

# Contents

About the Authors .....	iv
About the Cover .....	viii
Preface .....	xix

<b>CHAPTER 1 Overview of Compilation .....</b>	<b>1</b>
--	----------

<b>1.1</b> Introduction .....	1
<b>1.2</b> Compiler Structure .....	6
<b>1.3</b> Overview of Translation .....	9
1.3.1 The Front End .....	10
1.3.2 The Optimizer .....	14
1.3.3 The Back End .....	15
<b>1.4</b> Summary and Perspective .....	21
Chapter Notes .....	22
Exercises .....	23

<b>CHAPTER 2 Scanners.....</b>	<b>25</b>
--------------------------------	-----------

<b>2.1</b> Introduction .....	25
<b>2.2</b> Recognizing Words .....	27
2.2.1 A Formalism for Recognizers .....	29
2.2.2 Recognizing More Complex Words .....	31
<b>2.3</b> Regular Expressions .....	34
2.3.1 Formalizing the Notation .....	35
2.3.2 Examples .....	36
2.3.3 Closure Properties of REs .....	39
<b>2.4</b> From Regular Expression to Scanner .....	42
2.4.1 Nondeterministic Finite Automata .....	43
2.4.2 Regular Expression to NFA: Thompson's Construction .....	45
2.4.3 NFA to DFA: The Subset Construction .....	47
2.4.4 DFA to Minimal DFA: Hopcroft's Algorithm .....	53
2.4.5 Using a DFA as a Recognizer .....	57
<b>2.5</b> Implementing Scanners .....	59
2.5.1 Table-Driven Scanners .....	60
2.5.2 Direct-Coded Scanners .....	65
2.5.3 Hand-Coded Scanners .....	69
2.5.4 Handling Keywords .....	72

<b>2.6</b>	Advanced Topics .....	74
2.6.1	DFA to Regular Expression .....	74
2.6.2	Another Approach to DFA Minimization: Brzozowski's Algorithm .....	75
2.6.3	Closure-Free Regular Expressions .....	77
<b>2.7</b>	Chapter Summary and Perspective .....	78
	Chapter Notes .....	78
	Exercises .....	80
<b>CHAPTER 3 Parsers.....</b>		<b>83</b>
<b>3.1</b>	Introduction .....	83
<b>3.2</b>	Expressing Syntax .....	85
3.2.1	Why Not Regular Expressions? .....	85
3.2.2	Context-Free Grammars .....	86
3.2.3	More Complex Examples .....	89
3.2.4	Encoding Meaning into Structure .....	92
3.2.5	Discovering a Derivation for an Input String .....	95
<b>3.3</b>	Top-Down Parsing .....	96
3.3.1	Transforming a Grammar for Top-Down Parsing .....	98
3.3.2	Top-Down Recursive-Descent Parsers .....	108
3.3.3	Table-Driven LL(1) Parsers .....	110
<b>3.4</b>	Bottom-Up Parsing .....	116
3.4.1	The LR(1) Parsing Algorithm .....	118
3.4.2	Building LR(1) Tables .....	124
3.4.3	Errors in the Table Construction .....	136
<b>3.5</b>	Practical Issues .....	141
3.5.1	Error Recovery .....	141
3.5.2	Unary Operators .....	142
3.5.3	Handling Context-Sensitive Ambiguity .....	143
3.5.4	Left versus Right Recursion .....	144
<b>3.6</b>	Advanced Topics .....	147
3.6.1	Optimizing a Grammar .....	148
3.6.2	Reducing the Size of LR(1) Tables .....	150
<b>3.7</b>	Summary and Perspective .....	155
	Chapter Notes .....	156
	Exercises .....	157

**CHAPTER 4 Context-Sensitive Analysis.....****161**

<b>4.1</b>	Introduction .....	161
<b>4.2</b>	An Introduction to Type Systems .....	164
	4.2.1 The Purpose of Type Systems .....	165
	4.2.2 Components of a Type System .....	170
<b>4.3</b>	The Attribute-Grammar Framework .....	182
	4.3.1 Evaluation Methods .....	186
	4.3.2 Circularity .....	187
	4.3.3 Extended Examples .....	187
	4.3.4 Problems with the Attribute-Grammar Approach .....	194
<b>4.4</b>	Ad Hoc Syntax-Directed Translation .....	198
	4.4.1 Implementing Ad Hoc Syntax-Directed Translation .....	199
	4.4.2 Examples .....	202
<b>4.5</b>	Advanced Topics .....	211
	4.5.1 Harder Problems in Type Inference .....	211
	4.5.2 Changing Associativity .....	213
<b>4.6</b>	Summary and Perspective .....	215
	Chapter Notes .....	216
	Exercises .....	217

**CHAPTER 5 Intermediate Representations.....****221**

<b>5.1</b>	Introduction .....	221
	5.1.1 A Taxonomy of Intermediate Representations .....	223
<b>5.2</b>	Graphical IRs .....	226
	5.2.1 Syntax-Related Trees .....	226
	5.2.2 Graphs .....	230
<b>5.3</b>	Linear IRs .....	235
	5.3.1 Stack-Machine Code .....	237
	5.3.2 Three-Address Code .....	237
	5.3.3 Representing Linear Codes .....	238
	5.3.4 Building a Control-Flow Graph from a Linear Code .....	241
<b>5.4</b>	Mapping Values to Names .....	243
	5.4.1 Naming Temporary Values .....	244
	5.4.2 Static Single-Assignment Form .....	246
	5.4.3 Memory Models .....	250

<b>5.5</b>	Symbol Tables .....	253
5.5.1	Hash Tables .....	254
5.5.2	Building a Symbol Table .....	255
5.5.3	Handling Nested Scopes .....	256
5.5.4	The Many Uses for Symbol Tables .....	261
5.5.5	Other Uses for Symbol Table Technology .....	263
<b>5.6</b>	Summary and Perspective .....	264
	Chapter Notes .....	264
	Exercises .....	265
<b>CHAPTER 6 The Procedure Abstraction .....</b>		<b>269</b>
<b>6.1</b>	Introduction .....	269
<b>6.2</b>	Procedure Calls .....	272
<b>6.3</b>	Name Spaces .....	276
6.3.1	Name Spaces of Algol-like Languages .....	276
6.3.2	Runtime Structures to Support Algol-like Languages .....	280
6.3.3	Name Spaces of Object-Oriented Languages .....	285
6.3.4	Runtime Structures to Support Object-Oriented Languages .....	290
<b>6.4</b>	Communicating Values Between Procedures .....	297
6.4.1	Passing Parameters .....	297
6.4.2	Returning Values .....	301
6.4.3	Establishing Addressability .....	301
<b>6.5</b>	Standardized Linkages .....	308
<b>6.6</b>	Advanced Topics .....	312
6.6.1	Explicit Heap Management .....	313
6.6.2	Implicit Deallocation .....	317
<b>6.7</b>	Summary and Perspective .....	322
	Chapter Notes .....	323
	Exercises .....	324
<b>CHAPTER 7 Code Shape.....</b>		<b>331</b>
<b>7.1</b>	Introduction .....	331
<b>7.2</b>	Assigning Storage Locations .....	334
7.2.1	Placing Runtime Data Structures .....	335
7.2.2	Layout for Data Areas .....	336
7.2.3	Keeping Values in Registers .....	340
<b>7.3</b>	Arithmetic Operators .....	342
7.3.1	Reducing Demand for Registers .....	344

7.3.2 Accessing Parameter Values .....	345
7.3.3 Function Calls in an Expression .....	347
7.3.4 Other Arithmetic Operators .....	348
7.3.5 Mixed-Type Expressions .....	348
7.3.6 Assignment as an Operator .....	349
<b>7.4 Boolean and Relational Operators .....</b>	<b>350</b>
7.4.1 Representations .....	351
7.4.2 Hardware Support for Relational Operations .....	353
<b>7.5 Storing and Accessing Arrays .....</b>	<b>359</b>
7.5.1 Referencing a Vector Element .....	359
7.5.2 Array Storage Layout .....	361
7.5.3 Referencing an Array Element .....	362
7.5.4 Range Checking .....	367
<b>7.6 Character Strings .....</b>	<b>369</b>
7.6.1 String Representations .....	370
7.6.2 String Assignment .....	370
7.6.3 String Concatenation .....	372
7.6.4 String Length .....	373
<b>7.7 Structure References .....</b>	<b>374</b>
7.7.1 Understanding Structure Layouts .....	375
7.7.2 Arrays of Structures .....	376
7.7.3 Unions and Runtime Tags .....	377
7.7.4 Pointers and Anonymous Values .....	378
<b>7.8 Control-Flow Constructs .....</b>	<b>380</b>
7.8.1 Conditional Execution .....	381
7.8.2 Loops and Iteration .....	384
7.8.3 Case Statements .....	388
<b>7.9 Procedure Calls .....</b>	<b>392</b>
7.9.1 Evaluating Actual Parameters .....	393
7.9.2 Saving and Restoring Registers .....	394
<b>7.10 Summary and Perspective .....</b>	<b>396</b>
Chapter Notes .....	397
Exercises .....	398
<b>CHAPTER 8 Introduction to Optimization .....</b>	<b>405</b>
<b>8.1 Introduction .....</b>	<b>405</b>
<b>8.2 Background .....</b>	<b>407</b>
8.2.1 Examples .....	408
8.2.2 Considerations for Optimization .....	412
8.2.3 Opportunities for Optimization .....	415

<b>8.3</b>	Scope of Optimization .....	417
<b>8.4</b>	Local Optimization .....	420
	8.4.1 Local Value Numbering .....	420
	8.4.2 Tree-Height Balancing .....	428
<b>8.5</b>	Regional Optimization .....	437
	8.5.1 Superlocal Value Numbering .....	437
	8.5.2 Loop Unrolling .....	441
<b>8.6</b>	Global Optimization .....	445
	8.6.1 Finding Uninitialized Variables with Live Information .....	445
	8.6.2 Global Code Placement .....	451
<b>8.7</b>	Interprocedural Optimization .....	457
	8.7.1 Inline Substitution .....	458
	8.7.2 Procedure Placement .....	462
	8.7.3 Compiler Organization for Interprocedural Optimization .....	467
<b>8.8</b>	Summary and Perspective .....	469
	Chapter Notes .....	470
	Exercises .....	471
<b>CHAPTER 9 Data-Flow Analysis .....</b>		<b>475</b>
<b>9.1</b>	Introduction .....	475
<b>9.2</b>	Iterative Data-Flow Analysis .....	477
	9.2.1 Dominance .....	478
	9.2.2 Live-Variable Analysis .....	482
	9.2.3 Limitations on Data-Flow Analysis .....	487
	9.2.4 Other Data-Flow Problems .....	490
<b>9.3</b>	Static Single-Assignment Form .....	495
	9.3.1 A Simple Method for Building SSA Form .....	496
	9.3.2 Dominance Frontiers .....	497
	9.3.3 Placing $\phi$ -Functions .....	500
	9.3.4 Renaming .....	505
	9.3.5 Translation Out of SSA Form .....	510
	9.3.6 Using SSA Form .....	515
<b>9.4</b>	Interprocedural Analysis .....	519
	9.4.1 Call-Graph Construction .....	520
	9.4.2 Interprocedural Constant Propagation .....	522
<b>9.5</b>	Advanced Topics .....	526
	9.5.1 Structural Data-Flow Algorithms and Reducibility .....	527
	9.5.2 Speeding up the Iterative Dominance Framework .....	530

<b>9.6</b>	<b>Summary and Perspective .....</b>	533
	Chapter Notes .....	534
	Exercises .....	535
<b>CHAPTER 10 Scalar Optimizations.....</b>		<b>539</b>
<b>10.1</b>	<b>Introduction .....</b>	539
<b>10.2</b>	<b>Eliminating Useless and Unreachable Code .....</b>	544
	10.2.1 Eliminating Useless Code .....	544
	10.2.2 Eliminating Useless Control Flow .....	547
	10.2.3 Eliminating Unreachable Code .....	550
<b>10.3</b>	<b>Code Motion .....</b>	551
	10.3.1 Lazy Code Motion .....	551
	10.3.2 Code Hoisting .....	559
<b>10.4</b>	<b>Specialization .....</b>	560
	10.4.1 Tail-Call Optimization .....	561
	10.4.2 Leaf-Call Optimization .....	562
	10.4.3 Parameter Promotion .....	563
<b>10.5</b>	<b>Redundancy Elimination .....</b>	565
	10.5.1 Value Identity versus Name Identity .....	565
	10.5.2 Dominator-based Value Numbering .....	566
<b>10.6</b>	<b>Enabling Other Transformations .....</b>	569
	10.6.1 Superblock Cloning .....	570
	10.6.2 Procedure Cloning .....	571
	10.6.3 Loop Unswitching .....	572
	10.6.4 Renaming .....	573
<b>10.7</b>	<b>Advanced Topics .....</b>	575
	10.7.1 Combining Optimizations .....	575
	10.7.2 Strength Reduction .....	580
	10.7.3 Choosing an Optimization Sequence .....	591
<b>10.8</b>	<b>Summary and Perspective .....</b>	592
	Chapter Notes .....	593
	Exercises .....	594
<b>CHAPTER 11 Instruction Selection .....</b>		<b>597</b>
<b>11.1</b>	<b>Introduction .....</b>	597
<b>11.2</b>	<b>Code Generation .....</b>	600
<b>11.3</b>	<b>Extending the Simple Treewalk Scheme .....</b>	603
<b>11.4</b>	<b>Instruction Selection via Tree-Pattern Matching .....</b>	610
	11.4.1 Rewrite Rules .....	611
	11.4.2 Finding a Tiling .....	616
	11.4.3 Tools .....	620

<b>11.5</b>	Instruction Selection via Peephole Optimization .....	621
11.5.1	Peephole Optimization .....	622
11.5.2	Peephole Transformers .....	629
<b>11.6</b>	Advanced Topics .....	632
11.6.1	Learning Peephole Patterns .....	632
11.6.2	Generating Instruction Sequences .....	633
<b>11.7</b>	Summary and Perspective .....	634
	Chapter Notes .....	635
	Exercises .....	637
<b>CHAPTER 12 Instruction Scheduling .....</b>		<b>639</b>
<b>12.1</b>	Introduction .....	639
<b>12.2</b>	The Instruction-Scheduling Problem .....	643
12.2.1	Other Measures of Schedule Quality .....	648
12.2.2	What Makes Scheduling Hard? .....	649
<b>12.3</b>	Local List Scheduling .....	651
12.3.1	The Algorithm .....	651
12.3.2	Scheduling Operations with Variable Delays .....	654
12.3.3	Extending the Algorithm .....	655
12.3.4	Tie Breaking in the List-Scheduling Algorithm .....	655
	12.3.5 Forward versus Backward List Scheduling .....	656
	12.3.6 Improving the Efficiency of List Scheduling .....	660
<b>12.4</b>	Regional Scheduling .....	661
12.4.1	Scheduling Extended Basic Blocks .....	661
12.4.2	Trace Scheduling .....	663
12.4.3	Cloning for Context .....	664
<b>12.5</b>	Advanced Topics .....	666
12.5.1	The Strategy of Software Pipelining .....	666
12.5.2	An Algorithm for Software Pipelining .....	670
<b>12.6</b>	Summary and Perspective .....	673
	Chapter Notes .....	673
	Exercises .....	675
<b>CHAPTER 13 Register Allocation.....</b>		<b>679</b>
<b>13.1</b>	Introduction .....	679
<b>13.2</b>	Background Issues .....	681
13.2.1	Memory versus Registers .....	681
13.2.2	Allocation versus Assignment .....	682
13.2.3	Register Classes .....	683
<b>13.3</b>	Local Register Allocation and Assignment .....	684
13.3.1	Top-Down Local Register Allocation .....	685

13.3.2 Bottom-Up Local Register Allocation .....	686
13.3.3 Moving Beyond Single Blocks .....	689
<b>13.4 Global Register Allocation and Assignment .....</b>	<b>693</b>
13.4.1 Discovering Global Live Ranges .....	696
13.4.2 Estimating Global Spill Costs .....	697
13.4.3 Interferences and the Interference Graph .....	699
13.4.4 Top-Down Coloring .....	702
13.4.5 Bottom-Up Coloring .....	704
13.4.6 Coalescing Copies to Reduce Degree .....	706
13.4.7 Comparing Top-Down and Bottom-Up Global Allocators .....	708
13.4.8 Encoding Machine Constraints in the Interference Graph .....	711
<b>13.5 Advanced Topics .....</b>	<b>713</b>
13.5.1 Variations on Graph-Coloring Allocation .....	713
13.5.2 Global Register Allocation over SSA Form .....	717
<b>13.6 Summary and Perspective .....</b>	<b>718</b>
Chapter Notes .....	719
Exercises .....	720
 <b>APPENDIX A ILOC.....</b>	<b>725</b>
<b>A.1 Introduction .....</b>	<b>725</b>
<b>A.2 Naming Conventions .....</b>	<b>727</b>
<b>A.3 Individual Operations .....</b>	<b>728</b>
A.3.1 Arithmetic .....	728
A.3.2 Shifts .....	729
A.3.3 Memory Operations .....	729
A.3.4 Register-to-Register Copy Operations .....	730
<b>A.4 Control-Flow Operations .....</b>	<b>731</b>
A.4.1 Alternate Comparison and Branch Syntax .....	732
A.4.2 Jumps .....	732
<b>A.5 Representing SSA Form .....</b>	<b>733</b>
 <b>APPENDIX B Data Structures.....</b>	<b>737</b>
<b>B.1 Introduction .....</b>	<b>737</b>
<b>B.2 Representing Sets .....</b>	<b>738</b>
B.2.1 Representing Sets as Ordered Lists .....	739
B.2.2 Representing Sets as Bit Vectors .....	741
B.2.3 Representing Sparse Sets .....	741
<b>B.3 Implementing Intermediate Representations .....</b>	<b>743</b>
B.3.1 Graphical Intermediate Representations .....	743
B.3.2 Linear Intermediate Forms .....	748

<b>B.4</b>	Implementing Hash Tables .....	750
B.4.1	Choosing a Hash Function .....	750
B.4.2	Open Hashing .....	752
B.4.3	Open Addressing .....	754
B.4.4	Storing Symbol Records .....	756
B.4.5	Adding Nested Lexical Scopes .....	757
<b>B.5</b>	A Flexible Symbol-Table Design .....	760
<b>BIBLIOGRAPHY .....</b>		<b>765</b>
<b>INDEX .....</b>		<b>787</b>