A First Course in Logic

An introduction to model theory, proof theory, computability, and complexity

SHAWN HEDMAN Department of Mathematics, Florida Southern College



OXFORD

UNIVERSITY PRESS

Great Clarendon Street, Oxford OX2 6DP

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide in

Oxford New York

Auckland Bangkok Buenos Aires Cape Town Chennai Dar es Salaam Delhi Hong Kong Istanbul Karachi Kolkata Kuala Lumpur Madrid Melbourne Mexico City Mumbai Nairobi São Paulo Shanghai Taipei Tokyo Toronto

Oxford is a registered trade mark of Oxford University Press in the UK and in certain other countries

Published in the United States by Oxford University Press Inc., New York

© Oxford University Press 2004

The moral rights of the author have been asserted

Database right Oxford University Press (maker)

First published 2004

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without the prior permission in writing of Oxford University Press, or as expressly permitted by law, or under terms agreed with the appropriate reprographics rights organization. Enquiries concerning reproduction outside the scope of the above should be sent to the Rights Department, Oxford University Press, at the address above

You must not circulate this book in any other binding or cover and you must impose this same condition on any acquirer

A catalogue record for this title is available from the British Library Library of Congress Cataloging in Publication Data

Data available ISBN 0-19-852980-5 (Hbk) ISBN 0-19-852981-3 (Pbk)

 $10 \ 9 \ 8 \ 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1$

Typeset by Newgen Imaging Systems (P) Ltd., Chennai, India Printed in Great Britain on acid-free paper by Biddles Ltd., King's Lynn, Norfolk

Contents

1	Prop	oositional logic	1
	1.1	What is propositional logic?	1
	1.2	Validity, satisfiability, and contradiction	7
	1.3	Consequence and equivalence	9
	1.4	Formal proofs	12
	1.5	Proof by induction	22
		1.5.1 Mathematical induction	23
		1.5.2 Induction on the complexity of formulas	25
	1.6	Normal forms	27
	1.7	Horn formulas	32
	1.8	Resolution	37
		1.8.1 Clauses	37
		1.8.2 Resolvents	38
		1.8.3 Completeness of resolution	40
	1.9	Completeness and compactness	44
2	Stru	ctures and first-order logic	53
2	Stru 2.1	ctures and first-order logic The language of first-order logic	53 53
2	Stru 2.1 2.2	ctures and first-order logic The language of first-order logic The syntax of first-order logic	53 53 54
2	Stru 2.1 2.2 2.3	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures	53 53 54 57
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures	53 53 54 57 66
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures 2.4.1 Graphs	53 53 54 57 66 66
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures 2.4.1 Graphs 2.4.2 Relational databases	53 53 54 57 66 66 66 69
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures 2.4.1 Graphs 2.4.2 Relational databases 2.4.3 Linear orders	53 53 54 57 66 66 69 70
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logicThe language of first-order logicThe syntax of first-order logicSemantics and structuresExamples of structures2.4.1Graphs2.4.2Relational databases2.4.3Linear orders2.4.4Number systems	53 53 54 57 66 66 69 70 72
2	Stru 2.1 2.2 2.3 2.4	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures 2.4.1 Graphs 2.4.2 Relational databases 2.4.3 Linear orders 2.4.4 Number systems The size of a structure	53 53 54 57 66 66 69 70 72 73
2	Stru 2.1 2.2 2.3 2.4 2.5 2.6	ctures and first-order logic The language of first-order logic The syntax of first-order logic Semantics and structures Examples of structures 2.4.1 Graphs 2.4.2 Relational databases 2.4.3 Linear orders 2.4.4 Number systems The size of a structure Relations between structures	53 53 54 57 66 66 69 70 72 73 79
2	Stru 2.1 2.2 2.3 2.4 2.5 2.6	ctures and first-order logicThe language of first-order logicThe syntax of first-order logicSemantics and structuresExamples of structures2.4.1 Graphs2.4.2 Relational databases2.4.3 Linear orders2.4.4 Number systemsThe size of a structureRelations between structures2.6.1 Embeddings	53 53 54 57 66 66 69 70 72 73 79 80
2	Stru 2.1 2.2 2.3 2.4 2.5 2.6	ctures and first-order logicThe language of first-order logicThe syntax of first-order logicSemantics and structuresExamples of structures2.4.1 Graphs2.4.2 Relational databases2.4.3 Linear orders2.4.4 Number systemsThe size of a structureRelations between structures2.6.1 Embeddings2.6.2 Substructures	53 53 54 57 66 66 69 70 72 73 79 80 83
2	 Stru 2.1 2.2 2.3 2.4 	ctures and first-order logicThe language of first-order logicThe syntax of first-order logicSemantics and structuresExamples of structures2.4.1Graphs2.4.2Relational databases2.4.3Linear orders2.4.4Number systemsThe size of a structureRelations between structures2.6.1Embeddings2.6.2Substructures2.6.3Diagrams	53 53 54 57 66 66 69 70 72 73 79 80 83 86

3	Pro	of theory	99
	3.1	Formal proofs	100
	3.2	Normal forms	109
		3.2.1 Conjunctive prenex normal form	109
		3.2.2 Skolem normal form	111
	3.3	Herbrand theory	113
		3.3.1 Herbrand structures	113
		3.3.2 Dealing with equality	116
		3.3.3 The Herbrand method	118
	3.4	Resolution for first-order logic	120
		3.4.1 Unification	121
		3.4.2 Resolution	124
	3.5	SLD-resolution	128
	3.6	Prolog	137
4	Proj	perties of first-order logic	147
	4.1	The countable case	147
	4.2	Cardinal knowledge	152
		4.2.1 Ordinal numbers	153
		4.2.2 Cardinal arithmetic	156
		4.2.3 Continuum hypotheses	161
	4.3	Four theorems of first-order logic	163
	4.4	Amalgamation of structures	170
	4.5	Preservation of formulas	174
		4.5.1 Supermodels and submodels	175
		4.5.2 Unions of chains	179
	4.6	Amalgamation of vocabularies	183
	4.7	The expressive power of first-order logic	189
5	First	t-order theories	198
	5.1	Completeness and decidability	199
	5.2	Categoricity	205
	5.3	Countably categorical theories	211
		5.3.1 Dense linear orders	211
		5.3.2 Ryll-Nardzewski et al.	214
	5.4	The Random graph and 0–1 laws	216
	5.5	Quantifier elimination	221
		5.5.1 Finite relational vocabularies	222
		5.5.2 The general case	228
	5.6	Model-completeness	233
	5.7	Minimal theories	239

х

	5.8	Fields and vector spaces	247
	5.9	Some algebraic geometry	257
6	Models of countable theories		
	6.1	Types	267
	6.2	Isolated types	271
	6.3	Small models of small theories	275
		6.3.1 Atomic models	276
		6.3.2 Homogeneity	277
		6.3.3 Prime models	279
	6.4	Big models of small theories	280
		6.4.1 Countable saturated models	281
		6.4.2 Monster models	285
	6.5	Theories with many types	286
	6.6	The number of nonisomorphic models	289
	6.7	A touch of stability	290
7	Computability and complexity		299
	7.1	Computable functions and Church's thesis	301
		7.1.1 Primitive recursive functions	302
		7.1.2 The Ackermann function	307
		7.1.3 Recursive functions	309
	7.2	Computable sets and relations	312
	7.3	Computing machines	316
	7.4	Codes	320
	7.5	Semi-decidable decision problems	327
	7.6	Undecidable decision problems	332
		7.6.1 Nonrecursive sets	332
		7.6.2 The arithmetic hierarchy	335
	7.7	Decidable decision problems	337
		7.7.1 Examples	338
		7.7.2 Time and space	344
		7.7.3 Nondeterministic polynomial-time	347
	7.8	NP-completeness	348
8	The	incompleteness theorems	357
	8.1	Axioms for first-order number theory	358
	8.2	The expressive power of first-order number theory	362
	8.3	Gödel's First Incompleteness theorem	370
	8.4	Gödel codes	374
	8.5	Gödel's Second Incompleteness theorem	380
	8.6	Goodstein sequences	383

 \mathbf{xi}

9	Beyond first-order logic		388
	9.1	Second-order logic	388
	9.2	Infinitary logics	392
	9.3	Fixed-point logics	395
	9.4	Lindström's theorem	400
10	Finite model theory		408
	10.1	Finite-variable logics	408
	10.2	Classical failures	412
	10.3	Descriptive complexity	417
	10.4	Logic and the $\mathbf{P} = \mathbf{NP}$ problem	423
Bibliography			426
Index			428

xii