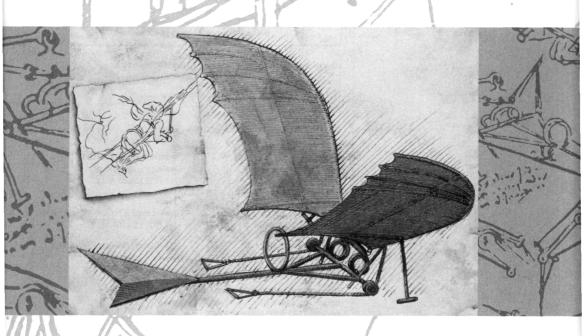
## Introduction to the Theory of COMPUTATION

THIRD EDITION



## MICHAEL SIPSER



Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

## CONTENTS

	Pre		ci
			κi
		To the educator	
		The first edition xi	
		Feedback to the author xii	ii
		Acknowledgments xi	V
	Pre	face to the Second Edition xvi	ii
	Pre	face to the Third Edition xx	a
0	Intr	oduction	1
	0.1	Automata, Computability, and Complexity	1
		Complexity theory	2
		Computability theory	3
		Automata theory	3
	0.2	Mathematical Notions and Terminology	3
		Sets	3
		Sequences and tuples	6
			7
		Graphs	0
		Strings and languages	3
		Boolean logic	4
		Summary of mathematical terms	6
	0.3	Definitions, Theorems, and Proofs	7
		Finding proofs	7
	0.4	Types of Proof	1
		Proof by construction	1
		Proof by contradiction	1
		Proof by induction	2
		Exercises, Problems, and Solutions	5

P	art (	One: Automata and Languages	29
1	Reg	gular Languages	31
	1.1	Finite Automata	. 31
		Formal definition of a finite automaton	. 35
		Examples of finite automata	
		Formal definition of computation	
		Designing finite automata	
		The regular operations	
	1.2	Nondeterminism	
		Formal definition of a nondeterministic finite automaton	
		Equivalence of NFAs and DFAs	
		Closure under the regular operations	
	1.3	Regular Expressions	
		Formal definition of a regular expression	
		Equivalence with finite automata	
	1.4	Nonregular Languages	
	1. 1	The pumping lemma for regular languages	
		Exercises, Problems, and Solutions	
		Lacress, 1700cms, and Sommons	. 02
2	Cor	ntext-Free Languages	101
	2.1	Context-Free Grammars	. 102
		Formal definition of a context-free grammar	
		Examples of context-free grammars	
		Designing context-free grammars	. 106
		Ambiguity	. 107
		Chomsky normal form	. 108
	2.2	Pushdown Automata	. 111
		Formal definition of a pushdown automaton	. 113
		Examples of pushdown automata	
		Equivalence with context-free grammars	
	2.3	Non-Context-Free Languages	
		The pumping lemma for context-free languages	
	2.4	Deterministic Context-Free Languages	
		Properties of DCFLs	
		Deterministic context-free grammars	
		Relationship of DPDAs and DCFGs	
		Parsing and LR(k) Grammars	
		Exercises, Problems, and Solutions	
	_		
Pa	art T	Two: Computability Theory	163
3	The	Church-Turing Thesis	165
	3.1	Turing Machines	
		Formal definition of a Turing machine	

			CONTENTS	vii
		Examples of Turing machines		. 170
	3.2	Variants of Turing Machines		
	J.2	Multitape Turing machines		. 176
		Nondeterministic Turing machines		. 178
		Enumerators		
		Equivalence with other models		
	3.3	The Definition of Algorithm		
	3.5	Hilbert's problems		
		Terminology for describing Turing machines .		
		Exercises, Problems, and Solutions		
4	Dec	cidability		193
•	4.1	Decidable Languages		
	1.1	Decidable problems concerning regular language		
		Decidable problems concerning regular language  Decidable problems concerning context-free lan		
	4.2	Undecidability		
	1.2	The diagonalization method		
		An undecidable language		
		A Turing-unrecognizable language		
		Exercises, Problems, and Solutions		
_	D - d	L - 21-212 c		215
5		lucibility		215
	5.1	Undecidable Problems from Language Theory .		
	r 2	Reductions via computation histories		
	5.2	A Simple Undecidable Problem		
	5.3	Mapping Reducibility		
		Computable functions		
		Formal definition of mapping reducibility		
		Exercises, Problems, and Solutions		. 239
6		anced Topics in Computability Theory		245
	6.1	The Recursion Theorem		
		Self-reference		
		Terminology for the recursion theorem		. 249
		Applications		
	6.2	Decidability of logical theories		
		A decidable theory		
		An undecidable theory		. 257
	6.3	Turing Reducibility		
	6.4	A Definition of Information		. 261
		Minimal length descriptions		. 262
		Optimality of the definition		. 266
		Incompressible strings and randomness		
		Exercises, Problems, and Solutions		

Pa	art T	Three: Complexity Theory	273
7	Tim	ne Complexity	275
	7.1	Measuring Complexity	 275
		Big-O and small-o notation	
		Analyzing algorithms	
		Complexity relationships among models	 282
	7.2	The Class P	
		Polynomial time	
		Examples of problems in P	
	7.3	The Class NP	
		Examples of problems in NP	
		The P versus NP question	
	7.4	NP-completeness	
	,	Polynomial time reducibility	
		Definition of NP-completeness	
		The Cook–Levin Theorem	
	7.5	Additional NP-complete Problems	
	1.5	The vertex cover problem	
		The Hamiltonian path problem	
		The subset sum problem	
		Exercises, Problems, and Solutions	
		Exercises, Problems, and Solutions	 322
8	Space	ce Complexity	331
	8.1	Savitch's Theorem	
	8.2	The Class PSPACE	
	8.3	PSPACE-completeness	
		The TQBF problem	
		Winning strategies for games	
		Generalized geography	 343
	8.4	The Classes L and NL	 348
	8.5	NL-completeness	 351
		Searching in graphs	 353
	8.6	NL equals coNL	
		Exercises, Problems, and Solutions	
9	Intr	actability	363
,	9.1	·	
	9.1	Hierarchy Theorems	
	0.2		
	9.2	Relativization	 3/0
	0.3	Limits of the diagonalization method	 3//
	9.3	Circuit Complexity	
		Exercises, Problems, and Solutions	 388
10		anced Topics in Complexity Theory	393
	10.1	Approximation Algorithms	 393

		CONTENTS	'^
10.2	Probabilistic Algorithms		396
10.2	The class BPP		
	Primality		
	Read-once branching programs		
10 3	Alternation		
10.5	Alternating time and space		
	The Polynomial time hierarchy		
10.4	Interactive Proof Systems		
10	Graph nonisomorphism		
	Definition of the model		
	IP = PSPACE		
10.5	Parallel Computation		
	Uniform Boolean circuits		
	The class NC		
	P-completeness		
10.6	Cryptography		
	Secret keys		
	Public-key cryptosystems		
	One-way functions		
	Trapdoor functions		
	Exercises, Problems, and Solutions		
Selec	ted Bibliography		443
Index	ζ.		448