

Contents

I Artificial Intelligence

| | |
|--|-----------|
| 1 Introduction | 19 |
| 1.1 What Is AI? | 19 |
| 1.2 The Foundations of Artificial Intelligence | 23 |
| 1.3 The History of Artificial Intelligence | 35 |
| 1.4 The State of the Art | 45 |
| 1.5 Risks and Benefits of AI | 49 |
| Summary | 52 |
| Bibliographical and Historical Notes | 53 |
| 2 Intelligent Agents | 54 |
| 2.1 Agents and Environments | 54 |
| 2.2 Good Behavior: The Concept of Rationality | 57 |
| 2.3 The Nature of Environments | 60 |
| 2.4 The Structure of Agents | 65 |
| Summary | 78 |
| Bibliographical and Historical Notes | 78 |

II Problem-solving

| | |
|---|------------|
| 3 Solving Problems by Searching | 81 |
| 3.1 Problem-Solving Agents | 81 |
| 3.2 Example Problems | 84 |
| 3.3 Search Algorithms | 89 |
| 3.4 Uninformed Search Strategies | 94 |
| 3.5 Informed (Heuristic) Search Strategies | 102 |
| 3.6 Heuristic Functions | 115 |
| Summary | 122 |
| Bibliographical and Historical Notes | 124 |
| 4 Search in Complex Environments | 128 |
| 4.1 Local Search and Optimization Problems | 128 |
| 4.2 Local Search in Continuous Spaces | 137 |
| 4.3 Search with Nondeterministic Actions | 140 |
| 4.4 Search in Partially Observable Environments | 144 |
| 4.5 Online Search Agents and Unknown Environments | 152 |
| Summary | 159 |
| Bibliographical and Historical Notes | 160 |
| 5 Constraint Satisfaction Problems | 164 |
| 5.1 Defining Constraint Satisfaction Problems | 164 |
| 5.2 Constraint Propagation: Inference in CSPs | 169 |



Contents

| | | |
|---|--|------------|
| 5.3 | Backtracking Search for CSPs | 175 |
| 5.4 | Local Search for CSPs | 181 |
| 5.5 | The Structure of Problems | 183 |
| | Summary | 187 |
| | Bibliographical and Historical Notes | 188 |
| 6 | Adversarial Search and Games | 192 |
| 6.1 | Game Theory | 192 |
| 6.2 | Optimal Decisions in Games | 194 |
| 6.3 | Heuristic Alpha–Beta Tree Search | 202 |
| 6.4 | Monte Carlo Tree Search | 207 |
| 6.5 | Stochastic Games | 210 |
| 6.6 | Partially Observable Games | 214 |
| 6.7 | Limitations of Game Search Algorithms | 219 |
| | Summary | 220 |
| | Bibliographical and Historical Notes | 221 |
| III Knowledge, reasoning, and planning | | |
| 7 | Logical Agents | 226 |
| 7.1 | Knowledge-Based Agents | 227 |
| 7.2 | The Wumpus World | 228 |
| 7.3 | Logic | 232 |
| 7.4 | Propositional Logic: A Very Simple Logic | 235 |
| 7.5 | Propositional Theorem Proving | 240 |
| 7.6 | Effective Propositional Model Checking | 250 |
| 7.7 | Agents Based on Propositional Logic | 255 |
| | Summary | 264 |
| | Bibliographical and Historical Notes | 265 |
| 8 | First-Order Logic | 269 |
| 8.1 | Representation Revisited | 269 |
| 8.2 | Syntax and Semantics of First-Order Logic | 274 |
| 8.3 | Using First-Order Logic | 283 |
| 8.4 | Knowledge Engineering in First-Order Logic | 289 |
| | Summary | 295 |
| | Bibliographical and Historical Notes | 296 |
| 9 | Inference in First-Order Logic | 298 |
| 9.1 | Propositional vs. First-Order Inference | 298 |
| 9.2 | Unification and First-Order Inference | 300 |
| 9.3 | Forward Chaining | 304 |
| 9.4 | Backward Chaining | 311 |
| 9.5 | Resolution | 316 |
| | Summary | 327 |
| | Bibliographical and Historical Notes | 328 |



| | |
|--|------------|
| 10 Knowledge Representation | 332 |
| 10.1 Ontological Engineering | 332 |
| 10.2 Categories and Objects | 335 |
| 10.3 Events | 340 |
| 10.4 Mental Objects and Modal Logic | 344 |
| 10.5 Reasoning Systems for Categories | 347 |
| 10.6 Reasoning with Default Information | 351 |
| Summary | 355 |
| Bibliographical and Historical Notes | 356 |
| 11 Automated Planning | 362 |
| 11.1 Definition of Classical Planning | 362 |
| 11.2 Algorithms for Classical Planning | 366 |
| 11.3 Heuristics for Planning | 371 |
| 11.4 Hierarchical Planning | 374 |
| 11.5 Planning and Acting in Nondeterministic Domains | 383 |
| 11.6 Time, Schedules, and Resources | 392 |
| 11.7 Analysis of Planning Approaches | 396 |
| Summary | 397 |
| Bibliographical and Historical Notes | 398 |
| IV Uncertain knowledge and reasoning | |
| 12 Quantifying Uncertainty | 403 |
| 12.1 Acting under Uncertainty | 403 |
| 12.2 Basic Probability Notation | 406 |
| 12.3 Inference Using Full Joint Distributions | 413 |
| 12.4 Independence | 415 |
| 12.5 Bayes' Rule and Its Use | 417 |
| 12.6 Naive Bayes Models | 420 |
| 12.7 The Wumpus World Revisited | 422 |
| Summary | 425 |
| Bibliographical and Historical Notes | 426 |
| 13 Probabilistic Reasoning | 430 |
| 13.1 Representing Knowledge in an Uncertain Domain | 430 |
| 13.2 The Semantics of Bayesian Networks | 432 |
| 13.3 Exact Inference in Bayesian Networks | 445 |
| 13.4 Approximate Inference for Bayesian Networks | 453 |
| 13.5 Causal Networks | 467 |
| Summary | 471 |
| Bibliographical and Historical Notes | 472 |
| 14 Probabilistic Reasoning over Time | 479 |
| 14.1 Time and Uncertainty | 479 |
| 14.2 Inference in Temporal Models | 483 |



Contents

| | | |
|-----------|---|------------|
| 14.3 | Hidden Markov Models | 491 |
| 14.4 | Kalman Filters | 497 |
| 14.5 | Dynamic Bayesian Networks | 503 |
| | Summary | 514 |
| | Bibliographical and Historical Notes | 515 |
| 15 | Making Simple Decisions | 518 |
| 15.1 | Combining Beliefs and Desires under Uncertainty | 518 |
| 15.2 | The Basis of Utility Theory | 519 |
| 15.3 | Utility Functions | 522 |
| 15.4 | Multiattribute Utility Functions | 530 |
| 15.5 | Decision Networks | 534 |
| 15.6 | The Value of Information | 537 |
| 15.7 | Unknown Preferences | 543 |
| | Summary | 547 |
| | Bibliographical and Historical Notes | 547 |
| 16 | Making Complex Decisions | 552 |
| 16.1 | Sequential Decision Problems | 552 |
| 16.2 | Algorithms for MDPs | 562 |
| 16.3 | Bandit Problems | 571 |
| 16.4 | Partially Observable MDPs | 578 |
| 16.5 | Algorithms for Solving POMDPs | 580 |
| | Summary | 585 |
| | Bibliographical and Historical Notes | 586 |
| 17 | Multiagent Decision Making | 589 |
| 17.1 | Properties of Multiagent Environments | 589 |
| 17.2 | Non-Cooperative Game Theory | 595 |
| 17.3 | Cooperative Game Theory | 616 |
| 17.4 | Making Collective Decisions | 622 |
| | Summary | 635 |
| | Bibliographical and Historical Notes | 636 |
| 18 | Probabilistic Programming | 641 |
| 18.1 | Relational Probability Models | 642 |
| 18.2 | Open-Universe Probability Models | 648 |
| 18.3 | Keeping Track of a Complex World | 655 |
| 18.4 | Programs as Probability Models | 660 |
| | Summary | 664 |
| | Bibliographical and Historical Notes | 665 |
| V | Machine Learning | |
| 19 | Learning from Examples | 669 |
| 19.1 | Forms of Learning | 669 |



| | | |
|-----------|---|------------|
| 19.2 | Supervised Learning | 671 |
| 19.3 | Learning Decision Trees | 675 |
| 19.4 | Model Selection and Optimization | 683 |
| 19.5 | The Theory of Learning | 690 |
| 19.6 | Linear Regression and Classification | 694 |
| 19.7 | Nonparametric Models | 704 |
| 19.8 | Ensemble Learning | 714 |
| 19.9 | Developing Machine Learning Systems | 722 |
| | Summary | 732 |
| | Bibliographical and Historical Notes | 733 |
| 20 | Knowledge in Learning | 739 |
| 20.1 | A Logical Formulation of Learning | 739 |
| 20.2 | Knowledge in Learning | 747 |
| 20.3 | Explanation-Based Learning | 750 |
| 20.4 | Learning Using Relevance Information | 754 |
| 20.5 | Inductive Logic Programming | 758 |
| | Summary | 767 |
| | Bibliographical and Historical Notes | 768 |
| 21 | Learning Probabilistic Models | 772 |
| 21.1 | Statistical Learning | 772 |
| 21.2 | Learning with Complete Data | 775 |
| 21.3 | Learning with Hidden Variables: The EM Algorithm | 788 |
| | Summary | 797 |
| | Bibliographical and Historical Notes | 798 |
| 22 | Deep Learning | 801 |
| 22.1 | Simple Feedforward Networks | 802 |
| 22.2 | Computation Graphs for Deep Learning | 807 |
| 22.3 | Convolutional Networks | 811 |
| 22.4 | Learning Algorithms | 816 |
| 22.5 | Generalization | 819 |
| 22.6 | Recurrent Neural Networks | 823 |
| 22.7 | Unsupervised Learning and Transfer Learning | 826 |
| 22.8 | Applications | 833 |
| | Summary | 835 |
| | Bibliographical and Historical Notes | 836 |
| 23 | Reinforcement Learning | 840 |
| 23.1 | Learning from Rewards | 840 |
| 23.2 | Passive Reinforcement Learning | 842 |
| 23.3 | Active Reinforcement Learning | 848 |
| 23.4 | Generalization in Reinforcement Learning | 854 |
| 23.5 | Policy Search | 861 |
| 23.6 | Apprenticeship and Inverse Reinforcement Learning | 863 |



Contents

| | |
|---|-----|
| 23.7 Applications of Reinforcement Learning | 866 |
| Summary | 869 |
| Bibliographical and Historical Notes | 870 |

VI Communicating, perceiving, and acting

| | |
|---|------------|
| 24 Natural Language Processing | 874 |
| 24.1 Language Models | 874 |
| 24.2 Grammar | 884 |
| 24.3 Parsing | 886 |
| 24.4 Augmented Grammars | 892 |
| 24.5 Complications of Real Natural Language | 896 |
| 24.6 Natural Language Tasks | 900 |
| Summary | 901 |
| Bibliographical and Historical Notes | 902 |
| 25 Deep Learning for Natural Language Processing | 907 |
| 25.1 Word Embeddings | 907 |
| 25.2 Recurrent Neural Networks for NLP | 911 |
| 25.3 Sequence-to-Sequence Models | 915 |
| 25.4 The Transformer Architecture | 919 |
| 25.5 Pretraining and Transfer Learning | 922 |
| 25.6 State of the art | 926 |
| Summary | 929 |
| Bibliographical and Historical Notes | 929 |
| 26 Robotics | 932 |
| 26.1 Robots | 932 |
| 26.2 Robot Hardware | 933 |
| 26.3 What kind of problem is robotics solving? | 937 |
| 26.4 Robotic Perception | 938 |
| 26.5 Planning and Control | 945 |
| 26.6 Planning Uncertain Movements | 963 |
| 26.7 Reinforcement Learning in Robotics | 965 |
| 26.8 Humans and Robots | 968 |
| 26.9 Alternative Robotic Frameworks | 975 |
| 26.10 Application Domains | 978 |
| Summary | 981 |
| Bibliographical and Historical Notes | 982 |
| 27 Computer Vision | 988 |
| 27.1 Introduction | 988 |
| 27.2 Image Formation | 989 |
| 27.3 Simple Image Features | 995 |
| 27.4 Classifying Images | 1002 |
| 27.5 Detecting Objects | 1006 |



| | | |
|------------------------|--|-------------|
| 27.6 | The 3D World | 1008 |
| 27.7 | Using Computer Vision | 1013 |
| | Summary | 1026 |
| | Bibliographical and Historical Notes | 1027 |
| VII Conclusions | | |
| 28 | Philosophy, Ethics, and Safety of AI | 1032 |
| 28.1 | The Limits of AI | 1032 |
| 28.2 | Can Machines Really Think? | 1035 |
| 28.3 | The Ethics of AI | 1037 |
| | Summary | 1056 |
| | Bibliographical and Historical Notes | 1057 |
| 29 | The Future of AI | 1063 |
| 29.1 | AI Components | 1063 |
| 29.2 | AI Architectures | 1069 |
| A | Mathematical Background | 1074 |
| A.1 | Complexity Analysis and $O()$ Notation | 1074 |
| A.2 | Vectors, Matrices, and Linear Algebra | 1076 |
| A.3 | Probability Distributions | 1078 |
| | Bibliographical and Historical Notes | 1080 |
| B | Notes on Languages and Algorithms | 1081 |
| B.1 | Defining Languages with Backus–Naur Form (BNF) | 1081 |
| B.2 | Describing Algorithms with Pseudocode | 1082 |
| B.3 | Online Supplemental Material | 1083 |
| | Bibliography | 1084 |
| | Index | 1119 |