Programming language pragmatics (2. ed.).

Book · .	lanuary 2006		
Source: DB	LP		
CITATION	S	READS	
179		18,802	
1 autho	r:		
	Michael L. Scott		
CE	University of Rochester		
	252 PUBLICATIONS 10,012 CITATIONS		
	SEE PROFILE		
	SELFROTIE		
Some o	f the authors of this publication are also working on these related projects:		
Project	Programming Language Pragmatics View project		

Programming Language Pragmatics THIRD EDITION

Michael L. Scott

Department of Computer Science University of Rochester





Contents

	Foreword	xxi
	Preface	xxiii
il L	FOUNDATIONS	3
I	Introduction	5
	1.1 The Art of Language Design	7
	1.2 The Programming Language Spectrum	10
	1.3 Why Study Programming Languages?	14
	1.4 Compilation and Interpretation	16
	1.5 Programming Environments	24
	 I.6 An Overview of Compilation I.6.1 Lexical and Syntax Analysis I.6.2 Semantic Analysis and Intermediate Code Generation I.6.3 Target Code Generation I.6.4 Code Improvement 	25 27 29 33 33
	1.7 Summary and Concluding Remarks	35
	1.8 Exercises	36
	1.9 Explorations	37
	1.10 Bibliographic Notes	39
2	Programming Language Syntax	41
	2.1 Specifying Syntax: Regular Expressions and Context-Free Grammars2.1.1 Tokens and Regular Expressions2.1.2 Context-Free Grammars	42 43 46
	2.1.3 Derivations and Parse Trees	48

	2.2	Scanning 2.2.1 Generating a Finite Automaton 2.2.2 Scanner Code 2.2.3 Table-Driven Scanning 2.2.4 Lexical Errors 2.2.5 Pragmas		51 55 60 63 63
	2.3	Parsing 2.3.1 Recursive Descent 2.3.2 Table-Driven Top-Down Parsing 2.3.3 Bottom-Up Parsing 2.3.4 Syntax Errors	© I ·	67 70 76 87 99
	2.4	Theoretical Foundations 2.4.1 Finite Automata 2.4.2 Push-Down Automata 2.4.3 Grammar and Language Classes	© 3 © 3 © 8 © 9	• 100
		Summary and Concluding Remarks		101
		Exercises		102 108
		Explorations Bibliographic Notes		100
3		- ,		111
3		nes, Scopes, and Bindings The Notion of Binding Time		112
		Object Lifetime and Storage Management 3.2.1 Static Allocation 3.2.2 Stack-Based Allocation 3.2.3 Heap-Based Allocation 3.2.4 Garbage Collection		114 115 117 118
	3.3	Scope Rules 3.3.1 Static Scoping 3.3.2 Nested Subroutines 3.3.3 Declaration Order 3.3.4 Modules 3.3.5 Module Types and Classes 3.3.6 Dynamic Scoping		121 123 124 127 132 136
	3.4	Implementing Scope 3.4.1 Symbol Tables 3.4.2 Association Lists and Central Reference Tables	© 29 © 29 © 33	• 143
	3.5	The Meaning of Names within a Scope		144 144

3.5.2 Overloading 3.5.3 Polymorphism and Related Concepts 148 3.6 The Binding of Referencing Environments 3.6.1 Subroutine Closures 3.6.2 First-Class Values and Unlimited Extent 3.6.3 Object Closures 157 3.7 Macro Expansion 159 3.8 Separate Compilation 3.8.1 Separate Compilation in C 3.8.2 Packages and Automatic Header Inference 3.8.3 Nodule Hierarchies 3.9 Summary and Concluding Remarks 3.10 Exercises 3.11 Explorations 3.12 Bibliographic Notes 172 4 Semantic Analysis 4.1 The Role of the Semantic Analyzer 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 4.4 Action Routines 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5 Space Management for Attributes 4.6 Decorating a Syntax Tree 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 210 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 5.2.2 Data Representation 5.2.2 Integer Arithmetic 5.2.2 Data Representation 5.2.2 Integer Arithmetic 665 5.2.2 Data Representation 5.2.2 Integer Arithmetic 666			Contents	ΧI
3.6.1 Subroutine Closures 3.6.2 First-Class Values and Unlimited Extent 3.6.3 Object Closures 157 3.7 Macro Expansion 159 3.8 Separate Compilation 3.8.1 Separate Compilation in C 3.8.2 Packages and Automatic Header Inference 3.8.3 Module Hierarchies 3.9 Summary and Concluding Remarks 3.10 Exercises 3.11 Explorations 3.11 Explorations 3.12 Bibliographic Notes 4.1 The Role of the Semantic Analyzer 4.2 Attribute Grammars 4.3 Evaluating Attributes 4.4 Action Routines 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 4.5.2 Top-Down Evaluation 4.5 Summary and Concluding Remarks 204 4.6 Decorating a Syntax Tree 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 210 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6 68 5 213		8		
3.8 Separate Compilation 3.8.1 Separate Compilation in C 3.8.2 Packages and Automatic Header Inference 3.8.3 Module Hierarchies 3.9 Summary and Concluding Remarks 3.10 Exercises 3.11 Explorations 3.12 Bibliographic Notes 4 Semantic Analysis 4.1 The Role of the Semantic Analyzer 4.2 Attribute Grammars 4.3 Evaluating Attributes 4.4 Action Routines 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 6 949 4.7 Summary and Concluding Remarks 2.04 4.8 Exercises 4.9 Explorations 4.10 Bibliographic Notes 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6 949 5 161 6 40 6 162 6 163	3.0	3.6.1 Subroutine Closures3.6.2 First-Class Values and Unlimited Extent		153 154
3.8.1 Separate Compilation in C 3.8.2 Packages and Automatic Header Inference 3.8.3 Module Hierarchies 3.9 Summary and Concluding Remarks 3.10 Exercises 3.11 Explorations 3.12 Bibliographic Notes 4 Semantic Analysis 4.1 The Role of the Semantic Analyzer 4.2 Attribute Grammars 4.3 Evaluating Attributes 4.4 Action Routines 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 6 49 4.7 Summary and Concluding Remarks 4.8 Exercises 4.9 Explorations 4.10 Bibliographic Notes 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6 69	3.7	7 Macro Expansion		159
3.10 Exercises 163 3.11 Explorations 171 3.12 Bibliographic Notes 172 4 Semantic Analysis 175 4.1 The Role of the Semantic Analyzer 176 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes 945 4.5.1 Bottom-Up Evaluation 949 4.5.2 Top-Down Evaluation 954 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 965 5.2 Data Representation 968 5.2.1 Integer Arithmetic 969	3.6	3.8.1 Separate Compilation in C3.8.2 Packages and Automatic Header Inference	© 40 © 42	161
3.11 Explorations 171 3.12 Bibliographic Notes 172 4 Semantic Analysis 175 4.1 The Role of the Semantic Analyzer 176 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes 049 4.5.1 Bottom-Up Evaluation 049 4.5.2 Top-Down Evaluation 054 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 065 1213 5.1 The Memory Hierarchy 066 5.2 Data Representation 068 5.2.1 Integer Arithmetic 0669	3.9	9 Summary and Concluding Remarks		162
3.12 Bibliographic Notes 172 4 Semantic Analysis 175 4.1 The Role of the Semantic Analyzer 176 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes 649 4.5.1 Bottom-Up Evaluation 649 4.5.2 Top-Down Evaluation 654 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 665 5.1 The Memory Hierarchy 666 5.2 Data Representation 688 5.2.1 Integer Arithmetic 669	3.10) Exercises		163
4 Semantic Analysis 4.1 The Role of the Semantic Analyzer 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 9 49 4.5.2 Top-Down Evaluation 9 54 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 5.1 The Memory Hierarchy 6 66 5.2 Data Representation 5.2 Data Representation 6 68 5.2.1 Integer Arithmetic	3.1	l Explorations		171
4.1 The Role of the Semantic Analyzer 176 4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes 49 196 4.5.1 Bottom-Up Evaluation 49 196 4.5.2 Top-Down Evaluation 54 197 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 665 213 5.1 The Memory Hierarchy 666 5.2 Data Representation 68 5.2.1 Integer Arithmetic 68	3.12	2 Bibliographic Notes		172
4.2 Attribute Grammars 180 4.3 Evaluating Attributes 182 4.4 Action Routines 191 4.5 Space Management for Attributes	4 Ser	nantic Analysis		175
4.3 Evaluating Attributes 4.4 Action Routines 191 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 6.54 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 6.65 · 213 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6.68 5.2.1 Integer Arithmetic	4.	The Role of the Semantic Analyzer		176
4.4 Action Routines 4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 6 54 4.6 Decorating a Syntax Tree 197 4.7 Summary and Concluding Remarks 204 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6 68 5.2.1 Integer Arithmetic	4.2	2 Attribute Grammars		180
4.5 Space Management for Attributes 4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 4.6 Decorating a Syntax Tree 4.7 Summary and Concluding Remarks 4.8 Exercises 4.9 Explorations 4.10 Bibliographic Notes 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic	4	B Evaluating Attributes		182
4.5.1 Bottom-Up Evaluation 4.5.2 Top-Down Evaluation 4.6 Decorating a Syntax Tree 4.7 Summary and Concluding Remarks 4.8 Exercises 4.9 Explorations 4.10 Bibliographic Notes 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic	4.4	4 Action Routines		191
4.7 Summary and Concluding Remarks 4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture 5.1 The Memory Hierarchy 5.2 Data Representation 5.2.1 Integer Arithmetic 6 68 5.2.1 Integer Arithmetic	4.5	4.5.1 Bottom-Up Evaluation	© 49	196
4.8 Exercises 205 4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture © 65 · 213 5.1 The Memory Hierarchy © 66 5.2 Data Representation © 68 5.2.1 Integer Arithmetic © 69	4.0	6 Decorating a Syntax Tree		197
4.9 Explorations 209 4.10 Bibliographic Notes 210 5 Target Machine Architecture © 65 · 213 5.1 The Memory Hierarchy © 66 5.2 Data Representation © 68 5.2.1 Integer Arithmetic © 69	4.7	7 Summary and Concluding Remarks		204
4.10 Bibliographic Notes 210 5 Target Machine Architecture © 65 · 213 5.1 The Memory Hierarchy © 66 5.2 Data Representation © 68 5.2.1 Integer Arithmetic © 69	4.8	3 Exercises		205
5 Target Machine Architecture © 65 · 213 5.1 The Memory Hierarchy © 66 5.2 Data Representation © 68 5.2.1 Integer Arithmetic © 69	4.9	Explorations		209
5.1 The Memory Hierarchy © 66 5.2 Data Representation © 68 5.2.1 Integer Arithmetic © 69	4.10) Bibliographic Notes		210
5.2 Data Representation © 68 5.2. I Integer Arithmetic © 69	5 Tar	get Machine Architecture	© 65 ·	213
5.2. I Integer Arithmetic 69	5.	The Memory Hierarchy	© 66	
· -	5	·	_	

5.3	Instruction Set Architecture 5.3.1 Addressing Modes	© 75 © 75	
	5.3.2 Conditions and Branches	© 76	
5.4	Architecture and Implementation 5.4.1 Microprogramming 5.4.2 Microprocessors 5.4.3 RISC 5.4.4 Multithreading and Multicore 5.4.5 Two Example Architectures: The x86 and MIPS	© 78 © 79 © 80 © 81 © 82 © 84	
5.5	Compiling for Modern Processors 5.5.1 Keeping the Pipeline Full 5.5.2 Register Allocation	© 91 © 91 © 96	
5.6	Summary and Concluding Remarks	© 101	
5.7	Exercises	© 103	
5.8	Explorations	© 107	
5.9	Bibliographic Notes	© 109	
6 Con	atrol Flow		219
6.1	Expression Evaluation 6.1.1 Precedence and Associativity 6.1.2 Assignments 6.1.3 Initialization 6.1.4 Ordering within Expressions 6.1.5 Short-Circuit Evaluation		220 222 224 233 235 238
6.2	Structured and Unstructured Flow 6.2.1 Structured Alternatives to goto 6.2.2 Continuations		241 242 245
6.3	Sequencing		246
6.4	Selection 6.4.1 Short-Circuited Conditions 6.4.2 Case/Switch Statements		247 248 25 I
6.5	Iteration 6.5.1 Enumeration-Controlled Loops 6.5.2 Combination Loops		256 256 261

			Contents	3	ĸiii
		6.5.3 Iterators6.5.4 Generators in Icon6.5.5 Logically Controlled Loops	© III	• 2	262 268 268
	6.6	Recursion 6.6.1 Iteration and Recursion 6.6.2 Applicative- and Normal-Order Evaluation		,	270 271 275
	6.7	Nondeterminacy	© 115	• :	277
	6.8	Summary and Concluding Remarks		:	278
	6.9	Exercises		2	279
	6.10	Explorations		2	285
	6.11	Bibliographic Notes		2	287
7	Data	a Types		:	289
	7.1	Type Systems 7.1.1 Type Checking 7.1.2 Polymorphism 7.1.3 The Meaning of "Type" 7.1.4 Classification of Types 7.1.5 Orthogonality			290 291 291 293 294 301
	7.2	Type Checking 7.2.1 Type Equivalence 7.2.2 Type Compatibility 7.2.3 Type Inference 7.2.4 The ML Type System	© 125	:	303 303 310 314 316
	7.3	Records (Structures) and Variants (Unions) 7.3.1 Syntax and Operations 7.3.2 Memory Layout and Its Impact 7.3.3 With Statements 7.3.4 Variant Records (Unions)	© 135 © 139		317 318 319 323 324
	7.4	Arrays 7.4.1 Syntax and Operations 7.4.2 Dimensions, Bounds, and Allocation 7.4.3 Memory Layout		:	325 326 330 335
	7.5	Strings		:	342
	7.6	Sets		;	344
	7.7	Pointers and Recursive Types 7.7.1 Syntax and Operations			345 346

xiv Contents

	7.7.2 Dangling References7.7.3 Garbage Collection	© 149	•	356 357
7.8	Lists			364
7.9	Files and Input/Output 7.9.1 Interactive I/O 7.9.2 File-Based I/O 7.9.3 Text I/O	© 153 © 153 © 154 © 156	•	367
7.10	Equality Testing and Assignment			368
7.11	Summary and Concluding Remarks			37 I
7.12	Exercises			373
7.13	Explorations			379
7.14	Bibliographic Notes			380
8 Subi	routines and Control Abstraction			383
8.1	Review of Stack Layout			384
8.2	Calling Sequences 8.2.1 Displays 8.2.2 Case Studies: C on the MIPS; Pascal on the x86 8.2.3 Register Windows 8.2.4 In-Line Expansion	© 169 © 173 © 181	•	386 389 389 390 391
8.3	Parameter Passing 8.3.1 Parameter Modes 8.3.2 Call-by-Name 8.3.3 Special-Purpose Parameters 8.3.4 Function Returns	© 185		393 394 402 403 408
8.4	Generic Subroutines and Modules 8.4.1 Implementation Options 8.4.2 Generic Parameter Constraints 8.4.3 Implicit Instantiation 8.4.4 Generics in C++, Java, and C#	© 189	•	410 412 414 416 417
8.5	Exception Handling 8.5.1 Defining Exceptions 8.5.2 Exception Propagation 8.5.3 Implementation of Exceptions			418 421 423 425
8.6	Coroutines 8.6.1 Stack Allocation 8.6.2 Transfer			428 430 432

		Contents	χV
	8.6.3 Implementation of Iterators8.6.4 Discrete Event Simulation	© 201 © 205	· 433
8.7	Events		434
	8.7.1 Sequential Handlers 8.7.2 Thread-Based Handlers		434 436
8.8	Summary and Concluding Remarks		438
8.9	Exercises		439
8.10	Explorations		446
8.11	Bibliographic Notes		447
9 Data	Abstraction and Object Orientation		449
9.1	Object-Oriented Programming		45 I
9.2	Encapsulation and Inheritance 9.2.1 Modules 9.2.2 Classes 9.2.3 Nesting (Inner Classes) 9.2.4 Type Extensions 9.2.5 Extending without Inheritance		460 460 463 465 466 468
9.3	Initialization and Finalization 9.3.1 Choosing a Constructor 9.3.2 References and Values 9.3.3 Execution Order 9.3.4 Garbage Collection		469 470 472 475 477
9.4	Dynamic Method Binding 9.4.1 Virtual and Nonvirtual Methods 9.4.2 Abstract Classes 9.4.3 Member Lookup 9.4.4 Polymorphism 9.4.5 Object Closures		478 480 482 482 486 489
9.5	Multiple Inheritance 9.5.1 Semantic Ambiguities 9.5.2 Replicated Inheritance 9.5.3 Shared Inheritance 9.5.4 Mix-In Inheritance	© 215 © 217 © 220 © 222 © 223	• 491
9.6	Object-Oriented Programming Revisited 9.6.1 The Object Model of Smalltalk	© 227	492 • 493
9.7	Summary and Concluding Remarks		494

	9.8	Exercises		495
		Explorations		498
		Bibliographic Notes		499
arras turas	, o	Sibilog, aprile 1 voces		.,,
	A	LTERNATIVE PROGRAMMING MODELS		503
10	Fund	ctional Languages		505
	10.1	Historical Origins		506
	10.2	Functional Programming Concepts		507
	10.3	A Review/Overview of Scheme 10.3.1 Bindings 10.3.2 Lists and Numbers 10.3.3 Equality Testing and Searching 10.3.4 Control Flow and Assignment 10.3.5 Programs as Lists 10.3.6 Extended Example: DFA Simulation		509 512 513 514 515 517
	10.4	Evaluation Order Revisited 10.4.1 Strictness and Lazy Evaluation 10.4.2 I/O: Streams and Monads		521 523 525
	10.5	Higher-Order Functions		530
	10.6	Theoretical Foundations 10.6.1 Lambda Calculus 10.6.2 Control Flow 10.6.3 Structures	© 237 © 239 © 242 © 244	• 534
	10.7	Functional Programming in Perspective		534
	10.8	Summary and Concluding Remarks		537
	10.9	Exercises		538
	10.10	Explorations		542
	10.11	Bibliographic Notes		543
П	Logi	c Languages		545
	11.1	Logic Programming Concepts		546
	11.2	Prolog 11.2.1 Resolution and Unification 11.2.2 Lists		547 549 550

			Contents	XVII
		II.2.3 ArithmeticII.2.4 Search/Execution OrderII.2.5 Extended Example: Tic-Tac-ToeII.2.6 Imperative Control FlowII.2.7 Database Manipulation		551 552 554 557 561
	11.3	Theoretical Foundations 11.3.1 Clausal Form 11.3.2 Limitations 11.3.3 Skolemization	© 253 © 254 © 255 © 257	• 566
	11.4	Logic Programming in Perspective 11.4.1 Parts of Logic Not Covered 11.4.2 Execution Order 11.4.3 Negation and the "Closed World" Assumption		566 566 567 568
	11.5	Summary and Concluding Remarks		570
	11.6	Exercises		571
	11.7	Explorations		573
	11.8	Bibliographic Notes		573
12	Con	currency		575
	12.1	Background and Motivation 12.1.1 The Case for Multithreaded Programs 12.1.2 Multiprocessor Architecture		576 579 581
	12.2	Concurrent Programming Fundamentals 12.2.1 Communication and Synchronization 12.2.2 Languages and Libraries 12.2.3 Thread Creation Syntax 12.2.4 Implementation of Threads		586 587 588 589 598
	12.3	Implementing Synchronization 12.3.1 Busy-Wait Synchronization 12.3.2 Nonblocking Algorithms 12.3.3 Memory Consistency Models 12.3.4 Scheduler Implementation 12.3.5 Semaphores		603 604 607 610 613 617
	12.4	Language-Level Mechanisms 12.4.1 Monitors 12.4.2 Conditional Critical Regions 12.4.3 Synchronization in Java		619 619 624 626

xviii Contents

		12.4.4 Transactional Memory 12.4.5 Implicit Synchronization		629 633
	12.5	Message Passing 12.5.1 Naming Communication Partners 12.5.2 Sending 12.5.3 Receiving 12.5.4 Remote Procedure Call	© 263 © 263 © 267 © 272 © 278	• 637
	12.6	Summary and Concluding Remarks		638
	12.7	Exercises		640
	12.8	Explorations		645
	12.9	Bibliographic Notes		647
13	Scrip	oting Languages		649
	13.1	What Is a Scripting Language? 13.1.1 Common Characteristics		650 652
	13.2	Problem Domains 13.2.1 Shell (Command) Languages 13.2.2 Text Processing and Report Generation 13.2.3 Mathematics and Statistics 13.2.4 "Glue" Languages and General-Purpose Scripting 13.2.5 Extension Languages		655 655 663 667 668 676
	13.3	Scripting the World Wide Web 13.3.1 CGI Scripts 13.3.2 Embedded Server-Side Scripts 13.3.3 Client-Side Scripts 13.3.4 Java Applets 13.3.5 XSLT	© 287	680 681 686 686
	13.4	Innovative Features 13.4.1 Names and Scopes 13.4.2 String and Pattern Manipulation 13.4.3 Data Types 13.4.4 Object Orientation		691 691 696 704 710
	13.5	Summary and Concluding Remarks		717
	13.6	Exercises		718
	13.7	Explorations		723
	13.8	Bibliographic Notes		724

		CLOSER LOOK AT IMPLEMENTATION			727
		CLOSER LOOK AT THE LETTER TATION			121
14	Build	ding a Runnable Program			729
	14.1	Back-End Compiler Structure 14.1.1 A Plausible Set of Phases 14.1.2 Phases and Passes			729 730 734
	14.2	Intermediate Forms 14.2.1 Diana 14.2.2 The gcc IFs 14.2.3 Stack-Based Intermediate Forms	© 303 © 303 © 306	•	734 736
	14.3	Code Generation 14.3.1 An Attribute Grammar Example 14.3.2 Register Allocation			738 738 741
	14.4	Address Space Organization			744
	14.5	Assembly 14.5.1 Emitting Instructions 14.5.2 Assigning Addresses to Names			746 748 749
	14.6	Linking 14.6.1 Relocation and Name Resolution 14.6.2 Type Checking			750 751 751
	14.7	Dynamic Linking 14.7.1 Position-Independent Code 14.7.2 Fully Dynamic (Lazy) Linking	© 311 © 312 © 313	•	754
	14.8	Summary and Concluding Remarks			755
	14.9	Exercises			756
	14.10	Explorations			758
	14.11	Bibliographic Notes			759
15	Run-	time Program Management			761
	15.1	Virtual Machines 15.1.1 The Java Virtual Machine 15.1.2 The Common Language Infrastructure			764 766 775
	15.2	Late Binding of Machine Code 15.2.1 Just-in-Time and Dynamic Compilation 15.2.2 Binary Translation			784 785 791

Contents

xix

		15.2.3 Binary Rewriting15.2.4 Mobile Code and Sandboxing			795 797
	15.3	Inspection/Introspection 15.3.1 Reflection 15.3.2 Symbolic Debugging 15.3.3 Performance Analysis			799 799 806 809
	15.4	Summary and Concluding Remarks			811
	15.5	Exercises			812
	15.6	Explorations			815
	15.7	Bibliographic Notes			816
16	Code	e Improvement	©321	•	817
	16.1	Phases of Code Improvement	© 323		
	16.2	Peephole Optimization	© 325		
	16.3	Redundancy Elimination in Basic Blocks 16.3.1 A Running Example 16.3.2 Value Numbering	© 328 © 328 © 331		
	16.4	Global Redundancy and Data Flow Analysis 16.4.1 SSA Form and Global Value Numbering16.4.2 Global Common Subexpression Elimination	© 336 © 336 © 339		
	16.5	Loop Improvement I 16.5.1 Loop Invariants 16.5.2 Induction Variables	© 346 © 347 © 348		
	16.6	Instruction Scheduling	© 351		
	16.7	Loop Improvement II 16.7.1 Loop Unrolling and Software Pipelining 16.7.2 Loop Reordering	© 355 © 355 © 359		
	16.8	Register Allocation	© 366		
	16.9	Summary and Concluding Remarks	© 370		
	16.10	Bibliographic Notes	© 377		
Α	Prog	ramming Languages Mentioned			819
В	Lang	uage Design and Language Implementation			831
С	Num	nbered Examples			835
Bibliography				849	
Index				867	