, Quadrata Inc.
Cover Designer • Marshall Henrichs
Manufacturing Supervisor • Hugh Crawford

Library of Congress Cataloging-in-Publication Data

Fischler, Martin A.

Intelligence : the eye, the brain, and the computer.

Bibliography: p.

Includes index.

1. Artificial intelligence. 2. Machine learning.
3. Cognition. 4. Perception. I. Firschein, Oscar.
- II. Title.

Q335.F57 1987 006.3 86-3557

ISBN 0-201-12001-1

Reprinted with corrections April, 1987

Copyright © 1987 by Addison-Wesley Publishing Company, Inc. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher. Printed in the United States of America. Published simultaneously in Canada.

BCDEFGHIJ-HA-8987

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.

PREFACE

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

viii
PREFACE

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

We owe a major debt to three people for their extensive help with respect to both technical and organizational aspects of this book: Professor Walter Gong, San Jose State University; Dr. Richard Duda, Syntelligence; and Professor Nils Nilsson, Stanford University.

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.

We are grateful for the environment of the SRI Artificial Intelligence Center made possible by the past leadership of Peter Hart and Nils Nilsson, and now by Stan Rosen-schein. We acknowledge the earlier influence on our thinking by Russell Kirsch and David Willis.

We wish explicitly to acknowledge the contribution made by DARPA, whose enlightened support at the national level was critical to the development of artificial intelligence as a scientific discipline. In particular, we cite those technical monitors with whom we had direct contact with in our work in machine vision: Dave Carlstrom, Larry Druffel, Ron Ohlander, Bob Simpson, and (at a higher management level) Bob Kahn and Saul Amarel.

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.
O.F.

Contents



Part One

Foundations 1

1 Intelligence 3

What Is Intelligence? 3

- Theories of Intelligence 4
- Theories of Mind 8

How Can Intelligence Be Measured or Evaluated? 10

- Assessing Human Intelligence 10
- Assessing Machine Intelligence 12

Is Man The Only Intelligent Animal? 12

The Machinery of Intelligence

- Reliance on Paradigms 13
- Two Basic Paradigms 13

Artificial Intelligence (AI) 15

- The Mechanization of Thought 15
- The Computer and the Two Paradigms 18
- How Can We Distinguish Between Mechanical and Intelligent Behavior? 18
- The Role of Representation in Intelligent Behavior 20

SUMMARY AND DISCUSSION 20

CONTENTS

2 The Brain and The Computer 23

The Human Brain	24
• Evolution of the Brain	24
• Architecture of the Brain	30
The Computer	39
• The Nature of Computer Programs and Algorithms	40
• The Universal Turing Machine	43
Limitations on the Computational Ability of a Logical Device	43
• The Gödel Incompleteness Theorem	43
• Unsolvability by Machine	45
• Implications of Gödel's Theorem	46
• Computational Complexity—the Existence of Solvable but Intrinsically Difficult Problems	47
Limitations on the Computational Ability of a Physical Device	49
• Reliable Computation With Unreliable Components	51
DISCUSSION	55

Appendixes 58

2-1 The Nerve Cell and Nervous System Organization	58
2-2 The Digital Computer	61

3 The Representation of Knowledge 63

Representation: Concepts	64
• Form vs. Content of Knowledge	64
• Representing Knowledge	65
• The Relation Between a Representation and Things Represented	66
Role of Representation	67
Representations Employed in Human Thinking	67
• The Use of Models and Representations	68
• The Use of "Visual" Representations	69
Effectiveness of a Representation	69
Representations Employed in Artificial Intelligence	71
• Feature Space (or Decision Space)	74
• Decision Tree/Game Tree	75
• Isomorphic/Iconic/Analogical Representations	77
DISCUSSION	80



Part Two

Cognition	81
-----------	----

4	Reasoning and Problem Solving	83
---	-------------------------------	----

Human Reasoning	84
• Human Logical Reasoning	85
• Human Probabilistic Reasoning	86
Formal Reasoning and Problem Solving	87
• Requirements for a Problem Solver	87
• Categories of Reasoning	88
The Deductive Logic Formalism	90
• Propositional Calculus	90
• Propositional Resolution	91
• Predicates	93
• Quantifiers	93
• Semantics	93
• Computational Issues	94
• Nonstandard Logics	95
Inductive Reasoning	96
• Measures of Belief	97
• Bayesian Reasoning	98
• Belief Functions	100
• Representing a Problem in a Probabilistic Formalism	103
• Comments Concerning the Probabilistic Formalism	103
Additional Formalisms for Reasoning	106
• Algebraic/Mathematical Systems	106
• Heuristic Search	106
• Programming Systems that Facilitate Reasoning and Problem Solving	108
• Common-Sense Reasoning	109
Problem Solving and Theorem Proving	110
• Representing the Problem	111
• The Predicate Calculus Representation for the Monkey/Banana (M/B) Problem	112
• PROLOG Representation of the M/B Problem	113
• Production Rule (OPS-5) Representation for the M/B Problem	113
• General Problem Solver Representation for the M/B Problem	114
• Formalisms or Reasoning Systems?	115
• Relating Reasoning Formalisms to the Real World	115
DISCUSSION	116

xii
CONTENTS

Appendixes	117
4-1 AI Programming Languages	117
4-2 The Monkey/Bananas Problem	122
 5 Learning	 129
Human and Animal Learning	130
• Types of Animal Learning	131
• Piaget's Theory of Human Intellectual Development	132
Similarity	135
• Similarity Based on Exact Match	136
• Similarity Based on Approximate Match	137
Learning	137
• Model Instantiation: Parameter Learning	138
• Model Construction: Description Models	143
• Concept Learning	148
DISCUSSION	151
 Appendix	 152
5-1 Parameter Learning for an Implicit Model	152
 6 Language and Communication	 157
Language in Animals and Man	158
• Brain Structures Associated with Language Production and Understanding	159
• Human Acquisition of Language	161
• Animal Acquisition of Language	164
Language and Thought	165
Communication	167
• The Mechanics of Communication	167
• Vocabulary of Communication	168
• Understanding Language	169
Machine Understanding of Language	171
• Faking Understanding	171
• What Does it Mean for a Computer to Understand?	171
• The Study of Language	173
DISCUSSION	185

xiii
CONTENTS

Appendix	186
----------	-----

6-1 Representing Passing Algorithms	186
-------------------------------------	-----

7 Expert/Knowledge-Based Systems 189

Human Experts	190
Production Systems	191
• Control Structures Used in Production Systems	192
Production Systems in Psychological Modeling	195
Production Rule-Type Expert Systems	197
• Plausible Reasoning in Expert Systems	198
• Basic AI Issues	200
DISCUSSION	202

Appendix	202
----------	-----

7-1 PROSPECTOR Procedure for Hypothesis Updating	202
--	-----



Part Three

Perception (Vision)	205
---------------------	-----

8 Vision 207

The Nature of Organic Vision	207
The Evolution and Physiology of Organic Vision	209
• Seeing and the Evolution of Intelligence	209
• Evolution and Physiology of the Organic Eye	211
• Eye and Brain	213
The Psychology of Vision	220
• Perceiving the Visual World: Recognizing Patterns	220
• Perceptual Organization	224
• Visual Illusions	226
• Visual Thinking, Visual Memory, and Cultural Factors	229
DISCUSSION	232

xiv
CONTENTS

Appendixes	233
8-1 Color Vision and Light	233
8-2 Stereo Depth Perception and the Structure of the Human Visual Cortex	236
9 Computational Vision	239
Signals-to-Symbols Paradigm	241
Low Level Scene Analysis (LLSA)	242
• Image Acquisition (Scanning and Quantizing)	243
• Image Preprocessing (Thresholding and Smoothing)	245
• Detection of Local Discontinuities and Homogeneities (Edges, Texture, Color)	248
• Local Scene Geometry from a Single Image (Shape from Shading and Texture)	256
• Local Scene Geometry from Multiple Images (Stereo and Optic Flow)	259
Intermediate Level Scene Analysis (ILSA)	262
• Image/Scene Partitioning	264
• Edge Linking and Deriving a Line Sketch	269
• Recovering Three-Dimensional Scene Geometry from a Line Drawing	272
• Image Matching	276
• Object Labeling	278
• Model Selection and Instantiation	279
High Level Scene Analysis (HLSA)	281
• Image/Scene Description	281
• Knowledge Representation	283
• The Problem of High-Level Scene Analysis	285
• Reasoning About a Simple Scene	285
DISCUSSION	286
• A Basic Concern About Signals-to-Symbols	287
• Necessary Attributes of a Machine Vision System	288
• Summary	289
Appendixes	289
9-1 Mathematical Techniques for Information Integration	289
9-2 A Path-Finding Algorithm	297
9-3 Relational (Rubber Sheet) Image Matching	299
Epilogue	301
Bibliography	311
Index	325
