# Contents


Foreword viii
Preface x
About the Authors xiii

1 Introduction 1
1.1 Architecture and Components of an Actor . . . 2
1.2 Descriptive and Operational Models of Actions . . . 7
1.3 Responsible Research on Autonomous Actors . . . 9

I Deterministic State-Transition Systems 11

2 Deterministic Representation and Acting 13
2.1 Motivating Example . . . 13
2.2 State-Transition Systems . . . 14
2.3 State-Variable Representation . . . 17
2.4 Classical Representation . . . 22
2.5 Computational Complexity . . . 25
2.6 Acting . . . 25
2.7 Discussion and Bibliographic Notes . . . 29
2.8 Exercises . . . 32

3 Planning with Deterministic Models 35
3.1 Forward State-Space Search . . . 35
3.2 Heuristic Functions . . . 42
3.3 Backward Search . . . 52
3.4 Plan-Space Planning . . . 55
3.5 Repairing Plans . . . 61
3.6 Discussion and Bibliographic Notes . . . 62
3.7 Exercises . . . 68

4 Learning Deterministic Models 72
4.1 Learning Heuristics . . . 72
4.2 Learning Action Specifications . . . 76
4.3 Discussion and Bibliographic Notes . . . 87
4.4 Exercises . . . 94

II Hierarchical Task Networks 95

5 HTN Representation and Planning 97
5.1 Totally Ordered Tasks . . . 97
5.2 Partially Ordered Tasks . . . 106
5.3 Hybrid HTN/Classical Planning . . . 112

5.4 Heuristics, Expressivity, Complexity . . . 113
5.5 Refinement of Abstract Actions . . . 114
5.6 Discussion and Bibliographic Notes . . . 117
5.7 Exercises . . . 121

6 Acting with HTNs 123
6.1 Reactive HTN Acting . . . 124
6.2 Acting with an Online HTN Planner . . . 124
6.3 Discussion and Bibliographic Notes . . . 129
6.4 Exercises . . . 130

7 Learning HTN Methods 132
7.1 Learning Methods from Examples . . . 132
7.2 Learning Methods from Plans . . . 138
7.3 Planning to Learn . . . 141
7.4 Discussion and Bibliographic Notes . . . 141
7.5 Exercises . . . 143

III Probabilistic Models 146

8 Probabilistic Representation and Acting 147
8.1 Basic MDP Representation . . . 147
8.2 Structured Probabilistic Representations . . . 154
8.3 Modeling a Probabilistic Domain . . . 162
8.4 Acting with Probabilistic Models . . . 167
8.5 Discussion and Bibliographic Notes . . . 169
8.6 Exercises . . . 173

9 Planning with Probabilistic Models 175
9.1 Dynamic Programming Algorithms . . . 175
9.2 Heuristic Search Algorithms . . . 186
9.3 Heuristics and Search-Control Knowledge . . . 197
9.4 Linear Programming Approaches . . . 201
9.5 Online Probabilistic Approaches . . . 209
9.6 Discussion and Bibliographic Notes . . . 221
9.7 Exercises . . . 225

10 Reinforcement Learning 227
10.1 Principles of RL . . . 227
10.2 Tabular Value-Based RL . . . 229
10.3 Parametric Value-Based RL . . . 234
10.4 Neural Parametric Function Approximators . . . 241
10.5 Deep Value-Based RL . . . 245
10.6 Policy-Based RL . . . 250
10.7 Aided Reinforcement Learning . . . 253
10.8 Acting, Planning and Reinforcement Learning . . . 258
10.9 Discussion and Bibliographic Notes . . . 260
10.10 Exercises . . . 269

IV Nondeterministic Models 271

11 Acting with Nondeterministic Models 274
11.1 State Transition Systems . . . 274
11.2 Automata . . . 281
11.3 Behavior Trees . . . 291
11.4 Petri Nets . . . 294
11.5 Discussion and Bibliographic Notes . . . 303
11.6 Exercises . . . 305

12 Planning with Nondeterministic Models 309
12.1 And/Or Graph Search . . . 309
12.2 Determinization Techniques . . . 314
12.3 Planning via Symbolic Model Checking . . . 317
12.4 Synthesis of Automata . . . 328
12.5 Generating Behavior Trees . . . 331
12.6 Discussion and Bibliographic Notes . . . 334
12.7 Exercises . . . 340

13 Learning Nondeterministic Models 343
13.1 Nondeterministic Action Schema . . . 343
13.2 Offline Action Learning . . . 344
13.3 Discussion and Bibliographic Notes . . . 346
13.4 Exercises . . . 346

V Hierarchical Refinement Models 347

14 Acting with Hierarchical Refinement 348
14.1 Representation . . . 348
14.2 Refinement Acting Engine . . . 354
14.3 Extending the Refinement Acting Engine . . . 357
14.4 Discussion and Bibliographic Notes . . . 362
14.5 Exercises . . . 364

15 Hierarchical Refinement Planning 367
15.1 Refinement Planning Domains and Problems . . . 367
15.2 Utility Criteria and Optimal Approach . . . 368
15.3 An MCTS Planning Algorithm . . . 371
15.4 Discussion and Bibliographical Notes . . . 377
15.5 Exercises . . . 378

16 Learning Hierarchical Refinement Models 379
16.1 Learning to guide RAE and UPOM . . . 379
16.2 Learning Hierarchical Refinement Methods . . . 383
16.3 Discussion and Bibliographic Notes . . . 387
16.4 Exercises . . . 387

VI Temporal Models 388

17 Temporal Representation and Planning 390
17.1 Temporal Representation . . . 390
17.2 A Hybrid Temporal Planner . . . 402
17.3 Constraint Management . . . 409
17.4 Discussion and Bibliographic Notes . . . 413
17.5 Exercises . . . 415

18 Acting with Temporal Controllability 419
18.1 Controllable Temporal Networks . . . 419
18.2 A Dispatching Algorithm . . . 425
18.3 Acting without Temporal Refinement . . . 427
18.4 A Temporal Refinement Acting Engine . . . 429
18.5 An MCTS Temporal Planner . . . 432
18.6 Integrating Planning and Acting . . . 435
18.7 Discussion and Bibliographic Notes . . . 436
18.8 Exercises . . . 437

19 Learning for Temporal Acting and Planning 438
19.1 Learning Heuristics for Temporal Planning . . . 438
19.2 Learning Temporal Models . . . 439
19.3 Discussion and Bibliographic Notes . . . 443
19.4 Exercises . . . 445

VII Motion and Manipulation Models in Robotics 446

20 Motion and Manipulation Actions 448
20.1 Robots . . . 448
20.2 Motion . . . 451
20.3 Navigation . . . 471
20.4 Manipulation . . . 478
20.5 Discussion and Bibliographic Notes . . . 482
20.6 Exercises . . . 483

21 Task and Motion Planning 484
21.1 Motion Planning . . . 484
21.2 Manipulation planning . . . 496
21.3 Task, Motion and Manipulation Planning . . . 503
21.4 Discussion and Bibliographic Notes . . . 516
21.5 Exercises . . . 523

22 Learning for Movement Actions 525
22.1 Learning Sensory-Motor Skills . . . 525
22.2 Learning for Task and Motion Planning . . . 528
22.3 Discussion and Bibliographic Notes . . . 531
22.4 Exercises . . . 533

VIII Other Topics and Perspectives 535

23 Large Language Models for Acting and Planning 536
23.1 Principles of LLMs . . . . . 536
23.2 LLMs in Acting, Planning and Learning . . . . . 540

24 Perceiving, Monitoring and Goal Reasoning 546
24.1 Perceiving and Information Gathering . . . . . 546
24.2 Monitoring . . . . . 551
24.3 Goal Reasoning . . . . . 556

Appendices 558

A Graphs and Search 559
A.1 Nondeterministic State-Space Search . . . . . 559
A.2 And/Or Search . . . . . 562
A.3 Strongly Connected Components of a Graph . . . . . 562

B Other Mathematical Background 564
B.1 Metrics and distances . . . . . 564
B.2 Vectors and matrices . . . . . 564
B.3 Derivative and Gradient . . . . . 566

List of Algorithms 567
Bibliographic Abbreviations 571
Bibliography 573

Index 608