

Design Concepts in Programming Languages

Franklyn Turbak and David Gifford
with Mark A. Sheldon

The MIT Press
Cambridge, Massachusetts
London, England

©2008 Massachusetts Institute of Technology

All rights reserved. No part of this book may be reproduced in any form by any electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from the publisher.

MIT Press books may be purchased at special quantity discounts for business or sales promotional use. For information, please email special_sales@mitpress.mit.edu or write to Special Sales Department, The MIT Press, 55 Hayward Street, Cambridge, MA 02142.

This book was set in L^AT_EX by the authors, and was printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Turbak, Franklyn A.

Design concepts in programming languages / Franklyn A. Turbak and David K. Gifford, with Mark A. Sheldon.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-262-20175-9 (hardcover : alk. paper)

1. Programming languages (Electronic computers). I. Gifford, David K., 1954–.

II. Sheldon, Mark A. III. Title.

QA76.7.T845 2008

005.1—dc22

2008013841

10 9 8 7 6 5 4 3 2 1

Contents

Preface xix

Acknowledgments xxi

I Foundations 1

1 Introduction 3

- 1.1 Programming Languages 3
- 1.2 Syntax, Semantics, and Pragmatics 4
- 1.3 Goals 6
- 1.4 POSTFIX: A Simple Stack Language 8
 - 1.4.1 Syntax 8
 - 1.4.2 Semantics 9
 - 1.4.3 The Pitfalls of Informal Descriptions 14
- 1.5 Overview of the Book 15

2 Syntax 19

- 2.1 Abstract Syntax 20
- 2.2 Concrete Syntax 22
- 2.3 S-Expression Grammars Specify ASTs 23
 - 2.3.1 S-Expressions 23
 - 2.3.2 The Structure of S-Expression Grammars 24
 - 2.3.3 Phrase Tags 30
 - 2.3.4 Sequence Patterns 30
 - 2.3.5 Notational Conventions 32
 - 2.3.6 Mathematical Foundation of Syntactic Domains 36
- 2.4 The Syntax of PostFix 39

3 Operational Semantics 45

- 3.1 The Operational Semantics Game 45
- 3.2 Small-step Operational Semantics (SOS) 49
 - 3.2.1 Formal Framework 49
 - 3.2.2 Example: An SOS for POSTFIX 52
 - 3.2.3 Rewrite Rules 54
 - 3.2.4 Operational Execution 58

| | | |
|----------|---|------------|
| 3.2.5 | Progress Rules | 62 |
| 3.2.6 | Context-based Semantics | 71 |
| 3.3 | Big-step Operational Semantics | 75 |
| 3.4 | Operational Reasoning | 79 |
| 3.5 | Deterministic Behavior of EL | 80 |
| 3.6 | Termination of PostFix Programs | 84 |
| 3.6.1 | Energy | 84 |
| 3.6.2 | The Proof of Termination | 86 |
| 3.6.3 | Structural Induction | 88 |
| 3.7 | Safe POSTFIX Transformations | 89 |
| 3.7.1 | Observational Equivalence | 89 |
| 3.7.2 | Transform Equivalence | 92 |
| 3.7.3 | Transform Equivalence Implies Observational Equivalence | 96 |
| 3.8 | Extending POSTFIX | 100 |
| 4 | Denotational Semantics | 113 |
| 4.1 | The Denotational Semantics Game | 113 |
| 4.2 | A Denotational Semantics for EL | 117 |
| 4.2.1 | Step 1: Restricted ELMM | 117 |
| 4.2.2 | Step 2: Full ELMM | 120 |
| 4.2.3 | Step 3: ELM | 124 |
| 4.2.4 | Step 4: EL | 127 |
| 4.2.5 | A Denotational Semantics Is Not a Program | 128 |
| 4.3 | A Denotational Semantics for POSTFIX | 131 |
| 4.3.1 | A Semantic Algebra for POSTFIX | 131 |
| 4.3.2 | A Meaning Function for POSTFIX | 134 |
| 4.3.3 | Semantic Functions for POSTFIX: the Details | 142 |
| 4.4 | Denotational Reasoning | 145 |
| 4.4.1 | Program Equality | 145 |
| 4.4.2 | Safe Transformations: A Denotational Approach | 147 |
| 4.4.3 | Technical Difficulties | 150 |
| 4.5 | Relating Operational and Denotational Semantics | 150 |
| 4.5.1 | Soundness | 151 |
| 4.5.2 | Adequacy | 157 |
| 4.5.3 | Full Abstraction | 159 |
| 4.5.4 | Operational versus Denotational: A Comparison | 161 |

5 Fixed Points 163

- 5.1 The Fixed Point Game 163
 - 5.1.1 Recursive Definitions 163
 - 5.1.2 Fixed Points 166
 - 5.1.3 The Iterative Fixed Point Technique 168
- 5.2 Fixed Point Machinery 174
 - 5.2.1 Partial Orders 174
 - 5.2.2 Complete Partial Orders (CPOs) 182
 - 5.2.3 Pointedness 185
 - 5.2.4 Monotonicity and Continuity 187
 - 5.2.5 The Least Fixed Point Theorem 190
 - 5.2.6 Fixed Point Examples 191
 - 5.2.7 Continuity and Strictness 197
- 5.3 Reflexive Domains 201
- 5.4 Summary 203

II Dynamic Semantics 205**6 FL: A Functional Language 207**

- 6.1 Decomposing Language Descriptions 207
- 6.2 The Structure of FL 208
 - 6.2.1 FLK: The Kernel of the FL Language 209
 - 6.2.2 FL Syntactic Sugar 218
 - 6.2.3 The FL Standard Library 235
 - 6.2.4 Examples 239
- 6.3 Variables and Substitution 244
 - 6.3.1 Terminology 244
 - 6.3.2 Abstract Syntax DAGs and Stoy Diagrams 248
 - 6.3.3 Alpha-Equivalence 250
 - 6.3.4 Renaming and Variable Capture 251
 - 6.3.5 Substitution 253
- 6.4 An Operational Semantics for FLK 258
 - 6.4.1 FLK Evaluation 258
 - 6.4.2 FLK Simplification 270
- 6.5 A Denotational Semantics for FLK 275
 - 6.5.1 Semantic Algebra 275
 - 6.5.2 Valuation Functions 280
- 6.6 The Lambda Calculus 290

| | | |
|----------|---|------------|
| 6.6.1 | Syntax of the Lambda Calculus | 291 |
| 6.6.2 | Operational Semantics of the Lambda Calculus | 291 |
| 6.6.3 | Denotational Semantics of the Lambda Calculus | 296 |
| 6.6.4 | Representational Games | 297 |
| 7 | Naming | 307 |
| 7.1 | Parameter Passing | 309 |
| 7.1.1 | Call-by-Name vs. Call-by-Value: The Operational View | 310 |
| 7.1.2 | Call-by-Name vs. Call-by-Value: The Denotational View | 316 |
| 7.1.3 | Nonstrict versus Strict Pairs | 318 |
| 7.1.4 | Handling <code>rec</code> in a CBV Language | 320 |
| 7.1.5 | Thunking | 324 |
| 7.1.6 | Call-by-Denotation | 328 |
| 7.2 | Name Control | 332 |
| 7.2.1 | Hierarchical Scoping: Static and Dynamic | 334 |
| 7.2.2 | Multiple Namespaces | 347 |
| 7.2.3 | Nonhierarchical Scope | 352 |
| 7.3 | Object-oriented Programming | 362 |
| 7.3.1 | HOOK: An Object-oriented Kernel | 362 |
| 7.3.2 | HOOPLA | 368 |
| 7.3.3 | Semantics of HOOK | 370 |
| 8 | State | 383 |
| 8.1 | FL Is a Stateless Language | 384 |
| 8.2 | Simulating State in FL | 390 |
| 8.2.1 | Iteration | 390 |
| 8.2.2 | Single-Threaded Data Flow | 392 |
| 8.2.3 | Monadic Style | 394 |
| 8.2.4 | Imperative Programming | 397 |
| 8.3 | Mutable Data: FLIC | 397 |
| 8.3.1 | Mutable Cells | 397 |
| 8.3.2 | Examples of Imperative Programming | 400 |
| 8.3.3 | An Operational Semantics for FLICK | 405 |
| 8.3.4 | A Denotational Semantics for FLICK | 411 |
| 8.3.5 | Call-by-Name versus Call-by-Value Revisited | 425 |
| 8.3.6 | Referential Transparency, Interference, and Purity | 427 |
| 8.4 | Mutable Variables: FLAVAR | 429 |
| 8.4.1 | Mutable Variables | 429 |
| 8.4.2 | FLAVAR | 430 |
| 8.4.3 | Parameter-passing Mechanisms for FLAVAR | 432 |

9 Control 443

- 9.1 Motivation: Control Contexts and Continuations 443
- 9.2 Using Procedures to Model Control 446
 - 9.2.1 Representing Continuations as Procedures 446
 - 9.2.2 Continuation-Passing Style (CPS) 449
 - 9.2.3 Multiple-value Returns 450
 - 9.2.4 Nonlocal Exits 455
 - 9.2.5 Coroutines 457
 - 9.2.6 Error Handling 461
 - 9.2.7 Backtracking 465
- 9.3 Continuation-based Semantics of FLICK 471
 - 9.3.1 A Standard Semantics of FLICK 472
 - 9.3.2 A Computation-based Continuation Semantics of FLICK 482
- 9.4 Nonlocal Exits 493
 - 9.4.1 `label` and `jump` 494
 - 9.4.2 A Denotational Semantics for `label` and `jump` 497
 - 9.4.3 An Operational Semantics for `label` and `jump` 503
 - 9.4.4 `call-with-current-continuation` (`cwcc`) 505
- 9.5 Iterators: A Simple Coroutining Mechanism 506
- 9.6 Exception Handling 513
 - 9.6.1 `raise`, `handle`, and `trap` 515
 - 9.6.2 A Standard Semantics for Exceptions 519
 - 9.6.3 A Computation-based Semantics for Exceptions 524
 - 9.6.4 A Desugaring-based Implementation of Exceptions 527
 - 9.6.5 Examples Revisited 530

10 Data 539

- 10.1 Products 539
 - 10.1.1 Positional Products 541
 - 10.1.2 Named Products 549
 - 10.1.3 Nonstrict Products 551
 - 10.1.4 Mutable Products 561
- 10.2 Sums 567
- 10.3 Sum of Products 577
- 10.4 Data Declarations 583
- 10.5 Pattern Matching 590
 - 10.5.1 Introduction to Pattern Matching 590
 - 10.5.2 A Desugaring-based Semantics of `match` 594
 - 10.5.3 Views 605

III Static Semantics 615**11 Simple Types 617**

- 11.1 Static Semantics 617
- 11.2 What Is a Type? 620
- 11.3 Dimensions of Types 622
 - 11.3.1 Dynamic versus Static Types 623
 - 11.3.2 Explicit versus Implicit Types 625
 - 11.3.3 Simple versus Expressive Types 627
- 11.4 μ FLEX: A Language with Explicit Types 628
 - 11.4.1 Types 629
 - 11.4.2 Expressions 631
 - 11.4.3 Programs and Syntactic Sugar 634
 - 11.4.4 Free Identifiers and Substitution 636
- 11.5 Type Checking in μ FLEX 640
 - 11.5.1 Introduction to Type Checking 640
 - 11.5.2 Type Environments 643
 - 11.5.3 Type Rules for μ FLEX 645
 - 11.5.4 Type Derivations 648
 - 11.5.5 Monomorphism 655
- 11.6 Type Soundness 661
 - 11.6.1 What Is Type Soundness? 661
 - 11.6.2 An Operational Semantics for μ FLEX 662
 - 11.6.3 Type Soundness of μ FLEX 667
- 11.7 Types and Strong Normalization 673
- 11.8 Full FLEX: Typed Data and Recursive Types 675
 - 11.8.1 Typed Products 675
 - 11.8.2 Type Equivalence 679
 - 11.8.3 Typed Mutable Data 681
 - 11.8.4 Typed Sums 682
 - 11.8.5 Typed Lists 685
 - 11.8.6 Recursive Types 688
 - 11.8.7 Full FLEX Summary 696

12 Polymorphism and Higher-order Types 701

- 12.1 Subtyping 701
 - 12.1.1 FLEX/S: FLEX with Subtyping 702
 - 12.1.2 Dimensions of Subtyping 713
 - 12.1.3 Subtyping and Inheritance 723
- 12.2 Polymorphic Types 725

| | | |
|-----------|---|------------|
| 12.2.1 | Monomorphic Types Are Not Expressive | 725 |
| 12.2.2 | Universal Polymorphism: FLEX/SP | 727 |
| 12.2.3 | Deconstructible Data Types | 738 |
| 12.2.4 | Bounded Quantification | 745 |
| 12.2.5 | Ad Hoc Polymorphism | 748 |
| 12.3 | Higher-order Types: Descriptions and Kinds | 750 |
| 12.3.1 | Descriptions: FLEX/SPD | 750 |
| 12.3.2 | Kinds and Kind Checking: FLEX/SPDK | 758 |
| 12.3.3 | Discussion | 764 |
| 13 | Type Reconstruction | 769 |
| 13.1 | Introduction | 769 |
| 13.2 | μ FLARE: A Language with Implicit Types | 772 |
| 13.2.1 | μ FLARE Syntax and Type Erasure | 772 |
| 13.2.2 | Static Semantics of μ FLARE | 774 |
| 13.2.3 | Dynamic Semantics and Type Soundness of μ FLARE | 778 |
| 13.3 | Type Reconstruction for μ FLARE | 781 |
| 13.3.1 | Type Substitutions | 781 |
| 13.3.2 | Unification | 783 |
| 13.3.3 | The Type-Constraint-Set Abstraction | 787 |
| 13.3.4 | A Reconstruction Algorithm for μ FLARE | 790 |
| 13.4 | Let Polymorphism | 801 |
| 13.4.1 | Motivation | 801 |
| 13.4.2 | A μ FLARE Type System with Let Polymorphism | 803 |
| 13.4.3 | μ FLARE Type Reconstruction with Let Polymorphism | 808 |
| 13.5 | Extensions | 813 |
| 13.5.1 | The Full FLARE Language | 813 |
| 13.5.2 | Mutable Variables | 820 |
| 13.5.3 | Products and Sums | 821 |
| 13.5.4 | Sum-of-products Data Types | 826 |
| 14 | Abstract Types | 839 |
| 14.1 | Data Abstraction | 839 |
| 14.1.1 | A Point Abstraction | 840 |
| 14.1.2 | Procedural Abstraction Is Not Enough | 841 |
| 14.2 | Dynamic Locks and Keys | 843 |
| 14.3 | Existential Types | 847 |
| 14.4 | Nonce Types | 859 |
| 14.5 | Dependent Types | 869 |
| 14.5.1 | A Dependent Package System | 870 |

14.5.2 Design Issues with Dependent Types 877

15 Modules 889

- 15.1 An Overview of Modules and Linking 889
- 15.2 An Introduction to FLEX/M 891
- 15.3 Module Examples: Environments and Tables 901
- 15.4 Static Semantics of FLEX/M Modules 910
 - 15.4.1 Scoping 910
 - 15.4.2 Type Equivalence 911
 - 15.4.3 Subtyping 912
 - 15.4.4 Type Rules 912
 - 15.4.5 Implicit Projection 918
 - 15.4.6 Typed Pattern Matching 921
- 15.5 Dynamic Semantics of FLEX/M Modules 923
- 15.6 Loading Modules 925
 - 15.6.1 Type Soundness of `load` via a Load-Time Check 927
 - 15.6.2 Type Soundness of `load` via a Compile-Time Check 928
 - 15.6.3 Referential Transparency of `load` for File-Value Coherence 930
- 15.7 Discussion 932
 - 15.7.1 Scoping Limitations 932
 - 15.7.2 Lack of Transparent and Translucent Types 933
 - 15.7.3 The Coherence Problem 934
 - 15.7.4 Purity Issues 937

16 Effects Describe Program Behavior 943

- 16.1 Types, Effects, and Regions: What, How, and Where 943
- 16.2 A Language with a Simple Effect System 945
 - 16.2.1 Types, Effects, and Regions 945
 - 16.2.2 Type and Effect Rules 951
 - 16.2.3 Reconstructing Types and Effects: Algorithm *Z* 959
 - 16.2.4 Effect Masking Hides Unobservable Effects 972
 - 16.2.5 Effect-based Purity for Generalization 974
- 16.3 Using Effects to Analyze Program Behavior 978
 - 16.3.1 Control Transfers 978
 - 16.3.2 Dynamic Variables 983
 - 16.3.3 Exceptions 985
 - 16.3.4 Execution Cost Analysis 988
 - 16.3.5 Storage Deallocation and Lifetime Analysis 991
 - 16.3.6 Control Flow Analysis 995
 - 16.3.7 Concurrent Behavior 996

16.3.8 Mobile Code Security 999

IV Pragmatics 1003**17 Compilation 1005**

- 17.1 Why Do We Study Compilation? 1005
- 17.2 TORTOISE Architecture 1007
 - 17.2.1 Overview of TORTOISE 1007
 - 17.2.2 The Compiler Source Language: FLARE/V 1009
 - 17.2.3 Purely Structural Transformations 1012
- 17.3 Transformation 1: Desugaring 1013
- 17.4 Transformation 2: Globalization 1014
- 17.5 Transformation 3: Assignment Conversion 1019
- 17.6 Transformation 4: Type/Effect Reconstruction 1025
 - 17.6.1 Propagating Type and Effect Information 1026
 - 17.6.2 Effect-based Code Optimization 1026
- 17.7 Transformation 5: Translation 1030
 - 17.7.1 The Compiler Intermediate Language: FIL 1030
 - 17.7.2 Translating FLARE to FIL 1036
- 17.8 Transformation 6: Renaming 1038
- 17.9 Transformation 7: CPS Conversion 1042
 - 17.9.1 The Structure of TORTOISE CPS Code 1044
 - 17.9.2 A Simple CPS Transformation 1049
 - 17.9.3 A More Efficient CPS Transformation 1058
 - 17.9.4 CPS-Converting Control Constructs 1070
- 17.10 Transformation 8: Closure Conversion 1075
 - 17.10.1 Flat Closures 1076
 - 17.10.2 Variations on Flat Closure Conversion 1085
 - 17.10.3 Linked Environments 1090
- 17.11 Transformation 9: Lifting 1094
- 17.12 Transformation 10: Register Allocation 1098
 - 17.12.1 The FIL_{reg} Language 1098
 - 17.12.2 A Register Allocation Algorithm 1102
 - 17.12.3 The Expansion Phase 1104
 - 17.12.4 The Register Conversion Phase 1104
 - 17.12.5 The Spilling Phase 1112

| | | |
|-----------|---|-------------|
| 18 | Garbage Collection | 1119 |
| 18.1 | Why Garbage Collection? | 1119 |
| 18.2 | FRM: The FIL Register Machine | 1122 |
| 18.2.1 | The FRM Architecture | 1122 |
| 18.2.2 | FRM Descriptors | 1123 |
| 18.2.3 | FRM Blocks | 1127 |
| 18.3 | A Block Is Dead if It Is Unreachable | 1130 |
| 18.3.1 | Reference Counting | 1131 |
| 18.3.2 | Memory Tracing | 1132 |
| 18.4 | Stop-and-copy GC | 1133 |
| 18.5 | Garbage Collection Variants | 1141 |
| 18.5.1 | Mark-sweep GC | 1141 |
| 18.5.2 | Tag-free GC | 1141 |
| 18.5.3 | Conservative GC | 1142 |
| 18.5.4 | Other Variations | 1142 |
| 18.6 | Static Approaches to Automatic Deallocation | 1144 |
| A | A Metalanguage | 1147 |
| A.1 | The Basics | 1147 |
| A.1.1 | Sets | 1148 |
| A.1.2 | Boolean Operators and Predicates | 1151 |
| A.1.3 | Tuples | 1152 |
| A.1.4 | Relations | 1153 |
| A.2 | Functions | 1155 |
| A.2.1 | What Is a Function? | 1156 |
| A.2.2 | Application | 1158 |
| A.2.3 | More Function Terminology | 1159 |
| A.2.4 | Higher-order Functions | 1160 |
| A.2.5 | Multiple Arguments and Results | 1161 |
| A.2.6 | Lambda Notation | 1165 |
| A.2.7 | Recursion | 1168 |
| A.2.8 | Lambda Notation Is Not Lisp! | 1169 |
| A.3 | Domains | 1171 |
| A.3.1 | Motivation | 1171 |
| A.3.2 | Types | 1172 |
| A.3.3 | Product Domains | 1173 |
| A.3.4 | Sum Domains | 1176 |
| A.3.5 | Sequence Domains | 1181 |
| A.3.6 | Function Domains | 1184 |

| | | |
|----------|----------------------------------|-------------|
| A.4 | Metalinguage Summary | 1186 |
| A.4.1 | The Metalinguage Kernel | 1186 |
| A.4.2 | The Metalinguage Sugar | 1188 |
| B | Our Pedagogical Languages | 1197 |
| | References | 1199 |
| | Index | 1227 |