

Contents

Dedication	v
Preface	vii
Editors	xi
Contributors	xiii
Contents	xv

I General Methods in Knowledge Representation and Reasoning	1
1 Knowledge Representation and Classical Logic	3
Vladimir Lifschitz, Leora Morgenstern and David Plaisted	
1.1 Knowledge Representation and Classical Logic	3
1.2 Syntax, Semantics and Natural Deduction	4
1.2.1 Propositional Logic	4
1.2.2 First-Order Logic	8
1.2.3 Second-Order Logic	16
1.3 Automated Theorem Proving	18
1.3.1 Resolution in the Propositional Calculus	22
1.3.2 First-Order Proof Systems	25
1.3.3 Equality	37
1.3.4 Term Rewriting Systems	43
1.3.5 Confluence and Termination Properties	46
1.3.6 Equational Rewriting	50
1.3.7 Other Logics	55
1.4 Applications of Automated Theorem Provers	58
1.4.1 Applications Involving Human Intervention	59
1.4.2 Non-Interactive KR Applications of Automated Theorem Provers	61
1.4.3 Exploiting Structure	64
1.4.4 Prolog	65
1.5 Suitability of Logic for Knowledge Representation	67
1.5.1 Anti-logicist Arguments and Responses	67

Acknowledgements	74
Bibliography	74
2 Satisfiability Solvers	89
Carla P. Gomes, Henry Kautz, Ashish Sabharwal and Bart Selman	
2.1 Definitions and Notation	91
2.2 SAT Solver Technology—Complete Methods	92
2.2.1 The DPLL Procedure	92
2.2.2 Key Features of Modern DPLL-Based SAT Solvers	93
2.2.3 Clause Learning and Iterative DPLL	95
2.2.4 A Proof Complexity Perspective	100
2.2.5 Symmetry Breaking	104
2.3 SAT Solver Technology—Incomplete Methods	107
2.3.1 The Phase Transition Phenomenon in Random k -SAT	109
2.3.2 A New Technique for Random k -SAT: Survey Propagation	111
2.4 Runtime Variance and Problem Structure	112
2.4.1 Fat and Heavy Tailed Behavior	113
2.4.2 Backdoors	113
2.4.3 Restarts	115
2.5 Beyond SAT: Quantified Boolean Formulas and Model Counting	117
2.5.1 QBF Reasoning	117
2.5.2 Model Counting	120
Bibliography	122
3 Description Logics	135
Franz Baader, Ian Horrocks and Ulrike Sattler	
3.1 Introduction	135
3.2 A Basic DL and its Extensions	139
3.2.1 Syntax and Semantics of \mathcal{ALC}	140
3.2.2 Important Inference Problems	141
3.2.3 Important Extensions to \mathcal{ALC}	142
3.3 Relationships with other Formalisms	144
3.3.1 DLs and Predicate Logic	144
3.3.2 DLs and Modal Logic	145
3.4 Tableau Based Reasoning Techniques	146
3.4.1 A Tableau Algorithm for \mathcal{ALC}	146
3.4.2 Implementation and Optimization Techniques	150
3.5 Complexity	151
3.5.1 \mathcal{ALC} ABox Consistency is PSpace-complete	151
3.5.2 Adding General TBoxes Results in ExpTime-Hardness	154
3.5.3 The Effect of other Constructors	154
3.6 Other Reasoning Techniques	155
3.6.1 The Automata Based Approach	156
3.6.2 Structural Approaches	161
3.7 DLs in Ontology Language Applications	166
3.7.1 The OWL Ontology Language	166
3.7.2 OWL Tools and Applications	167

3.8 Further Reading	168
Bibliography	169
4 Constraint Programming	181
Francesca Rossi, Peter van Beek and Toby Walsh	
4.1 Introduction	181
4.2 Constraint Propagation	182
4.2.1 Local Consistency	183
4.2.2 Global Constraints	183
4.3 Search	184
4.3.1 Backtracking Search	184
4.3.2 Local Search	187
4.3.3 Hybrid Methods	188
4.4 Tractability	189
4.4.1 Tractable Constraint Languages	189
4.4.2 Tractable Constraint Graphs	191
4.5 Modeling	191
4.5.1 CP $\vee \neg$ CP	192
4.5.2 Viewpoints	192
4.5.3 Symmetry	193
4.6 Soft Constraints and Optimization	193
4.6.1 Modeling Soft Constraints	194
4.6.2 Searching for the Best Solution	195
4.6.3 Inference in Soft Constraints	195
4.7 Constraint Logic Programming	197
4.7.1 Logic Programs	197
4.7.2 Constraint Logic Programs	198
4.7.3 LP and CLP Languages	198
4.7.4 Other Programming Paradigms	199
4.8 Beyond Finite Domains	199
4.8.1 Intervals	199
4.8.2 Temporal Problems	200
4.8.3 Sets and other Datatypes	200
4.9 Distributed Constraint Programming	201
4.10 Application Areas	202
4.11 Conclusions	203
Bibliography	203
5 Conceptual Graphs	213
John F. Sowa	
5.1 From Existential Graphs to Conceptual Graphs	213
5.2 Common Logic	217
5.3 Reasoning with Graphs	223
5.4 Propositions, Situations, and Metalanguage	230
5.5 Research Extensions	233
Bibliography	235

6 Nonmonotonic Reasoning	239
Gerhard Brewka, Ilkka Niemelä and Mirosław Truszczyński	
6.1 Introduction	239
Rules with exceptions	240
The frame problem	240
About this chapter	241
6.2 Default Logic	242
6.2.1 Basic Definitions and Properties	242
6.2.2 Computational Properties	246
6.2.3 Normal Default Theories	249
6.2.4 Closed-World Assumption and Normal Defaults	250
6.2.5 Variants of Default Logic	252
6.3 Autoepistemic Logic	252
6.3.1 Preliminaries, Intuitions and Basic Results	253
6.3.2 Computational Properties	258
6.4 Circumscription	260
6.4.1 Motivation	260
6.4.2 Defining Circumscription	261
6.4.3 Semantics	263
6.4.4 Computational Properties	264
6.4.5 Variants	266
6.5 Nonmonotonic Inference Relations	267
6.5.1 Semantic Specification of Inference Relations	268
6.5.2 Default Conditionals	270
6.5.3 Discussion	272
6.6 Further Issues and Conclusion	272
6.6.1 Relating Default and Autoepistemic Logics	273
6.6.2 Relating Default Logic and Circumscription	275
6.6.3 Further Approaches	276
Acknowledgements	277
Bibliography	277
7 Answer Sets	285
Michael Gelfond	
7.1 Introduction	285
7.2 Syntax and Semantics of Answer Set Prolog	286
7.3 Properties of Logic Programs	292
7.3.1 Consistency of Logic Programs	292
7.3.2 Reasoning Methods for Answer Set Prolog	295
7.3.3 Properties of Entailment	297
7.3.4 Relations between Programs	298
7.4 A Simple Knowledge Base	300
7.5 Reasoning in Dynamic Domains	302
7.6 Extensions of Answer Set Prolog	307
7.7 Conclusion	309
Acknowledgements	310
Bibliography	310

8 Belief Revision	317
Pavlos Peppas	
8.1 Introduction	317
8.2 Preliminaries	318
8.3 The AGM Paradigm	318
8.3.1 The AGM Postulates for Belief Revision	319
8.3.2 The AGM Postulates for Belief Contraction	320
8.3.3 Selection Functions	323
8.3.4 Epistemic Entrenchment	325
8.3.5 System of Spheres	327
8.4 Belief Base Change	329
8.4.1 Belief Base Change Operations	331
8.4.2 Belief Base Change Schemes	332
8.5 Multiple Belief Change	335
8.5.1 Multiple Revision	336
8.5.2 Multiple Contraction	338
8.6 Iterated Revision	340
8.6.1 Iterated Revision with Enriched Epistemic Input	340
8.6.2 Iterated Revision with Simple Epistemic Input	343
8.7 Non-Prioritized Revision	346
8.8 Belief Update	349
8.9 Conclusion	352
Acknowledgements	353
Bibliography	353
9 Qualitative Modeling	361
Kenneth D. Forbus	
9.1 Introduction	361
9.1.1 Key Principles	362
9.1.2 Overview of Basic Qualitative Reasoning	363
9.2 Qualitative Mathematics	365
9.2.1 Quantities	365
9.2.2 Functions and Relationships	369
9.3 Ontology	371
9.3.1 Component Ontologies	372
9.3.2 Process Ontologies	373
9.3.3 Field Ontologies	374
9.4 Causality	374
9.5 Compositional Modeling	376
9.5.1 Model Formulation Algorithms	378
9.6 Qualitative States and Qualitative Simulation	379
9.7 Qualitative Spatial Reasoning	381
9.7.1 Topological Representations	381
9.7.2 Shape, Location, and Orientation Representations	382
9.7.3 Diagrammatic Reasoning	382
9.8 Qualitative Modeling Applications	383

9.8.1	Automating or Assisting Professional Reasoning	383
9.8.2	Education	384
9.8.3	Cognitive Modeling	386
9.9	Frontiers and Resources	387
	Bibliography	387
10	Model-based Problem Solving	395
	Peter Struss	
10.1	Introduction	395
10.2	Tasks	398
	10.2.1 Situation Assessment/Diagnosis	398
	10.2.2 Test Generation, Measurement Proposal, Diagnosability Analysis	399
	10.2.3 Design and Failure-Modes-and-Effects Analysis	401
	10.2.4 Proposal of Remedial Actions (Repair, Reconfiguration, Recovery, Therapy)	402
	10.2.5 Ingredients of Model-based Problem Solving	402
10.3	Requirements on Modeling	403
	10.3.1 Behavior Prediction and Consistency Check	404
	10.3.2 Validity of Behavior Modeling	405
	10.3.3 Conceptual Modeling	405
	10.3.4 (Automated) Model Composition	406
	10.3.5 Genericity	406
	10.3.6 Appropriate Granularity	407
10.4	Diagnosis	407
	10.4.1 Consistency-based Diagnosis with Component-oriented Models	408
	10.4.2 Computation of Diagnoses	418
	10.4.3 Solution Scope and Limitations of Component-Oriented Diagnosis	422
	10.4.4 Diagnosis across Time	423
	10.4.5 Abductive Diagnosis	431
	10.4.6 Process-Oriented Diagnosis	434
	10.4.7 Model-based Diagnosis in Control Engineering	438
10.5	Test and Measurement Proposal, Diagnosability Analysis	438
	10.5.1 Test Generation	439
	10.5.2 Entropy-based Test Selection	444
	10.5.3 Probe Selection	445
	10.5.4 Diagnosability Analysis	446
10.6	Remedy Proposal	446
	10.6.1 Integration of Diagnosis and Remedy Actions	448
	10.6.2 Component-oriented Reconfiguration	450
	10.6.3 Process-oriented Therapy Proposal	453
10.7	Other Tasks	454
	10.7.1 Configuration and Design	454
	10.7.2 Failure-Modes-and-Effects Analysis	456
	10.7.3 Debugging and Testing of Software	456

10.8 State and Challenges	458
Acknowledgements	460
Bibliography	460
11 Bayesian Networks	467
Adnan Darwiche	
11.1 Introduction	467
11.2 Syntax and Semantics of Bayesian Networks	468
11.2.1 Notational Conventions	468
11.2.2 Probabilistic Beliefs	469
11.2.3 Bayesian Networks	470
11.2.4 Structured Representations of CPTs	471
11.2.5 Reasoning about Independence	471
11.2.6 Dynamic Bayesian Networks	472
11.3 Exact Inference	473
11.3.1 Structure-Based Algorithms	474
11.3.2 Inference with Local (Parametric) Structure	479
11.3.3 Solving MAP and MPE by Search	480
11.3.4 Compiling Bayesian Networks	481
11.3.5 Inference by Reduction to Logic	482
11.3.6 Additional Inference Techniques	484
11.4 Approximate Inference	485
11.4.1 Inference by Stochastic Sampling	485
11.4.2 Inference as Optimization	486
11.5 Constructing Bayesian Networks	489
11.5.1 Knowledge Engineering	489
11.5.2 High-Level Specifications	490
11.5.3 Learning Bayesian Networks	493
11.6 Causality and Intervention	497
Acknowledgements	498
Bibliography	499
II Classes of Knowledge and Specialized Representations	511
12 Temporal Representation and Reasoning	513
Michael Fisher	
12.1 Temporal Structures	514
12.1.1 Instants and Durations	514
12.1.2 From Discreteness to Density	515
12.1.3 Granularity Hierarchies	516
12.1.4 Temporal Organisation	517
12.1.5 Moving in Real Time	517
12.1.6 Intervals	518
12.2 Temporal Language	520
12.2.1 Modal Temporal Logic	520
12.2.2 Back to the Future	521
12.2.3 Temporal Arguments and Reified Temporal Logics	521

12.2.4	Operators over Non-discrete Models	522
12.2.5	Intervals	523
12.2.6	Real-Time and Hybrid Temporal Languages	524
12.2.7	Quantification	525
12.2.8	Hybrid Temporal Logic and the Concept of “now”	528
12.3	Temporal Reasoning	528
12.3.1	Proof Systems	529
12.3.2	Automated Deduction	529
12.4	Applications	530
12.4.1	Natural Language	530
12.4.2	Reactive System Specification	531
12.4.3	Theorem-Proving	532
12.4.4	Model Checking	532
12.4.5	PSL/Sugar	534
12.4.6	Temporal Description Logics	534
12.5	Concluding Remarks	535
	Acknowledgements	535
	Bibliography	535
13	Qualitative Spatial Representation and Reasoning	551
	Anthony G. Cohn and Jochen Renz	
13.1	Introduction	551
13.1.1	What is Qualitative Spatial Reasoning?	551
13.1.2	Applications of Qualitative Spatial Reasoning	553
13.2	Aspects of Qualitative Spatial Representation	554
13.2.1	Ontology	554
13.2.2	Spatial Relations	556
13.2.3	Mereology	557
13.2.4	Mereotopology	557
13.2.5	Between Mereotopology and Fully Metric Spatial Representation	566
13.2.6	Mereogeometry	570
13.2.7	Spatial Vagueness	571
13.3	Spatial Reasoning	572
13.3.1	Deduction	574
13.3.2	Composition	575
13.3.3	Constraint-based Spatial Reasoning	576
13.3.4	Finding Efficient Reasoning Algorithms	578
13.3.5	Planar Realizability	581
13.4	Reasoning about Spatial Change	581
13.5	Cognitive Validity	582
13.6	Final Remarks	583
	Acknowledgements	584
	Bibliography	584

14 Physical Reasoning	597
Ernest Davis	
14.1 Architectures	600
14.1.1 Component Analysis	600
14.1.2 Process Model	601
14.2 Domain Theories	602
14.2.1 Rigid Object Kinematics	603
14.2.2 Rigid Object Dynamics	605
14.2.3 Liquids	608
14.3 Abstraction and Multiple Models	611
14.4 Historical and Bibliographical	614
14.4.1 Logic-based Representations	614
14.4.2 Solid Objects: Kinematics	615
14.4.3 Solid Object Dynamics	616
14.4.4 Abstraction and Multiple Models	616
14.4.5 Other	616
14.4.6 Books	617
Bibliography	618
15 Reasoning about Knowledge and Belief	621
Yoram Moses	
15.1 Introduction	621
15.2 The Possible Worlds Model	622
15.2.1 A Language for Knowledge and Belief	622
15.3 Properties of Knowledge	626
15.4 The Knowledge of Groups	628
15.4.1 Common Knowledge	629
15.4.2 Distributed Knowledge	632
15.5 Runs and Systems	633
15.6 Adding Time	635
15.6.1 Common Knowledge and Time	636
15.7 Knowledge-based Behaviors	637
15.7.1 Contexts and Protocols	637
15.7.2 Knowledge-based Programs	639
15.7.3 A Subtle kb Program	641
15.8 Beyond Square One	643
15.9 How to Reason about Knowledge and Belief	644
15.9.1 Concluding Remark	645
Bibliography	645
Further reading	647
16 Situation Calculus	649
Fangzhen Lin	
16.1 Axiomatizations	650
16.2 The Frame, the Ramification and the Qualification Problems	652
16.2.1 The Frame Problem—Reiter’s Solution	654
16.2.2 The Ramification Problem and Lin’s Solution	657

16.2.3	The Qualification Problem	660
16.3	Reiter's Foundational Axioms and Basic Action Theories	661
16.4	Applications	665
16.5	Concluding Remarks	667
	Acknowledgements	667
	Bibliography	667
17	Event Calculus	671
	Erik T. Mueller	
17.1	Introduction	671
17.2	Versions of the Event Calculus	672
17.2.1	Original Event Calculus (OEC)	672
17.2.2	Simplified Event Calculus (SEC)	674
17.2.3	Basic Event Calculus (BEC)	676
17.2.4	Event Calculus (EC)	679
17.2.5	Discrete Event Calculus (DEC)	681
17.2.6	Equivalence of DEC and EC	683
17.2.7	Other Versions	683
17.3	Relationship to other Formalisms	684
17.4	Default Reasoning	684
17.4.1	Circumscription	684
17.4.2	Computing Circumscription	685
17.4.3	Historical Note	686
17.4.4	Negation as Failure	687
17.5	Event Calculus Knowledge Representation	687
17.5.1	Parameters	687
17.5.2	Event Effects	688
17.5.3	Preconditions	689
17.5.4	State Constraints	689
17.5.5	Concurrent Events	690
17.5.6	Triggered Events	691
17.5.7	Continuous Change	692
17.5.8	Nondeterministic Effects	693
17.5.9	Indirect Effects	694
17.5.10	Partially Ordered Events	696
17.6	Action Language \mathcal{E}	697
17.7	Automated Event Calculus Reasoning	699
17.7.1	Prolog	699
17.7.2	Answer Set Programming	700
17.7.3	Satisfiability (SAT) Solving	700
17.7.4	First-Order Logic Automated Theorem Proving	700
17.8	Applications of the Event Calculus	700
	Bibliography	701
18	Temporal Action Logics	709
	Patrick Doherty and Jonas Kvarnström	
18.1	Introduction	709

18.1.1	PMON and TAL	710
18.1.2	Previous Work	711
18.1.3	Chapter Structure	713
18.2	Basic Concepts	713
18.3	TAL Narratives	716
18.3.1	The Russian Airplane Hijack Scenario	717
18.3.2	Narrative Background Specification	718
18.3.3	Narrative Specification	723
18.4	The Relation Between the TAL Languages $\mathcal{L}(\text{ND})$ and $\mathcal{L}(\text{FL})$	724
18.5	The TAL Surface Language $\mathcal{L}(\text{ND})$	725
18.5.1	Sorts, Terms and Variables	725
18.5.2	Formulas	726
18.5.3	Statements	727
18.6	The TAL Base Language $\mathcal{L}(\text{FL})$	728
18.6.1	Translation from $\mathcal{L}(\text{ND})$ to $\mathcal{L}(\text{FL})$	728
18.7	Circumscription and TAL	730
18.8	Representing Ramifications in TAL	735
18.9	Representing Qualifications in TAL	737
18.9.1	Enabling Fluents	738
18.9.2	Strong Qualification	740
18.9.3	Weak Qualification	740
18.9.4	Qualification: Not Only For Actions	741
18.9.5	Ramifications as Qualifications	742
18.10	Action Expressivity in TAL	742
18.11	Concurrent Actions in TAL	744
18.11.1	Independent Concurrent Actions	744
18.11.2	Interacting Concurrent Actions	745
18.11.3	Laws of Interaction	745
18.12	An Application of TAL: TALplanner	747
18.13	Summary	752
	Acknowledgements	752
	Bibliography	753
19	Nonmonotonic Causal Logic	759
	Hudson Turner	
19.1	Fundamentals	762
19.1.1	Finite Domain Propositional Logic	762
19.1.2	Causal Theories	763
19.2	Strong Equivalence	765
19.3	Completion	766
19.4	Expressiveness	768
19.4.1	Nondeterminism: Coin Tossing	768
19.4.2	Implied Action Preconditions: Moving an Object	768
19.4.3	Things that Change by Themselves: Falling Dominos	769
19.4.4	Things that Tend to Change by Themselves: Pendulum	769
19.5	High-Level Action Language $\mathcal{C}+$	770
19.6	Relationship to Default Logic	771

19.7 Causal Theories in Higher-Order Classical Logic	772
19.8 A Logic of Universal Causation	773
Acknowledgement	774
Bibliography	774
III Knowledge Representation in Applications	777
20 Knowledge Representation and Question Answering	779
Marcello Balduccini, Chitta Baral and Yuliya Lierler	
20.1 Introduction	779
20.1.1 Role of Knowledge Representation and Reasoning in QA	780
20.1.2 Architectural Overview of QA Systems Using Knowledge Representation and Reasoning	782
20.2 From English to Logical Theories	783
20.3 The COGEX Logic Prover of the LCC QA System	790
20.4 Extracting Relevant Facts from Logical Theories and its Use in the DD QA System about Dynamic Domains and Trips	792
20.4.1 The Overall Architecture of the DD System	793
20.4.2 From Logic Forms to QSR Facts: An Illustration	794
20.4.3 OSR: From QSR Relations to Domain Relations	796
20.4.4 An Early Travel Module of the DD System	798
20.4.5 Other Enhancements to the Travel Module	802
20.5 From Natural Language to Relevant Facts in the ASU QA System	803
20.6 Nutcracker—System for Recognizing Textual Entailment	806
20.7 Mueller’s Story Understanding System	810
20.8 Conclusion	813
Acknowledgements	815
Bibliography	815
21 The Semantic Web: Webizing Knowledge Representation	821
Jim Hendler and Frank van Harmelen	
21.1 Introduction	821
21.2 The Semantic Web Today	823
21.3 Semantic Web KR Language Design	826
21.3.1 Web Infrastructure	826
21.3.2 Webizing KR	827
21.3.3 Scalability and the Semantic Web	830
21.4 OWL—Defining a Semantic Web KR Language	831
21.5 Semantic Web KR Challenges	836
21.6 Beyond OWL	836
21.7 Conclusion	837
Acknowledgements	837
Bibliography	838
22 Automated Planning	841
Alessandro Cimatti, Marco Pistore and Paolo Traverso	
22.1 Introduction	841

22.2	The General Framework	843
22.2.1	Domains	843
22.2.2	Plans and Plan Executions	844
22.2.3	Goals and Problems	845
22.3	Strong Planning under Full Observability	845
22.4	Strong Cyclic Planning under Full Observability	847
22.5	Planning for Temporally Extended Goals under Full Observability	850
22.6	Conformant Planning	857
22.7	Strong Planning under Partial Observability	859
22.8	A Technological Overview	860
22.9	Conclusions	863
	Bibliography	864
23	Cognitive Robotics	869
	Hector Levesque and Gerhard Lakemeyer	
23.1	Introduction	869
23.2	Knowledge Representation for Cognitive Robots	870
23.2.1	Varieties of Actions	871
23.2.2	Sensing	871
23.2.3	Knowledge	872
23.3	Reasoning for Cognitive Robots	873
23.3.1	Projection via Progression and Regression	873
23.3.2	Reasoning in Closed and Open Worlds	875
23.4	High-Level Control for Cognitive Robots	876
23.4.1	Classical Planning	876
23.4.2	High-Level Offline Robot Programming	877
23.4.3	High-Level Online Robot Programming	879
23.5	Conclusion	881
	Bibliography	882
24	Multi-Agent Systems	887
	Wiebe van der Hoek and Michael Wooldridge	
24.1	Introduction	887
24.2	Representing Rational Cognitive States	888
24.2.1	A Logical Toolkit	890
24.2.2	Dynamic Epistemic Logic	891
24.2.3	Cohen and Levesque's Intention Logic	893
24.2.4	Rao and Georgeff's BDI Logics	896
24.2.5	The KARO Framework	899
24.2.6	Discussion	903
24.2.7	Cognitive Agent Logics in Practice	903
24.3	Representing the Strategic Structure of a System	909
24.3.1	Coalition Logic	910
24.3.2	Strategic Temporal Logic: ATL	913
24.3.3	Knowledge in Strategic Temporal Logics: ATEL	916
24.3.4	CL-PC	919
24.3.5	Applications of Strategic Cooperation Logics	920

24.4 Conclusions	920
Bibliography	920
25 Knowledge Engineering	929
Guus Schreiber	
25.1 Introduction	929
25.2 Baseline	929
25.3 Tasks and Problem-Solving Methods	930
25.3.1 Two Sample Problem-Solving Methods	930
25.3.2 The Notion of “Knowledge Role”	934
25.3.3 Specification Languages	935
25.4 Ontologies	936
25.4.1 Ontology Specification Languages	937
25.4.2 Types of Ontologies	938
25.4.3 Ontology Engineering	940
25.4.4 Ontologies and Data Models	941
25.5 Knowledge Elicitation Techniques ¹	941
Bibliography	943
Author Index	947
Subject Index	987