

Type Systems for Programming Languages

Benjamin C. Pierce
bcpierce@cis.upenn.edu

Working draft of January 15, 2000

This is preliminary draft of a book in progress. Comments, suggestions, and corrections are welcome.

Contents

Preface	8
1 Introduction	13
1.1 What is a Type System?	13
1.2 A Brief History of Type	14
1.3 Applications of Type Systems	16
1.4 Related Reading	16
2 Mathematical Preliminaries	18
2.1 Sets and Relations	18
2.2 Induction	18
2.3 Term Rewriting	19
3 Untyped Arithmetic Expressions	20
3.1 Basics	20
Syntax	21
Evaluation	21
3.2 Formalities	21
Syntax	21
Evaluation	25
3.3 Properties	27
3.4 Implementation	27
Syntax	27
Evaluation	28
3.5 Summary	28
3.6 Further Reading	30
4 The Untyped Lambda-Calculus	31
4.1 Basics	32
Syntax	33
Operational Semantics	34
4.2 Programming in the Lambda-Calculus	34

4.3	Is the Lambda-Calculus a Programming Language?	39
4.4	Formalities	39
	Syntax	39
	Substitution	40
	Operational Semantics	43
	Summary	43
4.5	Further Reading	44
5	Implementing the Lambda-Calculus	45
5.1	Nameless Representation of Terms	45
	Syntax	46
	Shifting and Substitution	48
	Evaluation	49
5.2	A Concrete Realization	49
	Syntax	50
	Shifting and Substitution	50
	Evaluation	51
5.3	Ordinary vs. Nameless Representations	51
6	Typed Arithmetic Expressions	52
6.1	Syntax	52
6.2	The Typing Relation	52
6.3	Properties of Typing and Reduction	53
	Typing Derivations	53
	Typechecking	54
	Safety = Preservation + Progress	54
6.4	Implementation	55
6.5	Summary	56
7	Simply Typed Lambda-Calculus	58
7.1	Syntax	58
7.2	The Typing Relation	59
7.3	Summary	61
7.4	Properties of Typing and Reduction	62
	Typechecking	62
	Typing and Substitution	64
	Type Soundness	64
7.5	Implementation	65
7.6	Further Reading	66

8	Extensions	67
8.1	Base Types	67
8.2	Unit type	67
8.3	Let bindings	68
8.4	Records and Tuples	68
8.5	Variants	72
8.6	General recursion	72
8.7	Lists	73
8.8	Lazy records and let-bindings	75
9	References	76
9.1	Further Reading	79
10	Exceptions	80
10.1	Errors	80
10.2	Exceptions	80
11	Type Equivalence	81
12	Definitions	83
12.1	Type Definitions	83
12.2	Term Definitions	85
13	Subtyping	86
13.1	The Subtype Relation	87
	Variance	88
	Summary	89
13.2	Metatheory of Subtyping	91
	Algorithmic Subtyping	91
	Minimal Typing	92
13.3	Implementation	96
13.4	Meets and Joins	97
13.5	Primitive Subtyping	99
13.6	The Bottom Type	99
13.7	Other stuff	99
14	Imperative Objects	100
14.1	Objects	100
14.2	Object Generators	102
14.3	Subtyping	103
14.4	Basic classes	104
14.5	Extending the Internal State	105
14.6	Classes with “Self”	106

15 Recursive Types	109
15.1 Examples	109
Lists	109
Hungry Functions	109
Recursive Values from Recursive Types	110
Untyped Lambda-Calculus, Redux	110
Recursive Objects	112
15.2 Equi-recursive Types	112
ML Implementation	114
15.3 Iso-recursive Types	115
15.4 Subtyping and Recursive Types	116
16 Case Study: Featherweight Java	117
17 Type Reconstruction	118
17.1 Substitution	118
17.2 Universal vs. Existential Type Variables	119
17.3 Constraint-Based Typing	121
17.4 Unification	125
17.5 Principal Typings	128
17.6 Further Reading	129
18 Universal Types	130
18.1 Motivation	130
18.2 Varieties of Polymorphism	131
18.3 Definitions	132
18.4 Examples	135
Warm-ups	135
Polymorphic Lists	136
Impredicative Encodings	136
18.5 Metatheory	139
Soundness	139
Strong Normalization	139
Erasure and Typeability	140
Type Reconstruction	141
18.6 Implementation	141
Nameless Representation of Types	141
ML Code	141
18.7 Further Reading	143