

Contents

3.6 The Binding of Referencing Environments	143
3.6.1 Subroutine Closures	143
3.6.2 First-Class Values and Unlimited CLOSURE Levels	145
3.6.3 Object Closures	147

3.7 Macro Expansion	159
---------------------	-----

3.8 Separate Compilation	161
--------------------------	-----

3.8.1 Separate Compilation in Cognisus	163
--	-----

3.8.2 Packages and Automatic Header Inclusion	163
---	-----

3.8.3 Module Hierarchies	163
--------------------------	-----

Foreword	xxi
----------	-----

Preface	xxiii
---------	-------

1.9 Summary and Concluding Remarks	163
------------------------------------	-----

1.9.1 Rethinking Automation	163
-----------------------------	-----

1.9.2 Rethinking Autotests	163
----------------------------	-----

1.9.3 Grammar and Language Design	163
-----------------------------------	-----

FOUNDATIONS

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
------------------------------	----

1.6 An Overview of Compilation	25
--------------------------------	----

1.6.1 Lexical and Syntax Analysis	27
-----------------------------------	----

1.6.2 Semantic Analysis and Intermediate Code Generation	29
--	----

1.6.3 Target Code Generation	33
------------------------------	----

1.6.4 Code Improvement	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 Grammars	42
--	----

2.1.1 Tokens and Regular Expressions	43
--------------------------------------	----

2.1.2 Context-Free Grammars	46
-----------------------------	----

2.1.3 Derivations and Parse Trees	48
-----------------------------------	----

Contents

2.2 Scanning	51
2.2.1 Generating a Finite Automaton	55
2.2.2 Scanner Code	60
2.2.3 Table-Driven Scanning	63
2.2.4 Lexical Errors	63
2.2.5 Pragmas	65
2.3 Parsing	67
2.3.1 Recursive Descent	70
2.3.2 Table-Driven Top-Down Parsing	76
2.3.3 Bottom-Up Parsing	87
2.3.4 Syntax Errors	99
2.4 Theoretical Foundations	100
2.4.1 Finite Automata	13
2.4.2 Push-Down Automata	18
2.4.3 Grammar and Language Classes	19
2.5 Summary and Concluding Remarks	101
2.6 Exercises	102
2.7 Explorations	108
2.8 Bibliographic Notes	109
3 Names, Scopes, and Bindings	111
3.1 The Notion of Binding Time	112
3.2 Object Lifetime and Storage Management	114
3.2.1 Static Allocation	115
3.2.2 Stack-Based Allocation	117
3.2.3 Heap-Based Allocation	118
3.2.4 Garbage Collection	120
3.3 Scope Rules	121
3.3.1 Static Scoping	123
3.3.2 Nested Subroutines	124
3.3.3 Declaration Order	127
3.3.4 Modules	132
3.3.5 Module Types and Classes	136
3.3.6 Dynamic Scoping	139
3.4 Implementing Scope	143
3.4.1 Symbol Tables	29
3.4.2 Association Lists and Central Reference Tables	33
3.5 The Meaning of Names within a Scope	144
3.5.1 Aliases	144

3.5.2 Overloading	146
3.5.3 Polymorphism and Related Concepts	148
3.6 The Binding of Referencing Environments	151
3.6.1 Subroutine Closures	153
3.6.2 First-Class Values and Unlimited Extent	154
3.6.3 Object Closures	157
3.7 Macro Expansion	159
3.8 Separate Compilation	161
3.8.1 Separate Compilation in C	161
3.8.2 Packages and Automatic Header Inference	162
3.8.3 Module Hierarchies	163
3.9 Summary and Concluding Remarks	162
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	196
4.5.1 Bottom-Up Evaluation	196
4.5.2 Top-Down Evaluation	200
4.6 Decorating a Syntax Tree	204
4.7 Summary and Concluding Remarks	204
4.8 Exercises	205
4.9 Explorations	209
4.10 Bibliographic Notes	210
5 Target Machine Architecture	213
5.1 The Memory Hierarchy	213
5.2 Data Representation	214
5.2.1 Integer Arithmetic	214
5.2.2 Floating-Point Arithmetic	216

5.3 Instruction Set Architecture	
5.3.1 Addressing Modes	75
5.3.2 Conditions and Branches	76
5.4 Architecture and Implementation	
5.4.1 Microprogramming	78
5.4.2 Microprocessors	79
5.4.3 RISC	80
5.4.4 Multithreading and Multicore	81
5.4.5 Two Example Architectures: The x86 and MIPS	82
5.5 Compiling for Modern Processors	
5.5.1 Keeping the Pipeline Full	84
5.5.2 Register Allocation	91
5.6 Summary and Concluding Remarks	
5.7 Exercises	91
5.8 Explorations	101
5.9 Bibliographic Notes	103

CORE ISSUES IN LANGUAGE DESIGN

6 Control Flow

6.1 Expression Evaluation	220
6.1.1 Precedence and Associativity	222
6.1.2 Assignments	224
6.1.3 Initialization	233
6.1.4 Ordering within Expressions	235
6.1.5 Short-Circuit Evaluation	238
6.2 Structured and Unstructured Flow	241
6.2.1 Structured Alternatives to <code>goto</code>	242
6.2.2 Continuations	245
6.3 Sequencing	246
6.4 Selection	247
6.4.1 Short-Circuited Conditions	248
6.4.2 Case/Switch Statements	251
6.5 Iteration	256
6.5.1 Enumeration-Controlled Loops	256
6.5.2 Combination Loops	261

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

5.3	7.7.2 Dangling References	5.2.3 Iterators	149	•	356
5.4	7.7.3 Garbage Collection	5.2.4 Generation 0 Root			357
7.8	Lists	5.2.5 Logically Connected Lists	376		364
7.9	Files and Input/Output	5.2.6 Recursion	153	•	367
7.9.1	Interactive I/O	5.2.7 Iteration and Recursion	153		
7.9.2	File-Based I/O	5.2.8 Allocation and Iteration	154		
7.9.3	Text I/O	5.2.9 Monads	156		
7.10	Equality Testing and Assignment	5.3 Summary	384		368
7.11	Summary and Concluding Remarks	5.3.1 Generics	391		371
7.12	Exercises	5.3.2 Explorations	391		373
7.13	Explorations	5.3.3 Bibliographic Notes	396		379
7.14	Bibliographic Notes	5.3.4 Data Types	403		380
8	Subroutines and Control Abstraction	5.4 Type Systems	107		383
8.1	Review of Stack Layout	5.4.1 Type Checking	109		384
8.2	Calling Sequences	5.4.2 Polymorphism	113		386
8.2.1	Displays	5.4.3 Type Matching	169	•	389
8.2.2	Case Studies: C on the MIPS; Pascal on the x86	5.4.4 Classification of Types	173	•	389
8.2.3	Register Windows	5.4.5 Type Equivalence	181	•	390
8.2.4	In-Line Expansion	5.4.6 Type Composition			391
8.3	Parameter Passing	5.4.7 Type Inference	393		393
8.3.1	Parameter Modes	5.4.8 Type Substitution	394		394
8.3.2	Call-by-Name	5.4.9 Type Constraints	185	•	402
8.3.3	Special-Purpose Parameters	5.4.10 Type Substitution			403
8.3.4	Function Returns	5.4.11 Records (Structures) and Variants			408
8.4	Generic Subroutines and Modules	5.4.12 Syntax and Object Layout	410		410
8.4.1	Implementation Options	5.4.13 Memory Layout	412		
8.4.2	Generic Parameter Constraints	5.4.14 With Statements			414
8.4.3	Implicit Instantiation	5.4.15 Abstract Record Types			416
8.4.4	Generics in C++, Java, and C#	5.4.16 Annot.	189	•	417
8.5	Exception Handling	5.4.17 Annotations			418
8.5.1	Defining Exceptions	5.4.18 Dimension Bounds			421
8.5.2	Exception Propagation	5.4.19 Memory Layout			423
8.5.3	Implementation of Exceptions	5.4.20 Spurios			425
8.6	Coroutines	5.4.21 Serializability	428		
8.6.1	Stack Allocation	5.4.22 Pointers and References			430
8.6.2	Transfer	5.4.23 Boxes and Queues			432

8.6.3 Implementation of Iterators	201	• 433
8.6.4 Discrete Event Simulation	205	• 433
8.7 Events		434
8.7.1 Sequential Handlers		434
8.7.2 Thread-Based Handlers		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		451
9.2 Encapsulation and Inheritance		460
9.2.1 Modules		460
9.2.2 Classes		463
9.2.3 Nesting (Inner Classes)		465
9.2.4 Type Extensions		466
9.2.5 Extending without Inheritance		468
9.3 Initialization and Finalization		469
9.3.1 Choosing a Constructor		470
9.3.2 References and Values		472
9.3.3 Execution Order		475
9.3.4 Garbage Collection		477
9.4 Dynamic Method Binding		478
9.4.1 Virtual and Nonvirtual Methods		480
9.4.2 Abstract Classes		482
9.4.3 Member Lookup		482
9.4.4 Polymorphism		486
9.4.5 Object Closures		489
9.5 Multiple Inheritance	215	• 491
9.5.1 Semantic Ambiguities	217	610
9.5.2 Replicated Inheritance	220	613
9.5.3 Shared Inheritance	222	617
9.5.4 Mix-In Inheritance	223	619
9.6 Object-Oriented Programming Revisited		492
9.6.1 The Object Model of Smalltalk	227	• 493
9.7 Summary and Concluding Remarks		494

9.8 Exercises	495
9.9 Explorations	498
9.10 Bibliographic Notes	499
III ALTERNATIVE PROGRAMMING MODELS	503
10 Functional Languages	505
10.1 Historical Origins	506
10.2 Functional Programming Concepts	507
10.3 A Review/Overview of Scheme	509
10.3.1 Bindings	512
10.3.2 Lists and Numbers	513
10.3.3 Equality Testing and Searching	514
10.3.4 Control Flow and Assignment	515
10.3.5 Programs as Lists	517
10.3.6 Extended Example: DFA Simulation	519
10.4 Evaluation Order Revisited	521
10.4.1 Strictness and Lazy Evaluation	523
10.4.2 I/O: Streams and Monads	525
10.5 Higher-Order Functions	530
10.6 Theoretical Foundations	534
10.6.1 Lambda Calculus	239
10.6.2 Control Flow	242
10.6.3 Structures	244
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
11 Logic Languages	545
11.1 Logic Programming Concepts	546
11.2 Prolog	547
11.2.1 Resolution and Unification	549
11.2.2 Lists	550

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

12.4.4 Transactional Memory	629
12.4.5 Implicit Synchronization	633
12.5 Message Passing	637
12.5.1 Naming Communication Partners	637
12.5.2 Sending	637
12.5.3 Receiving	637
12.5.4 Remote Procedure Call	637
12.6 Summary and Concluding Remarks	638
12.7 Exercises	640
12.8 Explorations	645
12.9 Bibliographic Notes	647
13 Scripting Languages	649
13.1 What Is a Scripting Language?	650
13.1.1 Common Characteristics	652
13.2 Problem Domains	655
13.2.1 Shell (Command) Languages	655
13.2.2 Text Processing and Report Generation	663
13.2.3 Mathematics and Statistics	667
13.2.4 “Glue” Languages and General-Purpose Scripting	668
13.2.5 Extension Languages	676
13.3 Scripting the World Wide Web	680
13.3.1 CGI Scripts	680
13.3.2 Embedded Server-Side Scripts	681
13.3.3 Client-Side Scripts	686
13.3.4 Java Applets	686
13.3.5 XSLT	689
13.4 Innovative Features	691
13.4.1 Names and Scopes	691
13.4.2 String and Pattern Manipulation	696
13.4.3 Data Types	704
13.4.4 Object Orientation	710
13.5 Summary and Concluding Remarks	717
13.6 Exercises	718
13.7 Explorations	723
13.8 Bibliographic Notes	724

IV A CLOSER LOOK AT IMPLEMENTATION	727
14 Building a Runnable Program	729
14.1 Back-End Compiler Structure	729
14.1.1 A Plausible Set of Phases	730
14.1.2 Phases and Passes	734
14.2 Intermediate Forms	303 • 734
14.2.1 Diana	303
14.2.2 The <code>gcc</code> IFs	306
14.2.3 Stack-Based Intermediate Forms	736
14.3 Code Generation	738
14.3.1 An Attribute Grammar Example	738
14.3.2 Register Allocation	741
14.4 Address Space Organization	744
14.5 Assembly	746
14.5.1 Emitting Instructions	748
14.5.2 Assigning Addresses to Names	749
14.6 Linking	750
14.6.1 Relocation and Name Resolution	751
14.6.2 Type Checking	751
14.7 Dynamic Linking	311 • 754
14.7.1 Position-Independent Code	312
14.7.2 Fully Dynamic (Lazy) Linking	313
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	764
15.1.1 The Java Virtual Machine	766
15.1.2 The Common Language Infrastructure	775
15.2 Late Binding of Machine Code	784
15.2.1 Just-in-Time and Dynamic Compilation	785
15.2.2 Binary Translation	791

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