

Contents

I Artificial Intelligence

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| 1.1 | What is AI? | 1 |
| | Acting humanly: The Turing Test approach | 2 |
| | Thinking humanly: The cognitive modeling approach | 3 |
| | Thinking rationally: The “laws of thought” approach | 4 |
| | Acting rationally: The rational agent approach | 4 |
| 1.2 | The Foundations of Artificial Intelligence | 5 |
| | Philosophy (428 B.C.–present) | 5 |
| | Mathematics (c. 800–present) | 7 |
| | Economics (1776–present) | 9 |
| | Neuroscience (1861–present) | 10 |
| | Psychology (1879–present) | 12 |
| | Computer engineering (1940–present) | 14 |
| | Control theory and Cybernetics (1948–present) | 15 |
| | Linguistics (1957–present) | 16 |
| 1.3 | The History of Artificial Intelligence | 16 |
| | The gestation of artificial intelligence (1943–1955) | 16 |
| | The birth of artificial intelligence (1956) | 17 |
| | Early enthusiasm, great expectations (1952–1969) | 18 |
| | A dose of reality (1966–1973) | 21 |
| | Knowledge-based systems: The key to power? (1969–1979) | 22 |
| | AI becomes an industry (1980–present) | 24 |
| | The return of neural networks (1986–present) | 25 |
| | AI becomes a science (1987–present) | 25 |
| | The emergence of intelligent agents (1995–present) | 27 |
| 1.4 | The State of the Art | 27 |
| 1.5 | Summary | 28 |
| | Bibliographical and Historical Notes | 29 |
| | Exercises | 30 |
| 2 | Intelligent Agents | 32 |
| 2.1 | Agents and Environments | 32 |
| 2.2 | Good Behavior: The Concept of Rationality | 34 |
| | Performance measures | 35 |
| | Rationality | 35 |
| | Omniscience, learning, and autonomy | 36 |
| 2.3 | The Nature of Environments | 38 |
| | Specifying the task environment | 38 |
| | Properties of task environments | 40 |
| 2.4 | The Structure of Agents | 44 |
| | Agent programs | 44 |
| | Simple reflex agents | 46 |
| | Model-based reflex agents | 48 |

| | |
|---|-----------|
| Goal-based agents | 49 |
| Utility-based agents | 51 |
| Learning agents | 51 |
| 2.5 Summary | 54 |
| Bibliographical and Historical Notes | 55 |
| Exercises | 56 |
| | |
| II Problem-solving | |
| | |
| 3 Solving Problems by Searching | 59 |
| 3.1 Problem-Solving Agents | 59 |
| Well-defined problems and solutions | 62 |
| Formulating problems | 62 |
| 3.2 Example Problems | 64 |
| Toy problems | 64 |
| Real-world problems | 67 |
| 3.3 Searching for Solutions | 69 |
| Measuring problem-solving performance | 71 |
| 3.4 Uninformed Search Strategies | 73 |
| Breadth-first search | 73 |
| Depth-first search | 75 |
| Depth-limited search | 77 |
| Iterative deepening depth-first search | 78 |
| Bidirectional search | 79 |
| Comparing uninformed search strategies | 81 |
| 3.5 Avoiding Repeated States | 81 |
| 3.6 Searching with Partial Information | 83 |
| Sensorless problems | 84 |
| Contingency problems | 86 |
| 3.7 Summary | 87 |
| Bibliographical and Historical Notes | 88 |
| Exercises | 89 |
| | |
| 4 Informed Search and Exploration | 94 |
| 4.1 Informed (Heuristic) Search Strategies | 94 |
| Greedy best-first search | 95 |
| A* search: Minimizing the total estimated solution cost | 97 |
| Memory-bounded heuristic search | 101 |
| Learning to search better | 104 |
| 4.2 Heuristic Functions | 105 |
| The effect of heuristic accuracy on performance | 106 |
| Inventing admissible heuristic functions | 107 |
| Learning heuristics from experience | 109 |
| 4.3 Local Search Algorithms and Optimization Problems | 110 |
| Hill-climbing search | 111 |
| Simulated annealing search | 115 |
| Local beam search | 115 |
| Genetic algorithms | 116 |
| 4.4 Local Search in Continuous Spaces | 119 |

| | | |
|--|---|------------|
| 4.5 | Online Search Agents and Unknown Environments | 122 |
| | Online search problems | 123 |
| | Online search agents | 125 |
| | Online local search | 126 |
| | Learning in online search | 127 |
| 4.6 | Summary | 129 |
| | Bibliographical and Historical Notes | 130 |
| | Exercises | 134 |
| 5 | Constraint Satisfaction Problems | 137 |
| 5.1 | Constraint Satisfaction Problems | 137 |
| 5.2 | Backtracking Search for CSPs | 141 |
| | Variable and value ordering | 143 |
| | Propagating information through constraints | 144 |
| | Intelligent backtracking: looking backward | 148 |
| 5.3 | Local Search for Constraint Satisfaction Problems | 150 |
| 5.4 | The Structure of Problems | 151 |
| 5.5 | Summary | 155 |
| | Bibliographical and Historical Notes | 156 |
| | Exercises | 158 |
| 6 | Adversarial Search | 161 |
| 6.1 | Games | 161 |
| 6.2 | Optimal Decisions in Games | 162 |
| | Optimal strategies | 163 |
| | The minimax algorithm | 165 |
| | Optimal decisions in multiplayer games | 165 |
| 6.3 | Alpha–Beta Pruning | 167 |
| 6.4 | Imperfect, Real-Time Decisions | 171 |
| | Evaluation functions | 171 |
| | Cutting off search | 173 |
| 6.5 | Games That Include an Element of Chance | 175 |
| | Position evaluation in games with chance nodes | 177 |
| | Complexity of expectiminimax | 177 |
| | Card games | 179 |
| 6.6 | State-of-the-Art Game Programs | 180 |
| 6.7 | Discussion | 183 |
| 6.8 | Summary | 185 |
| | Bibliographical and Historical Notes | 186 |
| | Exercises | 189 |
| III Knowledge and reasoning | | |
| 7 | Logical Agents | 194 |
| 7.1 | Knowledge-Based Agents | 195 |
| 7.2 | The Wumpus World | 197 |
| 7.3 | Logic | 200 |
| 7.4 | Propositional Logic: A Very Simple Logic | 204 |
| | Syntax | 204 |

| | | |
|----------|---|------------|
| | Semantics | 206 |
| | A simple knowledge base | 208 |
| | Inference | 208 |
| | Equivalence, validity, and satisfiability | 210 |
| 7.5 | Reasoning Patterns in Propositional Logic | 211 |
| | Resolution | 213 |
| | Forward and backward chaining | 217 |
| 7.6 | Effective propositional inference | 220 |
| | A complete backtracking algorithm | 221 |
| | Local-search algorithms | 222 |
| | Hard satisfiability problems | 224 |
| 7.7 | Agents Based on Propositional Logic | 225 |
| | Finding pits and wumpuses using logical inference | 225 |
| | Keeping track of location and orientation | 227 |
| | Circuit-based agents | 227 |
| | A comparison | 231 |
| 7.8 | Summary | 232 |
| | Bibliographical and Historical Notes | 233 |
| | Exercises | 236 |
| 8 | First-Order Logic | 240 |
| 8.1 | Representation Revisited | 240 |
| 8.2 | Syntax and Semantics of First-Order Logic | 245 |
| | Models for first-order logic | 245 |
| | Symbols and interpretations | 246 |
| | Terms | 248 |
| | Atomic sentences | 248 |
| | Complex sentences | 249 |
| | Quantifiers | 249 |
| | Equality | 253 |
| 8.3 | Using First-Order Logic | 253 |
| | Assertions and queries in first-order logic | 253 |
| | The kinship domain | 254 |
| | Numbers, sets, and lists | 256 |
| | The wumpus world | 258 |
| 8.4 | Knowledge Engineering in First-Order Logic | 260 |
| | The knowledge engineering process | 261 |
| | The electronic circuits domain | 262 |
| 8.5 | Summary | 266 |
| | Bibliographical and Historical Notes | 267 |
| | Exercises | 268 |
| 9 | Inference in First-Order Logic | 272 |
| 9.1 | Propositional vs. First-Order Inference | 272 |
| | Inference rules for quantifiers | 273 |
| | Reduction to propositional inference | 274 |
| 9.2 | Unification and Lifting | 275 |
| | A first-order inference rule | 275 |
| | Unification | 276 |

| | | |
|-----------|---|------------|
| | Storage and retrieval | 278 |
| 9.3 | Forward Chaining | 280 |
| | First-order definite clauses | 280 |
| | A simple forward-chaining algorithm | 281 |
| | Efficient forward chaining | 283 |
| 9.4 | Backward Chaining | 287 |
| | A backward chaining algorithm | 287 |
| | Logic programming | 289 |
| | Efficient implementation of logic programs | 290 |
| | Redundant inference and infinite loops | 292 |
| | Constraint logic programming | 294 |
| 9.5 | Resolution | 295 |
| | Conjunctive normal form for first-order logic | 295 |
| | The resolution inference rule | 297 |
| | Example proofs | 297 |
| | Completeness of resolution | 300 |
| | Dealing with equality | 303 |
| | Resolution strategies | 304 |
| | Theorem provers | 306 |
| 9.6 | Summary | 310 |
| | Bibliographical and Historical Notes | 310 |
| | Exercises | 315 |
| 10 | Knowledge Representation | 320 |
| 10.1 | Ontological Engineering | 320 |
| 10.2 | Categories and Objects | 322 |
| | Physical composition | 324 |
| | Measurements | 325 |
| | Substances and objects | 327 |
| 10.3 | Actions, Situations, and Events | 328 |
| | The ontology of situation calculus | 329 |
| | Describing actions in situation calculus | 330 |
| | Solving the representational frame problem | 332 |
| | Solving the inferential frame problem | 333 |
| | Time and event calculus | 334 |
| | Generalized events | 335 |
| | Processes | 337 |
| | Intervals | 338 |
| | Fluents and objects | 339 |
| 10.4 | Mental Events and Mental Objects | 341 |
| | A formal theory of beliefs | 341 |
| | Knowledge and belief | 343 |
| | Knowledge, time, and action | 344 |
| 10.5 | The Internet Shopping World | 344 |
| | Comparing offers | 348 |
| 10.6 | Reasoning Systems for Categories | 349 |
| | Semantic networks | 350 |
| | Description logics | 353 |
| 10.7 | Reasoning with Default Information | 354 |

| | |
|--|-----|
| Open and closed worlds | 354 |
| Negation as failure and stable model semantics | 356 |
| Circumscription and default logic | 358 |
| 10.8 Truth Maintenance Systems | 360 |
| 10.9 Summary | 362 |
| Bibliographical and Historical Notes | 363 |
| Exercises | 369 |

IV Planning

| | |
|---|------------|
| 11 Planning | 375 |
| 11.1 The Planning Problem | 375 |
| The language of planning problems | 377 |
| Expressiveness and extensions | 378 |
| Example: Air cargo transport | 380 |
| Example: The spare tire problem | 381 |
| Example: The blocks world | 381 |
| 11.2 Planning with State-Space Search | 382 |
| Forward state-space search | 382 |
| Backward state-space search | 384 |
| Heuristics for state-space search | 386 |
| 11.3 Partial-Order Planning | 387 |
| A partial-order planning example | 391 |
| Partial-order planning with unbound variables | 393 |
| Heuristics for partial-order planning | 394 |
| 11.4 Planning Graphs | 395 |
| Planning graphs for heuristic estimation | 397 |
| The GRAPHPLAN algorithm | 398 |
| Termination of GRAPHPLAN | 401 |
| 11.5 Planning with Propositional Logic | 402 |
| Describing planning problems in propositional logic | 402 |
| Complexity of propositional encodings | 405 |
| 11.6 Analysis of Planning Approaches | 407 |
| 11.7 Summary | 408 |
| Bibliographical and Historical Notes | 409 |
| Exercises | 412 |
| 12 Planning and Acting in the Real World | 417 |
| 12.1 Time, Schedules, and Resources | 417 |
| Scheduling with resource constraints | 420 |
| 12.2 Hierarchical Task Network Planning | 422 |
| Representing action decompositions | 423 |
| Modifying the planner for decompositions | 425 |
| Discussion | 427 |
| 12.3 Planning and Acting in Nondeterministic Domains | 430 |
| 12.4 Conditional Planning | 433 |
| Conditional planning in fully observable environments | 433 |
| Conditional planning in partially observable environments | 437 |
| 12.5 Execution Monitoring and Replanning | 441 |

| | | |
|------|--|-----|
| 12.6 | Continuous Planning | 445 |
| 12.7 | MultiAgent Planning | 449 |
| | Cooperation: Joint goals and plans | 450 |
| | Multibody planning | 451 |
| | Coordination mechanisms | 452 |
| | Competition | 454 |
| 12.8 | Summary | 454 |
| | Bibliographical and Historical Notes | 455 |
| | Exercises | 459 |

V Uncertain knowledge and reasoning

| | | |
|-----------|---|------------|
| 13 | Uncertainty | 462 |
| 13.1 | Acting under Uncertainty | 462 |
| | Handling uncertain knowledge | 463 |
| | Uncertainty and rational decisions | 465 |
| | Design for a decision-theoretic agent | 466 |
| 13.2 | Basic Probability Notation | 466 |
| | Propositions | 467 |
| | Atomic events | 468 |
| | Prior probability | 468 |
| | Conditional probability | 470 |
| 13.3 | The Axioms of Probability | 471 |
| | Using the axioms of probability | 473 |
| | Why the axioms of probability are reasonable | 473 |
| 13.4 | Inference Using Full Joint Distributions | 475 |
| 13.5 | Independence | 477 |
| 13.6 | Bayes' Rule and Its Use | 479 |
| | Applying Bayes' rule: The simple case | 480 |
| | Using Bayes' rule: Combining evidence | 481 |
| 13.7 | The Wumpus World Revisited | 483 |
| 13.8 | Summary | 486 |
| | Bibliographical and Historical Notes | 487 |
| | Exercises | 489 |
| 14 | Probabilistic Reasoning | 492 |
| 14.1 | Representing Knowledge in an Uncertain Domain | 492 |
| 14.2 | The Semantics of Bayesian Networks | 495 |
| | Representing the full joint distribution | 495 |
| | Conditional independence relations in Bayesian networks | 499 |
| 14.3 | Efficient Representation of Conditional Distributions | 500 |
| 14.4 | Exact Inference in Bayesian Networks | 504 |
| | Inference by enumeration | 504 |
| | The variable elimination algorithm | 507 |
| | The complexity of exact inference | 509 |
| | Clustering algorithms | 510 |
| 14.5 | Approximate Inference in Bayesian Networks | 511 |
| | Direct sampling methods | 511 |
| | Inference by Markov chain simulation | 516 |

| | | |
|-----------|--|------------|
| 14.6 | Extending Probability to First-Order Representations | 519 |
| 14.7 | Other Approaches to Uncertain Reasoning | 523 |
| | Rule-based methods for uncertain reasoning | 524 |
| | Representing ignorance: Dempster–Shafer theory | 525 |
| | Representing vagueness: Fuzzy sets and fuzzy logic | 526 |
| 14.8 | Summary | 528 |
| | Bibliographical and Historical Notes | 528 |
| | Exercises | 533 |
| 15 | Probabilistic Reasoning over Time | 537 |
| 15.1 | Time and Uncertainty | 537 |
| | States and observations | 538 |
| | Stationary processes and the Markov assumption | 538 |
| 15.2 | Inference in Temporal Models | 541 |
| | Filtering and prediction | 542 |
| | Smoothing | 544 |
| | Finding the most likely sequence | 547 |
| 15.3 | Hidden Markov Models | 549 |
| | Simplified matrix algorithms | 549 |
| 15.4 | Kalman Filters | 551 |
| | Updating Gaussian distributions | 553 |
| | A simple one-dimensional example | 554 |
| | The general case | 556 |
| | Applicability of Kalman filtering | 557 |
| 15.5 | Dynamic Bayesian Networks | 559 |
| | Constructing DBNs | 560 |
| | Exact inference in DBNs | 563 |
| | Approximate inference in DBNs | 565 |
| 15.6 | Speech Recognition | 568 |
| | Speech sounds | 570 |
| | Words | 572 |
| | Sentences | 574 |
| | Building a speech recognizer | 576 |
| 15.7 | Summary | 578 |
| | Bibliographical and Historical Notes | 578 |
| | Exercises | 581 |
| 16 | Making Simple Decisions | 584 |
| 16.1 | Combining Beliefs and Desires under Uncertainty | 584 |
| 16.2 | The Basis of Utility Theory | 586 |
| | Constraints on rational preferences | 586 |
| | And then there was Utility | 588 |
| 16.3 | Utility Functions | 589 |
| | The utility of money | 589 |
| | Utility scales and utility assessment | 591 |
| 16.4 | Multiattribute Utility Functions | 593 |
| | Dominance | 594 |
| | Preference structure and multiattribute utility | 596 |
| 16.5 | Decision Networks | 597 |

| | | |
|-----------|---|------------|
| | Representing a decision problem with a decision network | 598 |
| | Evaluating decision networks | 599 |
| 16.6 | The Value of Information | 600 |
| | A simple example | 600 |
| | A general formula | 601 |
| | Properties of the value of information | 602 |
| | Implementing an information-gathering agent | 603 |
| 16.7 | Decision-Theoretic Expert Systems | 604 |
| 16.8 | Summary | 607 |
| | Bibliographical and Historical Notes | 607 |
| | Exercises | 609 |
| 17 | Making Complex Decisions | 613 |
| 17.1 | Sequential Decision Problems | 613 |
| | An example | 613 |
| | Optimality in sequential decision problems | 616 |
| 17.2 | Value Iteration | 618 |
| | Utilities of states | 619 |
| | The value iteration algorithm | 620 |
| | Convergence of value iteration | 620 |
| 17.3 | Policy Iteration | 624 |
| 17.4 | Partially observable MDPs | 625 |
| 17.5 | Decision-Theoretic Agents | 629 |
| 17.6 | Decisions with Multiple Agents: Game Theory | 631 |
| 17.7 | Mechanism Design | 640 |
| 17.8 | Summary | 643 |
| | Bibliographical and Historical Notes | 644 |
| | Exercises | 646 |

VI Learning

| | | |
|-----------|---|------------|
| 18 | Learning from Observations | 649 |
| 18.1 | Forms of Learning | 649 |
| 18.2 | Inductive Learning | 651 |
| 18.3 | Learning Decision Trees | 653 |
| | Decision trees as performance elements | 653 |
| | Expressiveness of decision trees | 655 |
| | Inducing decision trees from examples | 655 |
| | Choosing attribute tests | 659 |
| | Assessing the performance of the learning algorithm | 660 |
| | Noise and overfitting | 661 |
| | Broadening the applicability of decision trees | 663 |
| 18.4 | Ensemble Learning | 664 |
| 18.5 | Why Learning Works: Computational Learning Theory | 668 |
| | How many examples are needed? | 669 |
| | Learning decision lists | 670 |
| | Discussion | 672 |
| 18.6 | Summary | 673 |
| | Bibliographical and Historical Notes | 674 |

| | |
|--|------------|
| Exercises | 676 |
| 19 Knowledge in Learning | 678 |
| 19.1 A Logical Formulation of Learning | 678 |
| Examples and hypotheses | 678 |
| Current-best-hypothesis search | 680 |
| Least-commitment search | 683 |
| 19.2 Knowledge in Learning | 686 |
| Some simple examples | 687 |
| Some general schemes | 688 |
| 19.3 Explanation-Based Learning | 690 |
| Extracting general rules from examples | 691 |
| Improving efficiency | 693 |
| 19.4 Learning Using Relevance Information | 694 |
| Determining the hypothesis space | 695 |
| Learning and using relevance information | 695 |
| 19.5 Inductive Logic Programming | 697 |
| An example | 699 |
| Top-down inductive learning methods | 701 |
| Inductive learning with inverse deduction | 703 |
| Making discoveries with inductive logic programming | 705 |
| 19.6 Summary | 707 |
| Bibliographical and Historical Notes | 708 |
| Exercises | 710 |
| 20 Statistical Learning Methods | 712 |
| 20.1 Statistical Learning | 712 |
| 20.2 Learning with Complete Data | 716 |
| Maximum-likelihood parameter learning: Discrete models | 716 |
| Naive Bayes models | 718 |
| Maximum-likelihood parameter learning: Continuous models | 719 |
| Bayesian parameter learning | 720 |
| Learning Bayes net structures | 722 |
| 20.3 Learning with Hidden Variables: The EM Algorithm | 724 |
| Unsupervised clustering: Learning mixtures of Gaussians | 725 |
| Learning Bayesian networks with hidden variables | 727 |
| Learning hidden Markov models | 731 |
| The general form of the EM algorithm | 731 |
| Learning Bayes net structures with hidden variables | 732 |
| 20.4 Instance-Based Learning | 733 |
| Nearest-neighbor models | 733 |
| Kernel models | 735 |
| 20.5 Neural Networks | 736 |
| Units in neural networks | 737 |
| Network structures | 738 |
| Single layer feed-forward neural networks (perceptrons) | 740 |
| Multilayer feed-forward neural networks | 744 |
| Learning neural network structures | 748 |
| 20.6 Kernel Machines | 749 |

| | | |
|-----------|---|------------|
| 20.7 | Case Study: Handwritten Digit Recognition | 752 |
| 20.8 | Summary | 754 |
| | Bibliographical and Historical Notes | 755 |
| | Exercises | 759 |
| 21 | Reinforcement Learning | 763 |
| 21.1 | Introduction | 763 |
| 21.2 | Passive Reinforcement Learning | 765 |
| | Direct utility estimation | 766 |
| | Adaptive dynamic programming | 767 |
| | Temporal difference learning | 767 |
| 21.3 | Active Reinforcement Learning | 771 |
| | Exploration | 771 |
| | Learning an Action-Value Function | 775 |
| 21.4 | Generalization in Reinforcement Learning | 777 |
| | Applications to game-playing | 780 |
| | Application to robot control | 780 |
| 21.5 | Policy Search | 781 |
| 21.6 | Summary | 784 |
| | Bibliographical and Historical Notes | 785 |
| | Exercises | 788 |

VII Communicating, perceiving, and acting

| | | |
|-----------|--|------------|
| 22 | Communication | 790 |
| 22.1 | Communication as Action | 790 |
| | Fundamentals of language | 791 |
| | The component steps of communication | 792 |
| 22.2 | A Formal Grammar for a Fragment of English | 795 |
| | The Lexicon of \mathcal{E}_0 | 795 |
| | The Grammar of \mathcal{E}_0 | 796 |
| 22.3 | Syntactic Analysis (Parsing) | 798 |
| | Efficient parsing | 800 |
| 22.4 | Augmented Grammars | 806 |
| | Verb subcategorization | 808 |
| | Generative capacity of augmented grammars | 809 |
| 22.5 | Semantic Interpretation | 810 |
| | The semantics of an English fragment | 811 |
| | Time and tense | 812 |
| | Quantification | 813 |
| | Pragmatic Interpretation | 815 |
| | Language generation with DCGs | 817 |
| 22.6 | Ambiguity and Disambiguation | 818 |
| | Disambiguation | 820 |
| 22.7 | Discourse Understanding | 821 |
| | Reference resolution | 821 |
| | The structure of coherent discourse | 823 |
| 22.8 | Grammar Induction | 824 |
| 22.9 | Summary | 826 |

| | |
|---|------------|
| Bibliographical and Historical Notes | 827 |
| Exercises | 831 |
| 23 Probabilistic Language Processing | 834 |
| 23.1 Probabilistic Language Models | 834 |
| Probabilistic context-free grammars | 836 |
| Learning probabilities for PCFGs | 839 |
| Learning rule structure for PCFGs | 840 |
| 23.2 Information Retrieval | 840 |
| Evaluating IR systems | 842 |
| IR refinements | 844 |
| Presentation of result sets | 845 |
| Implementing IR systems | 846 |
| 23.3 Information Extraction | 848 |
| 23.4 Machine Translation | 850 |
| Machine translation systems | 852 |
| Statistical machine translation | 853 |
| Learning probabilities for machine translation | 856 |
| 23.5 Summary | 857 |
| Bibliographical and Historical Notes | 858 |
| Exercises | 861 |
| 24 Perception | 863 |
| 24.1 Introduction | 863 |
| 24.2 Image Formation | 865 |
| Images without lenses: the pinhole camera | 865 |
| Lens systems | 866 |
| Light: the photometry of image formation | 867 |
| Color: the spectrophotometry of image formation | 868 |
| 24.3 Early Image Processing Operations | 869 |
| Edge detection | 870 |
| Image segmentation | 872 |
| 24.4 Extracting Three-Dimensional Information | 873 |
| Motion | 875 |
| Binocular stereopsis | 876 |
| Texture gradients | 879 |
| Shading | 880 |
| Contour | 881 |
| 24.5 Object Recognition | 885 |
| Brightness-based recognition | 887 |
| Feature-based recognition | 888 |
| Pose Estimation | 890 |
| 24.6 Using Vision for Manipulation and Navigation | 892 |
| 24.7 Summary | 894 |
| Bibliographical and Historical Notes | 895 |
| Exercises | 898 |
| 25 Robotics | 901 |
| 25.1 Introduction | 901 |

| | | |
|------|--|-----|
| 25.2 | Robot Hardware | 903 |
| | Sensors | 903 |
| | Effectors | 904 |
| 25.3 | Robotic Perception | 907 |
| | Localization | 908 |
| | Mapping | 913 |
| | Other types of perception | 915 |
| 25.4 | Planning to Move | 916 |
| | Configuration space | 916 |
| | Cell decomposition methods | 919 |
| | Skeletonization methods | 922 |
| 25.5 | Planning uncertain movements | 923 |
| | Robust methods | 924 |
| 25.6 | Moving | 926 |
| | Dynamics and control | 927 |
| | Potential field control | 929 |
| | Reactive control | 930 |
| 25.7 | Robotic Software Architectures | 932 |
| | Subsumption architecture | 932 |
| | Three-layer architecture | 933 |
| | Robotic programming languages | 934 |
| 25.8 | Application Domains | 935 |
| 25.9 | Summary | 938 |
| | Bibliographical and Historical Notes | 939 |
| | Exercises | 942 |

VIII Conclusions

| | | |
|-----------|--|------------|
| 26 | Philosophical Foundations | 947 |
| 26.1 | Weak AI: Can Machines Act Intelligently? | 947 |
| | The argument from disability | 948 |
| | The mathematical objection | 949 |
| | The argument from informality | 950 |
| 26.2 | Strong AI: Can Machines Really Think? | 952 |
| | The mind–body problem | 954 |
| | The “brain in a vat” experiment | 955 |
| | The brain prosthesis experiment | 956 |
| | The Chinese room | 958 |
| 26.3 | The Ethics and Risks of Developing Artificial Intelligence | 960 |
| 26.4 | Summary | 964 |
| | Bibliographical and Historical Notes | 964 |
| | Exercises | 967 |
| 27 | AI: Present and Future | 968 |
| 27.1 | Agent Components | 968 |
| 27.2 | Agent Architectures | 970 |
| 27.3 | Are We Going in the Right Direction? | 972 |

| | | |
|----------|--|-------------|
| 27.4 | What if AI Does Succeed? | 974 |
| A | Mathematical background | 977 |
| A.1 | Complexity Analysis and $O()$ Notation | 977 |
| | Asymptotic analysis | 977 |
| | NP and inherently hard problems | 978 |
| A.2 | Vectors, Matrices, and Linear Algebra | 979 |
| A.3 | Probability Distributions | 981 |
| | Bibliographical and Historical Notes | 983 |
| B | Notes on Languages and Algorithms | 984 |
| B.1 | Defining Languages with Backus–Naur Form (BNF) | 984 |
| B.2 | Describing Algorithms with Pseudocode | 985 |
| B.3 | Online Help | 985 |
| | Bibliography | 987 |
| | Index | 1045 |