

Table of Contents

1	Introduction	1
1.1	Language Processors	1
1.1.1	Exercises for Section 1.1	3
1.2	The Structure of a Compiler	4
1.2.1	Lexical Analysis	5
1.2.2	Syntax Analysis	8
1.2.3	Semantic Analysis	8
1.2.4	Intermediate Code Generation	9
1.2.5	Code Optimization	10
1.2.6	Code Generation	10
1.2.7	Symbol-Table Management	11
1.2.8	The Grouping of Phases into Passes	11
1.2.9	Compiler-Construction Tools	12
1.3	The Evolution of Programming Languages	12
1.3.1	The Move to Higher-level Languages	13
1.3.2	Impacts on Compilers	14
1.3.3	Exercises for Section 1.3	14
1.4	The Science of Building a Compiler	15
1.4.1	Modeling in Compiler Design and Implementation	15
1.4.2	The Science of Code Optimization	15
1.5	Applications of Compiler Technology	17
1.5.1	Implementation of High-Level Programming Languages	17
1.5.2	Optimizations for Computer Architectures	19
1.5.3	Design of New Computer Architectures	21
1.5.4	Program Translations	22
1.5.5	Software Productivity Tools	23
1.6	Programming Language Basics	25
1.6.1	The Static/Dynamic Distinction	25
1.6.2	Environments and States	26
1.6.3	Static Scope and Block Structure	28
1.6.4	Explicit Access Control	31
1.6.5	Dynamic Scope	31
1.6.6	Parameter Passing Mechanisms	33

1.6.7	Aliasing	35
1.6.8	Exercises for Section 1.6	35
1.7	Summary of Chapter 1	36
1.8	References for Chapter 1	38
2	A Simple Syntax-Directed Translator	39
2.1	Introduction	40
2.2	Syntax Definition	42
2.2.1	Definition of Grammars	42
2.2.2	Derivations	44
2.2.3	Parse Trees	45
2.2.4	Ambiguity	47
2.2.5	Associativity of Operators	48
2.2.6	Precedence of Operators	48
2.2.7	Exercises for Section 2.2	51
2.3	Syntax-Directed Translation	52
2.3.1	Postfix Notation	53
2.3.2	Synthesized Attributes	54
2.3.3	Simple Syntax-Directed Definitions	56
2.3.4	Tree Traversals	56
2.3.5	Translation Schemes	57
2.3.6	Exercises for Section 2.3	60
2.4	Parsing	60
2.4.1	Top-Down Parsing	61
2.4.2	Predictive Parsing	64
2.4.3	When to Use ϵ -Productions	65
2.4.4	Designing a Predictive Parser	66
2.4.5	Left Recursion	67
2.4.6	Exercises for Section 2.4	68
2.5	A Translator for Simple Expressions	68
2.5.1	Abstract and Concrete Syntax	69
2.5.2	Adapting the Translation Scheme	70
2.5.3	Procedures for the Nonterminals	72
2.5.4	Simplifying the Translator	73
2.5.5	The Complete Program	74
2.6	Lexical Analysis	76
2.6.1	Removal of White Space and Comments	77
2.6.2	Reading Ahead	78
2.6.3	Constants	78
2.6.4	Recognizing Keywords and Identifiers	79
2.6.5	A Lexical Analyzer	81
2.6.6	Exercises for Section 2.6	84
2.7	Symbol Tables	85
2.7.1	Symbol Table Per Scope	86
2.7.2	The Use of Symbol Tables	89

2.8	Intermediate Code Generation	91
2.8.1	Two Kinds of Intermediate Representations	91
2.8.2	Construction of Syntax Trees	92
2.8.3	Static Checking	97
2.8.4	Three-Address Code	99
2.8.5	Exercises for Section 2.8	105
2.9	Summary of Chapter 2	105
3	Lexical Analysis	109
3.1	The Role of the Lexical Analyzer	109
3.1.1	Lexical Analysis Versus Parsing	110
3.1.2	Tokens, Patterns, and Lexemes	111
3.1.3	Attributes for Tokens	112
3.1.4	Lexical Errors	113
3.1.5	Exercises for Section 3.1	114
3.2	Input Buffering	115
3.2.1	Buffer Pairs	115
3.2.2	Sentinels	116
3.3	Specification of Tokens	116
3.3.1	Strings and Languages	117
3.3.2	Operations on Languages	119
3.3.3	Regular Expressions	120
3.3.4	Regular Definitions	123
3.3.5	Extensions of Regular Expressions	124
3.3.6	Exercises for Section 3.3	125
3.4	Recognition of Tokens	128
3.4.1	Transition Diagrams	130
3.4.2	Recognition of Reserved Words and Identifiers	132
3.4.3	Completion of the Running Example	133
3.4.4	Architecture of a Transition-Diagram-Based Lexical Analyzer	134
3.4.5	Exercises for Section 3.4	136
3.5	The Lexical-Analyzer Generator Lex	140
3.5.1	Use of Lex	140
3.5.2	Structure of Lex Programs	141
3.5.3	Conflict Resolution in Lex	144
3.5.4	The Lookahead Operator	144
3.5.5	Exercises for Section 3.5	146
3.6	Finite Automata	147
3.6.1	Nondeterministic Finite Automata	147
3.6.2	Transition Tables	148
3.6.3	Acceptance of Input Strings by Automata	149
3.6.4	Deterministic Finite Automata	149
3.6.5	Exercises for Section 3.6	151
3.7	From Regular Expressions to Automata	152

3.7.1	Conversion of an NFA to a DFA	152
3.7.2	Simulation of an NFA	156
3.7.3	Efficiency of NFA Simulation	157
3.7.4	Construction of an NFA from a Regular Expression	159
3.7.5	Efficiency of String-Processing Algorithms	163
3.7.6	Exercises for Section 3.7	166
3.8	Design of a Lexical-Analyzer Generator	166
3.8.1	The Structure of the Generated Analyzer	167
3.8.2	Pattern Matching Based on NFA's	168
3.8.3	DFA's for Lexical Analyzers	170
3.8.4	Implementing the Lookahead Operator	171
3.8.5	Exercises for Section 3.8	172
3.9	Optimization of DFA-Based Pattern Matchers	173
3.9.1	Important States of an NFA	173
3.9.2	Functions Computed From the Syntax Tree	175
3.9.3	Computing <i>nullable</i> , <i>firstpos</i> , and <i>lastpos</i>	176
3.9.4	Computing <i>followpos</i>	177
3.9.5	Converting a Regular Expression Directly to a DFA	179
3.9.6	Minimizing the Number of States of a DFA	180
3.9.7	State Minimization in Lexical Analyzers	184
3.9.8	Trading Time for Space in DFA Simulation	185
3.9.9	Exercises for Section 3.9	186
3.10	Summary of Chapter 3	187
3.11	References for Chapter 3	189

4	Syntax Analysis	191
4.1	Introduction	192
4.1.1	The Role of the Parser	192
4.1.2	Representative Grammars	193
4.1.3	Syntax Error Handling	194
4.1.4	Error-Recovery Strategies	195
4.2	Context-Free Grammars	197
4.2.1	The Formal Definition of a Context-Free Grammar	197
4.2.2	Notational Conventions	198
4.2.3	Derivations	199
4.2.4	Parse Trees and Derivations	201
4.2.5	Ambiguity	203
4.2.6	Verifying the Language Generated by a Grammar	204
4.2.7	Context-Free Grammars Versus Regular Expressions	205
4.2.8	Exercises for Section 4.2	206
4.3	Writing a Grammar	209
4.3.1	Lexical Versus Syntactic Analysis	209
4.3.2	Eliminating Ambiguity	210
4.3.3	Elimination of Left Recursion	212
4.3.4	Left Factoring	214

4.3.5	Non-Context-Free Language Constructs	215
4.3.6	Exercises for Section 4.3	216
4.4	Top-Down Parsing	217
4.4.1	Recursive-Descent Parsing	219
4.4.2	FIRST and FOLLOW	220
4.4.3	LL(1) Grammars	222
4.4.4	Nonrecursive Predictive Parsing	226
4.4.5	Error Recovery in Predictive Parsing	228
4.4.6	Exercises for Section 4.4	231
4.5	Bottom-Up Parsing	233
4.5.1	Reductions	234
4.5.2	Handle Pruning	235
4.5.3	Shift-Reduce Parsing	236
4.5.4	Conflicts During Shift-Reduce Parsing	238
4.5.5	Exercises for Section 4.5	240
4.6	Introduction to LR Parsing: Simple LR	241
4.6.1	Why LR Parsers?	241
4.6.2	Items and the LR(0) Automaton	242
4.6.3	The LR-Parsing Algorithm	248
4.6.4	Constructing SLR-Parsing Tables	252
4.6.5	Viable Prefixes	256
4.6.6	Exercises for Section 4.6	257
4.7	More Powerful LR Parsers	259
4.7.1	Canonical LR(1) Items	260
4.7.2	Constructing LR(1) Sets of Items	261
4.7.3	Canonical LR(1) Parsing Tables	265
4.7.4	Constructing LALR Parsing Tables	266
4.7.5	Efficient Construction of LALR Parsing Tables	270
4.7.6	Compaction of LR Parsing Tables	275
4.7.7	Exercises for Section 4.7	277
4.8	Using Ambiguous ⁴ Grammars	278
4.8.1	Precedence and Associativity to Resolve Conflicts	279
4.8.2	The “Dangling-Else” Ambiguity	281
4.8.3	Error Recovery in LR Parsing	283
4.8.4	Exercises for Section 4.8	285
4.9	Parser Generators	287
4.9.1	The Parser Generator Yacc	287
4.9.2	Using Yacc with Ambiguous Grammars	291
4.9.3	Creating Yacc Lexical Analyzers with Lex	294
4.9.4	Error Recovery in Yacc	295
4.9.5	Exercises for Section 4.9	297
4.10	Summary of Chapter 4	297
4.11	References for Chapter 4	300

5	Syntax-Directed Translation	303
5.1	Syntax-Directed Definitions	304
5.1.1	Inherited and Synthesized Attributes	304
5.1.2	Evaluating an SDD at the Nodes of a Parse Tree	306
5.1.3	Exercises for Section 5.1	309
5.2	Evaluation Orders for SDD's	310
5.2.1	Dependency Graphs	310
5.2.2	Ordering the Evaluation of Attributes	312
5.2.3	S-Attributed Definitions	312
5.2.4	L-Attributed Definitions	313
5.2.5	Semantic Rules with Controlled Side Effects	314
5.2.6	Exercises for Section 5.2	317
5.3	Applications of Syntax-Directed Translation	318
5.3.1	Construction of Syntax Trees	318
5.3.2	The Structure of a Type	321
5.3.3	Exercises for Section 5.3	323
5.4	Syntax-Directed Translation Schemes	324
5.4.1	Postfix Translation Schemes	324
5.4.2	Parser-Stack Implementation of Postfix SDT's	325
5.4.3	SDT's With Actions Inside Productions	327
5.4.4	Eliminating Left Recursion From SDT's	328
5.4.5	SDT's for L-Attributed Definitions	331
5.4.6	Exercises for Section 5.4	336
5.5	Implementing L-Attributed SDD's	337
5.5.1	Translation During Recursive-Descent Parsing	338
5.5.2	On-The-Fly Code Generation	340
5.5.3	L-Attributed SDD's and LL Parsing	343
5.5.4	Bottom-Up Parsing of L-Attributed SDD's	348
5.5.5	Exercises for Section 5.5	352
5.6	Summary of Chapter 5	353
5.7	References for Chapter 5	354
6	Intermediate-Code Generation	357
6.1	Variants of Syntax Trees	358
6.1.1	Directed Acyclic Graphs for Expressions	359
6.1.2	The Value-Number Method for Constructing DAG's	360
6.1.3	Exercises for Section 6.1	362
6.2	Three-Address Code	363
6.2.1	Addresses and Instructions	364
6.2.2	Quadruples	366
6.2.3	Triples	367
6.2.4	Static Single-Assignment Form	369
6.2.5	Exercises for Section 6.2	370
6.3	Types and Declarations	370
6.3.1	Type Expressions	371

6.3.2	Type Equivalence	372
6.3.3	Declarations	373
6.3.4	Storage Layout for Local Names	373
6.3.5	Sequences of Declarations	376
6.3.6	Fields in Records and Classes	376
6.3.7	Exercises for Section 6.3	378
6.4	Translation of Expressions	378
6.4.1	Operations Within Expressions	378
6.4.2	Incremental Translation	380
6.4.3	Addressing Array Elements	381
6.4.4	Translation of Array References	383
6.4.5	Exercises for Section 6.4	384
6.5	Type Checking	386
6.5.1	Rules for Type Checking	387
6.5.2	Type Conversions	388
6.5.3	Overloading of Functions and Operators	390
6.5.4	Type Inference and Polymorphic Functions	391
6.5.5	An Algorithm for Unification	395
6.5.6	Exercises for Section 6.5	398
6.6	Control Flow	399
6.6.1	Boolean Expressions	399
6.6.2	Short-Circuit Code	400
6.6.3	Flow-of-Control Statements	401
6.6.4	Control-Flow Translation of Boolean Expressions	403
6.6.5	Avoiding Redundant Gotos	405
6.6.6	Boolean Values and Jumping Code	408
6.6.7	Exercises for Section 6.6	408
6.7	Backpatching	410
6.7.1	One-Pass Code Generation Using Backpatching	410
6.7.2	Backpatching for Boolean Expressions	411
6.7.3	Flow-of-Control Statements	413
6.7.4	Break-, Continue-, and Goto-Statements	416
6.7.5	Exercises for Section 6.7	417
6.8	Switch-Statements	418
6.8.1	Translation of Switch-Statements	419
6.8.2	Syntax-Directed Translation of Switch-Statements	420
6.8.3	Exercises for Section 6.8	421
6.9	Intermediate Code for Procedures	422
6.10	Summary of Chapter 6	424
6.11	References for Chapter 6	425

7 Run-Time Environments	427
7.1 Storage Organization	427
7.1.1 Static Versus Dynamic Storage Allocation	429
7.2 Stack Allocation of Space	430
7.2.1 Activation Trees	430
7.2.2 Activation Records	433
7.2.3 Calling Sequences	436
7.2.4 Variable-Length Data on the Stack	438
7.2.5 Exercises for Section 7.2	440
7.3 Access to Nonlocal Data on the Stack	441
7.3.1 Data Access Without Nested Procedures	442
7.3.2 Issues With Nested Procedures	442
7.3.3 A Language With Nested Procedure Declarations	443
7.3.4 Nesting Depth	443
7.3.5 Access Links	445
7.3.6 Manipulating Access Links	447
7.3.7 Access Links for Procedure Parameters	448
7.3.8 Displays	449
7.3.9 Exercises for Section 7.3	451
7.4 Heap Management	452
7.4.1 The Memory Manager	453
7.4.2 The Memory Hierarchy of a Computer	454
7.4.3 Locality in Programs	455
7.4.4 Reducing Fragmentation	457
7.4.5 Manual Deallocation Requests	460
7.4.6 Exercises for Section 7.4	463
7.5 Introduction to Garbage Collection	463
7.5.1 Design Goals for Garbage Collectors	464
7.5.2 Reachability	466
7.5.3 Reference Counting Garbage Collectors	468
7.5.4 Exercises for Section 7.5	470
7.6 Introduction to Trace-Based Collection	470
7.6.1 A Basic Mark-and-Sweep Collector	471
7.6.2 Basic Abstraction	473
7.6.3 Optimizing Mark-and-Sweep	475
7.6.4 Mark-and-Compact Garbage Collectors	476
7.6.5 Copying collectors	478
7.6.6 Comparing Costs	482
7.6.7 Exercises for Section 7.6	482
7.7 Short-Pause Garbage Collection	483
7.7.1 Incremental Garbage Collection	483
7.7.2 Incremental Reachability Analysis	485
7.7.3 Partial-Collection Basics	487
7.7.4 Generational Garbage Collection	488
7.7.5 The Train Algorithm	490

7.7.6	Exercises for Section 7.7	493
7.8	Advanced Topics in Garbage Collection	494
7.8.1	Parallel and Concurrent Garbage Collection	495
7.8.2	Partial Object Relocation	497
7.8.3	Conservative Collection for Unsafe Languages	498
7.8.4	Weak References	498
7.8.5	Exercises for Section 7.8	499
7.9	Summary of Chapter 7	500
7.10	References for Chapter 7	502
8	Code Generation	505
8.1	Issues in the Design of a Code Generator	506
8.1.1	Input to the Code Generator	507
8.1.2	The Target Program	507
8.1.3	Instruction Selection	508
8.1.4	Register Allocation	510
8.1.5	Evaluation Order	511
8.2	The Target Language	512
8.2.1	A Simple Target Machine Model	512
8.2.2	Program and Instruction Costs	515
8.2.3	Exercises for Section 8.2	516
8.3	Addresses in the Target Code	518
8.3.1	Static Allocation	518
8.3.2	Stack Allocation	520
8.3.3	Run-Time Addresses for Names	522
8.3.4	Exercises for Section 8.3	524
8.4	Basic Blocks and Flow Graphs	525
8.4.1	Basic Blocks	526
8.4.2	Next-Use Information	528
8.4.3	Flow Graphs	529
8.4.4	Representation of Flow Graphs	530
8.4.5	Loops	531
8.4.6	Exercises for Section 8.4	531
8.5	Optimization of Basic Blocks	533
8.5.1	The DAG Representation of Basic Blocks	533
8.5.2	Finding Local Common Subexpressions	534
8.5.3	Dead Code Elimination	535
8.5.4	The Use of Algebraic Identities	536
8.5.5	Representation of Array References	537
8.5.6	Pointer Assignments and Procedure Calls	539
8.5.7	Reassembling Basic Blocks From DAG's	539
8.5.8	Exercises for Section 8.5	541
8.6	A Simple Code Generator	542
8.6.1	Register and Address Descriptors	543
8.6.2	The Code-Generation Algorithm	544

8.6.3	Design of the Function <i>getReg</i>	547
8.6.4	Exercises for Section 8.6	548
8.7	Peephole Optimization	549
8.7.1	Eliminating Redundant Loads and Stores	550
8.7.2	Eliminating Unreachable Code	550
8.7.3	Flow-of-Control Optimizations	551
8.7.4	Algebraic Simplification and Reduction in Strength	552
8.7.5	Use of Machine Idioms	552
8.7.6	Exercises for Section 8.7	553
8.8	Register Allocation and Assignment	553
8.8.1	Global Register Allocation	553
8.8.2	Usage Counts	554
8.8.3	Register Assignment for Outer Loops	556
8.8.4	Register Allocation by Graph Coloring	556
8.8.5	Exercises for Section 8.8	557
8.9	Instruction Selection by Tree Rewriting	558
8.9.1	Tree-Translation Schemes	558
8.9.2	Code Generation by Tiling an Input Tree	560
8.9.3	Pattern Matching by Parsing	563
8.9.4	Routines for Semantic Checking	565
8.9.5	General Tree Matching	565
8.9.6	Exercises for Section 8.9	567
8.10	Optimal Code Generation for Expressions	567
8.10.1	Ershov Numbers	567
8.10.2	Generating Code From Labeled Expression Trees	568
8.10.3	Evaluating Expressions with an Insufficient Supply of Registers	570
8.10.4	Exercises for Section 8.10	572
8.11	Dynamic Programming Code-Generation	573
8.11.1	Contiguous Evaluation	574
8.11.2	The Dynamic Programming Algorithm	575
8.11.3	Exercises for Section 8.11	577
8.12	Summary of Chapter 8	578
8.13	References for Chapter 8	579
9	Machine-Independent Optimizations	583
9.1	The Principal Sources of Optimization	584
9.1.1	Causes of Redundancy	584
9.1.2	A Running Example: Quicksort	585
9.1.3	Semantics-Preserving Transformations	586
9.1.4	Global Common Subexpressions	588
9.1.5	Copy Propagation	590
9.1.6	Dead-Code Elimination	591
9.1.7	Code Motion	592
9.1.8	Induction Variables and Reduction in Strength	592

9.1.9	Exercises for Section 9.1	596
9.2	Introduction to Data-Flow Analysis	597
9.2.1	The Data-Flow Abstraction	597
9.2.2	The Data-Flow Analysis Schema	599
9.2.3	Data-Flow Schemas on Basic Blocks	600
9.2.4	Reaching Definitions	601
9.2.5	Live-Variable Analysis	608
9.2.6	Available Expressions	610
9.2.7	Summary	614
9.2.8	Exercises for Section 9.2	615
9.3	Foundations of Data-Flow Analysis	618
9.3.1	Semilattices	618
9.3.2	Transfer Functions	623
9.3.3	The Iterative Algorithm for General Frameworks	626
9.3.4	Meaning of a Data-Flow Solution	628
9.3.5	Exercises for Section 9.3	631
9.4	Constant Propagation	632
9.4.1	Data-Flow Values for the Constant-Propagation Framework	633
9.4.2	The Meet for the Constant-Propagation Framework	633
9.4.3	Transfer Functions for the Constant-Propagation Framework	634
9.4.4	Monotonicity of the Constant-Propagation Framework	635
9.4.5	Nondistributivity of the Constant-Propagation Framework	635
9.4.6	Interpretation of the Results	637
9.4.7	Exercises for Section 9.4	637
9.5	Partial-Redundancy Elimination	639
9.5.1	The Sources of Redundancy	639
9.5.2	Can All Redundancy Be Eliminated?	642
9.5.3	The Lazy-Code-Motion Problem	644
9.5.4	Anticipation of Expressions	645
9.5.5	The Lazy-Code-Motion Algorithm	646
9.5.6	Exercises for Section 9.5	655
9.6	Loops in Flow Graphs	655
9.6.1	Dominators	656
9.6.2	Depth-First Ordering	660
9.6.3	Edges in a Depth-First Spanning Tree	661
9.6.4	Back Edges and Reducibility	662
9.6.5	Depth of a Flow Graph	665
9.6.6	Natural Loops	665
9.6.7	Speed of Convergence of Iterative Data-Flow Algorithms	667
9.6.8	Exercises for Section 9.6	669
9.7	Region-Based Analysis	672
9.7.1	Regions	672
9.7.2	Region Hierarchies for Reducible Flow Graphs	673

9.7.3	Overview of a Region-Based Analysis	676
9.7.4	Necessary Assumptions About Transfer Functions	678
9.7.5	An Algorithm for Region-Based Analysis	680
9.7.6	Handling Nonreducible Flow Graphs	684
9.7.7	Exercises for Section 9.7	686
9.8	Symbolic Analysis	686
9.8.1	Affine Expressions of Reference Variables	687
9.8.2	Data-Flow Problem Formulation	689
9.8.3	Region-Based Symbolic Analysis	694
9.8.4	Exercises for Section 9.8	699
9.9	Summary of Chapter 9	700
9.10	References for Chapter 9	703
10	Instruction-Level Parallelism	707
10.1	Processor Architectures	708
10.1.1	Instruction Pipelines and Branch Delays	708
10.1.2	Pipelined Execution	709
10.1.3	Multiple Instruction Issue	710
10.2	Code-Scheduling Constraints	710
10.2.1	Data Dependence	711
10.2.2	Finding Dependences Among Memory Accesses	712
10.2.3	Tradeoff Between Register Usage and Parallelism	713
10.2.4	Phase Ordering Between Register Allocation and Code Scheduling	716
10.2.5	Control Dependence	716
10.2.6	Speculative Execution Support	717
10.2.7	A Basic Machine Model	719
10.2.8	Exercises for Section 10.2	720
10.3	Basic-Block Scheduling	721
10.3.1	Data-Dependence Graphs	722
10.3.2	List Scheduling of Basic Blocks	723
10.3.3	Prioritized Topological Orders	725
10.3.4	Exercises for Section 10.3	726
10.4	Global Code Scheduling	727
10.4.1	Primitive Code Motion	728
10.4.2	Upward Code Motion	730
10.4.3	Downward Code Motion	731
10.4.4	Updating Data Dependences	732
10.4.5	Global Scheduling Algorithms	732
10.4.6	Advanced Code Motion Techniques	736
10.4.7	Interaction with Dynamic Schedulers	737
10.4.8	Exercises for Section 10.4	737
10.5	Software Pipelining	738
10.5.1	Introduction	738
10.5.2	Software Pipelining of Loops	740

10.5.3 Register Allocation and Code Generation	743
10.5.4 Do-Across Loops	743
10.5.5 Goals and Constraints of Software Pipelining	745
10.5.6 A Software-Pipelining Algorithm	749
10.5.7 Scheduling Acyclic Data-Dependence Graphs	749
10.5.8 Scheduling Cyclic Dependence Graphs	751
10.5.9 Improvements to the Pipelining Algorithms	758
10.5.10 Modular Variable Expansion	758
10.5.11 Conditional Statements	761
10.5.12 Hardware Support for Software Pipelining	762
10.5.13 Exercises for Section 10.5	763
10.6 Summary of Chapter 10	765
10.7 References for Chapter 10	766
11 Optimizing for Parallelism and Locality	769
11.1 Basic Concepts	771
11.1.1 Multiprocessors	772
11.1.2 Parallelism in Applications	773
11.1.3 Loop-Level Parallelism	775
11.1.4 Data Locality	777
11.1.5 Introduction to Affine Transform Theory	778
11.2 Matrix Multiply: An In-Depth Example	782
11.2.1 The Matrix-Multiplication Algorithm	782
11.2.2 Optimizations	785
11.2.3 Cache Interference	788
11.2.4 Exercises for Section 11.2	788
11.3 Iteration Spaces	788
11.3.1 Constructing Iteration Spaces from Loop Nests	788
11.3.2 Execution Order for Loop Nests	791
11.3.3 Matrix Formulation of Inequalities	791
11.3.4 Incorporating Symbolic Constants	793
11.3.5 Controlling the Order of Execution	793
11.3.6 Changing Axes	798
11.3.7 Exercises for Section 11.3	799
11.4 Affine Array Indexes	801
11.4.1 Affine Accesses	802
11.4.2 Affine and Nonaffine Accesses in Practice	803
11.4.3 Exercises for Section 11.4	804
11.5 Data Reuse	804
11.5.1 Types of Reuse	805
11.5.2 Self Reuse	806
11.5.3 Self-Spatial Reuse	809
11.5.4 Group Reuse	811
11.5.5 Exercises for Section 11.5	814
11.6 Array Data-Dependence Analysis	815

11.6.1	Definition of Data Dependence of Array Accesses	816
11.6.2	Integer Linear Programming	817
11.6.3	The GCD Test	818
11.6.4	Heuristics for Solving Integer Linear Programs	820
11.6.5	Solving General Integer Linear Programs	823
11.6.6	Summary	825
11.6.7	Exercises for Section 11.6	826
11.7	Finding Synchronization-Free Parallelism	828
11.7.1	An Introductory Example	828
11.7.2	Affine Space Partitions	830
11.7.3	Space-Partition Constraints	831
11.7.4	Solving Space-Partition Constraints	835
11.7.5	A Simple Code-Generation Algorithm	838
11.7.6	Eliminating Empty Iterations	841
11.7.7	Eliminating Tests from Innermost Loops	844
11.7.8	Source-Code Transforms	846
11.7.9	Exercises for Section 11.7	851
11.8	Synchronization Between Parallel Loops	853
11.8.1	A Constant Number of Synchronizations	853
11.8.2	Program-Dependence Graphs	854
11.8.3	Hierarchical Time	857
11.8.4	The Parallelization Algorithm	859
11.8.5	Exercises for Section 11.8	860
11.9	Pipelining	861
11.9.1	What is Pipelining?	861
11.9.2	Successive Over-Relaxation (SOR): An Example	863
11.9.3	Fully Permutable Loops	864
11.9.4	Pipelining Fully Permutable Loops	864
11.9.5	General Theory	867
11.9.6	Time-Partition Constraints	868
11.9.7	Solving Time-Partition Constraints by Farkas' Lemma .	872
11.9.8	Code Transformations	875
11.9.9	Parallelism With Minimum Synchronization	880
11.9.10	Exercises for Section 11.9	882
11.10	Locality Optimizations	884
11.10.1	Temporal Locality of Computed Data	885
11.10.2	Array Contraction	885
11.10.3	Partition Interleaving	887
11.10.4	Putting it All Together	890
11.10.5	Exercises for Section 11.10	892
11.11	Other Uses of Affine Transforms	893
11.11.1	Distributed memory machines	894
11.11.2	Multi-Instruction-Issue Processors	895
11.11.3	Vector and SIMD Instructions	895
11.11.4	Prefetching	896

11.12 Summary of Chapter 11	897
11.13 References for Chapter 11	899
12 Interprocedural Analysis	903
12.1 Basic Concepts	904
12.1.1 Call Graphs	904
12.1.2 Context Sensitivity	906
12.1.3 Call Strings	908
12.1.4 Cloning-Based Context-Sensitive Analysis	910
12.1.5 Summary-Based Context-Sensitive Analysis	911
12.1.6 Exercises for Section 12.1	914
12.2 Why Interprocedural Analysis?	916
12.2.1 Virtual Method Invocation	916
12.2.2 Pointer Alias Analysis	917
12.2.3 Parallelization	917
12.2.4 Detection of Software Errors and Vulnerabilities	917
12.2.5 SQL Injection	918
12.2.6 Buffer Overflow	920
12.3 A Logical Representation of Data Flow	921
12.3.1 Introduction to Datalog	921
12.3.2 Datalog Rules	922
12.3.3 Intensional and Extensional Predicates	924
12.3.4 Execution of Datalog Programs	927
12.3.5 Incremental Evaluation of Datalog Programs	928
12.3.6 Problematic Datalog Rules	930
12.3.7 Exercises for Section 12.3	932
12.4 A Simple Pointer-Analysis Algorithm	933
12.4.1 Why is Pointer Analysis Difficult	934
12.4.2 A Model for Pointers and References	935
12.4.3 Flow Insensitivity	936
12.4.4 The Formulation in Datalog	937
12.4.5 Using Type Information	938
12.4.6 Exercises for Section 12.4	939
12.5 Context-Insensitive Interprocedural Analysis	941
12.5.1 Effects of a Method Invocation	941
12.5.2 Call Graph Discovery in Datalog	943
12.5.3 Dynamic Loading and Reflection	944
12.5.4 Exercises for Section 12.5	945
12.6 Context-Sensitive Pointer Analysis	945
12.6.1 Contexts and Call Strings	946
12.6.2 Adding Context to Datalog Rules	949
12.6.3 Additional Observations About Sensitivity	949
12.6.4 Exercises for Section 12.6	950
12.7 Datalog Implementation by BDD's	951
12.7.1 Binary Decision Diagrams	951

12.7.2 Transformations on BDD's	953
12.7.3 Representing Relations by BDD's	954
12.7.4 Relational Operations as BDD Operations	954
12.7.5 Using BDD's for Points-to Analysis	957
12.7.6 Exercises for Section 12.7	958
12.8 Summary of Chapter 12	958
12.9 References for Chapter 12	961
A A Complete Front End	965
A.1 The Source Language	965
A.2 Main	966
A.3 Lexical Analyzer	967
A.4 Symbol Tables and Types	970
A.5 Intermediate Code for Expressions	971
A.6 Jumping Code for Boolean Expressions	974
A.7 Intermediate Code for Statements	978
A.8 Parser	981
A.9 Creating the Front End	986
B Finding Linearly Independent Solutions	989
Index	993