

CONTENTS

	ABOUT THE AUTHORS	iv
	ACKNOWLEDGMENTS	xix
	PREFACE	xxi
	ABOUT THE WEBSITE	xxiii
	PART I	
	AI AND GAMES	1
CHAPTER		
1	INTRODUCTION	3
	1.1 WHAT IS AI?	4
	1.1.1 Academic AI	5
	1.1.2 Game AI	7
	1.2 MODEL OF GAME AI	8
	1.2.1 Movement	9
	1.2.2 Decision Making	10
	1.2.3 Strategy	10
	1.2.4 Infrastructure	11
	1.2.5 Agent-Based AI	11
	1.2.6 In the Book	12
	1.3 ALGORITHMS, DATA STRUCTURES, AND REPRESENTATIONS	12
	1.3.1 Algorithms	12
	1.3.2 Representations	15
		v

1.4	ON THE WEBSITE	16
1.4.1	Programs	16
1.4.2	Libraries	17
1.5	LAYOUT OF THE BOOK	18

CHAPTER

2	GAME AI	19
2.1	THE COMPLEXITY FALLACY	19
2.1.1	When Simple Things Look Good	19
2.1.2	When Complex Things Look Bad	20
2.1.3	The Perception Window	21
2.1.4	Changes of Behavior	21
2.2	THE KIND OF AI IN GAMES	22
2.2.1	Hacks	22
2.2.2	Heuristics	23
2.2.3	Algorithms	24
2.3	SPEED AND MEMORY	25
2.3.1	Processor Issues	25
2.3.2	Memory Concerns	28
2.3.3	PC Constraints	29
2.3.4	Console Constraints	29
2.4	THE AI ENGINE	31
2.4.1	Structure of an AI Engine	32
2.4.2	Toolchain Concerns	33
2.4.3	Putting It All Together	34

PART II

TECHNIQUES 37

CHAPTER

3	MOVEMENT	39
3.1	THE BASICS OF MOVEMENT ALGORITHMS	40
3.1.1	Two-Dimensional Movement	41
3.1.2	Statics	42
3.1.3	Kinematics	45
3.2	KINEMATIC MOVEMENT ALGORITHMS	49
3.2.1	Seek	49

3.2.2	Wandering	53
3.2.3	On the Website	55
3.3	STEERING BEHAVIORS	55
3.3.1	Steering Basics	55
3.3.2	Variable Matching	56
3.3.3	Seek and Flee	56
3.3.4	Arrive	59
3.3.5	Align	62
3.3.6	Velocity Matching	66
3.3.7	Delegated Behaviors	67
3.3.8	Pursue and Evade	68
3.3.9	Face	71
3.3.10	Looking Where You're Going	72
3.3.11	Wander	73
3.3.12	Path Following	76
3.3.13	Separation	82
3.3.14	Collision Avoidance	84
3.3.15	Obstacle and Wall Avoidance	90
3.3.16	Summary	95
3.4	COMBINING STEERING BEHAVIORS	95
3.4.1	Blending and Arbitration	96
3.4.2	Weighted Blending	96
3.4.3	Priorities	103
3.4.4	Cooperative Arbitration	107
3.4.5	Steering Pipeline	108
3.5	PREDICTING PHYSICS	120
3.5.1	Aiming and Shooting	121
3.5.2	Projectile Trajectory	121
3.5.3	The Firing Solution	123
3.5.4	Projectiles with Drag	126
3.5.5	Iterative Targeting	128
3.6	JUMPING	134
3.6.1	Jump Points	135
3.6.2	Landing Pads	138
3.6.3	Hole Fillers	143
3.7	COORDINATED MOVEMENT	144
3.7.1	Fixed Formations	144
3.7.2	Scalable Formations	146
3.7.3	Emergent Formations	146
3.7.4	Two-Level Formation Steering	147
3.7.5	Implementation	151

3.7.6	Extending to More than Two Levels	157
3.7.7	Slot Roles and Better Assignment	159
3.7.8	Slot Assignment	162
3.7.9	Dynamic Slots and Plays	166
3.7.10	Tactical Movement	168
3.8	MOTOR CONTROL	171
3.8.1	Output Filtering	172
3.8.2	Capability-Sensitive Steering	174
3.8.3	Common Actuation Properties	175
3.9	MOVEMENT IN THE THIRD DIMENSION	178
3.9.1	Rotation in Three Dimensions	178
3.9.2	Converting Steering Behaviors to Three Dimensions	180
3.9.3	Align	180
3.9.4	Align to Vector	181
3.9.5	Face	183
3.9.6	Look Where You're Going	186
3.9.7	Wander	186
3.9.8	Faking Rotation Axes	188
	EXERCISES	192

CHAPTER**4****PATHFINDING**

		197
4.1	THE PATHFINDING GRAPH	198
4.1.1	Graphs	198
4.1.2	Weighted Graphs	199
4.1.3	Directed Weighted Graphs	202
4.1.4	Terminology	203
4.1.5	Representation	203
4.2	DIJKSTRA	204
4.2.1	The Problem	205
4.2.2	The Algorithm	206
4.2.3	Pseudo-Code	210
4.2.4	Data Structures and Interfaces	212
4.2.5	Performance of Dijkstra	214
4.2.6	Weaknesses	214
4.3	A*	215
4.3.1	The Problem	216
4.3.2	The Algorithm	216
4.3.3	Pseudo-Code	220
4.3.4	Data Structures and Interfaces	223

4.3.5	Implementation Notes	228
4.3.6	Algorithm Performance	228
4.3.7	Node Array A*	229
4.3.8	Choosing a Heuristic	231
4.4	WORLD REPRESENTATIONS	237
4.4.1	Tile Graphs	239
4.4.2	Dirichlet Domains	241
4.4.3	Points of Visibility	244
4.4.4	Navigation Meshes	246
4.4.5	Non-Translational Problems	251
4.4.6	Cost Functions	251
4.4.7	Path Smoothing	251
4.5	IMPROVING ON A*	255
4.6	HIERARCHICAL PATHFINDING	255
4.6.1	The Hierarchical Pathfinding Graph	256
4.6.2	Pathfinding on the Hierarchical Graph	259
4.6.3	Hierarchical Pathfinding on Exclusions	262
4.6.4	Strange Effects of Hierarchies on Pathfinding	263
4.6.5	Instanced Geometry	265
4.7	OTHER IDEAS IN PATHFINDING	271
4.7.1	Open Goal Pathfinding	272
4.7.2	Dynamic Pathfinding	272
4.7.3	Other Kinds of Information Reuse	273
4.7.4	Low Memory Algorithms	273
4.7.5	Interruptible Pathfinding	274
4.7.6	Pooling Planners	275
4.8	CONTINUOUS TIME PATHFINDING	276
4.8.1	The Problem	276
4.8.2	The Algorithm	277
4.8.3	Implementation Notes	281
4.8.4	Performance	281
4.8.5	Weaknesses	282
4.9	MOVEMENT PLANNING	282
4.9.1	Animations	282
4.9.2	Movement Planning	283
4.9.3	Example	286
4.9.4	Footfalls	287
	EXERCISES	288

CHAPTER

5

DECISION MAKING

	293
5.1 OVERVIEW OF DECISION MAKING	293
5.2 DECISION TREES	295
5.2.1 The Problem	295
5.2.2 The Algorithm	295
5.2.3 Pseudo-Code	300
5.2.4 On the Website	302
5.2.5 Knowledge Representation	303
5.2.6 Implementation Nodes	303
5.2.7 Performance of Decision Trees	304
5.2.8 Balancing the Tree	304
5.2.9 Beyond the Tree	305
5.2.10 Random Decision Trees	306
5.3 STATE MACHINES	309
5.3.1 The Problem	311
5.3.2 The Algorithm	311
5.3.3 Pseudo-Code	311
5.3.4 Data Structures and Interfaces	312
5.3.5 On the Website	315
5.3.6 Performance	316
5.3.7 Implementation Notes	316
5.3.8 Hard-Coded FSM	316
5.3.9 Hierarchical State Machines	318
5.3.10 Combining Decision Trees and State Machines	331
5.4 BEHAVIOR TREES	334
5.4.1 Implementing Behavior Trees	340
5.4.2 Pseudo-Code	340
5.4.3 Decorators	345
5.4.4 Concurrency and Timing	351
5.4.5 Adding Data to Behavior Trees	361
5.4.6 Reusing Trees	365
5.4.7 Limitations of Behavior Trees	370
5.5 FUZZY LOGIC	371
5.5.1 A Warning	371
5.5.2 Introduction to Fuzzy Logic	371
5.5.3 Fuzzy Logic Decision Making	381
5.5.4 Fuzzy State Machines	390

5.6	MARKOV SYSTEMS	395
5.6.1	Markov Processes	396
5.6.2	Markov State Machine	398
5.7	GOAL-ORIENTED BEHAVIOR	401
5.7.1	Goal-Oriented Behavior	402
5.7.2	Simple Selection	404
5.7.3	Overall Utility	406
5.7.4	Timing	408
5.7.5	Overall Utility GOAP	413
5.7.6	GOAP with IDA*	418
5.7.7	Smelly GOB	425
5.8	RULE-BASED SYSTEMS	427
5.8.1	The Problem	428
5.8.2	The Algorithm	433
5.8.3	Pseudo-Code	433
5.8.4	Data Structures and Interfaces	434
5.8.5	Implementation Notes	441
5.8.6	Rule Arbitration	441
5.8.7	Unification	443
5.8.8	Rete	445
5.8.9	Extensions	455
5.8.10	Where Next	459
5.9	BLACKBOARD ARCHITECTURES	459
5.9.1	The Problem	459
5.9.2	The Algorithm	460
5.9.3	Pseudo-Code	461
5.9.4	Data Structures and Interfaces	462
5.9.5	Performance	464
5.9.6	Other Things Are Blackboard Systems	465
5.10	SCRIPTING	466
5.10.1	Language Facilities	467
5.10.2	Embedding	468
5.10.3	Choosing a Language	468
5.10.4	A Language Selection	470
5.10.5	Rolling Your Own	474
5.10.6	Scripting Languages and Other AI	479
5.11	ACTION EXECUTION	480
5.11.1	Types of Action	480
5.11.2	The Algorithm	484
5.11.3	Pseudo-Code	485
5.11.4	Data Structures and Interfaces	487

5.11.5 Implementation Notes	489
5.11.6 Performance	490
5.11.7 Putting It All Together	490

CHAPTER

6	TACTICAL AND STRATEGIC AI	493
6.1	WAYPOINT TACTICS	494
6.1.1	Tactical Locations	494
6.1.2	Using Tactical Locations	502
6.1.3	Generating the Tactical Properties of a Waypoint	507
6.1.4	Automatically Generating the Waypoints	512
6.1.5	The Condensation Algorithm	513
6.2	TACTICAL ANALYSES	518
6.2.1	Representing the Game Level	518
6.2.2	Simple Influence Maps	519
6.2.3	Terrain Analysis	525
6.2.4	Learning with Tactical Analyses	527
6.2.5	A Structure for Tactical Analyses	528
6.2.6	Map Flooding	533
6.2.7	Convolution Filters	538
6.2.8	Cellular Automata	549
6.3	TACTICAL PATHFINDING	553
6.3.1	The Cost Function	553
6.3.2	Tactic Weights and Concern Blending	555
6.3.3	Modifying the Pathfinding Heuristic	557
6.3.4	Tactical Graphs for Pathfinding	557
6.3.5	Using Tactical Waypoints	558
6.4	COORDINATED ACTION	559
6.4.1	Multi-Tier AI	559
6.4.2	Emergent Cooperation	565
6.4.3	Scripting Group Actions	568
6.4.4	Military Tactics	573
	EXERCISES	576

CHAPTER

7	LEARNING	579
7.1	LEARNING BASICS	579
7.1.1	Online or Offline Learning	579
7.1.2	Intra-Behavior Learning	580
7.1.3	Inter-Behavior Learning	581

7.1.4	A Warning	581
7.1.5	Over-Learning	582
7.1.6	The Zoo of Learning Algorithms	582
7.1.7	The Balance of Effort	582
7.2	PARAMETER MODIFICATION	583
7.2.1	The Parameter Landscape	583
7.2.2	Hill Climbing	585
7.2.3	Extensions to Basic Hill Climbing	588
7.2.4	Annealing	591
7.3	ACTION PREDICTION	596
7.3.1	Left or Right	596
7.3.2	Raw Probability	596
7.3.3	String Matching	597
7.3.4	<i>N</i> -Grams	597
7.3.5	Window Size	601
7.3.6	Hierarchical <i>N</i> -Grams	602
7.3.7	Application in Combat	605
7.4	DECISION LEARNING	606
7.4.1	Structure of Decision Learning	606
7.4.2	What Should You Learn?	607
7.4.3	Four Techniques	607
7.5	NAIVE BAYES CLASSIFIERS	608
7.5.1	Implementation Notes	612
7.6	DECISION TREE LEARNING	613
7.6.1	ID3	613
7.6.2	ID3 with Continuous Attributes	622
7.6.3	Incremental Decision Tree Learning	626
7.7	REINFORCEMENT LEARNING	631
7.7.1	The Problem	631
7.7.2	The Algorithm	632
7.7.3	Pseudo-Code	635
7.7.4	Data Structures and Interfaces	636
7.7.5	Implementation Notes	637
7.7.6	Performance	637
7.7.7	Tailoring Parameters	638
7.7.8	Weaknesses and Realistic Applications	641
7.7.9	Other Ideas in Reinforcement Learning	644
7.8	ARTIFICIAL NEURAL NETWORKS	646
7.8.1	Overview	647
7.8.2	The Problem	649

7.8.3	The Algorithm	650
7.8.4	Pseudo-Code	654
7.8.5	Data Structures and Interfaces	655
7.8.6	Implementation Caveats	657
7.8.7	Performance	658
7.8.8	Other Approaches	658
	EXERCISES	662

CHAPTER

8

BOARD GAMES 667

8.1	GAME THEORY	668
8.1.1	Types of Games	668
8.1.2	The Game Tree	669
8.2	MINIMAXING	671
8.2.1	The Static Evaluation Function	672
8.2.2	Minimaxing	674
8.2.3	The Minimaxing Algorithm	675
8.2.4	Negamaxing	678
8.2.5	AB Pruning	681
8.2.6	The AB Search Window	684
8.2.7	Negascout	686
8.3	TRANSPPOSITION TABLES AND MEMORY	689
8.3.1	Hashing Game States	689
8.3.2	What to Store in the Table	692
8.3.3	Hash Table Implementation	693
8.3.4	Replacement Strategies	694
8.3.5	A Complete Transposition Table	695
8.3.6	Transposition Table Issues	696
8.3.7	Using Opponent's Thinking Time	696
8.4	MEMORY-ENHANCED TEST ALGORITHMS	697
8.4.1	Implementing Test	697
8.4.2	The MTD Algorithm	699
8.4.3	Pseudo-Code	700
8.5	OPENING BOOKS AND OTHER SET PLAYS	701
8.5.1	Implementing an Opening Book	702
8.5.2	Learning for Opening Books	702
8.5.3	Set Play Books	703

8.6	FURTHER OPTIMIZATIONS	703
8.6.1	Iterative Deepening	704
8.6.2	Variable Depth Approaches	705
8.7	TURN-BASED STRATEGY GAMES	706
8.7.1	Impossible Tree Size	706
8.7.2	Real-Time AI in a Turn-Based Game	708
	EXERCISES	708

PART III

SUPPORTING TECHNOLOGIES 711

CHAPTER

9	EXECUTION MANAGEMENT	713
9.1	SCHEDULING	714
9.1.1	The Scheduler	714
9.1.2	Interruptible Processes	722
9.1.3	Load-Balancing Scheduler	724
9.1.4	Hierarchical Scheduling	726
9.1.5	Priority Scheduling	728
9.2	ANYTIME ALGORITHMS	731
9.3	LEVEL OF DETAIL	732
9.3.1	Graphics Level of Detail	732
9.3.2	AI LOD	732
9.3.3	Scheduling LOD	733
9.3.4	Behavioral LOD	734
9.3.5	Group LOD	740
9.3.6	In Summary	743
	EXERCISES	744

CHAPTER

10	WORLD INTERFACING	745
10.1	COMMUNICATION	745
10.2	GETTING KNOWLEDGE EFFICIENTLY	746
10.2.1	Polling	746
10.2.2	Events	747
10.2.3	Determining What Approach to Use	748

10.3	EVENT MANAGERS	748
10.3.1	Implementation	750
10.3.2	Event Casting	753
10.3.3	Inter-Agent Communication	755
10.4	POLLING STATIONS	756
10.4.1	Pseudo-Code	756
10.4.2	Performance	757
10.4.3	Implementation Notes	757
10.4.4	Abstract Polling	758
10.5	SENSE MANAGEMENT	759
10.5.1	Faking It	760
10.5.2	What Do We Know?	760
10.5.3	Sensory Modalities	761
10.5.4	Region Sense Manager	767
10.5.5	Finite Element Model Sense Manager	775
	EXERCISES	783

CHAPTER

11

	TOOLS AND CONTENT CREATION	785
11.0.1	Toolchains Limit AI	786
11.0.2	Where AI Knowledge Comes from	786
11.1	KNOWLEDGE FOR PATHFINDING AND WAYPOINT TACTICS	786
11.1.1	Manually Creating Region Data	787
11.1.2	Automatic Graph Creation	789
11.1.3	Geometric Analysis	790
11.1.4	Data Mining	793
11.2	KNOWLEDGE FOR MOVEMENT	795
11.2.1	Obstacles	795
11.2.2	High-Level Staging	797
11.3	KNOWLEDGE FOR DECISION MAKING	798
11.3.1	Object Types	798
11.3.2	Concrete Actions	798
11.4	THE TOOLCHAIN	799
11.4.1	Data-Driven Editors	799
11.4.2	AI Design Tools	800
11.4.3	Remote Debugging	801
11.4.4	Plug-Ins	802
	EXERCISES	802

PART IV**DESIGNING GAME AI****805****CHAPTER****12****DESIGNING GAME AI**

807

12.1 THE DESIGN 807

12.1.1 Example 808

12.1.2 Evaluating the Behaviors 809

12.1.3 Selecting Techniques 811

12.1.4 The Scope of One Game 813

12.2 SHOOTERS 814

12.2.1 Movement and Firing 814

12.2.2 Decision Making 816

12.2.3 Perception 817

12.2.4 Pathfinding and Tactical AI 818

12.2.5 Shooter-Like Games 818

12.3 DRIVING 820

12.3.1 Movement 821

12.3.2 Pathfinding and Tactical AI 822

12.3.3 Driving-Like Games 823

12.4 REAL-TIME STRATEGY 823

12.4.1 Pathfinding 824

12.4.2 Group Movement 825

12.4.3 Tactical and Strategic AI 825

12.4.4 Decision Making 826

12.5 SPORTS 827

12.5.1 Physics Prediction 827

12.5.2 Playbooks and Content Creation 828

12.6 TURN-BASED STRATEGY GAMES 828

12.6.1 Timing 829

12.6.2 Helping the Player 830

CHAPTER**13****AI-BASED GAME GENRES**

831

13.1 TEACHING CHARACTERS 831

13.1.1 Representing Actions 832

13.1.2 Representing the World 832

13.1.3 Learning Mechanism 833

13.1.4 Predictable Mental Models and Pathological States	835
13.2 FLOCKING AND HERDING GAMES	836
13.2.1 Making the Creatures	836
13.2.2 Tuning Steering for Interactivity	837
13.2.3 Steering Behavior Stability	838
13.2.4 Ecosystem Design	838
APPENDIX	
REFERENCES	841
A.1 BOOKS, PERIODICALS, AND PAPERS	841
A.2 GAMES	842
INDEX	847