

# 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
<b>4</b>	<b>Denotational Semantics</b>	<b>113</b>
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  $\mu$ 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  $\mu$ FLEX 640
  - 11.5.1 Introduction to Type Checking 640
  - 11.5.2 Type Environments 643
  - 11.5.3 Type Rules for  $\mu$ 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  $\mu$ FLEX 662
  - 11.6.3 Type Soundness of  $\mu$ 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
<b>13</b>	<b>Type Reconstruction</b>	<b>769</b>
13.1	Introduction	769
13.2	$\mu$ FLARE: A Language with Implicit Types	772
13.2.1	$\mu$ FLARE Syntax and Type Erasure	772
13.2.2	Static Semantics of $\mu$ FLARE	774
13.2.3	Dynamic Semantics and Type Soundness of $\mu$ FLARE	778
13.3	Type Reconstruction for $\mu$ 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 $\mu$ FLARE	790
13.4	Let Polymorphism	801
13.4.1	Motivation	801
13.4.2	A $\mu$ FLARE Type System with Let Polymorphism	803
13.4.3	$\mu$ 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
<b>14</b>	<b>Abstract Types</b>	<b>839</b>
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<sub>reg</sub> 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	Metalanguage Summary	1186
A.4.1	The Metalanguage Kernel	1186
A.4.2	The Metalanguage Sugar	1188
<b>B</b>	<b>Our Pedagogical Languages</b>	<b>1197</b>
<b>References</b>	<b>1199</b>	
<b>Index</b>	<b>1227</b>	