PART I
ARTIFICIAL INTELLIGENCE: ITS ROOTS
AND SCOPE

Artificial Intelligence—An Attempted Definition  1

1  AI: HISTORY AND APPLICATIONS  3

1.1 From Eden to ENIAC: Attitudes toward Intelligence, Knowledge, and Human Artifice  3

1.1.1 Historical Foundations  4
1.1.2 The Development of Logic  7
1.1.3 The Turing Test  10
1.1.4 Biological and Social Models of Intelligence: Agent-Oriented Problem Solving  13

1.2 Overview of AI Application Areas  17

1.2.1 Game Playing  18
1.2.2 Automated Reasoning and Theorem Proving  19
1.2.3 Expert Systems  20
1.2.4 Natural Language Understanding and Semantic Modeling  22
1.2.5 Modeling Human Performance  23
PART II
ARTIFICIAL INTELLIGENCE AS REPRESENTATION AND SEARCH

Knowledge Representation  34
Problem Solving as Search  41

2  THE PREDICATE CALCULUS  47

2.0  Introduction  47
2.1  The Propositional Calculus  47
  2.1.1  Symbols and Sentences  47
  2.1.2  The Semantics of the Propositional Calculus  49
2.2  The Predicate Calculus  52
  2.2.1  The Syntax of Predicates and Sentences  52
  2.2.2  A Semantics for the Predicate Calculus  58
2.3  Using Inference Rules to Produce Predicate Calculus Expressions  64
  2.3.1  Inference Rules  64
  2.3.2  Unification  68
  2.3.3  A Unification Example  72
2.4  Application: A Logic-Based Financial Advisor  75
3  STRUCTURES AND STRATEGIES FOR STATE SPACE SEARCH  81

3.0  Introduction  81

3.1  Graph Theory  84

3.1.1  Structures for State Space Search  84
3.1.2  State Space Representation of Problems  87

3.2  Strategies for State Space Search  93

3.2.1  Data-Driven and Goal-Driven Search  93
3.2.2  Implementing Graph Search  96
3.2.3  Depth-First and Breadth-First Search  99
3.2.4  Depth-First Search with Iterative Deepening  106

3.3  Using the State Space to Represent Reasoning with the Predicate Calculus  107

3.3.1  State Space Description of a Logical System  107
3.3.2  AND/Or Graphs  109
3.3.3  Further Examples and Applications  111

3.4  Epilogue and References  121

3.5  Exercises  121

4  HEURISTIC SEARCH  123

4.0  Introduction  123

4.1  An Algorithm for Heuristic Search  127

4.1.1  Implementing “Best-First” Search  127
4.1.2  Implementing Heuristic Evaluation Functions  131
4.1.3  Heuristic Search and Expert Systems  136

4.2  Admissibility, Monotonicity, and Informedness  139
5 CONTROL AND IMPLEMENTATION OF STATE SPACE SEARCH 159

5.0 Introduction 159

5.1 Recursion-Based Search 160
5.1.1 Recursion 160
5.1.2 Recursive Search 161

5.2 Pattern-Directed Search 164
5.2.1 Example: Recursive Search in the Knight's Tour Problem 165
5.2.2 Refining the Pattern-search Algorithm 168

5.3 Production Systems 171
5.3.1 Definition and History 171
5.3.2 Examples of Production Systems 174
5.3.3 Control of Search in Production Systems 180
5.3.4 Advantages of Production Systems for AI 184

5.4 Predicate Calculus and Planning 186

5.5 The Blackboard Architecture for Problem Solving 196

5.6 Epilogue and References 198

5.7 Exercises 199
PART III
REPRESENTATIONS FOR KNOWLEDGE-BASED PROBLEM SOLVING

6 KNOWLEDGE-INTENSIVE PROBLEM SOLVING 207

6.0 Introduction 207

6.1 Overview of Expert System Technology 210
  6.1.1 The Design of Rule-Based Expert Systems 210
  6.1.2 Selecting a Problem for Expert System Development 212
  6.1.3 The Knowledge Engineering Process 214
  6.1.4 Conceptual Models and Their Role in Knowledge Acquisition 216

6.2 Rule-based Expert Systems 219
  6.2.1 The Production System and Goal-driven Problem Solving 220
  6.2.2 Explanation and Transparency in Goal-driven Reasoning 224
  6.2.3 Using the Production System for Data-driven Reasoning 226
  6.2.4 Heuristics and Control in Expert Systems 229
  6.2.5 Conclusions: Rule-Based Reasoning 230

6.3 Model-based Reasoning 231
  6.3.1 Introduction 231

6.4 Case-based Reasoning 235
  6.4.1 Introduction 235

6.5 The Knowledge-Representation Problem 240

6.6 Epilogue and References 245

6.7 Exercises 246
7 REASONING WITH UNCERTAIN OR INCOMPLETE INFORMATION  247

7.0 Introduction  247

7.1 The Statistical Approach to Uncertainty  249

7.1.1 Bayesian Reasoning  250
7.1.2 Bayesian Belief Networks  254
7.1.3 The Dempster–Shafer Theory of Evidence  259
7.1.4 The Stanford Certainty Factor Algebra  263
7.1.5 Causal Networks  266

7.2 Introduction to Nonmonotonic Systems  269

7.2.1 Logics for Nonmonotonic Reasoning  269
7.2.2 Logics Based on Minimum Models  273
7.2.3 Truth Maintenance Systems  275
7.2.4 Set Cover and Logic Based Abduction (Stern 1996)  281

7.3 Reasoning with Fuzzy Sets  284

7.4 Epilogue and References  289

7.5 Exercises  290

8 KNOWLEDGE REPRESENTATION  293

8.0 Knowledge Representation Languages  293

8.1 Issues in Knowledge Representation  295

8.2 A Survey of Network Representation  297

8.2.1 Associationist Theories of Meaning  297
8.2.2 Early Work in Semantic Nets  301
8.2.3 Standardization of Network Relationships  303

8.3 Conceptual Graphs: A Network Representation Language  309

8.3.1 Introduction to Conceptual Graphs  309
8.3.2 Types, Individuals, and Names 311
8.3.3 The Type Hierarchy 313
8.3.4 Generalization and Specialization 314
8.3.5 Propositional Nodes 317
8.3.6 Conceptual Graphs and Logic 318

8.4 Structured Representations 320
8.4.1 Frames 320
8.4.2 Scripts 324

8.5 Issues in Knowledge Representation 328
8.5.1 Hierarchies, Inheritance, and Exceptions 328
8.5.2 Naturalness, Efficiency, and Plasticity 331

8.6 Epilogue and References 334

8.7 Exercises 335

PART IV
LANGUAGES AND PROGRAMMING TECHNIQUES
FOR ARTIFICIAL INTELLIGENCE

Languages, Understanding, and Levels of Abstraction 340

Desired Features of AI Language 342

An Overview of LISP and PROLOG 349

Object-Oriented Programming 352

Hybrid Environments 353

A Hybrid Example 354

Selecting an Implementation Language 356
9 AN INTRODUCTION TO PROLOG 357

9.0 Introduction 357

9.1 Syntax for Predicate Calculus Programming 358

9.1.1 Representing Facts and Rules 358
9.1.2 Creating, Changing, and Monitoring the PROLOG Environment 362
9.1.3 Recursion-Based Search in PROLOG 364
9.1.4 Recursive Search in PROLOG 366
9.1.5 The Use of Cut to Control Search in PROLOG 369

9.2 Abstract Data Types (ADTs) in PROLOG 371

9.2.1 The ADT Stack 371
9.2.2 The ADT Queue 373
9.2.3 The ADT Priority Queue 373
9.2.4 The ADT Set 374

9.3 A Production System Example in PROLOG 375

9.4 Designing Alternative Search Strategies 381

9.4.1 Depth-First Search Using the Closed List 381
9.4.2 Breadth-First Search in PROLOG 383
9.4.3 Best-First Search in PROLOG 384

9.5 A PROLOG Planner 386

9.6 PROLOG: Meta-Predicates, Types, and Unification 389

9.6.1 Meta-Logical Predicates 389
9.6.2 Types in PROLOG 391
9.6.3 Unification, the Engine for Predicate Matching and Evaluation 394

9.7 Meta-Interpreters in PROLOG 397

9.7.1 An Introduction to Meta-Interpreters: PROLOG in PROLOG 397
9.7.2 Shell for a Rule-Based Expert System 401
9.7.3 Semantic Nets in PROLOG 410
9.7.4 Frames and Schemata in PROLOG 412
10  AN INTRODUCTION TO LISP  425

10.0  Introduction  425

10.1  LISP: A Brief Overview  426
   10.1.1  Symbolic Expressions, the Syntactic Basis of LISP  426
   10.1.2  Control of LISP Evaluation: quote and eval  430
   10.1.3  Programming in LISP: Creating New Functions  431
   10.1.4  Program Control in LISP: Conditionals and Predicates  433
   10.1.5  Functions, Lists, and Symbolic Computing  436
   10.1.6  Lists as Recursive Structures  438
   10.1.7  Nested Lists, Structure, and car/cdr Recursion  441
   10.1.8  Binding Variables Using set  444
   10.1.9  Defining Local Variables Using let  446
   10.1.10  Data Types in Common LISP  448
   10.1.11  Conclusion  449

10.2  Search in LISP: A Functional Approach to the Farmer, Wolf, Goat, and Cabbage Problem  449

10.3  Higher-Order Functions and Procedural Abstraction  455
   10.3.1  Maps and Filters  455
   10.3.2  Functional Arguments and Lambda Expressions  457

10.4  Search Strategies in LISP  459
   10.4.1  Breadth-First and Depth-First Search  459
   10.4.2  Best-First Search  462

10.5  Pattern Matching in LISP  463

10.6  A Recursive Unification Function  465
10.6.1 Implementing the Unification Algorithm 465
10.6.2 Implementing Substitution Sets Using Association Lists 467

10.7 Interpreters and Embedded Languages 469

10.8 Logic Programming in LISP 472
10.8.1 A Simple Logic Programming Language 472
10.8.2 Streams and Stream Processing 474
10.8.3 A Stream-Based Logic Programming Interpreter 477

10.9 Streams and Delayed Evaluation 482

10.10 An Expert System Shell in LISP 486
10.10.1 Implementing Certainty Factors 486
10.10.2 Architecture of lisp-shell 488
10.10.3 User Queries and Working Memory 490
10.10.4 Classification Using lisp-shell 491

10.11 Network Representations and Inheritance 494
10.11.1 Representing Semantic Nets in LISP 494
10.11.2 Implementing Inheritance 497

10.12 Object-Oriented Programming Using CLOS 497
10.12.1 Defining Classes and Instances in CLOS 499
10.12.2 Defining Generic Functions and Methods 501
10.12.3 Inheritance in CLOS 503
10.12.4 Advanced Features of CLOS 505
10.12.5 Example: A Thermostat Simulation 505

10.13 Epilogue and References 511

10.14 Exercises 511
PART V
ADVANCED TOPICS FOR AI PROBLEM SOLVING

Natural Language, Automated Reasoning, and Learning 517

11  UNDERSTANDING NATURAL LANGUAGE 519

11.0  Role of Knowledge in Language Understanding 519

11.1  Language Understanding: A Symbolic Approach 522
  11.1.1  Introduction 522
  11.1.2  Stages of Language Analysis 523

11.2  Syntax 524
  11.2.1  Specification and Parsing Using Context-Free Grammars 524

12  Further Issues in Automated Reasoning 593
  12.4  Uniform Representations for Weak Method Solutions 593
  12.4.2  Alternative Inference Rules 597
  12.4.3  Search Strategies and Their Use 599

12.5  Epilogue and References 600

12.6  Exercises 601

13  MACHINE LEARNING: SYMBOL-BASED 603

13.0  Introduction 603

13.1  A Framework for Symbol-based Learning 606

13.2  Version Space Search 612
  13.2.1  Generalization Operators and the Concept Space 612
  13.2.2  The Candidate Elimination Algorithm 613
  13.2.3  LEX: Inducing Search Heuristics 620
  13.2.4  Evaluating Candidate Elimination 623
12 AUTOMATED REASONING 559

12.0 Introduction to Weak Methods in Theorem Proving 559
12.1 The General Problem Solver and Difference Tables 560
12.2 Resolution Theorem Proving 566
  12.2.1 Introduction 566
  12.2.2 Producing the Clause Form for Resolution Refutations 568
  12.2.3 The Binary Resolution Proof Procedure 573
  12.2.4 Strategies and Simplification Techniques for Resolution 578
  12.2.5 Answer Extraction from Resolution Refutations 583
12.3 PROLOG and Automated Reasoning 587
  12.3.1 Introduction 587
  12.3.2 Logic Programming and PROLOG 588
12.4 Further Issues in Automated Reasoning 593
  12.4.1 Uniform Representations for Weak Method Solutions 593
  12.4.2 Alternative Inference Rules 597
  12.4.3 Search Strategies and Their Use 599
12.5 Epilogue and References 600
12.6 Exercises 601

13 MACHINE LEARNING: SYMBOL-BASED 603

13.0 Introduction 603
13.1 A Framework for Symbol-based Learning 606
13.2 Version Space Search 612
  13.2.1 Generalization Operators and the Concept Space 612
  13.2.2 The Candidate Elimination Algorithm 613
  13.2.3 LEX: Inducing Search Heuristics 620
  13.2.4 Evaluating Candidate Elimination 623
13.3 The ID3 Decision Tree Induction Algorithm 624
  13.3.1 Top-Down Decision Tree Induction 627
  13.3.2 Information Theoretic Test Selection 628
  13.3.3 Evaluating ID3 632
  13.3.4 Decision Tree Data Issues: Bagging, Boosting 632

13.4 Inductive Bias and Learnability 633
  13.4.1 Inductive Bias 634
  13.4.2 The Theory of Learnability 636

13.5 Knowledge and Learning 638
  13.5.1 Meta-DENDRAL 639
  13.5.2 Explanation-Based Learning 640
  13.5.3 EBL and Knowledge-Level Learning 645
  13.5.4 Analogical Reasoning 646

13.6 Unsupervised Learning 649
  13.6.1 Discovery and Unsupervised Learning 649
  13.6.2 Conceptual Clustering 651
  13.6.3 COBWEBS and the Structure of Taxonomic Knowledge 653

13.7 Epilogue and References 658

13.8 Exercises 659

14 MACHINE LEARNING: CONNECTIONIST 661

14.0 Introduction 661

14.1 Foundations for Connectionist Networks 663
  14.1.1 Early History 663

14.2 Perceptron Learning 666
  14.2.1 The Perceptron Training Algorithm 666
  14.2.2 An Example: Using a Perceptron Network to Classify 668
  14.2.3 The Delta Rule 672
14.3 Backpropagation Learning 675
  14.3.1 Deriving the Backpropagation Algorithm 675
  14.3.2 Backpropagation Example 1: NETalk 679
  14.3.3 Backpropagation Example 2: Exclusive-or 681

14.4 Competitive Learning 682
  14.4.1 Winner-Take-All Learning for Classification 682
  14.4.2 A Kohonen Network for Learning Prototypes 684
  14.4.3 Grossberg Learning and Counterpropagation 686

14.5 Hebbian Coincidence Learning 690
  14.5.1 Introduction 690
  14.5.2 An Example of Unsupervised Hebbian Learning 691
  14.5.3 Supervised Hebbian Learning 694
  14.5.4 Associative Memory and the Linear Associator 696

14.6 Attractor Networks or "Memories" 701
  14.6.1 Introduction 701
  14.6.2 BAM, the Bi-directional Associative Memory 702
  14.6.3 Examples of BAM Processing 704
  14.6.4 Autoassociative Memory and Hopfield Nets 706

14.7 Epilogue and References 711

14.8 Exercises 712

15 MACHINE LEARNING: SOCIAL AND EMERGENT 713

15.0 Social and Emergent Models of Learning 713

15.1 The Genetic Algorithm 715
  15.1.3 Two Examples: CNF Satisfaction and the Traveling Salesperson 717
  15.1.4 Evaluating the Genetic Algorithm 721

15.2 Classifier Systems and Genetic Programming 725
  15.2.1 Classifier Systems 725
  15.2.2 Programming with Genetic Operators 730
15.3 Artificial Life and Society-based Learning 736
  15.3.1 The "Game of Life" 737
  15.3.2 Evolutionary Programming 740
  15.3.3 A Case Study in Emergence (Crutchfield and Mitchell 1994) 743

15.4 Epilogue and References 747

15.5 Exercises 748

PART VI
EPILOGUE

Reflections on the Nature of Intelligence 751

16 ARTIFICIAL INTELLIGENCE AS EMPIRICAL ENQUIRY 753

16.0 Introduction 753

16.1 Artificial Intelligence: A Revised Definition 755
  16.1.1 Intelligence and the Physical Symbol System 756
  16.1.2 Minds, Brains, and Neural Computing 759
  16.1.3 Agents, Emergence, and Intelligence 761
  16.1.4 Situated Actors and the Existential Mind 764

16.2 Cognitive Science: An Overview 766
  16.2.1 The Analysis of Human Performance 766
  16.2.2 The Production System and Human Cognition 767

16.3 Current Issues in Machine Learning 770

16.4 Understanding Intelligence: Issues and Directions 775

16.5 Epilogue and References 780

Bibliography 781
Author Index 803
Subject Index 809
Acknowledgements 823