Contents

Pre	reface			xi	
1	Program Analysis				
	1.1	Under	standing Software Behavior	1	
	1.2	Progra	am Analysis Applications and Challenges	2	
	1.3	Conce	pts in Program Analysis	4	
		1.3.1	What to Analyze	4	
		1.3.2	Static versus Dynamic	6	
		1.3.3	A Hard Limit: Uncomputability	7	
		1.3.4	Automation and Scalability	8	
		1.3.5	Approximation: Soundness and Completeness	9	
	1.4	Familie	es of Program Analysis Techniques	12	
		1.4.1	Testing: Checking a Set of Finite Executions	12	
		1.4.2	Assisted Proof: Relying on User-Supplied Invariants	13	
		1.4.3	Model Checking: Exhaustive Exploration of Finite Systems	14	
		1.4.4	Conservative Static Analysis: Automatic, Sound, and Incomplete		
			Approach	15	
		1.4.5	Bug Finding: Error Search, Automatic, Unsound, Incomplete,		
			Based on Heuristics	16	
		1.4.6	Summary	17	
	1.5	Roadn	пар	17	
2	A G	entle Int	troduction to Static Analysis	19	
	2.1	Semar	ntics and Analysis Goal: A Reachability Problem	19	
	2.2	•			
	2.3				
		2.3.1	Abstraction of Initialization	32	
		2.3.2	Abstraction of Post-Conditions	32	
		2.3.3	Abstraction of Non-Deterministic Choice	36	
		2.3.4	Abstraction of Non-Deterministic Iteration	37	
		2.3.5	Verification of the Property of Interest	43	
	2.4	A Com	nputable Abstract Semantics: Transitional Style	44	

viii Contents

		2.4.1	Semantics as State Transitions	45
		2.4.2	Abstraction of States	48
		2.4.3	Abstraction of State Transitions	48
		2.4.4	Analysis by Global Iterations	51
	2.5	Core P	Principles of a Static Analysis	56
3	A Ge	neral S	static Analysis Framework Based on a Compositional Semantics	59
	3.1	Semar	ntics	60
		3.1.1	A Simple Programming Language	60
		3.1.2	Concrete Semantics	60
	3.2	Abstra	ctions	65
		3.2.1	The Concept of Abstraction	65
		3.2.2	Non-Relational Abstraction	69
		3.2.3	Relational Abstraction	72
	3.3	Compu	utable Abstract Semantics	74
		3.3.1	Abstract Interpretation of Assignment	76
		3.3.2	Abstract Interpretation of Conditional Branching	79
		3.3.3	Abstract Interpretation of Loops	82
		3.3.4	Putting Everything Together	90
	3.4	The De	esign of an Abstract Interpreter	92
4	A General Static Analysis Framework Based on a Transitional Semantics			95
	4.1	Semar	ntics as State Transitions	96
		4.1.1	Concrete Semantics	96
		4.1.2	Recipe for Defining a Concrete Transitional Semantics	100
	4.2	Abstra	ct Semantics as Abstract State Transitions	101
		4.2.1	Abstraction of the Semantic Domain	102
		4.2.2	Abstraction of Semantic Functions	105
		4.2.3	Recipe for Defining an Abstract Transition Semantics	107
	4.3	Analys	is Algorithms Based on Global Iterations	109
		4.3.1	Basic Algorithms	109
		4.3.2	Worklist Algorithm	110
	4.4	Use Ex	xample of the Framework	112
		4.4.1	Simple Imperative Language	112
		4.4.2	Concrete State Transition Semantics	114
		4.4.3	Abstract State	115
		4.4.4	Abstract State Transition Semantics	116
5	Adva	Advanced Static Analysis Techniques		
	5.1	Constr	ruction of Abstract Domains	120
		5.1.1	Abstraction of Boolean-Numerical Properties	120
		5.1.2	Describing Conjunctive Properties	122
		5.1.3	Describing Properties Involving Case Splits	126
		5.1.4	Construction of an Abstract Domain	130
	5.2	Advand	ced Iteration Techniques	131

Contents ix

		5.2.1	Loop Unrolling	131	
		5.2.2	Fixpoint Approximation with More Precise Widening Iteration	133	
		5.2.3	Refinement of an Abstract Approximation of a Least Fixpoint	135	
	5.3	Sparse	Analysis	137	
		5.3.1	Exploiting Spatial Sparsity	139	
		5.3.2	Exploiting Temporal Sparsity	140	
		5.3.3	Precision-Preserving Def-Use Chain by Pre-Analysis	142	
	5.4	Modula	ar Analysis	143	
		5.4.1	Parameterization, Summary, and Scalability	144	
		5.4.2	Case Study	145	
	5.5	Backwa	ard Analysis	147	
		5.5.1	Forward Semantics and Backward Semantics	147	
		5.5.2	Backward Analysis and Applications	148	
		5.5.3	Precision Refinement by Combined Forward and Backward Analysis	150	
6	Prac	Practical Use of Static Analysis Tools			
	6.1	Analysi	is Assumptions and Goals	153	
	6.2	Setting	Up the Static Analysis of a Program	159	
		6.2.1	Definition of the Source Code and Proof Goals	159	
		6.2.2	Parameters to Guide the Analysis	162	
	6.3	Inspect	ting Analysis Results	166	
	6.4	Deploy	ment of a Static Analysis Tool	170	
7	Stat	Static Analysis Tool Implementation			
	7.1	Concre	ete Semantics and Concrete Interpreter	174	
	7.2	Abstrac	ct Domain Implementation	180	
	7.3	Static A	Analysis of Expressions and Conditions	183	
	7.4	Static A	Analysis Based on a Compositional Semantics	186	
	7.5	Static A	Analysis Based on a Transitional Semantics	190	
8	Stat	ic Analy	sis for Advanced Programming Features	195	
	8.1	For a L	anguage with Pointers and Dynamic Memory Allocations	196	
		8.1.1	Language and Concrete Semantics	196	
		8.1.2	An Abstract Semantics	199	
	8.2	For a L	anguage with Functions and Recursive Calls	203	
		8.2.1	Language and Concrete Semantics	203	
		8.2.2	An Abstract Semantics	206	
	8.3	Abstrac	ctions for Data Structures	212	
		8.3.1	Arrays	212	
		8.3.2	Buffers and Strings	217	
		8.3.3	Pointers	219	
		8.3.4	Dynamic Heap Allocation	223	
	8.4	Abstrac	ction for Control Flow Structures	229	
		8.4.1	Functions and Procedures	230	
		8.4.2	Parallelism	237	

x Contents

9	Clas	ses of Semantic Properties and Verification by Static Analysis	243
	9.1	Trace Properties	243
		9.1.1 Safety	244
		9.1.2 Liveness	247
		9.1.3 General Trace Properties	250
	9.2	Beyond Trace Properties: Information Flows and Other Properties	251
10	Specialized Static Analysis Frameworks		
	10.1	Static Analysis by Equations	258
		10.1.1 Data-Flow Analysis	258
	10.2	Static Analysis by Monotonic Closure	262
		10.2.1 Pointer Analysis	263
		10.2.2 Higher-Order Control-Flow Analysis	265
	10.3	Static Analysis by Proof Construction	268
		10.3.1 Type Inference	268
11	Sum	mary and Perspectives	275
A	Reference for Mathematical Notions and Notations		
	A.1	Sets	277
	A.2	Logical Connectives	277
	A.3	Definitions and Proofs by Induction	278
	A.4	Functions	278
	A.5	Order Relations and Ordered Sets	278
	A.6	Operators over Ordered Structures and Fixpoints	279
В	Proofs of Soundness		281
	B.1 Properties of Galois Connections		
	B.2	Proofs of Soundness for Chapter 3	282
		B.2.1 Soundness of the Abstract Interpretation of Expressions	282
		B.2.2 Soundness of the Abstract Interpretation of Conditions	283
		B.2.3 Soundness of the Abstract Join Operator	283
		B.2.4 Abstract Iterates with Widening	283
		B.2.5 Soundness of the Abstract Interpretation of Commands	285
	B.3	Proofs of Soundness for Chapter 4	286
		B.3.1 Transitional-Style Static Analysis over Finite-Height Domains	286
		B.3.2 Transitional-Style Static Analysis with Widening	287
		B.3.3 Use Example of the Transitional-Style Static Analysis	288
Bibli	ograp	hy	291
Indo	v		207