

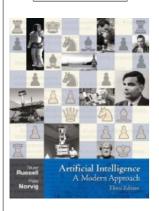
Table of Contents for AI: A Modern Approach

AIMA Home
Code
Contents
Courses

Instructors

Errata

Search AIMA



Part I: Artificial Intelligence

Chapter 1: Introduction ... 1

- 1.1. What Is AI? ... 1
 - 1.1.1. Acting humanly: The Turing Test approach ... 2
 - 1.1.2. Thinking humanly: The cognitive modeling approach ... 3
 - 1.1.3. Thinking rationally: The ``laws of thought" approach ... 4
 - 1.1.4. Acting rationally: The rational agent approach ... 4
- 1.2. The Foundations of Artificial Intelligence ... 5
 - 1.2.1. Philosophy ... 5
 - 1.2.2. Mathematics ... 7
 - 1.2.3. Economics ... 9
 - 1.2.4. Neuroscience ... 10
 - 1.2.5. Psychology ... 12
 - 1.2.6. Computer engineering ... 13
 - 1.2.7. Control theory and cybernetics ... 15
 - 1.2.8. Linguistics ... 15
- 1.3. The History of Artificial Intelligence ... 16
 - 1.3.1. The gestation of artificial intelligence (1943--1955) ... 16
 - 1.3.2. The birth of artificial intelligence (1956) ... 17
 - 1.3.3. Early enthusiasm, great expectations (1952--1969) ... 18
 - 1.3.4. A dose of reality (1966--1973) ... 20
 - 1.3.5. Knowledge-based systems: The key to power? (1969--1979) ... 22
 - 1.3.6. AI becomes an industry (1980--present) ... 24
 - 1.3.7. The return of neural networks (1986--present) ... 24
 - 1.3.8. AI adopts the scientific method (1987--present) ... 25
 - 1.3.9. The emergence of intelligent agents (1995--present) ... 26
 - 1.3.10. The availability of very large data sets (2001--present) ... 27
- 1.4. The State of the Art ... 28
- 1.5. Summary ... 29

Bibliographical and Historical Notes ... 30

Exercises ... 31

Chapter 2: Intelligent Agents ... 34

- 2.1. Agents and Environments ... 34
- 2.2. Good Behavior: The Concept of Rationality ... 36
 - 2.2.1. Rationality ... 37
 - 2.2.2. Omniscience, learning, and autonomy ... 38
- 2.3. The Nature of Environments ... 40

- 2.3.1. Specifying the task environment ... 40
- 2.3.2. Properties of task environments ... 41
- 2.4. The Structure of Agents ... 46
 - 2.4.1. Agent programs ... 46
 - 2.4.2. Simple reflex agents ... 48
 - 2.4.3. Model-based reflex agents ... 50
 - 2.4.4. Goal-based agents ... 52
 - 2.4.5. Utility-based agents ... 53
 - 2.4.6. Learning agents ... 54
 - 2.4.7. How the components of agent programs work ... 57
- 2.5. Summary ... 59

Bibliographical and Historical Notes ... 59

Exercises ... 61

Part II: Problem-solving

Chapter 3: Solving Problems by Searching ... 64

- 3.1. Problem-Solving Agents ... 64
 - 3.1.1. Well-defined problems and solutions ... 66
 - 3.1.2. Formulating problems ... 68
- 3.2. Example Problems ... 69
 - 3.2.1. Toy problems ... 70
 - 3.2.2. Real-world problems ... 73
- 3.3. Searching for Solutions ... 75
 - 3.3.1. Infrastructure for search algorithms ... 78
 - 3.3.2. Measuring problem-solving performance ... 80
- 3.4. Uninformed Search Strategies ... 81
 - 3.4.1. Breadth-first search ... 81
 - 3.4.2. Uniform-cost search ... 83
 - 3.4.3. Depth-first search ... 85
 - 3.4.4. Depth-limited search ... 87
 - 3.4.5. Iterative deepening depth-first search ... 88
 - 3.4.6. Bidirectional search ... 90
 - 3.4.7. Comparing uninformed search strategies ... 91
- 3.5. Informed (Heuristic) Search Strategies ... 92
 - 3.5.1. Greedy best-first search ... 92
 - 3.5.2. A* search: Minimizing the total estimated solution cost ... 93 Conditions for optimality: Admissibility and consistency ... 94 Optimality of A* ... 95
 - 3.5.3. Memory-bounded heuristic search ... 99
 - 3.5.4. Learning to search better ... 102
- 3.6. Heuristic Functions ... 102
 - 3.6.1. The effect of heuristic accuracy on performance ... 103
 - 3.6.2. Generating admissible heuristics from relaxed problems ... 104
- 3.6.3. Generating admissible heuristics from subproblems: Pattern databases ... 106
- 3.6.4. Learning heuristics from experience ... 107
- 3.7. Summary ... 108

Bibliographical and Historical Notes ... 109 Exercises ... 112

Chapter 4: Beyond Classical Search ... 120

4.1. Local Search Algorithms and Optimization Problems 120
4.1.1. Hill-climbing search 122
4.1.2. Simulated annealing 125
4.1.3. Local beam search 125
4.1.4. Genetic algorithms 126
4.2. Local Search in Continuous Spaces 129
4.3. Searching with Nondeterministic Actions 133
4.3.1. The erratic vacuum world 133
4.3.2 AND-OR search trees 135
4.3.3. Try, try again 137
4.4. Searching with Partial Observations 138
4.4.1. Searching with no observation 138
4.4.2. Searching with observations 142
4.4.3. Solving partially observable problems 143
4.4.4. An agent for partially observable environments 144
4.5. Online Search Agents and Unknown Environments 147
4.5.1. Online search problems 147
4.5.2. Online search agents 149
4.5.3. Online local search 150
4.5.4. Learning in online search 153
4.6. Summary 153
Bibliographical and Historical Notes 154
Exercises 157

Chapter 5: Adversarial Search ... 161

5.1. Games 161
5.2. Optimal Decisions in Games 163
5.2.1. The minimax algorithm 165
5.2.2. Optimal decisions in multiplayer games 165
5.3. AlphaBeta Pruning 167
5.3.1. Move ordering 169
5.4. Imperfect Real-Time Decisions 171
5.4.1. Evaluation functions 171
5.4.2. Cutting off search 173
5.4.3. Forward pruning 174
5.4.4. Search versus lookup 176
5.5. Stochastic Games 177
5.5.1. Evaluation functions for games of chance 178
5.6. Partially Observable Games 180
5.6.1. Kriegspiel: Partially observable chess 180
5.6.2. Card games 183
5.7. State-of-the-Art Game Programs 185
5.8. Alternative Approaches 187
5.9. Summary 189

Bibliographical and Historical Notes ... 190 Exercises ... 195

Chapter 6: Constraint Satisfaction Problems ... 202

- 6.1. Defining Constraint Satisfaction Problems ... 202
 - 6.1.1. Example problem: Map coloring ... 203
 - 6.1.2. Example problem: Job-shop scheduling ... 204
 - 6.1.3. Variations on the CSP formalism ... 205
- 6.2. Constraint Propagation: Inference in CSPs ... 208
 - 6.2.1. Node consistency ... 208
 - 6.2.2. Arc consistency ... 208
 - 6.2.3. Path consistency ... 210
 - 6.2.4. *K*-consistency. ... 211
 - 6.2.5. Global constraints ... 211
 - 6.2.6. Sudoku example ... 212
- 6.3. Backtracking Search for CSPs ... 214
 - 6.3.1. Variable and value ordering ... 216
 - 6.3.2. Interleaving search and inference ... 217
 - 6.3.3. Intelligent backtracking: Looking backward ... 218
- 6.4. Local Search for CSPs ... 220
- 6.5. The Structure of Problems ... 222
- 6.6. Summary ... 227

Bibliographical and Historical Notes ... 227

Exercises ... 230

Part III: Knowledge, reasoning, and planning

Chapter 7: Logical Agents ... 234

- 7.1. Knowledge-Based Agents ... 235
- 7.2. The Wumpus World ... 236
- 7.3. Logic ... 240
- 7.4. Propositional Logic: A Very Simple Logic ... 243
 - 7.4.1. Syntax ... 244
 - 7.4.2. Semantics ... 245
 - 7.4.3. A simple knowledge base ... 246
 - 7.4.4. A simple inference procedure ... 247
- 7.5. Propositional Theorem Proving ... 249
 - 7.5.1. Inference and proofs ... 250
 - 7.5.2. Proof by resolution ... 252

Conjunctive normal form ... 253

A resolution algorithm ... 254

Completeness of resolution ... 255

- 7.5.3. Horn clauses and definite clauses ... 256
- 7.5.4. Forward and backward chaining ... 257

Table of Contents for Al: A Modern Approach
7.6. Effective Propositional Model Checking 259
7.6.1. A complete backtracking algorithm 260
7.6.2. Local search algorithms 262
7.6.3. The landscape of random SAT problems 263
7.7. Agents Based on Propositional Logic 265
7.7.1. The current state of the world 265
7.7.2. A hybrid agent 268
7.7.3. Logical state estimation 269
7.7.4. Making plans by propositional inference 271
7.8. Summary 274
Bibliographical and Historical Notes 275
Exercises 279
Chapter 8: First-Order Logic 285
8.1. Representation Revisited 285
8.1.1. The language of thought 286
8.1.2. Combining the best of formal and natural languages
8.2. Syntax and Semantics of First-Order Logic 290
8.2.1. Models for first-order logic 290
8.2.2. Symbols and interpretations 292
8.2.3. Terms 294
8.2.4. Atomic sentences 294
8.2.5. Complex sentences 295
8.2.6. Quantifiers 295
Universal quantification (∀) 295
Existential quantification (∃) 297
Nested quantifiers 297
Connections between ∀ and ∃ 298
8.2.7. Equality 299
8.2.8. An alternative semantics? 299
8.3. Using First-Order Logic 300
8.3.1. Assertions and queries in first-order logic 301
8.3.2. The kinship domain 301
8.3.3. Numbers, sets, and lists 303
8.3.4. The wumpus world 305

... 288

8.4. Knowledge Engineering in First-Order Logic ... 307

8.4.1. The knowledge-engineering process ... 307

8.4.2. The electronic circuits domain ... 309

Identify the task ... 309

Assemble the relevant knowledge ... 309

Decide on a vocabulary ... 310

Encode general knowledge of the domain ... 310

Encode the specific problem instance ... 311

Pose queries to the inference procedure ... 312

Debug the knowledge base ... 312

8.5. Summary ... 313

Bibliographical and Historical Notes ... 313

Exercises ... 315

Chapter 9: Inference in First-Order Logic ... 322

9.1. Propositional vs. First-Order Inference 322
9.1.1. Inference rules for quantifiers 322
9.1.2. Reduction to propositional inference 324
9.2. Unification and Lifting 325
9.2.1. A first-order inference rule 325
9.2.2. Unification 326
9.2.3. Storage and retrieval 327
9.3. Forward Chaining 330
9.3.1. First-order definite clauses 330
9.3.2. A simple forward-chaining algorithm 331
9.3.3. Efficient forward chaining 333
Matching rules against known facts 333
Incremental forward chaining 335
Irrelevant facts 336
9.4. Backward Chaining 337
9.4.1. A backward-chaining algorithm 337
9.4.2. Logic programming 339
9.4.3. Efficient implementation of logic programs 340
9.4.4. Redundant inference and infinite loops 342
9.4.5. Database semantics of Prolog 343
9.4.6. Constraint logic programming 344
9.5. Resolution 345
9.5.1. Conjunctive normal form for first-order logic 345
9.5.2. The resolution inference rule 347
9.5.3. Example proofs 347
9.5.4. Completeness of resolution 350
9.5.5. Equality 353
9.5.6. Resolution strategies 355
Practical uses of resolution theorem provers 356
9.6. Summary 357
Bibliographical and Historical Notes 357
Exercises 360
Chapter 10: Classical Planning 366

10.1. Definition of Classical Planning 366
10.1.1. Example: Air cargo transport 369
10.1.2. Example: The spare tire problem 370
10.1.3. Example: The blocks world 370
10.1.4. The complexity of classical planning 372
10.2. Algorithms for Planning as State-Space Search 373
10.2.1. Forward (progression) state-space search 373
10.2.2. Backward (regression) relevant-states search 374
10.2.3. Heuristics for planning 376
10.3. Planning Graphs 379
10.3.1. Planning graphs for heuristic estimation 381
10.3.2. The Graphplan algorithm 383
10.3.3. Termination of Graphplan 385
10.4. Other Classical Planning Approaches 387
10.4.1. Classical planning as Boolean satisfiability 387

- 10.4.2. Planning as first-order logical deduction: Situation calculus ... 388
- 10.4.3. Planning as constraint satisfaction ... 390
- 10.4.4. Planning as refinement of partially ordered plans ... 390
- 10.5. Analysis of Planning Approaches ... 392
- 10.6. Summary ... 393
- Bibliographical and Historical Notes ... 393
- Exercises ... 396

Chapter 11: Planning and Acting in the Real World ... 401

- 11.1. Time, Schedules, and Resources ... 401
 - 11.1.1. Representing temporal and resource constraints ... 402
 - 11.1.2. Solving scheduling problems ... 403
- 11.2. Hierarchical Planning ... 406
 - 11.2.1. High-level actions ... 406
 - 11.2.2. Searching for primitive solutions ... 408
 - 11.2.3. Searching for abstract solutions ... 410
- 11.3. Planning and Acting in Nondeterministic Domains ... 415
 - 11.3.1. Sensorless planning ... 417
 - 11.3.2. Contingent planning ... 421
 - 11.3.3. Online replanning ... 422
- 11.4. Multiagent Planning ... 425
 - 11.4.1. Planning with multiple simultaneous actions ... 426
 - 11.4.2. Planning with multiple agents: Cooperation and coordination ... 428
- 11.5. Summary ... 430

Bibliographical and Historical Notes ... 431

Exercises ... 435

Chapter 12: Knowledge Representation ... 437

- 12.1. Ontological Engineering ... 437
- 12.2. Categories and Objects ... 440
 - 12.2.1. Physical composition ... 441
 - 12.2.2. Measurements ... 444
 - 12.2.3. Objects: Things and stuff ... 445
- 12.3. Events ... 446
 - 12.3.1. Processes ... 447
 - 12.3.2. Time intervals ... 448
 - 12.3.3. Fluents and objects ... 449
- 12.4. Mental Events and Mental Objects ... 450
- 12.5. Reasoning Systems for Categories ... 453
 - 12.5.1. Semantic networks ... 454
 - 12.5.2. Description logics ... 456
- 12.6. Reasoning with Default Information ... 458
 - 12.6.1. Circumscription and default logic ... 458
 - 12.6.2. Truth maintenance systems ... 460
- 12.7. The Internet Shopping World ... 462
 - 12.7.1. Following links ... 464
 - 12.7.2. Comparing offers ... 466

12.8. Summary ... 467 Bibliographical and Historical Notes ... 468 Exercises ... 473

Part IV: Uncertain knowledge and reasoning

Chapter 13: Quantifying Uncertainty ... 480

13.1. Acting under Uncertainty 480
13.1.1. Summarizing uncertainty 481
13.1.2. Uncertainty and rational decisions 482
13.2. Basic Probability Notation 483
13.2.1. What probabilities are about 484
13.2.2. The language of propositions in probability assertions 486
13.2.3. Probability axioms and their reasonableness 488
13.3. Inference Using Full Joint Distributions 490
13.4. Independence 494
13.5. Bayes' Rule and Its Use 495
13.5.1. Applying Bayes' rule: The simple case 496
13.5.2. Using Bayes' rule: Combining evidence 497
13.6. The Wumpus World Revisited 499
13.7. Summary 503
Bibliographical and Historical Notes 503
Exercises 506

Chapter 14: Probabilistic Reasoning ... 510

14.1. Representing Knowledge in an Uncertain Domain 510
14.2. The Semantics of Bayesian Networks 513
14.2.1. Representing the full joint distribution 513
A method for constructing Bayesian networks 514
Compactness and node ordering 515
14.2.2. Conditional independence relations in Bayesian networks 517
14.3. Efficient Representation of Conditional Distributions 518
Bayesian nets with continuous variables 519
14.4. Exact Inference in Bayesian Networks 522
14.4.1. Inference by enumeration 523
14.4.2. The variable elimination algorithm 524
Operations on factors 526
Variable ordering and variable relevance 527
14.4.3. The complexity of exact inference 528
14.4.4. Clustering algorithms 529
14.5. Approximate Inference in Bayesian Networks 530
14.5.1. Direct sampling methods 530
Rejection sampling in Bayesian networks 532
Likelihood weighting 532

- 14.5.2. Inference by Markov chain simulation ... 535
 Gibbs sampling in Bayesian networks ... 536
 Why Gibbs sampling works ... 536
 14.6. Relational and First-Order Probability Models ... 539
 14.6.1. Possible worlds ... 540
 14.6.2. Relational probability models ... 542
- 14.6.3. Open-universe probability models ... 544 14.7. Other Approaches to Uncertain Reasoning ... 546
 - 14.7.1. Rule-based methods for uncertain reasoning ... 547
 - 14.7.2. Representing ignorance: Dempster--Shafer theory ... 549
 - 14.7.3. Representing vagueness: Fuzzy sets and fuzzy logic ... 550

14.8. Summary ... 551

Bibliographical and Historical Notes ... 552

Exercises ... 558

Chapter 15: Probabilistic Reasoning over Time ... 566

- 15.1. Time and Uncertainty ... 566
 - 15.1.1. States and observations ... 567
 - 15.1.2. Transition and sensor models ... 568
- 15.2. Inference in Temporal Models ... 570
 - 15.2.1. Filtering and prediction ... 571
 - 15.2.2. Smoothing ... 574
 - 15.2.3. Finding the most likely sequence ... 576
- 15.3. Hidden Markov Models ... 578
 - 15.3.1. Simplified matrix algorithms ... 579
 - 15.3.2. Hidden Markov model example: Localization ... 581
- 15.4. Kalman Filters ... 584
 - 15.4.1. Updating Gaussian distributions ... 584
 - 15.4.2. A simple one-dimensional example ... 585
 - 15.4.3. The general case ... 587
 - 15.4.4. Applicability of Kalman filtering ... 588
- 15.5. Dynamic Bayesian Networks ... 590
 - 15.5.1. Constructing DBNs ... 591
 - 15.5.2. Exact inference in DBNs ... 595
 - 15.5.3. Approximate inference in DBNs ... 596
- 15.6. Keeping Track of Many Objects ... 599
- 15.7. Summary ... 603

Bibliographical and Historical Notes ... 603

Exercises ... 606

Chapter 16: Making Simple Decisions ... 610

- 16.1. Combining Beliefs and Desires under Uncertainty ... 610
- 16.2. The Basis of Utility Theory ... 611
 - 16.2.1. Constraints on rational preferences ... 612
 - 16.2.2. Preferences lead to utility ... 613
- 16.3. Utility Functions ... 615
 - 16.3.1. Utility assessment and utility scales ... 615

- 16.3.2. The utility of money ... 616
- 16.3.3. Expected utility and post-decision disappointment ... 618
- 16.3.4. Human judgment and irrationality ... 619
- 16.4. Multiattribute Utility Functions ... 622
 - 16.4.1. Dominance ... 622
 - 16.4.2. Preference structure and multiattribute utility ... 624
 - Preferences without uncertainty ... 624
 - Preferences with uncertainty ... 625
- 16.5. Decision Networks ... 626
 - 16.5.1. Representing a decision problem with a decision network ... 626
 - 16.5.2. Evaluating decision networks ... 628
- 16.6. The Value of Information ... 628
 - 16.6.1. A simple example ... 629
 - 16.6.2. A general formula for perfect information ... 630
 - 16.6.3. Properties of the value of information ... 631
 - 16.6.4. Implementation of an information-gathering agent ... 632
- 16.7. Decision-Theoretic Expert Systems ... 633
- 16.8. Summary ... 636
- Bibliographical and Historical Notes ... 636
- Exercises ... 640

Chapter 17: Making Complex Decisions ... 645

- 17.1. Sequential Decision Problems ... 645
 - 17.1.1. Utilities over time ... 648
 - 17.1.2. Optimal policies and the utilities of states ... 650
- 17.2. Value Iteration ... 652
 - 17.2.1. The Bellman equation for utilities ... 652
 - 17.2.2. The value iteration algorithm ... 652
 - 17.2.3. Convergence of value iteration ... 654
- 17.3. Policy Iteration ... 656
- 17.4. Partially Observable MDPs ... 658
 - 17.4.1. Definition of POMDPs ... 658
 - 17.4.2. Value iteration for POMDPs ... 660
 - 17.4.3. Online agents for POMDPs ... 664
- 17.5. Decisions with Multiple Agents: Game Theory ... 666
 - 17.5.1. Single-move games ... 667
 - 17.5.2. Repeated games ... 673
 - 17.5.3. Sequential games ... 674
- 17.6. Mechanism Design ... 679
 - 17.6.1. Auctions ... 679
 - 17.6.2. Common goods ... 683
- 17.7. Summary ... 684
- Bibliographical and Historical Notes ... 685
- Exercises ... 688

Part V: Learning

Chapter 18: Learning from Examples ... 693

18.1. Forms of Learning 693
Components to be learned 694
Representation and prior knowledge 694
Feedback to learn from 694
18.2. Supervised Learning 695
18.3. Learning Decision Trees 697
18.3.1. The decision tree representation 698
18.3.2. Expressiveness of decision trees 698
18.3.3. Inducing decision trees from examples 699
18.3.4. Choosing attribute tests 703
18.3.5. Generalization and overfitting 705
18.3.6. Broadening the applicability of decision trees 706
18.4. Evaluating and Choosing the Best Hypothesis 708
18.4.1. Model selection: Complexity versus goodness of fit 709
18.4.2. From error rates to loss 710
18.4.3. Regularization 712
18.5. The Theory of Learning 713
18.5.1. PAC learning example: Learning decision lists 715
18.6. Regression and Classification with Linear Models 717
18.6.1. Univariate linear regression 718
18.6.2. Multivariate linear regression 720
18.6.3. Linear classifiers with a hard threshold 723
18.6.4. Linear classification with logistic regression 725
18.7. Artificial Neural Networks 727
18.7.1. Neural network structures 728
18.7.2. Single-layer feed-forward neural networks (perceptrons) 729
18.7.3. Multilayer feed-forward neural networks 731
18.7.4. Learning in multilayer networks 733
18.7.5. Learning neural network structures 736
18.8. Nonparametric Models 737
18.8.1. Nearest neighbor models 738
18.8.2. Finding nearest neighbors with k-d trees 739
18.8.3. Locality-sensitive hashing 740
18.8.4. Nonparametric regression 741
18.9. Support Vector Machines 744
18.10. Ensemble Learning 748
18.10.1. Online Learning 752
18.11. Practical Machine Learning 753
18.11.1. Case study: Handwritten digit recognition 753
18.11.2. Case study: Word senses and house prices 755
18.12. Summary 757
Bibliographical and Historical Notes 758
Exercises 763

Chapter 19: Knowledge in Learning ... 768

```
19.1. A Logical Formulation of Learning ... 768 19.1.1. Examples and hypotheses ... 768
```

19.1.2. Current-best-hypothesis search ... 770

19.1.3. Least-commitment search ... 773

19.2. Knowledge in Learning ... 777 19.2.1. Some simple examples ... 778 19.2.2. Some general schemes ... 778 19.3. Explanation-Based Learning ... 780 19.3.1. Extracting general rules from examples ... 781 19.3.2. Improving efficiency ... 783 19.4. Learning Using Relevance Information ... 784 19.4.1. Determining the hypothesis space ... 785 19.4.2. Learning and using relevance information ... 785 19.5. Inductive Logic Programming ... 788 19.5.1. An example ... 788 19.5.2. Top-down inductive learning methods ... 791 19.5.3. Inductive learning with inverse deduction ... 794 19.5.4. Making discoveries with inductive logic programming ... 796 19.6. Summary ... 797 Bibliographical and Historical Notes ... 798

Chapter 20: Learning Probabilistic Models ... 802

Exercises ... 801

20.1. Statistical Learning ... 802 20.2. Learning with Complete Data ... 806 20.2.1. Maximum-likelihood parameter learning: Discrete models ... 806 20.2.2. Naive Bayes models ... 808 20.2.3. Maximum-likelihood parameter learning: Continuous models ... 809 20.2.4. Bayesian parameter learning ... 810 20.2.5. Learning Bayes net structures ... 813 20.2.6. Density estimation with nonparametric models ... 814 20.3. Learning with Hidden Variables: The EM Algorithm ... 816 20.3.1. Unsupervised clustering: Learning mixtures of Gaussians ... 817 20.3.2. Learning Bayesian networks with hidden variables ... 820 20.3.3. Learning hidden Markov models ... 822 20.3.4. The general form of the EM algorithm ... 823 20.3.5. Learning Bayes net structures with hidden variables ... 824 20.4. Summary ... 825 Bibliographical and Historical Notes ... 825 Exercises ... 827

Chapter 21: Reinforcement Learning ... 830

```
21.1. Introduction ... 830
21.2. Passive Reinforcement Learning ... 832
21.2.1. Direct utility estimation ... 833
21.2.2. Adaptive dynamic programming ... 834
21.2.3. Temporal-difference learning ... 836
21.3. Active Reinforcement Learning ... 839
21.3.1. Exploration ... 839
21.3.2. Learning an action-utility function ... 842
21.4. Generalization in Reinforcement Learning ... 845
21.5. Policy Search ... 848
```

- 21.6. Applications of Reinforcement Learning ... 850
 - 21.6.1. Applications to game playing ... 850
 - 21.6.2. Application to robot control ... 851
- 21.7. Summary ... 853

Bibliographical and Historical Notes ... 854

Exercises ... 858

Part VI: Communicating, perceiving, and acting

Chapter 22: Natural Language Processing ... 860

- 22.1. Language Models ... 860
 - 22.1.1 N-gram character models ... 861
 - 22.1.2. Smoothing *n*-gram models ... 862
 - 22.1.3. Model evaluation ... 863
 - 22.1.4 N-gram word models ... 864
- 22.2. Text Classification ... 865
 - 22.2.1. Classification by data compression ... 866
- 22.3. Information Retrieval ... 867
 - 22.3.1. IR scoring functions ... 868
 - 22.3.2. IR system evaluation ... 869
 - 22.3.3. IR refinements ... 869
 - 22.3.4. The PageRank algorithm ... 870
 - 22.3.5. The HITS algorithm ... 872
 - 22.3.6. Question answering ... 872
- 22.4. Information Extraction ... 873
 - 22.4.1. Finite-state automata for information extraction ... 874
 - 22.4.2. Probabilistic models for information extraction ... 876
 - 22.4.3. Conditional random fields for information extraction ... 878
 - 22.4.4. Ontology extraction from large corpora ... 879
 - 22.4.5. Automated template construction ... 880
 - 22.4.6. Machine reading ... 881
- 22.5. Summary ... 882

Bibliographical and Historical Notes ... 883

Exercises ... 885

Chapter 23: Natural Language for Communication ... 888

- 23.1. Phrase Structure Grammars ... 888
 - 23.1.1. The lexicon of E_0 ... 890
 - 23.1.2. The Grammar of E_0 ... 890
- 23.2. Syntactic Analysis (Parsing) ... 892
 - 23.2.1. Learning probabilities for PCFGs ... 895
 - 23.2.2. Comparing context-free and Markov models ... 896
- 23.3. Augmented Grammars and Semantic Interpretation ... 897

- 23.3.1. Lexicalized PCFGs ... 897 23.3.2. Formal definition of augmented grammar rules ... 898 23.3.3. Case agreement and subject--verb agreement ... 899 23.3.4. Semantic interpretation ... 900 23.3.5. Complications ... 902 23.4. Machine Translation ... 907 23.4.1. Machine translation systems ... 908 23.4.2. Statistical machine translation ... 909 23.5. Speech Recognition ... 912 23.5.1. Acoustic model ... 914 23.5.2. Language model ... 917 23.5.3. Building a speech recognizer ... 917
- 23.6. Summary ... 918

Bibliographical and Historical Notes ... 919

Exercises ... 923

Exercises ... 969

Chapter 24: Perception ... 928

24.1. Image Formation ... 929 24.1.1. Images without lenses: The pinhole camera ... 929 24.1.2. Lens systems ... 931 24.1.3. Scaled orthographic projection ... 932 24.1.4. Light and shading ... 932 24.1.5. Color ... 935 24.2. Early Image-Processing Operations ... 935 24.2.1. Edge detection ... 936 24.2.2. Texture ... 939 24.2.3. Optical flow ... 939 24.2.4. Segmentation of images ... 941 24.3. Object Recognition by Appearance ... 942 24.3.1. Complex appearance and pattern elements ... 944 24.3.2. Pedestrian detection with HOG features ... 945 24.4. Reconstructing the 3D World ... 947 24.4.1. Motion parallax ... 948 24.4.2. Binocular stereopsis ... 949 24.4.3. Multiple views ... 951 24.4.4. Texture ... 951 24.4.5. Shading ... 952 24.4.6. Contour ... 953 24.4.7. Objects and the geometric structure of scenes ... 954 24.5. Object Recognition from Structural Information ... 957 24.5.1. The geometry of bodies: Finding arms and legs ... 958 24.5.2. Coherent appearance: Tracking people in video ... 959 24.6. Using Vision ... 961 24.6.1. Words and pictures ... 962 24.6.2. Reconstruction from many views ... 962 24.6.3. Using vision for controlling movement ... 963 24.7. Summary ... 965 Bibliographical and Historical Notes ... 966

Chapter 25: Robotics ... 971

25.1. Introduction ... 971 25.2. Robot Hardware ... 973 25.2.1. Sensors ... 973 25.2.2. Effectors ... 975 25.3. Robotic Perception ... 978 25.3.1. Localization and mapping ... 979 25.3.2. Other types of perception ... 984 25.3.3. Machine learning in robot perception ... 985 25.4. Planning to Move ... 986 25.4.1. Configuration space ... 986 25.4.2. Cell decomposition methods ... 989 25.4.3. Modified cost functions ... 991 25.4.4. Skeletonization methods ... 991 25.5. Planning Uncertain Movements ... 993 25.5.1. Robust methods ... 994 25.6. Moving ... 997 25.6.1. Dynamics and control ... 997 25.6.2. Potential-field control ... 999 25.6.3. Reactive control ... 1001 25.6.4. Reinforcement learning control ... 1002 25.7. Robotic Software Architectures ... 1003 25.7.1. Subsumption architecture ... 1003 25.7.2. Three-layer architecture ... 1004 25.7.3. Pipeline architecture ... 1005 25.8. Application Domains ... 1006 25.9. Summary ... 1010

Part VII: Conclusions

Bibliographical and Historical Notes ... 1011

Exercises ... 1014

Chapter 26: Philosophical Foundations ... 1020

```
26.1. Weak AI: Can Machines Act Intelligently? ... 1020
26.1.1. The argument from disability ... 1021
26.1.2. The mathematical objection ... 1022
26.1.3. The argument from informality ... 1024
26.2. Strong AI: Can Machines Really Think? ... 1026
26.2.1. Mental states and the brain in a vat ... 1028
26.2.2. Functionalism and the brain replacement experiment ... 1029
26.2.3. Biological naturalism and the Chinese Room ... 1031
26.2.4. Consciousness, qualia, and the explanatory gap ... 1033
26.3. The Ethics and Risks of Developing Artificial Intelligence ... 1034
26.4. Summary ... 1040
Bibliographical and Historical Notes ... 1040
Exercises ... 1043
```

Chapter 27: AI: The Present and Future ... 1044

- 27.1. Agent Components ... 1044
- 27.2. Agent Architectures ... 1047
- 27.3. Are We Going in the Right Direction? ... 1049
- 27.4. What If AI Does Succeed? ... 1051

Chapter A: Mathematical background ... 1053

- A.1. Complexity Analysis and O() Notation ... 1053
 - A.1.1. Asymptotic analysis ... 1053
 - A.1.2. NP and inherently hard problems ... 1054
- A.2. Vectors, Matrices, and Linear Algebra ... 1055
- A.3. Probability Distributions ... 1057

Bibliographical and Historical Notes ... 1059

Chapter B: Notes on Languages and Algorithms ... 1060

- B.1. Defining Languages with Backus--Naur Form (BNF) ... 1060
- B.2. Describing Algorithms with Pseudocode ... 1061
- B.3. Online Help ... 1062

Bibliography ... 1063

Index ... 1109

AI: A Modern Approach

Modified: Nov 17, 2009