Multiagent Systems

second edition

edited by Gerhard Weiss

The MIT Press Cambridge, Massachusetts London, England

Contents

	Pref	ace	Х	XXXV
		Reader Structu	bject of This Book ● Main Features of This Book ● rship and Prerequisites ● Changes from the First Edition ● ure and Chapters ● The Exercises ● How to Use This Book ● and More – The Website of the Book ● Acknowledgments	
	Con	tributin	ng Authors	xliii
Pa	<u>art I</u>	Age	nt Architectures and Organizations	1
1	Inte	lligent A	Agents	3
	Mick	hael Woo	oldridge	
	1	Introdu	uction	3
	2		Are Agents?	4
		2.1	Examples of Agents	7
		2.2	Intelligent Agents	8
		2.3	Agents and Objects	10
		2.4	Agents and Expert Systems	12
		2.5	Sources and Further Reading	13
	3	Archit	ectures for Intelligent Agents	13
		3.1	Logic-Based Architectures	14
			3.1.1 Sources and Further Reading	19
		3.2	Reactive Architectures	20
			3.2.1 The Subsumption Architecture	21
			3.2.2 Markov Decision Processes	25
			3.2.3 Sources and Further Reading	27
		3.3	Belief-Desire-Intention Architectures	28
			3.3.1 Sources and Further Reading	35
		3.4	Layered Architectures	36

			3.4.1	TouringMachines		38
			3.4.2	InteRRaP		40
			3.4.3	Sources and Further Reading		42
	4	Conclu	sions			42
	5	Exercis	ses			42
	Refe	rences.	• • • • •		•••	45
2	Mult	tiagent (Organizat	ions		51
	Virgi	nia Digr	num and Ji	ılian Padget		
	1	Introdu	ction			51
	2	Backgr	ound			53
		2.1	From Inte	elligent Agents to Multiagent Systems		53
		2.2	From Mu	ltiagent Systems to Multiagent Organizations		55
		2.3	Sources of	of Inspiration		56
			2.3.1	Organization as Structure		56
			2.3.2	Organization as Institution		58
			2.3.3	Organization as Agent		59
		2.4	Autonom	y and Regulation		60
		2.5		Scenario		62
	3	Multiag	gent Organ	izations		62
		3.1		tion Concepts		64
		3.2	Example	of Organization Modeling: The OperA Framew	vork	65
			3.2.1	The Social Structure		68
			3.2.2	The Interaction Structure		70
			3.2.3	The Normative Structure		71
			3.2.4	The Communication Structure		72
	4	Institut	ions			72
		4.1	Organizat	tions, Institutions, and Norms		73
		4.2	Events an	d States		75
		4.3	Obligatio	ns, Permission, and Power	• •	77
		4.4	Example	of Institutional Modeling: InstAL	•	78
			4.4.1	The Formal Model	• •	78
			4.4.2	The Conference Scenario		78
	5	Agents	in Organiz	zations		82
	6	Evoluti	on of Orga	anizations		85
		6.1	Organizat	tional Adaptation		86
		6.2	Emergent	Organizations	•••	87
	7	Conclu	sions			88
	8	Exercis	ses			89
	Refe	rences .				92

Pa	art II	[Co	mmunication	99
3	Age	nt Com	munication	101
	Amit	K. Cho	ppra and Munindar P. Singh	
	1	Introd	uction	. 101
		1.1	Autonomy and Its Implications	. 102
		1.2	Criteria for Evaluation	. 105
	2	Conce	ptual Foundations of Communication in MAS	. 106
		2.1	Communicative Acts	. 106
		2.2	Agent Communication Primitives	. 107
	3	Traditi	ional Software Engineering Approaches	. 108
		3.1	Choreographies	. 110
		3.2	Sequence Diagrams	. 111
		3.3	State Machines	. 112
		3.4	Evaluation with Respect to MAS	. 113
	4	Traditi	ional AI Approaches	. 114
		4.1	KQML	. 115
		4.2	FIPA ACL	. 116
		4.3	Evaluation with Respect to MAS	. 117
	5	Comm	itment-Based Multiagent Approaches	. 118
		5.1	Commitments	. 118
		5.2	Commitment Protocol Specification	. 119
		5.3	Evaluation with Respect to MAS	. 121
	6	Engine	eering with Agent Communication	. 122
		6.1	Programming with Communications	. 123
		6.2	Modeling Communications	. 124
			6.2.1 Business Patterns	. 125
			6.2.2 Enactment Patterns	. 125
			6.2.3 Semantic Antipatterns	. 126
		6.3	Communication-Based Methodologies	. 127
	7	Advan	ced Topics and Challenges	. 128
		7.1	Primacy of Meaning	. 128
		7.2	Verifying Compliance	. 129
		7.3	Protocol Refinement and Aggregation	. 129
		7.4	Role Conformance	. 130
	8	Conclu	usions	. 130
	9	Exerci	ses	. 133
	Refe	rences .		. 136

4	Neg	otiation	and Bargaining	143
	Shah	een Fat	ima and Iyad Rahwan	
	1		uction	143
	2		ts of Negotiation	
	3		Theoretic Approaches for Single-Issue Negotiation	
		3.1	Cooperative Models of Single-Issue Negotiation	
		3.2	Non-Cooperative Models of Single-Issue Negotiation	
	4	Game-	Theoretic Approaches for Multi-Issue Negotiation	
		4.1	Cooperative Models of Multi-Issue Negotiation	
		4.2	Non-Cooperative Models of Multi-Issue Negotiation	
	5	Heuris	tic Approaches for Multi-Issue Negotiation	
		5.1	Heuristics for Generating Counteroffers	
		5.2	Heuristics for Predicting Opponent's Preferences and	
			Generating Counteroffers	163
		5.3	Heuristics for Generating Optimal Agendas	
		5.4	Heuristics for Reasoning about Deliberation Cost	
	6		iating with Humans	
	7	•	nentation-Based Negotiation	
	8	-		
	9		ses	
	-			
5	Arg	umenta	tion among Agents	177
	-	Rahwai		
	1 <i>yuu</i> 1			177
	2			
	2	2.1	Is an Argument?	
		2.1	Arguments as Chained Inference Rules	
		2.2	Argument as an Instance of a Scheme	
	2		Abstract Arguments	
	3		ating an Argument	
	4	•	Abstract Amount Company	
		4.1	Abstract Argument Games	
	_	4.2	Dialogue Systems	
	5	-	gic Argumentation and Game Theory	
		5.1	Glazer and Rubinstein's Model	
		5.2	Game Theory Background	
			5.2.1 Mechanism Design	
			5.2.2 The Revelation Principle	
		5.3	Argumentation Mechanism Design	
		5.4	Case Study: Implementing the Grounded Semantics	198

6	The Argument Interchange Format)1
7	Conclusion)4
8	Exercises)5
Refe	rences)6

Part III Basic Coordination

6	Com	putatio	nal Social	Choice	213
	Felix	Brandt,	Vincent C	onitzer, and Ulle Endriss	
	1	Introdu	ction		213
		1.1	Introducto	ory Example	214
		1.2	History of	f the Field	216
		1.3	Applicati	ons	217
		1.4	Chapter C	Dutline	219
	2	Prefere	nce Aggre	gation	219
		2.1	Social We	elfare Functions	219
		2.2	Social Ch	oice Functions	223
			2.2.1	The Weak Axiom of Revealed Preference	223
			2.2.2	Contraction and Expansion Consistency	224
	3	Voting			226
		3.1	Voting Ru	ıles	227
			3.1.1	Scoring Rules	227
			3.1.2	Condorcet Extensions	229
			3.1.3	Other Rules	231
		3.2	Manipula	tion	232
			3.2.1	The Gibbard-Satterthwaite Impossibility	233
			3.2.2	Restricted Domains of Preferences	233
			3.2.3	Computational Hardness of Manipulation	235
			3.2.4	Probabilistic Voting Rules	238
			3.2.5	Irresolute Voting Rules	239
		3.3	Possible a	and Necessary Winners	240
	4	Combin	natorial Do	omains	241
		4.1	Preferenc	e Representation	243
		4.2	Sequentia	l Voting	245
		4.3	Voting wi	th Compactly Represented Preferences	246
	5	Fair Di	vision .		247
		5.1	Preferenc	e Representation	249
		5.2		and Efficiency	
		5.3	Computin	g Fair and Efficient Allocations	253

211

	5.4	Convergence to Fair and Efficient Allocations		255
6	Conc	usion		257
	6.1	Additional Topics		258
	6.2	Further Reading		259
7	Exerc	ises		260
Ref	erences		•••	266
Me	chanisn	n Design and Auctions		285
Kev	in Leytc	n-Brown and Yoav Shoham		
1	Introd	luction		285
2	Mech	anism Design with Unrestricted Preferences		286
	2.1	Implementation		
	2.2	The Revelation Principle		288
	2.3	Impossibility of General, Dominant-Strategy		
		Implementation		291
3	Quasi	linear Preferences		
	3.1	Mechanism Design in the Quasilinear Setting		292
4	Effici	ent Mechanisms		
	4.1	Groves Mechanisms		
	4.2	The VCG Mechanism		
	4.3	Properties of VCG		301
		4.3.1 VCG and Individual Rationality		
		4.3.2 VCG and Weak Budget Balance		
		4.3.3 Drawbacks of VCG		
	4.4	Budget Balance and Efficiency		
5	Single	e-Good Auctions		
	5.1	Canonical Auction Families		
		5.1.1 English Auctions		305
		5.1.2 Japanese Auctions		
		5.1.3 Dutch Auctions		
		5.1.4 Sealed-Bid Auctions		
	5.2	Auctions as Bayesian Mechanisms		306
	5.3	Second-Price, Japanese, and English Auctions		
	5.4	First-Price and Dutch Auctions		
	5.5	Revenue Equivalence		
6	Positi	on Auctions \ldots \ldots \ldots \ldots \ldots \ldots		
7		inatorial Auctions		
8		usions		
9	Exerc			

.

8	Com	putatio	nal Coalit	tion Formation	329
	Edith	ı Elkind,	Talal Rah	wan, and Nicholas R. Jennings	
	1	Introdu	ction	· · · · · · · · · · · · · · · · · · ·	329
		1.1		al Games: A Bird's Eye View	
	2	Definit		· · · · · · · · · · · · · · · · · · ·	
		2.1		S	
		2.2		es of Characteristic Function Games	
			2.2.1	Monotone Games	333
			2.2.2	Superadditive Games	333
			2.2.3	Convex Games	
			2.2.4	Simple Games	335
	3	Solutio	n Concept	······································	335
		3.1	Shapley V	Value	335
		3.2	Banzhaf	Index	337
		3.3	Core		338
			3.3.1	The Core of Simple Games	339
			3.3.2	The Core of Convex Games	340
		3.4	The Leas	t Core	341
		3.5	Other Sol	lution Concepts	342
	4	Repres	entation Fo	ormalisms	343
		4.1	Weighted	Voting Games	344
			4.1.1	Computational Issues	345
			4.1.2	Expressivity and Vector Weighted Voting Games	346
		4.2	Combina	torial Optimization Games	348
			4.2.1	Induced Subgraph Games	348
			4.2.2	Network Flow Games	
			4.2.3	Matching and Assignment Games	349
		4.3	-	e Representation Languages	
			4.3.1	Marginal Contribution Nets	
			4.3.2	Synergy Coalition Groups	
			4.3.3	Skill-Based Representations	
			4.3.4	Agent-Type Representation	
	5			re Generation	
		5.1	-	presentation	
		5.2		Programming Algorithms	
		5.3	-	8	356
			5.3.1	Identifying Subspaces with Worst-Case Guar-	
				antees	
			5.3.2	Integer Partition-Based Search	359
			5.3.3	Integer Programming	360

		5.4	Metaheu	uristic Algorithms	. 361
		5.5	Coalitio	n Structure Generation under Compact Represen-	
			tations .	· · · · · · · · · · · · · · · · · · ·	362
			5.5.1	Distributed Constraint Optimization	362
			5.5.2	Marginal Contribution Nets	. 364
			5.5.3	Coalitional Skill Games	. 366
	۱.		5.5.4	Agent-Type Representation	. 368
		5.6	Constrai	ined Coalition Formation	. 369
	6	Concl	usions		. 372
	7	Exerc	ises		. 372
	Refe			· · · · · · · · · · · · · · · · · · ·	
9	т	at and I	Donutatio	n in Multiagant Systems	381
9			-	n in Multiagent Systems	301
				l Laurent Vercouter	
	1			•••••••••••••••••••••••••••••••••••••••	
	2			Representation of Trust and Reputation Values	
		2.1		Representation	
		2.2		cal Values	
		2.3	-	ive Labels	
		2.4	Probabil	lity Distribution and Fuzzy Sets	384
		2.5		d Reputation as Beliefs	
		2.6		iability of a Value	
	3	Trust	Processes	in Multiagent Systems	388
		3.1	General	Overview of Trust-Related Processes	388
		3.2	Trust Ev	valuations	390
			3.2.1	Filtering the Inputs	391
			3.2.2	Statistical Aggregation	392
			3.2.3	Logical Beliefs Generation	. 393
		3.3	Trust De	ecision	394
			3.3.1	Single Trust Values and	
				Probability Distributions	. 395
			3.3.2	Trust Beliefs	395
		3.4	Coping	with the Diversity of Trust Models	396
	4	Reput	ation in M	lultiagent Societies	396
		4.1	Reputati	ion-Building Process	398
			4.1.1	Communicated Image as a Source for	
				Reputation	398
			4.1.2	Communicated Reputation	
			4.1.3	Inherited Reputation	
			4.1.4	Putting It All Together	

,

		4.2	Centralize	ed vs. Decentralized Models	. 4	402
			4.2.1	Centralized Approaches	. 4	402
			4.2.2	Decentralized Approaches	• •	403
		4.3	Using Re	putation	. 4	404
			4.3.1	Reputation as a Source of Trust	• •	404
			4.3.2	Reputation for Social Order	. 4	405
		4.4	Pitfalls W	Vhen Using Reputation	• •	405
			4.4.1	Unfair Ratings	• 4	405
			4.4.2	Ballot-Stuffing	• 4	406
			4.4.3	Dynamic Personality		
			4.4.4	Whitewashing		
			4.4.5	Collusion	• 4	406
			4.4.6	Sybil Attacks	• 4	407
			4.4.7	Reputation Lag Exploitation		
	5	Trust, I	*	and Other Agreement Technologies		
		5.1	•	tation		
		5.2		on		
		5.3				
		5.4	-	tions		
		5.5	-	es and Semantics		
	6					
	7					
	Refe	rences.			• 4	415
P۶	rt IV	/ Dis	tributed	l Cognitive Abilities	4	21
					•	
10	Mult	iagent l	Learning		4	423
	Karl	Tuyls ar	nd Kagan '	Tumer		
	1	Introdu	ction		. 4	423
	2	Challer	nges in Mu	Iltiagent Learning	. 4	425
		2.1	State, Act	tion, and Outcome Space Problems	. 4	426
		2.2	Multiager	nt Credit Assignment Problem	. 4	426
		2.3	Agent Re	wards and System Dynamics	. 4	427
		2.4	Two Sim	ple Multiagent Learning Paradigms	. 4	429
			2.4.1	Action-Value Learning	. 4	430
			2.4.2	Direct Policy Adjustment	. 4	431
	3	Reinfor	rcement Le	earning for Multiagent Systems	. 4	432
		3.1	Markov I	Decision Processes	. 4	433
		3.2	Action Se	election and Exploration-Exploitation Dilemma	. 4	434

		3.3	Model-Free and Model-Based Approaches	435
		3.4	Multiagent MDP Formulations	437
		3.5	Markov Games	438
		3.6	State-of-the-Art Algorithms	439
			3.6.1 Joint Action Learning	439
			3.6.2 Nash-Q Learning	440
			3.6.3 Gradient Ascent Algorithms	441
			3.6.4 Other Approaches	442
	4	Evoluti	ionary Game Theory as a Multiagent Learning Paradigm	443
		4.1	Matrix Games	443
		4.2	Solution Concepts	444
		4.3	Evolutionary Stable Strategies	445
		4.4	Replicator Dynamics	446
		4.5	The Role of Game Theory for Multiagent Learning	447
		4.6	Evolutionary Game Theory as a Theoretical Framework .	448
	5	Swarm	Intelligence as a Multiagent Learning Paradigm	451
		5.1	Ant Colony Optimization	453
		5.2	Bee Colony Optimization	
	6	Neuro-	Evolution as a Multiagent Learning Paradigm	457
		6.1	Evolutionary Algorithm Basics	458
		6.2	Linking Multiagent Reinforcement Learning to the	
			Neuro-Evolutionary Approach	
	7	Case St	tudy: Air Traffic Control	
		7.1	Motivation	
		7.2	Simulation and System Performance	
		7.3	Agent-Based Air Traffic	
		7.4	Multiagent Air Traffic Results	
		7.5	Summary	
	8		isions	
	9		ses	
	Refe	rences.		475
11	Mult	tiagent]	Planning, Control, and Execution	485
		U	nd Shlomo Zilberstein	
	1	Introdu	uction	485
	2	Charac	terizing Multiagent Planning and Control	487
	3	Coordi	nation Prior to Local Planning	488
		3.1	Social Laws and Conventions	489
		3.2	Organizational Structuring	490
			3.2.1 Organizational Design	491

.

Contents

			3.2.2	Organizational Execution and Functionally-	
				Accurate Cooperation	493
		3.3	The Cont	ract-Net Protocol and Role Assignment	495
	4	Local H	Planning P	rior to Coordination	497
		4.1	State-Spa	ce Techniques	498
		4.2		ce Techniques	
			4.2.1	Single-Agent Plans	499
			4.2.2	Multiagent Plans	501
			4.2.3	Multiagent Plan Coordination by Plan Modifi-	
				cation	505
		4.3	Hierarchi	cal Multiagent Plan Coordination	510
	5	Decisio	on-Theoret	ic Multiagent Planning	512
		5.1	Models for	or Decision-Theoretic Multiagent Planning	513
			5.1.1	Solution Representation and Evaluation	515
			5.1.2	The Complexity of DEC-POMDPs	
		5.2	Solving F	Vinite-Horizon DEC-POMDPs	519
		5.3	Solving I	nfinite-Horizon DEC-POMDPs	
			5.3.1	Correlated Joint Controllers	523
			5.3.2	Policy Iteration for Infinite-Horizon	
				DEC-POMDPs	524
			5.3.3	Optimizing Fixed-Size Controllers Using	
				Non-Linear Programming	
	6			tion	
		6.1	•	nt Plan Monitoring	
		6.2	-	nt Plan Recovery	
		6.3	-	nt Continuous Planning	
	7				
	8				
	Refe	rences.			539
12	Dict	vibutod	Constrain	t Handling and Optimization	547
14					547
			armenn, M Iennings	leritxell Vinyals, Alex Rogers, and	
			0		517
	1 2				
	L			raint Handling	
		2.1 2.2		t Networks	
	3			ed Constraint Processing	
	3	3.1		0	
		3.1	3.1.1	ld Applications	
			3.1.1	Meeting Scheduling	552

.

		3.1.2 Target Tracking	553
	3.2	Exemplar and Benchmarking Problems	
4		ion Techniques: Complete Algorithms	
-	4.1	Search-Based: ADOPT	
	4.2	Dynamic Programming: DPOP	
5		ion Techniques: Approximate Algorithms	
	5.1	Local Greedy Approximate Algorithms	
		5.1.1 The Distributed Stochastic Algorithm	
		5.1.2 The Maximum Gain Message Algorithm	
	5.2	GDL-Based Approximate Algorithms	
		5.2.1 The Max-Sum Algorithm	
6	Soluti	ion Techniques with Quality Guarantees	. 570
	6.1	Off-line Guarantees	. 571
	6.2	Online Guarantees	. 574
7	Concl	lusions	. 577
8	Exerc	ises	. 578
Ref	erences		. 580
D (I	7 D		505
Part V	<u>V</u> De	velopment and Engineering	585
	_	velopment and Engineering ing Multiagent Systems	585 587
13 Pro	gramm		
13 Pro	ogramm ael H. B	ing Multiagent Systems	587
13 Pro Raf	ogramm ael H. B	ning Multiagent Systems Bordini and Jürgen Dix	587 . 587
13 Pro Raf	ogramm <i>ael H. B</i> Introd	ing Multiagent Systems Bordini and Jürgen Dix luction	587 . 587 . 589
13 Pro Raf	ogramm <i>Gael H. B</i> Introd 1.1 1.2	ing Multiagent Systems Bordini and Jürgen Dix luction Relation to Other Chapters Organization of This Chapter	587 . 587 . 589 . 589
13 Pro <i>Raf</i> 1	ogramm <i>Gael H. B</i> Introd 1.1 1.2	Ling Multiagent Systems Bordini and Jürgen Dix Huction	587 . 587 . 589 . 589 . 590
13 Pro <i>Raf</i> 1	ogramm <i>ael H. B</i> Introd 1.1 1.2 From	Aing Multiagent Systems Bordini and Jürgen Dix Iuction	587 . 587 . 589 . 589 . 590 . 590
13 Pro <i>Raf</i> 1	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2	Aing Multiagent Systems Bordini and Jürgen Dix Buction Relation to Other Chapters Organization of This Chapter Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP)	587 . 587 . 589 . 589 . 590 . 590 . 591
13 Pro <i>Raft</i> 1 2	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2	Aing Multiagent Systems Bordini and Jürgen Dix Huction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP)	587 . 587 . 589 . 589 . 590 . 590 . 591 . 593
13 Pro <i>Raft</i> 1 2	ogramm ael H. B Introd 1.1 1.2 From 2.1 2.2 Abstr	Aing Multiagent Systems Bordini and Jürgen Dix Buction Relation to Other Chapters Organization of This Chapter Organization of This Chapter AGENT0 to Modern Agent Languages ABrief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) Actions in the MAOP Paradigm	587 . 587 . 589 . 589 . 590 . 590 . 591 . 593 . 593
13 Pro <i>Raft</i> 1 2	bgramm <i>Tael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1	Aing Multiagent Systems Bordini and Jürgen Dix Buction Relation to Other Chapters Organization of This Chapter Organization of This Chapter AGENT0 to Modern Agent Languages ABrief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) Agent Level	587 . 587 . 589 . 590 . 590 . 591 . 593 . 593 . 595
13 Pro <i>Raft</i> 1 2	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3	Aing Multiagent Systems Bordini and Jürgen Dix Buction Buction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) actions in the MAOP Paradigm Agent Level Environment Level	587 . 587 . 589 . 590 . 590 . 591 . 593 . 595 . 596
13 Pro <i>Raft</i> 1 2 3	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3	Aing Multiagent Systems Bordini and Jürgen Dix Buction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) actions in the MAOP Paradigm Agent Level Environment Level	587 . 587 . 589 . 590 . 590 . 591 . 593 . 593 . 595 . 596 . 596
13 Pro <i>Raft</i> 1 2 3	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3 Exam	Aing Multiagent Systems Bordini and Jürgen Dix Iuction	587 . 587 . 589 . 590 . 590 . 591 . 593 . 595 . 596 . 596 . 596 . 596
13 Pro <i>Raft</i> 1 2 3	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3 Exam	Aing Multiagent Systems Bordini and Jürgen Dix Buction Buction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) actions in the MAOP Paradigm Agent Level Environment Level Social Level JASON	587 . 587 . 589 . 590 . 590 . 591 . 593 . 593 . 595 . 596 . 596 . 596 . 596 . 597
13 Pro <i>Raft</i> 1 2 3	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3 Exam	Aing Multiagent Systems Bordini and Jürgen Dix Huction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) actions in the MAOP Paradigm Agent Level Social Level social Level JASON 4.1.1	587 . 587 . 589 . 590 . 590 . 591 . 593 . 595 . 596 . 596 . 596 . 597 . 598
13 Pro <i>Raft</i> 1 2 3	bgramm <i>ael H. B</i> Introd 1.1 1.2 From 2.1 2.2 Abstr 3.1 3.2 3.3 Exam	Aing Multiagent Systems Bordini and Jürgen Dix Buction Relation to Other Chapters Organization of This Chapter AGENT0 to Modern Agent Languages A Brief History of Agent-Oriented Programming (AOP) Features of Multiagent-Oriented Programing (MAOP) actions in the MAOP Paradigm Agent Level Environment Level Social Level JASON 4.1.1 Beliefs	587 . 587 . 589 . 590 . 590 . 591 . 593 . 593 . 595 . 596 . 596 . 596 . 596 . 597 . 598 . 599

		4.3	Approaches Based on Executable Logics	603
			4.3.1 METATEM	607
			4.3.2 ConGolog and IndiGolog	608
	5	Organi	ization and Environment Programming	609
		5.1	Organizations	609
			5.1.1 Moise	610
			5.1.2 Other Approaches	611
		5.2	Environments	611
			5.2.1 CARTAGO	613
			5.2.2 EIS	617
	6	Examp	ble of Full MAOP in JaCaMo	620
		6.1	The Application Scenario	621
		6.2	Organization Program	623
		6.3	Agent Programs	
		6.4	Environment Program	628
	7	Conclu	isions	629
	8	Exercis	ses	630
	Refe	rences.		633
11	Snoo	ificatio	n and Varifaction of Multiagant Systems	641
14	-		87	041
	0		and Michael Fisher	<i>.</i>
	1	Introdu	uction	
	-			
	-	1.1	Why Logic, Specification, and Verification?	642
	-	1.1 1.2	Why Logic, Specification, and Verification?	642 644
		1.1 1.2 1.3	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This Chapter	642 644 644
	2	1.1 1.2 1.3 Agent	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecification	642 644 644 644
		1.1 1.2 1.3 Agent 2.1	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification Languages	642 644 644 644 644
		1.1 1.2 1.3 Agent	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics	642 644 644 644 644 646
		1.1 1.2 1.3 Agent 2.1	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL	642 644 644 644 644 646 648
		1.1 1.2 1.3 Agent 2.1	Why Logic, Specification, and Verification?	642 644 644 644 644 646 648 649
		1.1 1.2 1.3 Agent 2.1 2.2	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*	642 644 644 644 646 646 648 649 650
		1.1 1.2 1.3 Agent 2.1 2.2	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic Logic	 642 644 644 644 646 648 649 650 652
		1.1 1.2 1.3 Agent 2.1 2.2	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic LogicCombinations	642 644 644 644 646 648 649 650 652 653
		1.1 1.2 1.3 Agent 2.1 2.2	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic LogicCombinations2.4.1BDI	642 644 644 644 646 648 649 650 652 653 653
		1.1 1.2 1.3 Agent 2.1 2.2	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic Logic2.4.1BDI2.4.2KARO	642 644 644 644 646 648 649 650 652 653 653 653
		1.1 1.2 1.3 Agent 2.1 2.2 2.3 2.4	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic LogicCombinations2.4.1BDI2.4.2KARO2.4.3Dynamic Epistemic Logic	642 644 644 644 646 648 649 650 652 653 653 653
	2	 1.1 1.2 1.3 Agent 2.1 2.2 2.3 2.4 2.5 	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*Approaches Based on Dynamic LogicCombinations2.4.1BDI2.4.2KARO2.4.3Dynamic Epistemic LogicSample Specifications	642 644 644 644 646 648 649 650 652 653 653 653 654 654
		 1.1 1.2 1.3 Agent 2.1 2.2 2.3 2.4 2.5 From S 	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*2.2.3ATL and ATL*Approaches Based on Dynamic Logic2.4.1BDI2.4.2KARO2.4.3Dynamic Epistemic LogicSpecifications to Implementations	642 644 644 644 646 648 649 650 652 653 653 653 654 654
	2	 1.1 1.2 1.3 Agent 2.1 2.2 2.3 2.4 2.5 	Why Logic, Specification, and Verification?Limits and Relation to Other ChaptersOrganization of This ChapterSpecificationLogics of Agency and Specification LanguagesApproaches Based on Temporal Logics2.2.1LTL2.2.2CTL and CTL*Approaches Based on Dynamic LogicCombinations2.4.1BDI2.4.2KARO2.4.3Dynamic Epistemic LogicSample Specifications	 642 644 644 644 646 648 649 650 653 653 654 656 656

		3.3	Synthesis	657
		3.4	Specifications as Programs	658
	4	Formal	Verification	
		4.1	What Is Formal Verification?	659
		4.2	Deductive Verification	660
		4.3	Algorithmic Verification	660
		4.4	Program Verification	662
		4.5	Runtime Verification	663
	5	Deduct	ive Verification of Agents	663
		5.1	The Problem	664
		5.2	Direct Proof	665
		5.3	Use of Logic Programming	666
		5.4	Example	667
	6	Algorit	hmic Verification of Agent Models	667
		6.1	The Representation and Size of the Model	668
		6.2	(Im-)Perfect Information, (Im-)Perfect Recall	
		6.3	Modular Interpreted Systems	671
		6.4	MC Complexity for LTL, CTL, ATL, and MIS	
		6.5	Model Checking Agent Language Models	
	7	Ų	hmic Verification of Agent Programs	
		7.1	General Problem	
		7.2	AIL Semantic Toolkit	
		7.3	Multiple Semantic Definitions	
		7.4	Model Checking AIL Through MCAPL/AJPF	
	-	7.5	Example	
	8		sions	
	9		es	
	Refe	rences.		683
15	A gon	t_Orion	ted Software Engineering	695
13	0			075
			koff and Lin Padgham	60 F
	1		ction	
	2	1.1	History of AOSE	
	2		Concepts	
	3		g Example \ldots \ldots \ldots \ldots \ldots \ldots	
	4		ements	
	5	•		
	6		d Design	
		6.1	Example Design: BDI Platform	
			6.1.1 Initial Structure	/19

6.1.2

	5	Exercis	ses	799
	Refe	rences .		800
17	Gam	ie-Theo	oretic Foundations of Multiagent Systems	811
	Edith	n Elkind	and Evangelos Markakis	
	1	Introdu	uction	811
	2	Norma	ll-Form Games	812
		2.1	Dominant Strategy	814
		2.2	Nash Equilibrium	816
		2.3	Mixed Strategies and Mixed Nash Equilibrium	818
		2.4	Elimination of Dominated Strategies	820
		2.5	Games with Infinite Action Spaces	821
			2.5.1 Games with Differentiable Payoff Functions	823
		2.6	Zero-Sum Games	824
		2.7	Computational Aspects	827
	3	Extens	ive-Form Games	828
		3.1	Nash Equilibrium and Critiques	831
		3.2	Subgame-Perfect Equilibrium	832
		3.3	Backward Induction	834
	4	Bayesi	an Games	836
		4.1	Two Examples	837
		4.2	Formal Definitions	840
	5	Conclu	isions	842
	6	Exercis	ses	842
	Refe	rences .		847

Subject Index

849