

Concept index

- \mathcal{A} (automatically generated function in identifier cross-reference), 39
- abbreviations, type, 529
- abstract classes, 622, 624, 656–662, 708
 - Collection, 642
 - Integer, 664
 - LargeInteger, 669
 - Number, 663
- abstract data types, *see* abstract types
- abstract machine(s), 30, 67
 - further reading, 246
 - Impcore, 30
 - for implementation, 246
 - μ Scheme, 144
 - μ Scheme+, 211
 - μ Smalltalk, 678–679
 - representations
 - μ Smalltalk, 686–687
 - in semantics, 211
- abstract-machine semantics, 244
- abstract syntax, 14, 15, 67
 - exceptions, 589
 - Impcore, 27–28
 - μ ML, 485–486
 - μ Scheme (in ML), 306–307
 - μ Scheme (in C), 144–145
 - μ Scheme+, 225–226
 - μ Scheme+ stack frames, 225–226
 - μ Smalltalk, 687–688
 - nano-ML, 404–405
 - Typed Impcore, 332–333
 - Typed μ Scheme, 361
- abstract-syntax trees, 27–28
 - in C, 41–43
- abstract types, 455, 525, 538, 585
 - in C, 39
 - as components of modules, 538
 - design choices, 580–583
 - equality and, 634
 - examples, 526
 - and exceptions, 583–584
 - in Java, 707
 - limitations, 585
 - objects vs, 625–627
 - proofs of correctness, 588
 - in real languages, 580–583
- abstraction(s), 527, 528, *see also* data abstraction
 - immutable, 545
 - mutable, 545
 - syntactic, *see* macros
- abstraction functions, 545, 549 (defined), 586, 708
- circular lists, 673
- complex numbers, 551
- data structures, typical and, 549–551
- dictionaries, 549
- examples, 552
- natural numbers, 670, 671
- priority queues, 550, 552
- sets, 548
 - two-dimensional points, 551
- abstraction, functional, 36
- access paths, 561 (defined)
 - absolute, 559
 - environment lookup, 574
 - of modules or components, 559
 - pseudo-bindings, 563, 574
 - relative, 575
- accessor(s), *see* observers
- accessor functions for records, 107
- accumulating parameters, 99–101
- ad hoc* polymorphism, 132, 544, *see also* overloading
- algebraic data types, 317, 501
 - compile-time checks, 499–500
 - extensions, 503
 - generalized, 503
 - in μ ML, 466–476
 - in Molecule, 535
 - origins, 502
 - polymorphic, 462–463
 - in real languages, 499–501
 - recursive, 463–464
- algebraic laws, 98
 - association lists, 106, 112
 - binary-tree nodes, 109
 - in calculational proofs, 115
 - case expressions, 476–477
 - continuation-passing style and, 138

Concept index

750

- algebraic laws (continued)
 - currying and uncurrying, 126
 - equality of S-expressions, 104
 - finite maps, 112
 - further reading, 175
 - has? (μ Scheme function), 103
 - higher-order list functions, 130
 - if expressions, 112
 - and imperative features, 403
 - insertion sort, 101
 - length of a list, 98
 - length of appended lists, 115
 - list append, 99
 - list insertion, 101
 - list primitives, 111
 - list reversal, 100
 - membership in S-expressions, 103
 - notation for lists, condensed, 99
 - operator classifications and, 111–112
 - pair types, 349
 - product types, 349
 - proofs of, 114, 115
 - set functions, 105
 - simplifying code with, 113
 - solving conjunctive normal form, 141, 142
 - soundness, 65
 - in specifications, 547, 548
 - substitutions, 409–410
 - testable properties as, 110
 - tree-node functions, 109
 - tuple types, 349
 - uses, 175
- algebraic specification, 547, 548
- allocation, 259
 - in functional languages, 205
 - implementations, 162 (μ Scheme), 266 (μ Scheme+)
- interfaces, 154
 - in μ Scheme+, 266
 - mutability and, 545
 - in procedural languages, 206
- `allOf`, 541, 552, 555
- alpha-conversion (renaming)
 - type variables, 368–369
- and (\wedge , type intersection), 564
- and, meaning in ML, 303
- answer(s), 708
 - to messages, 610 (defined)
- answer (verb form)
 - in Smalltalk, 612
- answer types
 - in continuation-passing style, 138
- APIs, 527, 586
 - examples, 531–532
- append, 99 (μ Scheme), 475 (μ ML)
 - proof of laws, 114
- applicative languages, 402
- apply primitive (exercise), 198
- arguments, variable number of, 169
- arithmetic, multiprecision, *see* multiprecision arithmetic
- arity
 - μ Smalltalk message names, 627
 - primitives, 313
- arrays
 - associative, *see* finite maps
 - implementation (μ Smalltalk), 661–662
 - semantics, 345
 - syntax, 343–345
 - type checking, 348
 - types for, 343
 - typing rules, 346–348
- arrow types
 - typing rules, 348
- ascriptions
 - of a module type to a module, 564
 - in Standard ML, 441
 - type checking, 564
- assignment
 - to Boolean variables, 138
 - satisfying a Boolean formula, 138
- assignment (syntactic form `set`)
 - implementations
 - Impcore, 49
 - μ Scheme, 156
 - μ Scheme+, 230
 - operational semantics
 - Impcore, 34
 - μ Scheme, 145
 - μ Smalltalk, 680
 - small-step semantics, 217
 - typing rules
 - Typed Impcore, 335
 - Typed μ Scheme, 363
- association lists, 105–107, 646, S73
 - algebraic laws, 106, 112
 - attributes, 105
 - continuations and, 136–137
 - equality, 132–133
 - in full Scheme, 169
 - keys, 105
 - sets of, 132–135
- associative arrays, *see* finite maps
- ASTs, *see* abstract-syntax trees
- @ (instantiation), 352, 358, 412
 - examples, 358
 - implicit, 413
 - typing rules, 365
- atoms, 172, S95
 - in μ Scheme, 92
 - in Prolog, S43

- autognostic principle, 626, 708
- automatic instantiation, 409
- automatic memory management, 288
 - benefits, 257
 - performance, 260
- \mathcal{B} (basis function in identifier cross-reference), 39
- backtracking
 - using continuation-passing style, 138–143
 - visualizations, 139
- Backus-Naur Form, 17
- base types, 343
 - Typed Impcore, 333
- basis, 26 (defined), 67
 - Impcore, 29
 - initial, *see* initial basis
 - Typed μ Scheme, 382
- bearskins, 588
- begin
 - operational semantics
 - Impcore, 35
 - μ Scheme, 149
 - μ Smalltalk, 681
 - syntactic sugar, 167
 - typing rules
 - nano-ML, 413 (nondeterministic), 446 (constraint-based)
 - Typed Impcore, 336
 - Typed μ Scheme, 363
- behavior(s), μ Smalltalk
 - representation, 687
 - semantics, 678–679
- behavioral specifications, 527
 - examples, 529, 547
- behavioral subtyping, 627, 708, 713
- big-step semantics, *see* operational semantics
- bignums, *see* large integers
- binary operations
 - on abstract types, 555–557
 - on objects, 662–673
 - primitives, embedded as, 313
- binary search trees
 - exercises, 508–509
 - representation invariants, 550
- binary trees
 - algebraic laws, 109
 - encoded as S-expressions, 109–110
 - exercises, 508–509
 - inference rules, to define, 109
 - μ Scheme, 109–110
 - traversals
 - breadth-first, 118–120
 - inorder, 181
 - level-order, 118–120
 - postorder, 181
- binary trees (continued)
 - traversals (continued)
 - preorder, 110
- binding(s)
 - access paths, 563, 574
 - in Molecule type-checking environments, 563
- binding occurrences
 - type variables, 371 (defined)
- black magic, decision procedure for, S45
- black objects, 261
 - in copying collection, 273
 - examples, 275
 - in mark-sweep collection, 269
- blocks (μ Smalltalk), 618, 627–629, 708
 - bootstrapping, 698
 - closures and, 618
 - evaluation, 691
 - operational semantics, 681
 - protocol, 630, 638–641
- BNF, 17
- Boolean(s)
 - Church encoding, 655
 - μ Smalltalk, 630
 - bootstrapping, 697–699
- boolean?, 92
- Boolean classes
 - implementations, 655
 - protocol, 639
- Boolean operators, short-circuit, 164–165
- Boolean satisfiability, 138–139
 - solver, 139–143
- bootstrapping, μ Smalltalk
 - blocks, Booleans, literals, 698–699
- bound occurrences
 - of type variables, 371
- bound type variables, 371 (defined)
- bound variables, 315–317
- brackets
 - square vs round, 117
 - as tokens, 17
- breadth-first traversals, 118–120
- break, 202, 206–207 (examples)
 - real implementations, 239
- Brown, Troy, 635
- bugs, μ Scheme, false reports of, 154
- Byrd boxes, 139, 175
- C programming
 - advantages and disadvantages, 301
 - conventions, 39–40
 - interfaces, 40
 - ML programming vs, 314–315
 - scope rules, 74
 - static variables, 124
 - caar, cadr, cdar, and so on, 96

Concept index

751

Concept index

752

- calculational proofs, 114–116, *see also* equational reasoning
- form, 114
- organization, 115
- calculus
 - as a form of abstract machine, 241
- call/cc, 172, 242–243, 244, 247, 255 (examples)
- call stacks, 65, 239, 244, 288
- canvases (μ Smalltalk), 618–619
- capitalization
 - in C programs, 39–40
 - of value constructors, 469–471
- capture
 - of type variables, 369, 373
 - in type-lambda, 365
- capture-avoiding substitution, 165–167, 365, 373–375
- implementations, 374–375
- specification (rules), 374
- for type variables, 365
- type-lambda and, 377–378
- car, 94, 172
 - implementations, 162
 - operational semantics, 151
 - origin of name, 94
- cascade, message (Smalltalk-80), 706
- case expressions, 457, 459, 501
 - algebraic laws, 476–477
 - benefits, 501
 - equational reasoning, 476–479
 - evaluation, 490–494
 - examples, 459–466, 475–476
 - operational semantics, 490–494
 - semantics, informal, 468–469
 - type inference, 495–499
 - typing rules, 349, 495–496 (non-deterministic), 497–499 (constraint-based)
- catch (in μ Scheme+), 204
- catching an exception, 208
- categories, syntactic, *see* syntactic categories
- cdar, caar, cdr, and so on, 96
- cdr, 94, 172
 - operational semantics, 151
 - origin of name, 94
- CESK machine, 243, 246
- characteristic functions (of sets), 187
- check-assert, 23, 26
- check-error, 23, 25
- check-expect, 23–26
 - in μ Smalltalk using =, 635
- check-principal-type, 402
- check-type, 402
- checked run-time errors, 40
- Church encodings
 - Booleans, 655
- Church-Rosser theorem, 246
- Circle (μ Smalltalk class), 620
- circular lists, 673
 - abstraction function, 673
 - representation invariants, 673
- class(es), 610, 708
 - abstract, 622
 - creation, 695
 - definitions, 614
 - modules vs, 588
 - representations, 686, 694–695
- Class (μ Smalltalk class), 696–697
- class Collection, 656–658
- class definitions
 - operational semantics, 685
- class hierarchies
 - collections, 642
 - integers, 651
 - numbers, 649
 - Smalltalk-80, 704–707
- class instance variables
 - Smalltalk-80, 704
- class List, 674–677
- class Magnitude, 656
- class Metaclass, 696–697
- class methods, 614, 708
- class Object, 696
- class objects, 630
- Class protocol, 638
- class protocols, 613
- class True, 655
- class UndefinedObject, 696
- class variables
 - Smalltalk-80, 704
- classifications
 - of operators, 111–112, 546
- clausal definitions, 318, 480 (defined), 501, 516
 - benefits, 501
 - examples, 480–482
- clauses (Prolog), S95
- client code, 526 (defined), 527, 530, 586
- closing
 - over free type variables, 414
- closures, 122–125, 172
 - application semantics, 147
 - further reading, 175
 - implementation, 122–124
 - in μ Smalltalk, 691
 - in operational semantics, 147, 681
 - representations
 - C, 152
 - nano-ML, 405
 - semantics, 147–149
 - static scoping and, 148
- CLU, 526
 - further reading, 588

CLU (continued)
 mutable types vs immutable types, 545
 program correctness and, 585
CNF, *see* conjunctive normal form
 code chunks, 39
coerce: method, 663
 coercions (μ Smalltalk), 667–669
 collection(s), 708
 examples, 645
 implementations, 656–662
 inheritance, 649
 μ Smalltalk protocols, 642–649
 Collection (μ Smalltalk class), 656–658
 collection hierarchies, 642
 Smalltalk-80, 705–706
 Collection protocol, 643, 644
 coloring invariant, 261 (defined)
 Common Lisp, 89, 174, 713
 CommonLoops, 713
 commutative diagrams, 477
 compilation, 68
 of pattern matching, 500–501, 503
 compiling with continuations, 247
 complex operations, 555–557, 662–673, 709
 examples, 666
 components of modules, 528 (defined)
 declarations of, 538
 exported, 538
 of intersection types, 541
 nested modules, 539
 public, 538
 strengthening, 570
 types, 538
 values, 538
 composition
 of functions, *see* function composition
 of substitutions, 410–411
 conclusions
 in inference rules, 31
 concrete syntax, 14, 15, 69
 curried functions, impact on, 126
 exceptions, 589
 Impcore, 17–19
 Impcore vs C, 12
 μ ML, 467
 μ Scheme, 92, 93
 μ Smalltalk, 627–629
 rationale, 611
 Molecule, 535
 core layer, 536
 module layer, 537
 nano-ML, 404
 partial application, impact on, 126
 Smalltalk-80, 702–704
 Typed Impcore, 330–331

concrete syntax (continued)
 Typed μ Scheme, 352, 353
 cond (Scheme form), 163–164
 conditional expressions
 algebraic laws, 112
 implementations
 μ Scheme+, 230–231
 method dispatch vs, 623, 654–656
 object-oriented programming,
 deprecated in, 655
 operational semantics
 Impcore, 34
 μ Scheme, 149
 small-step semantics, 217–218
 type inference, 413, 418, 421
 typing rules
 nano-ML, 413 (nondeterministic), 418 (explicit substitutions), 421 (constraints)
 Typed Impcore, 335
 Typed μ Scheme, 363
 conjunctions, 420
 constraint solving, 429
 conjunctive normal form, 139
 representation (μ Scheme), 140
 cons, 94, 172
 implementations, 161, 473
 operational semantics, 151
 origin of name, 94
 cons cell, 94, 95 (defined)
 Cons protocol, 675
 constraint(s), type-equality, 441
 grammar, 420
 implementations, 436
 trivial, 420
 in type inference, 420–428
 typing judgment, 420
 unsolvable, 424
 constraint satisfaction, 428 (defined)
 constraint solving, 418, 428–431, 441
 conjunction, 429
 examples, 431
 implementations, 436–437
 simple type equality, 429–430
 constructed values, 457 (defined), 501
 μ ML, 457
 Molecule, 534
 “constructor”
 pitfalls as a technical term, 111
 constructor(s), 111
 algebraic data types and, 457
 of Molecule values, 533
 names for abstract syntax, 42
 smart (in binary tries), 513
 constructor functions
 for records, 108
 contexts, evaluation, *see* evaluation contexts

Concept index
 753

Concept index

754

- continuation(s), 136–138, 244
 - blocks in Smalltalk as, 640
 - compiling with, 247
 - defined by evaluation context, 242
 - delimited, 243, S358–359
 - entering, 242
 - exceptions and, 209–210
 - failure, 136, 139, S239
 - first-class, 242
 - further reading, 246, 247
 - in real languages, 242–243
 - solutions, finding with, 142
 - success, 136, 139
 - undelimited, 243, 245
- continuation-passing style, 138–143
 - for backtracking, 138–143
 - direct style vs, 138
 - further reading, 175
 - identifying, 138, 170
 - in Smalltalk, 610, 640
 - in Smalltalk conditionals, 655
- continue, 202
 - examples, 206–207
 - real implementations, 239
- contravariance
 - of function arrow in subtyping, 606
- control (control operator), 247
- control flow, 201
 - using continuations, 136–138
- control operators, 201–202, 206–210, 244, 248–249 (exercises)
 - big-step judgment forms, 677
 - in big-step semantics, 679
 - break, 202
 - continue, 202
 - control, 247
 - long-goto, 204
 - long-label, 204
 - in μ Scheme+, 202–204
 - μ Smalltalk return, 677
 - operational semantics, 210, 221–222
 - prompt, 247
 - in real languages, 239–240
 - reset, 247
 - return, 202
 - shift, 247
 - throw, 202
 - try-catch, 204
- conventions, coding
 - C, 39–40
 - ML, 301–303
- CoordPair
 - implementation, 615
 - protocols, 613
- copying garbage collection, 271–279
 - C code, 276–278
- copying garbage collection (continued)
 - examples, 274–276
 - in μ Scheme+, 276–278
 - performance, 278–279
- copying phase
 - in μ Scheme+ garbage collector, 273
- core languages, 26, 162, 214
 - layer in Molecule, 534
 - in μ Scheme, 120
- Core μ Scheme+, 214
 - operational semantics, 215–223
- cost models of abstractions, 546
- crash, μ Scheme, causes of, 154
- creators (class of operations), 111
 - introduction forms and, 347
 - in protocols, 614
- creators, producers, and observers, 111–112
 - type systems and, 347
- curried functions, 125–127
 - concrete syntax and, 126
- curried modules, 575
- Curry-Howard isomorphism, 347, 727–729
- currying and uncurrying, 125–127
 - algebraic laws, 126
 - higher-order functions, 126
- Darcy, Lord, investigator for the Anglo-French empire, S45
- data abstraction, 455, 525, 586, 709
 - benefits, 525
 - binary operations and, 662–673
 - closed systems and, 626
 - design, 545–554
 - equality and, 634
 - examples, 525–526, 546–548
 - further reading, 587
 - in object-oriented languages, 625–627
 - open systems and, 626
- data definitions
 - μ ML, 466, 471–472
 - typing rules, 487–489
- database (of Prolog clauses), S46
- datatype definitions, *see also data definitions*
 - desiderata, 457
 - generativity, 472
 - μ ML, 471–473
 - typing, 471–473
- De Morgan's laws
 - for exists? and all?, 131
 - in solving Boolean formulas, 189
- dead objects, 289
- dead variables, 289

debugging
 closures (μ Scheme), S331
 garbage collectors, 280–283
 by tracing calls and returns, 198
 by tracing evaluation, 224
 by tracing message sends, 640, 641
 decidability of type inference, 401
 declarations
 of exported components, 538
 of manifest types, 530
 syntactic category of, 16
define
 desugared into lambda, 120
 explained, 22
 in full Scheme, 169
 operational semantics
 Impcore, 38
 μ Scheme, 152
 typing rules
 nano-ML, 416 (nondeterministic)
 Typed Impcore, 337
 Typed μ Scheme, 366
 definition(s)
 class, 614
 extended, 18, 24–26
 Impcore, 27
 implementations of, 159–160
 syntactic category of, 16
 true, 18
 definition modules, 528, 581
 definitional interpreters, 69
 degenerate type schemes, 414
 delegation, 709
 in the implementation of Set, S563
 delimited continuations, 243, 244, S358–359
 further reading, 247
 denotational semantics, 246
 dependent function types, 541
 dependent types, 383, 727
 derivations, 56
 construction (how to), 58–59
 validity, 57–58
 desugaring, 68 (defined)
 define, 120, 152
 do-while, 66
 let, let*, letrec, 163
 val-rec, 396
 while*, 66
 dictionaries, *see* finite maps
 direct style, 138
 continuation-passing style vs, 138
 dispatch, dynamic, *see* method dispatch
 divergence, 245
do: (μ Smalltalk method), 642–645, 656
 examples, 617, 622, 657
 return within, 657

domains
 of Molecule type-checking environments, 563
 of substitutions, 410
 dot notation, 528
 double dispatch, 666–667
 duck typing, 627, 708
 dynamic dispatch, *see* method dispatch
 dynamic scoping, 148
 dynamic typing, 327
eager evaluation, 241
EBNF, 17, S9–10
effects, 110
either (elimination form for sum types), 350
elaboration, 452 (exercise), 573 (defined)
 exports, 573
 generic-module types, 573
 intersection types, 573
 μ ML, 489
 module types, 564, 571–574
 module-arrow types, 573
 Molecule rules, 572
 operator overloading and, 577
 overloading (Molecule), 576
 types (Molecule), 564, 571–574
 elimination forms, 347, 384, *see also introduction and elimination forms*
 exporting modules, 540
 generic modules, 541
 quantified types, 358
 elimination rules, 345 (defined)
 template, 346
embeddings, 308, 318
 of functions, 312–314
 of lists, 308
 of ML primitives into μ Scheme primitives, 312
 projections and, 308–309
 of Booleans, 308
 of integers, 308
 encapsulation, 586, 615
 environments, 28–29, 69
 copying, 144
 global variables (Impcore), 28
 global variables (μ Smalltalk), 678
 Impcore, 28
 implementation for Impcore, 54–55
 interface, 153
 lookup in Molecule, 574–576
 μ Scheme, 144
 representation in ML, 304–305
 typing
 Molecule, 562 (defined), 563
 nano-ML, 435

Concept index

755

- environments (continued)
 - typing (continued)
 - Typed μ Scheme, 361
- equality
 - algebraic laws, 104
 - of association lists, 132–133
 - in C, 633
 - of collection elements, 646
 - data abstraction and, 634
 - exercises, 718
 - in full Scheme, 633
 - in μ Scheme, 633
 - in OCaml, 634
 - overloading, 543
 - polymorphic, 633
 - of S-expressions, 104
 - in Standard ML, 633
 - syntactic form for (Typed Impcore), 332
 - of types (pitfalls), 332
 - typing rules (for Typed Impcore), 336
- equality constraints, *see* type-equality constraints
- equality types (Standard ML concept), 633, S217
- equational reasoning, 113–116, 183
 - with case expressions, 476–479
- equivalence
 - identity vs (in collections), 646
 - μ Smalltalk, 635
 - observational, 634
 - of types, *see* type equivalence
- erasure (of types), 380
- Erlang pattern matching, 499
- error(s)
 - categories of, 13–14
 - run-time, 40, 47
 - syntax, 47
- :error exception, 208–209
- evaluation, 69
 - block, 691
 - case expressions, 468–469
 - eager, 241
 - Impcore definitions, 22–23
 - Impcore expressions, 20–22
 - lazy, 241
 - message sends, 689–690
 - μ Smalltalk literals, 691
 - μ Smalltalk primitives, 692–693
 - modules, 541–542
 - Molecule, 537
 - overloading (Molecule), 577
 - polymorphism and, 380
 - return (μ Scheme+), 237
 - return (μ Smalltalk), 689
 - stack-based, 212–213, 227–239
 - strict, 241
- evaluation (continued)
 - tracing, 224–225
 - Typed μ Scheme, 380
- evaluation contexts, 202, 241, 245
 - stack frames and, 242
- evaluation order, 242
- evaluation stacks, 210–213, 245, 289, 730
 - analogous in real languages, 239
 - exercises, 250
 - instrumentation, 224–225
 - interface to (μ Scheme+), 224
 - memory management and, 229–230
- evaluators, 69
 - case expressions, 492–494
 - Impcore, 48–54
 - μ Scheme (C), 154–160
 - μ Scheme (ML), 309–312
 - μ Smalltalk, 688–694
- exceptions, 207–208, 318, 583
 - abstract types and, 583–584
 - catching, 208
 - continuations and, 209–210
 - examples, 208–209
 - implementations, 208, 246
 - raising, 207, 583
 - in real languages, 240, 583
 - syntax, 589
 - throwing, 207
- execution, *see* evaluation
- exhaustive pattern matches, 318
 - checks for, 499
- existentially quantified types, 503
 - from algebraic data types, S25
- export lists, 538
- exported components, 538
- exported names, 526, 527
- exporting modules, 539 (defined)
- exports module types
 - elaboration, 573
- expression(s)
 - syntactic category of, 16
 - type-level, 352, 357
- expression-oriented languages, 17, 69
- Extended Backus-Naur Form, 17, S9–10
- extended definitions, 18, 24–26
- facts (in Prolog), S45, S96
- failure continuations, 136, 139
 - in withHandlers, S239
- filtering, 172
 - examples, 206
 - higher-order functions, 127
 - methods, 645
 - visualizations, 129
- find
 - algebraic laws, 106
 - using continuations, 136–137

- finite maps, 105
 - algebraic laws, 112
- first-class functions, *see* functions, first class
- first-class values, 121
- fish in a barrel, shooting, S448
- flips (copying collection), 271
- Float protocol, 652
- folding, 173
 - higher-order functions, 128
 - to implement set functions, 131
 - methods, 645
 - visualizations, 129
- F_ω , 365
- form(s)
 - judgment, 30
 - syntactic, 15–17
- formation
 - of generic-module types, 541
 - of intersection types (Molecule), 541
 - of module types, 538–539
- formation rules, 345 (defined), 347, 384,
 - see also* type-formation rules
 - template, 346
- formation, introduction, and elimination, 347
 - Molecule, 538
- forwarding (action), 277–278
- forwarding pointers, 272–273, 289
- Fraction protocol, 652
- fraction(s) in μ Smalltalk
 - examples, 652
 - implementation, 664–666
- frames (on evaluation stacks), 210–211
- free lists, 266, 289
- free occurrences
 - of type variables, 371
- free type variables, 371 (defined)
 - implementations, 371, 372
 - inference rules, 371
- free variables, 173, 315–317, 318
 - formal definition, 316–317
 - in μ Scheme expressions, S328
- fresh locations, 144, 145
 - in function application (μ Scheme), 147
- fresh type constructors, 484
- fresh type variables, 433–434
- fresh variables, 165, 195, 196, S217
- freshness and generativity, 484
- from-space, 271 (defined)
- ftv (compute free type variables), 414
 - in nano-ML, 433
- function(s)
 - anonymous, 120
- function(s) (continued)
 - first-class, 120–122, 172
 - first-class, nested functions vs, 121
 - implementation, 122–124
 - first-order, 90, 122, 172
 - higher-order, *see* higher-order functions
 - nested, *see* nested functions
 - primitive
 - environment ϕ and, 30
 - typing rules, 348
 - user-defined
 - in Impcore environment ϕ , 30
 - variadic, 169, 322 (exercise)
- function?, 92
- function application
 - Impcore, 36
- implementations
 - Impcore, 50
 - μ Scheme (C), 156–157
 - μ Scheme (ML), 310
 - μ Scheme+, 231–234
- Lisp, 148
- μ Scheme, 147
- operational semantics
 - Impcore, 36, 37
 - Lisp, 148
 - μ Scheme, 147, 150
- small-step semantics, 218–220
- type inference, 419, 421
- typing rules
 - explicit substitutions, 419
 - nano-ML, 414 (nondeterministic), 421 (constraint-based)
 - Typed Impcore, 336
 - Typed μ Scheme, 365
- function composition, 125
- function environment ϕ (Impcore), 30
- function values, 120–122
- functional abstraction, 36
- functional programming
 - object-oriented programming vs, 624–625
 - procedural programming vs, 205–206
- functors
 - generic modules, 581
 - ML, 581
 - Prolog, S43, S52
- GADTs, 503, S25, S32–37
- garbage collection, 259 (defined), 289
 - benefits, 257
 - bugs, common, 280
 - compacting, 288
 - concurrent, 286
 - conservative, 283, 288

Concept index

757

- garbage collection (continued)
 - copying, 271–279, *see also* copying garbage collection
 - debugging, 280–283, 291
 - further reading, 291–292
 - generational, 286, 289
 - manual memory management vs, 291
 - mark-and-sweep, 266–271
 - mark-compact, 283
 - overhead, 259
 - parallel, 286
 - performance, 260, 270
 - in real systems, 285–287
 - write barrier, 286
- general, at least as, 410, 441
- generality
 - of types, 410
- generalization, 413, 423–424, 442
 - implementations, 434
 - let binding, 425–428
 - rationale, 435
 - soundness, 427
 - of types, 415 (defined), 423
- generalized algebraic data types, *see* GADTs
- generational garbage collection, 286
- generativity, 383, 483–485 (defined), 501
 - in C, 484
 - datatype definitions, 472
 - in μ ML, 484
 - in Molecule, 559, 578
 - in real languages, 580
 - of sealing in Molecule, 539
 - specification (μ ML), 487
 - in Standard ML, 484
 - of syntactic forms, 484
- generic(s), *see* polymorphism
- generic (defined by recursion over types), 132
- generic (parametrically polymorphic), 132, *see also* polymorphism
- generic module(s), 526, 540–541, 586
 - curried, 575
 - elimination of, 541
 - examples, 552, 560
 - instantiation of, 541
 - introduction of, 541
 - in real languages, 580
- generic-module types
 - elaboration, 573
 - examples, 540
- generic programming, 132
- global variables
 - environments (Impcore), 28
 - environments (μ Smalltalk), 678
 - semantics, 151–152
- goals (Prolog), S49, S96
- going wrong, 22, 328
- goto, 201
 - considered harmful, 201, 245
- grammars, 15, 69
- gray objects, 261
 - in copying collection, 273
 - examples, 275
 - in mark-sweep collection, 269
- ground clauses (Prolog), S53
- ground terms (Prolog), S53, S96
- ground types, 408
- has? (μ Scheme function)
 - algebraic laws, 103
- Haskell, 441
- head(s)
 - of Prolog clauses, S52
 - of Prolog rules, S97
- headroom
 - in garbage collection, 259, 270
- heap(s), 289
- heap allocation, 289
 - in μ Scheme+, 263
- heap growth
 - in copying collector, 278
- heap invariants
 - array heaps, 552
 - leftist heaps, 556
- heap(s), leftist, 555–557
- heap objects, 289
- heap pointer, 271 (defined)
- heaplimit, 271
- Heidi (broadcast on NBC), 526
- higher-order functions, 90, 121–122, 173
 - algebraic laws (lists), 130
 - for control flow, 136–138
 - currying and uncurrying, 126
 - for embedding, 312–314
 - exercises, 187–189
 - implementations, 129–131
 - on lists, 127–131
 - filtering, 127
 - searching, 127–128
 - transformation (mapping), 127
 - for random-number generation, 124–125
- Hindley-Milner type system, 401
 - in real languages, 441
- Hoare triples (as metaphor for moves in blocks world), S83
- holes
 - in Molecule typing contexts, 562
 - in small-step semantics, 210–222, 245
 - in stack frames, 210–223, 226
- Horn clauses, S46, S91
- hp (heap pointer), 271

hygiene, 166, 171
 in full Scheme macros, 171
 further reading, 175
 in substitution, 165–167
 in translations for μ Scheme, 162

idempotence (of substitutions), 411
 identifier cross-reference in this book, 39
 identity
 equivalence vs (in collections), 646
 identity substitution, 411
`idsubst` (identity substitution), 411
`if` expressions, *see* conditional expressions
`IFX` vs `IF`, 42
 ill-behaved programs, 14
 ill-formed programs, 13
 ill-typed programs, 13
 images, Smalltalk, 701
 immutability
 of abstractions, 545
`Impcore`, 12–87
 abstract syntax, 27–28
 concrete syntax, 12, 17–19
 environments, 28, 54–55
 evaluation, 20–23
 initial basis, 27
 interpreter
 environments, 44–45
 `eval`, 48–54
 interfaces, 41–47
 values, 43
 local variables, 66, 86
 operational semantics, 32–38
 semantics, informal, 20–22
 Simplified, 62
 imperative features, 402, 403
 implementation(s)
 allocation, 162 (μ Scheme)
 implementation modules, 527, 581
`implicit-data`, 472–473
 impredicative polymorphism, 540, 577
 in modules, 578
 impure languages, 403
 induction principles, 116
 inductively defined data, 116
 specified by recursion equations, 117
 inference rules, 31–32, *see also* operational semantics, typing rules
 binary trees, defining, 109
 case expressions
 evaluation, 490–494
 type inference, 495–499
 data definitions (μ ML), 487–489

inference rules (continued)
 elaboration
 μ ML, 489
 Molecule , 572
 evaluation
 case expressions, 490–494
`Impcore`, 32–38
 μ Scheme, 145–152
 μ Scheme+, 216–223
 pattern matching, 490–494
 form of, 31
 free type variables, 371
 free variables, 316–317
 instantiation, 56
 lists, defining, 116
 overloading (Molecule), 576
 pattern matching
 evaluation, 490–494
 type inference, 495–496
 as Prolog code, S45
 S-expressions, defining, 117
 soundness, 419
 substitution, capture-avoiding, 374
 type compatibility, 487–489
 type equivalence, 369–370
 type translation (μ ML), 489
 types, *see* typing rules
 information hiding, 455, 586
 further reading, 587
 inhabitants
 of intersection types, 541
 of a subtype or supertype, 561
 of types, 334, 388
 of the unit type, 349
 inheritance, 610, 709
 collections and, 649
 effect on dispatch, 631–633
 examples, 620–622
 of instance variables, 614
 initial basis, 26 (defined), 69
 `Impcore`, 30
 μ Scheme, 97
 μ Smalltalk, 636–653
 Molecule , 544
 nano-ML, 440
 Typed μ Scheme, 382
 initialization
 local variables (μ Scheme), 117
 μ Smalltalk examples, 615–616, 621
 of Smalltalk objects, 616, 624
 insertion sort, 101
 algebraic laws, 101
 instance(s), 442, 709
 of classes, 610
 of generic modules, 541
 of inference rules, 56
 of polymorphic functions, 356
 as qualified names, 541

Concept index

759

Concept index

760

- instance(s) (continued)
 - of templates, 166
- instance methods, 614
- instance protocols, 613
- instance relation between types (\leqslant), 410
- instance variables, 614, 624, 709
 - inheritance of, 614
 - in the μ Smalltalk interpreter, 686
 - visibility of, 624
- instantiation, 384, 409–413, 442
 - automatic, 409
 - examples (generic modules), 560
 - examples (types), 358–359
 - explicit, 409
 - of generic modules, 541, 560
 - typing rule, 575
 - implementations, 376, 411, 434
 - implicit, 409
 - of inference rules, 56
 - mistakes, common, with, 358
 - of ML types, 304
 - of ML type schemes, 410
 - of polymorphic functions, 356
 - of polymorphic values, 304 (ML), 371–376
 - quantified types and, 358
 - typing rule, 365
 - rationale, 435
 - of templates for syntactic sugar, 166
 - typing rules
 - generic modules, 575
 - quantified types, 365
- integer(s), *see also* natural numbers
 - implementations (μ Smalltalk), 664, 666–667
 - large, 666
 - small, 666
- integer hierarchy, 651
- Integer protocol, 651
- interfaces
 - in C code, 40
 - design, 545–554
 - design examples, 546–548
 - memory management and, 257
 - Molecule, 528–532
 - in real languages, 580–583
 - separate compilation and, 580
 - Smalltalk, *see* protocols
- InternalError exception, S219
- interpreters
 - Impcore, 38–55
 - μ Scheme (C), 152–162
 - μ Scheme (ML), 303–314
 - μ Scheme+, 223–239
 - μ Smalltalk, 685–700
 - Molecule, 579, S475–524
 - nano-ML, 433–440
- interpreters (continued)
 - Typed Impcore, 337–343
- intersection types
 - “and” operator (\wedge) and, 564
 - components, 541
 - elaboration, 573
 - formation, 541
 - idioms, 541
 - inhabitants, 541
 - Molecule, 541
 - principal module types and, 567
 - subtyping of, 564
- introduction and elimination forms
 - creators, producers, and observers related to, 347
- introduction forms, 347, 384
 - for functions, 348
 - for generic modules, 541
 - for modules, 539
 - for pairs, 348
 - for products, 348
 - for quantified types, 359
 - for sums, 349
- introduction rules, 345 (defined)
 - template, 346
- invariants, 586, 673–677, *see also* representation invariants
 - of stack-based eval, 227
- isKindOf:
 - correct usage, 637
- isMemberOf:
 - correct usage, 637
- it (automatically bound variable)
 - in Impcore, 54
 - in μ Scheme, 160
- iterators
 - observers, as a species of, 645
 - in Smalltalk, 645
- Java
 - abstract types, 707
 - Smalltalk vs, 707
- judgment(s), 30–31, 69
- judgment forms, xviii (table), 69
 - expressing “may differ”, 33
 - expressing “must differ”, 33
 - expressing “must equal”, 33
- keyed collections
 - implementations, 659–660
 - μ Smalltalk protocols, 646, 659
- KeyedCollection protocol, 647
- keys (in association lists), 105
- kind(s), 351–355, 384
 - checking, 378–380
 - implementation, 355–356
 - μ ML, 466
 - in nano-ML, unneeded, 409

kind(s) (continued)
 of primitive type constructors
 Typed μ Scheme, 356
 slogan, 357
 of type constructors, 352
 kinding judgments, 354, 355

lambda, 120–125
 dynamic scoping, 148
 exercises, 187–189
 implementations (C), 156
 implementations (ML), 310
 operational semantics, 147
 small-step semantics, 217
 typing rules
 nano-ML, 414 (nondeterministic),
 446 (constraint-based)
 Typed μ Scheme, 365

lambda abstraction, 120–122, 173

lambda-bound variables, 414, 442
 polymorphism and, 415

lambda calculus, 241
 inspiration for Lisp, 89

lambda expression, *see* lambda, lambda abstraction

Lambda: The Ultimate (further reading), 174

LAMBDA vs LAMBDA, 42

large integers, 666, *see also* multiprecision arithmetic, natural numbers
 invariants, 557

LargeInteger
 class definition, 669
 private methods, 668
 protocol, 651

laws, algebraic, *see* algebraic laws

lazy evaluation, 241

lazy sweeping, 266

leftist heaps, 555–557

length of a list
 algebraic laws, 98
 proof of laws, 114

let
 implementations
 μ Scheme (C), 157–158
 μ Scheme (ML), 310
 μ Scheme+, 231–232, 234–236
 Milner’s, 414, 425–428
 operational semantics, 146
 small-step semantics, 220
 syntactic sugar, 163
 typing rules
 nano-ML, 415 (nondeterministic),
 426 (constraint-based)
 Typed μ Scheme, 363

let binding, 117–120

let-bound variables, 414, 442

letrec, 120, 135
 implementations
 μ Scheme (C), 158–159
 μ Scheme (ML), 311
 μ Scheme+, 234–236
 operational semantics, 146–147,
 364
 polymorphism and, 416
 small-step semantics, 221
 syntactic sugar, 163
 type annotations, 364
 type inference, 415, 420
 typing rules
 nano-ML, 415 (nondeterministic),
 420 (substitutions)
 Typed μ Scheme, 364

let*
 assignment vs, 119
 implementations
 μ Scheme (C), 158
 μ Scheme (ML), 310
 μ Scheme+ (lowering), 214,
 S350
 in μ Scheme, 118
 operational semantics, 146
 syntactic sugar, 163
 typing rules
 Typed μ Scheme, 364

LETX vs LET, 42

lexical analysis, S191

lexical scoping, 148

lexical structure, 14, 15
 of all bridge languages, 17

μ ML value constructors, 469–471

lies, damn lies, and the logical interpretation of Prolog, S63

linear search
 higher-order functions, 127–128

Lisp
 bugs, 148
 conditional expressions, *see* cond
 function application, 148
 inspired by lambda calculus, 89
 recursion in, 90, 98

list(s)
 algebraic laws, 130
 append laws, 99
 in C interpreters, 45–46
 circular, 673
 constructors, 318
 filtering
 function filter, 127
 methods select: and reject:,
 645
 visualizations, 129

Concept index

761

Concept index

762

- list(s) (continued)
 - folding
 - functions `foldl` and `foldr`, 128
 - method `inject:into:`, 645
 - visualizations, 129
 - higher-order functions, 127–131
 - inference rules, defined by, 116
 - insertion laws, 101
 - mapping
 - function `map`, 127
 - method `collect:`, 645
 - visualizations, 129
 - μ ML, 473
 - μ Scheme, 94
 - μ Smalltalk examples, 648
 - μ Smalltalk methods, 643–645, 649
 - operations, 98–101
 - notation, condensed, 99
 - pattern matching on, 475–476
 - primitives' laws, 111
 - principles for programming with, 98–107
 - representation for sets, 104–105
 - reversal, 100
 - searching
 - functions `exists?` and `all?`, 127–128
 - method `detect:`, 643
 - selection
 - function `filter`, 127
 - methods `select:` and `reject:`, 645
 - visualizations, 129
 - transformation
 - function `map`, 127
 - method `collect:`, 645
 - list
 - full Scheme function, 96
 - μ Scheme primitive, 198 (exercise)
 - List (μ Smalltalk class), 674–677
 - list comprehensions
 - in a semantics for Prolog, S110
 - how to implement, S114
 - List protocol, 649
 - literal expressions
 - in μ Scheme, 95
 - μ Smalltalk
 - bootstrapping, 697–699
 - evaluation, 691
 - operational semantics
 - μ Smalltalk, 680
 - small-step semantics, 216
 - Smalltalk-80, 701
 - typing rules
 - Typed Impcore, 335
 - Typed μ Scheme, 363
 - literate programming, 39
 - live data, 289
- local variables
 - initialization (μ Scheme), 117
 - μ Scheme, 117–120
 - location(s), 173
 - fresh, 144, 145
 - of μ Scheme+ objects, 258
 - Molecule, 535
 - mutable, 122–124, 144, 145, 535
 - location semantics, 144–152, 173, 677–685
 - logic (as a programming language), S43–47
 - logic programming, S96
 - logical variables, S45, S96
 - long-goto, 204, 208
 - exercises, 251
 - implementations, 237
 - small-step semantics, 221–222
 - long-label, 204, 208
 - implementations, 236–237
 - small-step semantics, 221–222
 - loop(s)
 - operational semantics
 - Impcore, 35
 - μ Scheme, 149
 - typing rules
 - Typed Impcore, 336
 - Typed μ Scheme, 363
 - loop invariants, 586
 - lowering
 - implementation, 226
 - rules (μ Scheme+), 214, 216
 - semantics, 213–215
 - Lua, for object-oriented programming, 712
 - macros, 171, 373
 - further reading, 175
 - hygienic, 171 (defined)
 - magnitude(s), 709
 - implementations, 656
 - Magnitude (μ Smalltalk class), 656
 - Magnitude protocol, 649–651
 - major (garbage) collection, 286
 - managed heaps, 259 (defined), 289
 - allocation in μ Scheme+, 263
 - size and growth, 262–263
 - manifest types, 530, 538
 - in C, 39
 - as components, 538
 - in real languages, 580
 - mapping, 173
 - higher-order functions, 127
 - methods, 645
 - visualizations, 129
 - mark bits, 266, 290

mark phase
 in μ Scheme+ garbage collector, 268–270
 mark-and-sweep garbage collection, 266–271, 290
 performance, 270–271
 mark-compact garbage collection, 283
 marker methods, 636
 match compilation, 500–501, 503
 matching, *see* pattern matching
 materialization, 179
 “may differ,” in judgment forms, 33
 member? (μ Scheme function), 187
 membership in S-expressions
 algebraic laws, 103
 memory management, 257–299
 evaluation stacks, 229–230
 explicit, 289
 reference counting, 283–285
 memory safety, 240, 257, 290
 in C programs, 385
 message(s), 709
 private, *see* private messages
 to super, 621
 message cascades (Smalltalk-80), 706
 message categories, 613
 in Smalltalk-80, 703
 message names, 612
 arity, 627
 message not understood, 631, 709
 message passing, 609, 709
 basics, 610–611
 message patterns
 in Smalltalk-80, 703
 message selectors, 612 (defined), 631, 709
 message sends
 evaluation, 689–690
 operational semantics, 681–682
 metaclass(es), 630 (defined), 694–695
 in the μ Smalltalk interpreter, 686
 representation, 686
 Metaclass (μ Smalltalk class), 696–697
 metalanguages, 308 (defined), 318
 metatheoretic proofs, 59–66, 69, 116
 about data, 116–117
 construction (how to), 61–65
 example, 63–65
 small-step semantics and, 244
 utility of, 65–66
 metatheory, 59–66, 69, *see also* metatheoretic proofs
 exercises, 195
 metavariables, 70
 in operational semantics, 31
 program variables vs, 19
 for syntax, 19

method(s), 609, 614, 709
 class, 614
 complex, 662–673
 private, *see* private methods
 representations, 677, 686
 method dispatch, 610, 613, 631–633, 710
 conditionals vs, 623, 654–656
 examples, 632
 implementation, 690
 in Smalltalk, 623
 μ ML, 457–499
 abstract syntax, 485–486
 concrete syntax, 467
 predefined functions, 475–476
 predefined types, 464, 473–475
 values, 468, 486
 μ Scheme, 90–172
 abstract syntax, 144–145
 concrete syntax, 93
 initial basis, 97
 predefined functions, 96–100, 104–107, 125–128, S319–320
 primitive functions, 92–96
 primitives, 150–151
 values, 91–92, 145
 μ Scheme+, 202–239
 abstract syntax, 225–226
 introduction, 202–205
 μ Smalltalk, 610–700
 abstract machine, 678–679
 behaviors, 678–679
 concrete syntax, 627–629
 rationale, 611
 initialization, 616
 interfaces, *see* protocols
 predefined classes, 636–653
 primitive classes, 696–697
 primitives, 699–700
 operational semantics, 682
 values, 629–630
 Milner’s let, 414, 425–428
 Milner, Robin, 320, 401
 minor (garbage) collection, 286
 mixed arithmetic
 in μ Smalltalk, 651, 723–724
 in Smalltalk-80, 705
 ML programming
 advantages and disadvantages, 301–303
 C programming vs, 314–315
 conventions, 301–303
 quick reference, 320
 Modula-2, 586, 588
 Modula family, 526
 modular type checking, 558
 further reading, 588
 in real languages, 580

Concept index

763

Concept index

764

- module(s), 525, 527, 587
 - as components, 539
 - definitions, 539
 - desiderata, 527, 581–583
 - elimination forms, 540
 - evaluation, 541–542
 - examples, 528–529
 - exporting, 539
 - further reading, 588
 - generic, *see* generic modules
 - introduction forms, 539
 - nested, 539
 - in real languages, 581
 - objects and classes vs, 588
 - parameters, 540
 - polymorphism, 540–541
 - programming style, 526
 - in real languages, 527, 580–583
 - recursive, 588
 - representations, 541–542
 - uses, 540
- module arrow --m--> , 540
- module-arrow types
 - elaboration, 573
- module types, 528, 587
 - elaboration, 571–574
 - formation, 538–539
 - generic modules, 541
 - independence from modules, 529
 - principal, *see* principal module
 - types
 - in real languages, 581
 - realization, 568
 - rooted, 563
 - strengthening, 559, 570
 - subtyping, 564–566
 - uninhabited, 566
- Molecule, 526–580
 - concrete syntax, 536, 537
 - core layer, 534–538
 - module layer, 538–542
 - overloading, 543–544, 576–577
 - predefined modules, 544
 - primitive types, 544
 - Smalltalk vs, 615
 - subtyping, 564–566
 - syntactic categories, 539
 - type system, 558–579
 - design goals of, 558
 - overloading, 576
 - overview, 562
 - values, 535
- monomorphic functions, 131, 173
- monomorphic type systems, 331, 344, 384
 - limitations, 351
- monotypes, 384, 408, 442
- `msubsn`, 567 (defined)
- multiple arguments
 - functions consuming, 104
- multiple inheritance, 710
- multiple representations
 - with data abstraction, 555–557
 - in object-oriented programming, 662–673
- multiprecision arithmetic, 557
 - invariants, 557
- μML , alphabetized as micro- μML
- μScheme , alphabetized as micro- μScheme
- $\mu\text{Smalltalk}$, alphabetized as micro- $\mu\text{Smalltalk}$
- “must differ”
 - in judgment forms, 33
- “must equal”
 - as constraint \sim , 420
 - in judgment forms, 33
- mutability, 173, 545
 - of abstractions, 625
 - allocation and, 545
 - Molecule, 534, 535
 - of queues, S146
 - in Smalltalk, 625
- mutable locations, *see* locations, mutable
- mutable reference cells, 188, 318
- mutable state
 - of a machine, 11
 - in $\mu\text{Smalltalk}$ class representations, 694
 - shared, 174
 - in a resettable counter, 124
- mutable variables
 - avoided by `let*`, 119
- mutability
 - of abstractions, 545
- mutation, 402
 - in full Scheme, 169
 - observational equivalence and, 636
- mutators (class of operations), 112, 259, 290
 - in protocols, 614
- name(s)
 - $\mu\text{Smalltalk}$ denotations, 631
 - qualified, 528, 540
 - of value constructors for abstract syntax, 42
- name equivalence, 383, *see also* generativity, type equivalence
- name resolution
 - dynamic, 630
 - $\mu\text{Smalltalk}$, 630–631
 - static, 630

- nano-ML, 401–440
 - abstract syntax, 404–405
 - concrete syntax, 404
 - μ Scheme vs, 401
 - operational semantics, 405–407
 - primitive type constructors, 412
 - type system, 407–417
- Natural
 - class-definition template, 670
 - private methods, 671, 672
 - protocol, 652–653
- natural deduction, 32, 70
- natural numbers, S13–22
 - abstraction functions, representations, and invariants, 669–673, S14–15
- nested functions, 121–122, 173
- nested modules, 539
 - in real languages, 581
- nested patterns, 460–461
- new (μ Smalltalk message), 624
 - examples, 621
- new method
 - implementation, 695
- Newton-Raphson technique, 652
- nil (μ Smalltalk object), 630
 - implementation, 696
 - other languages vs, 630
- nondeterminism
 - in calculi, 241
 - in rules for nano-ML, 413–416
 - in semantics, 241
 - in typing, 416–417
- nonterminal symbols, 16
- :not-found exception, 209–210
- Noweb, 39
- null?, 92, 94
- nullary type constructors, 343
- number(s), 710
 - implementations (μ Smalltalk), 663–664
 - Smalltalk-80, 705
- number?, 92
- number hierarchy, 649
- Number protocol, 649–653
- numeric coercions
 - μ Smalltalk, 667–669
- O Lochlainn, Sean, forensic sorcerer, S45
- object(s), 455, 525, 609, 710
 - abstract types vs, 625–627
 - basics, 610–611
 - equality and, 634
 - modules vs, 588
 - in Prolog, S43
- object(s) (Prolog), S96
- Object (μ Smalltalk class), 696
 - implementation, 696
 - protocol, 637
- object identity, 634
 - observational equivalence vs, 635
- object languages, 308, 319
- object-oriented interfaces, *see* protocols
- object-oriented languages
 - origins and evolution, 609
- object-oriented programming, 455, 587
 - abstract classes, 656–662
 - binary operations, 662–673
 - classes, without, 707
 - decision-making code, 654–656
 - functional and procedural programming vs, 624–625
 - historical development, 712
 - invariants and, 673–677
 - in Lua, 712
 - sums of products in, 466
 - technique, 654–677
- Objective C, 712
- observational equivalence, 110, 634
 - in Impcore exercise, 77
 - μ Smalltalk, 635
 - mutation and, 636
 - object identity vs, 635
- observers (class of operations), 111, *see also* creators, producers, and observers
 - elimination forms and, 347
 - in protocols, 614
- OCaml, 399
 - equality, 634
- occurrence equivalence, 383, *see also* generativity, type equivalence
- occurs check, S96
 - in Prolog, S60
 - in type inference, 429
- operational semantics, 29–32, 68, 70, *see also* small-step semantics
- abstract-machine, 211
- assignment (set)
 - Impcore, 34
 - μ Scheme, 145
 - μ Smalltalk, 680
- big-step, 31
- blocks, 681
- car, 151
- cdr, 151
- class definitions, 685
- closures, 147, 681
- conditional expressions (*if*)
 - Impcore, 34
 - μ Scheme, 149
- cons, 151

Concept index

765

Concept index

766

- operational semantics (continued)
 - control operators, 210, 221–222, 683–684
 - Core μ Scheme+, 215–223
 - `define`
 - Impcore, 38
 - μ Scheme, 152
 - dynamic scoping, 148
 - function application
 - Impcore, 36, 37
 - Lisp, 148
 - μ Scheme, 147, 150
 - global variables, 151–152
 - Impcore, 32–38
 - `lambda`, 147
 - `lambda` (dynamic scoping), 148
 - `letrec`, 146, 364
 - literal expressions
 - μ Smalltalk, 680
 - loops
 - Impcore, 35
 - μ Scheme, 149
 - lowering, 213–215
 - message send, 681–682
 - μ Scheme, 144–152
 - μ Smalltalk vs, 677–678
 - μ Scheme+, 210–223
 - μ Smalltalk, 677–685
 - μ Scheme vs, 677–678
 - μ Smalltalk primitives, 682
 - mutation-free, 405–407
 - nano-ML, 405–407
 - natural-deduction, 32
 - nondeterministic, 241
 - reduction, 215
 - `return`
 - μ Scheme+, 222
 - μ Smalltalk, 683–684
 - sequencing (`begin`)
 - Impcore, 35
 - μ Scheme, 149
 - μ Smalltalk, 679
 - small-step, *see* small-step semantics
 - stack-based, 210–213
 - `super`, 680
 - uses, 240–242
 - `val`
 - Impcore, 38
 - μ Scheme, 151
 - μ Smalltalk, 685
 - nano-ML, 407
 - variables
 - Impcore, 32
 - μ Scheme, 145
 - μ Smalltalk, 680
 - nano-ML, 405
- operator classifications, 111–112, 546, *see also* creators, producers, and observers
- optimized tail calls, 170, 214
 - exercises, 251–252
 - further reading, 246
 - implementations, 238–239
 - in real languages, 239
- order of evaluation, 35, 403
- order type (μ ML), 474
- overheads
 - copying garbage collection, 279
 - mark-sweep garbage collection, 270
- overloading, 132, 383, 543–544
 - elaboration (Molecule), 576
 - evaluation (Molecule), 577
 - examples, 543–544
 - Molecule, 543, 576–577
 - parametric polymorphism vs, 383
 - in real languages, 584–585
 - resolution, 544
 - via type classes, 585, 589
- overriding (of methods), 614, 632, 710
- \mathcal{P} (primitive function in identifier cross-reference), 39
- pages (units of heap), 267–268
- pair type(s)
 - algebraic laws, 349
 - typing rules, 348–349
- pair type (μ ML), 464
- pangrams, 103
- parameters, accumulating, 101
- parametric polymorphism, *see* polymorphism, parametric
- partial application, 125–127
- paths, *see* access paths
- pattern(s), 319, 501
 - exhaustive, 499
 - μ ML, 466
 - nested, 460–461
 - overlapping, 500
 - redundant, 319, 500
- pattern matching, 319, 458, 501
 - benefits, 501
 - compilation, 500–501, 503
 - compile-time checks, 499–500
 - efficiency, 500–501, 503
 - equational reasoning, 476–479
 - in Erlang, 499
 - evaluation, 490–494
 - examples, 307, 309–312, 459–466, 475–476
 - exhaustive, 499
 - in ML, 307
 - nested patterns, 460–461
 - operational semantics, 490–494

pattern matching (continued)
 semantics, informal, 468–469
 syntactic sugar, 480–483
 type inference, 495–499
 typing rules, 495–496 (nondeterministic), 497–499 (constraint-based)
 ubiquitous, 480–483
 wildcards, 461
 phantom types, S37
 Pharo (Smalltalk system), 712
 phase(s)
 in language processing, 13–14
 phase distinction, S392
 π , *see* access paths
 π -calculus, 241, 247
 pictures (μ Smalltalk example), 616–618
 PLT Redex, 246
 polymorphic equality, 633
 polymorphic functions, 131
 recursive, 359–360
 polymorphic type(s), 319
 of list functions, 358
 polymorphic type systems, 328, 351–382, 384
 advantages, 351
 origins, 385
 polymorphic, recursive functions
 in Typed μ Scheme, 359
 polymorphism, 132, 173, 332, 344, 384
 ad hoc, 132, 544, *see also* overloading
 impredicative, 540, 577
 in modules, 578
 lambda-bound variables and, 415
 in μ Scheme, 131–136
 in ML, 304
 modules, 526
 in Molecule
 nano-ML vs, 577
 Typed μ Scheme vs, 577–578
 in nano-ML vs Molecule, 577
 parametric, 132, 384, 401
 of lists, 116
 predicative, 540, 577
 programming technique, 133–135
 in Scheme, 133–135
 species of, three, 132
 subtype, 132, 646
 in Typed μ Scheme vs Molecule, 577–578
 polytypes, 385, 408, 442
 limited to type environments, 413
 predefined functions, 26, 70, *see also* initial basis
 Impcore, 27
 μ ML, 475–476

predefined functions (continued)
 μ Scheme, 96–100, 104–107, 125–128, S319–320
 nano-ML, 440
 Typed Impcore, 331
 predefined modules
 Molecule, 544
 predefined types
 μ ML, 464, 473–475
 predicate(s) (in Prolog), S45, S96
 predicate logic, S96
 predicate transformers, 246
 predicative polymorphism, 540, 577
 premises
 in inference rules, 31
 of a Prolog clause, S52
 preservation (proof technique), 240
 primitive classes (μ Smalltalk), 696–697
 primitive functions, 26, 70, *see also* initial basis
 environment ϕ and, 30
 Impcore, 23–24
 μ Scheme, 92–96, 150–151, 160–162, 306, 312–314
 nano-ML, 440
 Typed μ Scheme, 381–382
 primitive type constructors
 Molecule, 544
 nano-ML, 412
 Typed μ Scheme, 381
 primitives, μ Smalltalk, 699–700
 evaluation, 692–693
 operational semantics, 682
 principal module types, 561, 566–571
 computing (how to), 568–571
 intersection and, 567
 subtyping and, 566
 principal type(s), 416–417, 442
 testing, 402, 417
 principal type schemes, 417
 printu, 23
 private messages
 in μ Smalltalk collection classes, 658
 Natural (μ Smalltalk class), recommended for, 670, 672
 in Smalltalk, 623
 private methods, 616, 623, 710
 examples, 668
 μ Smalltalk integer classes, 668
 Natural, 671, 672
 representations, exposing with, 664
 in Smalltalk, 710
 procedural programming, 11, 70, 201–202, 204
 functional programming vs, 206–207

Concept index

767

Concept index

768

- procedural programming (continued)
 - object-oriented programming vs, 624–625
- producers (class of operations), 111, *see also* creators, producers, and observers
 - introduction forms and, 347
 - in protocols, 614
- product types, 465
 - algebraic laws, 349
 - typing rules, 348
- program variables, *see also* variables
 - metavariables vs, 19
- program verification, 553
- programming conventions
 - C code, 39–40
 - ML code, 301–303
- progress and preservation (proof technique), 240
- projections, 308, 319, *see also* embeddings
- Prolog, S43, S95
 - arity, S50
 - “backward” execution in, S56
 - difference lists, S76
 - logical interpretation, S55
 - occurs check, S96
 - primitive predicates, S68
 - procedural interpretation, S61
 - logical interpretation vs, S63, S95
 - real, S90
 - semantics, S91
 - syntax, S90
 - semantics, S55
 - syntax, S52
 - unification, S60
- prompt (control operator), 247
- proof(s)
 - of abstract types, 588
 - calculational, *see* calculational proofs, equational reasoning
 - derivations, about, 59–66
 - derivations as, 56–59
 - metatheoretic, 59–66
 - about data, 116–117
 - in operational semantics, 55–66
 - by structural induction, 115
- proof principles
 - induction, 116
- proof techniques
 - small-step semantics, 240
- proper tail recursion, 170, 174, *see also* optimized tail calls
 - further reading, 246
- propositional logic, S97
- propositions as types, 347, 727–729
- protocols
 - of objects, 613
- prototypes
 - in object-oriented programming languages, 707
- public components, 538
- public names, 527
- pure expressions, 110
- pure languages, 403
- qualified names, 528, 540
 - from generic modules, 541
- quantification, existential
 - in algebraic data types, S25
- quantified types, 351, 356–360, 385
 - elimination form, 358
 - introduction form, 359
 - in nano-ML, 407–408
- quasiquotation, 169, 197 (exercise)
- Racket (Scheme dialect), 168
- raise an exception, 583
- random-number generation
 - higher-order functions, 124–125
- rational numbers
 - in μ Smalltalk, 664–666
- reachability, 258–261, 290
 - examples, 258–259
 - in μ Scheme+, 263–264
- realization
 - of module types, 567, 568
- receiver(s), 610, 612, 710
- receiver-first syntax
 - rationale, 611
- records
 - encoded as S-expressions, 107–109
 - exercises, 181, 196
 - μ Scheme, 107–109
 - Molecule, emulation in, 533
 - syntactic sugar, 167–168
 - Molecule, 542
 - types, 383
- recursion
 - difference lists, avoiding with, S77
 - example of evaluation, 99
 - on lists, 98–107
 - modules, 588
 - open, 710
- recursion equations (to define data), 117
- recursive definitions, 120
- recursive evaluation
 - stack-based evaluation vs, 211–213
- recursive functions
 - `letrec` and, 120, 135
 - polymorphic, 359–360
- recursive, polymorphic functions
 - in Typed μ Scheme, 359

recursive types, 465
 examples, 463–464
 redefinition
 of Smalltalk methods, 614
 Redex, 246
 reduction
 in a calculus, 241
 in parsing, S194
 reduction semantics, 241, 245
 further reading, 246
 redundant patterns, 319, 500
 reference cells, mutable, 188, 318
 reference counting (memory management), 259, 283–285, 290
 reflection, 711
 in μ Smalltalk, 630
 in Prolog, S93
 in Smalltalk-80, 630, 706–707
 relations, S97
 as a programming tool, S43–47
 rely-guarantee reasoning, 587
 to satisfy invariants, 552
 remembered set, 286
 renaming
 implementations, 375
 of type variables, 368–369
 of variables, S58
 representation invariants, 545, 550, 587, 711
 binary search trees, 550
 circular lists, 673
 complex numbers, 551
 data structures, typical and, 549–551
 dictionaries, 549
 environments, 54
 examples, 551–554, 556, 664
 floating-point numbers (μ Smalltalk), 652
 fractions (μ Smalltalk), 664
 large integers, 557
 leftist heaps, 556
 metaclasses, 694
 natural numbers, 670, 672
 priority queues, 550, 552
 rational numbers, 664
 sets, 548
 two-dimensional points, 551
 reserved words, 19
 reset (control operator), 247
 return, 202
 big-step judgment forms, 677
 in do: loop (Smalltalk), 657
 evaluation
 μ Scheme+, 237
 μ Smalltalk, 689
 μ Scheme+ control operator, 202
 μ Smalltalk control operator, 677

return (continued)
 operational semantics
 μ Scheme+, 222
 μ Smalltalk, 683–684
 real implementations, 239
 small-step semantics, 221–222
 return addresses, 239
 revelations (of type identities), 530
 reversal of lists, *see* lists, reversal
 RⁿRS Scheme standards, 168
 root(s), 260–261, 290
 of absolute access paths (Molecule), 559
 in μ Scheme+, 265
 of module types in environments, 563
 rooted module types, 563
 rules, S97
 inference, *see* inference rules
 lowering (μ Scheme+), 214
 in Prolog, S45
 typing, *see* typing rules
 run-time errors, 47
 checked, 40
 unchecked, 40
 S-expressions, 91–92, 174
 equality, 104
 fully general, 94
 functions involving, 103–104
 inference rules, defined by, 117
 limitations, 457
 ordinary, 92
 records, encoded with, 107–109
 trees, encoded with, 109–110
 safety properties, 240, *see also* memory
 safety, type safety
 satisfaction (of type-equality constraints), 428
 satisfiability, *see* Boolean satisfiability
 satisfying assignment, 138
 to logical variables in Prolog, S49
 Scheme, *see also* μ Scheme
 continuations, 172
 data abstraction in, 588
 equality, 633
 μ Scheme vs, 168–172
 Smalltalk blocks and, 638
 standards, 168
 scoping (dynamic, lexical, and static), 148
 scrutinees, 458, 459, 468, 502
 evaluated in case expressions, 490
 sealing, 532, 539
 examples, 558–560
 in real languages, 580
 in the subtype relation, 566
 type checking, 564

Concept index

769

Concept index

770

- sealing (continued)
 - type constructors and, 535
- search
 - with default result, 137
 - higher-order functions for, 127–128
 - using continuations, 136–143
- selection from lists
 - higher-order functions, 127
 - μ Smalltalk methods, 645
 - visualizations, 129
- selectors, *see* observers
- self, 615, 711
- Self (programming language), 609, 707
- semantics, big-step, *see* operational semantics
- semantics, denotational, *see* denotational semantics
- semantics, operational, *see* operational semantics
- semantics, small-step, *see* small-step semantics
- semispaces, 271
- sentinels
 - in μ Smalltalk lists, 673
- separately compiled interfaces
 - in real languages, 580
- sequenceable collections
 - implementations, 661–662
 - protocols, 648–649, 659
- SequenceableCollection protocol, 648
- sequencing, *see* begin
- set(s)
 - of association lists, 132–135
 - represented as lists, 104–105, 131
- set, *see* assignment, *see also* mutable variables
- set functions
 - algebraic laws, 105
 - polymorphism, 131–133
- shape(s), 611–612, 619–622
 - protocol, 620
- Shape, Smalltalk-80 class, 702
- shared mutable state, *see* mutable state, shared
- shift (control operator), 247
- shift-reduce parsing, S194
- short-circuit Boolean operators, 164–165, 174, 195, 320
- side effects, 16, 20, 343
- signatures, 528, 581
- simple equality constraints, 420
 - solving, 429–430
- Simplified Impcore, 62
- Simula 67, 586, 588, 609
 - inspiration for Smalltalk, 707, 712
- simultaneous substitution, 166, 365
- single inheritance, 711
- Skolem types, S31
- slots (in object-oriented languages), 707
- small integers, 666
- small-step semantics, 71, 210–213, 215–223, 245
 - function application, 218–220
 - further reading, 246
 - if, 217–218
 - lambda, 217
 - let, 220
 - letrec, 221
 - literal expressions, 216
 - long-goto, 221–222
 - long-label, 221–222
 - metatheoretic proofs and, 244
 - proof techniques, 240
 - return, 221–222
 - set, 217
 - tracing, 224–225
 - uses, 240–242
 - variables, 217
- SmallInteger
 - private methods, 668
 - protocol, 651
- Smalltalk-80, 700–707
 - binary messages, 703
 - class hierarchies, 642, 704–707
 - class instance variables, 704
 - class variables, 704
 - in simulations, S140
 - Collection hierarchy, 705–706
 - concrete syntax, 702–704
 - development, 711
 - images, 701
 - literals, 701
 - message cascades, 706
 - numbers, 705
 - as operating system, 700–701
 - precedence, 703
 - as programming language, 701–704
 - reflection, 706–707
 - syntax, 624
 - UndefinedObject class, 654
- smart constructors
 - in binary tries, 513
- solvers
 - Boolean formulas, 139–143
 - conjunctive normal form
 - code, 143
 - laws, 141, 142
 - type-equality constraints, 418, 428–431
- sorting, 101
- soundness, S97, *see also* type soundness
 - of algebraic laws, 65
 - generalization, 427
 - Molecule, 578

- soundness (continued)
 - proofs, 419
 - rules for explicit substitutions, 419
 - of type systems, 350
 - type-lambda, 377–378
- Spock, 588
- square brackets
 - in bridge languages, 117
 - recommended usage, 117
- square roots, 652
- Squeak (Smalltalk system), 712
- stack(s)
 - evaluation, 202, 730
 - in real languages, 239
 - tracing, 224–225
- stack allocation, 290
- stack-based evaluation
 - examples, 212–213
 - recursive evaluation vs, 211–213
- stack frames
 - abstract syntax, 225–226
 - evaluation contexts and, 242
 - μ Scheme+, 214
 - μ Smalltalk, 678
 - representation, 223–224
- standard libraries, 26, *see also* initial basis
- Standard ML, 526
 - equality, 633
- standards, Scheme, 168
- statements (syntactic category), 16
- static scoping, 148
- static typing, 327
 - sample guarantees, 328
- static variables (in C), 124
- stone knives, 588
- stop-the-world garbage collection, 260
- stores, 174
 - linear, 144
 - in location semantics, 144
 - single-threaded, 144, 154
- streams, S226–233
 - for reading from files, S237
- strengthening, 559, 570, 571
- strict evaluation, 241
- struct types, 383
- structural equivalence, 383
 - in type systems, 483
- structural induction, 115
- structured control-flow constructs, 11
- structured operational semantics, *see* operational semantics
- structured programming, 201–202
- structures (Standard ML form), 527
- subclasses, 711
 - examples, 620–622
 - subtypes vs, 713
- subclassResponsibility, 622, 624
 - examples, 621
- subgoals, S97
 - of a Prolog clause, S52
- substitution, 371–373, 409–412, 442, S97,
 - see also* substitutions
 - capture-avoiding, *see* capture-avoiding substitution
 - of equals for equals, 113
 - evaluation via, 166, 731
 - quantified types and, 356
 - simultaneous, 365
 - syntactic sugar and, 165–167
 - in translations for μ Scheme, 162
 - for type variables, 372
 - uses, 165–166
- substitutions, *see also* substitution
 - for abstract types, 567
 - algebraic laws, 409–410
 - composition, 410–411
 - creation, 411
 - explicit, 417
 - typing judgment, 418
 - generality, 442, S60
 - implementations, 410
 - interpretations, 409, 410
 - from manifest types, 567
 - Molecule, 579
 - most general, 442
 - type inference, 418–420
 - for variables, 411
 - subtype polymorphism, 132, 646
 - subtyping, 587
 - behavioral, 627, 708
 - direction of, 561
 - module types, 561, 564–566
 - Molecule, 564–566
 - rules for, 564
 - subclassing vs, 713
 - success continuations, 136, 139
 - sum types, 465
 - C, poor support in, 41
 - rules, 349–350
 - sums of products, 465–466, 502
 - in C, 465
 - in object-oriented languages, 466
 - programming techniques, 465–466
 - in Smalltalk, 624
 - super, 711
 - examples, 621
 - idiomatic usage, 632–633
 - messages to, 632
 - operational semantics, 680
 - superclasses, 610, 614, 624, 711
 - Shape example, 620
 - supertypes, direction of, 561
 - symbol(s) (μ Scheme values), 92
 - symbol(s) (μ Smalltalk objects), 630

Concept index

771

Concept index

772

- symbol?, 92
- symbol tables, *see* environments
- synerror, 47
- syntactic abstractions, *see* macros
- syntactic categories, 16, 71
 - Molecule, 539
 - types, 330
- syntactic forms, 15, 71
- syntactic proofs, 55–66
- syntactic sugar, 26, 66, 71, 162, 174
 - && and ||, S209
 - begin, 167
 - Boolean operators, 164–165
 - cond, 163–164
 - define, 152
 - described as, 120
 - Impcore, extending with, 66–67
 - implementation, 195–197
 - let, 163
 - let*, 163
 - letrec, 163
 - in μ Scheme+, 204–205
 - Molecule, 535, 537
 - pattern matching, 480–483
 - records, 167–168
 - Molecule, 542
 - short-circuit operators, 164–165
 - while*, do-while, and for, 66
- syntax, *see* abstract syntax or concrete syntax
- syntax errors, 47
- System F, 385
- θ (substitution), 409
- tables, *see* finite maps
- tail call(s), 170, *see also* optimized tail calls
 - in continuation-passing style, 170
 - further reading, 246
 - implementations, 238–239
 - optimized, 170, 214
 - proper, 214
- tail-call optimization, *see* optimized tail calls
- tail position, 253
- tail recursion, *see* tail calls
- takewhile, 206
- talent imitates; genius steals, S245
- term(s), 333, 385, S97
 - expressions, as theory-speak for, 333
 - in Prolog, S44
- term variables, 408
- theory (vs metatheory), 59
- throw, 202, 207–210
 - examples, 208–210
 - in real languages, 240
- throwing an exception, 207
- Tiger! Tiger! Tiger!, 56, 113, S13, S397
- TikzCanvas (μ Smalltalk class), 618–619
- to-space, 271 (defined)
- tokens, lexical, 14, S191
- tracing
 - message sends, 640, 641
 - μ Scheme calls, 198
 - small-step evaluation, 224–225
 - Smalltalk, S583
- transformation of lists
 - higher-order functions, 127
 - methods, 645
- tree(s)
 - encoded as S-expressions, 109–110
 - μ Scheme, 109–110
 - traversal(s), 110, 118, 266
 - traversal exercises, 181, 515
- tree-node functions
 - algebraic laws, 109
- tricolor marking, 261–262, 290
 - in concurrent and generational collectors, 286
 - in copying collectors, 273
 - examples, 274–276
 - in mark-sweep collectors, 269
- tries
 - exercises, 512–514
- trivial constraint, 420
- Trotsky, Leon, 136
- True (μ Smalltalk class), 655
- true definitions, 18
- try-catch, 204, 207–210
 - examples, 208–210
 - in real languages, 240
- tuple types
 - algebraic laws, 349
 - typing rules, 348
- type(s), 385, 442, *see also* type systems
 - algebraic notation for, 357
 - arrays, 343
 - dependent, 727
 - elaboration (Molecule), 571–574
 - inhabitants, 334
 - modules, *see* module types
 - Molecule, 535
 - nano-ML, 407–409
 - notation for, 357
 - principal, 416–417
 - quantified, 351, 356–360
 - representation
 - Typed μ Scheme, 357
 - Typed Impcore, 331
 - uninhabited, 334
 - user-defined, 459–476, 486–490, 502
 - uses, 327–328
- type abbreviations, 320, 484, 502, 529
 - in ML, 303

- type abstraction, 385, *see also*
 - type-lambda
 - implicit, 413
 - in ML, 412
 - typing rules, 365
- type annotations, 401
- type application, 358, 385, *see also* instantiation
 - implicit, 413
 - in ML, 412
 - typing rules, 365
- type ascriptions
 - in Standard ML, 441
- type checkers, 329, 385, *see also* type checking
 - arrays, 348
 - μ ML, 489, 497, 498
 - Molecule, S496–518
 - nano-ML, 437–439
 - Typed Impcore, 338–342
 - Typed μ Scheme, 366–367
- type checking, 327, *see also* type checkers
 - modular, 558
 - in real languages, 580
 - Molecule
 - definitions, 570–571
- type classes, 589
 - overloading and, 585
- type components, 538
- type constructors, 385
 - M (set of), 487
 - nano-ML, 407, 409
 - nullary, 343
 - representations (μ ML), 485
 - sealing and, 535
 - Typed Impcore, 333
- type declarations, manifest, 530
- typedef, 484
- type environments
 - nano-ML, 407–409
 - Typed Impcore, 333
- type equality, *see also* type equivalence
 - dire warning about, 332
- type-equality constraints, 418, 420–431, 442
 - grammar, 420
 - solving, 428–431
 - typing judgment, 420
- type equivalence, 367–370
 - Hindley-Milner, 412
 - μ ML, 483–485
 - Molecule, 559
 - nano-ML, 412
 - in real languages, 383
 - rules, 369–370
 - structural, 483
 - Typed Impcore, 332
- type equivalence (continued)
 - Typed μ Scheme, 370
 - type erasure, 380
 - type-formation rules, 345, 347
 - kinds vs, 352–355
 - modules, 538–539
 - template, 346
 - Typed Impcore, 334
 - type generativity, 483–485, *see also* generativity
 - type identity
 - examples, 559
 - type inference, 327, 401, 442
 - constraints for, 420–428
 - decidability, 401
 - implementations, 437–439
 - performance, 430
 - polymorphic types, 423–424
 - substitutions for, 418–420
 - type-lambda, 412, *see also* type abstraction
 - implicit, 413
 - side conditions, 377–378
 - soundness, 377–378
 - in Typed μ Scheme, 352, 359
 - typing rules, 365
 - variable capture and, 377–378
 - type-level expressions, 352, 357
 - type parameters, 132, 304, 327, 356
 - type predicates
 - μ Scheme, 92
 - for records, 108
 - type safety, 328–329
 - type schemes, 407–409, 442
 - canonical, 433
 - degenerate, 414
 - principal, 417
 - type soundness, 350–351
 - type synonyms, *see* type abbreviations
 - type systems, 327, 385
 - design (Molecule), 577–579
 - design goals (Molecule), 558
 - further reading, 385
 - loopholes, 376–377
 - μ ML, 483–486, 495–499
 - modules
 - further reading, 588
 - Molecule, 558–579
 - environment lookup, 574–576
 - formalism, 561–564
 - overloading, 576–577
 - overview, 562
 - soundness, 578
 - nano-ML, 407–417
 - in real languages, 383
 - restrictive, 328
 - soundness, 350–351
 - soundness (Molecule), 578

Concept index

773

Concept index

774

- type systems (continued)
 - subversion, 376–377
 - Typed Impcore, 333–337
 - Typed μ Scheme, 352–378
- type variables, 320, 356
 - captured by a naïve instantiation, 373
 - fresh, 433–434
 - nano-ML, 407
 - term variables vs, 408
 - understanding, 356
- typing
 - of definitions, 341, 366
 - nondeterministic, 416–417
- typing contexts
 - Molecule, 562
- typing judgments
 - Molecule, 565
 - nano-ML, 418 (explicit substitutions), 420 (constraints)
 - Typed Impcore, 335, 336
 - Typed μ Scheme, 363
- typing rules
 - arrays, 346–348
 - arrow types, 348
 - case expressions, 349, 495–496 (nondeterministic), 497–499 (constraint-based)
 - functions, 348
 - μ ML 495–496 (nondeterministic), 497–499 (constraint-based)
 - Molecule definitions, 569
 - nano-ML, 412 (nondeterministic), 416 (nondeterministic), 421 (constraint-based), 428 (constraint-based)
 - pairs, 348–349
 - pattern matching, 495–496 (nondeterministic), 497–499 (constraint-based)
 - products, 348
 - sums, 349–350, *see also* sum types
 - tuple types, 348
 - tuples, 348
 - Typed Impcore, 334–337
 - Typed μ Scheme, 361–366
 - typical, 348–350
 - unions, 349–350
- μ ML, alphabetized as micro-ML
- unchecked run-time errors, 40
 - in `getline_`, S165
 - in printing functions, 46
 - from unspecified values, 151
- uncurried functions, 125
- uncurrying, 126
- `UndefinedObject` (μ Smalltalk class), 630, 696
- undelimited continuations, 243, 245
- understood
 - message in Smalltalk, 631
- unfold, S230
- Unicode characters (μ Smalltalk), 641
- Unicode code points, 23
- unification, 417, 442, S97
 - in type inference, 417
- unifiers, 418
- uninhabited module types
 - examples, 566
- uninhabited types, 334
- union types
 - rules, 349–350
- unit tests, 24–26
- unit type, 334
- unreachability, *see* reachability
- unsafe functions
 - for printing, 46
- unsafe language features
 - uses, 328–329
- unspecified values, 146
 - in μ Scheme, 151
 - misuse by careless persons, S328
 - in Typed μ Scheme, 380
- unwinding (call stacks), 583
- μ Scheme, alphabetized as micro-Scheme
- use (extended-definition form), 23, 25
- user-defined functions
 - in Impcore environment ϕ , 30
- user-defined types, 459–476, 486–490, 502
- μ Smalltalk, alphabetized as micro-Smalltalk
- val, 22
 - operational semantics
 - Impcore, 38
 - μ Scheme, 151
 - μ Smalltalk, 685
 - semantic comparison, 402
 - typing rules
 - nano-ML, 416 (nondeterministic), 423 (constraint-based)
 - Typed Impcore, 337
 - Typed μ Scheme, 366
- val-rec, 402
 - rationale, 362
 - typing rules
 - nano-ML, 416 (nondeterministic)
 - Typed μ Scheme, 366
- valid derivations, 57–58
- value(s)
 - μ ML, 468, 486
 - μ Scheme, 91–92, 120, 145
 - μ Smalltalk, 629–630
 - in μ Smalltalk semantics, 677

- value(s) (continued)
 - Molecule, 535
 - nano-ML, 405
 - representations
 - μ Scheme (C), 152–153
 - μ Scheme (ML), 306
 - μ Smalltalk, 685–686
 - Typed Impcore, 332
 - unspecified, 146
- value components, 538
- value constructors, 320, 457, 466, 502
 - in Erlang, 499
 - misspelled, 470
 - in Molecule, 533
 - names usable for abstract syntax, 42
 - in patterns, 458
 - polymorphic, 462–463
 - Prolog equivalent of, S52
 - representations (μ ML), 490
 - value variables vs, 468–471
- value restriction
 - exercises, 452
 - in ML, S81
- value semantics, 174, 405–407
- value variables, 466
 - value constructors vs, 468–471
- “varargs”, *see* variadic functions
- variable(s), *see also* metavariables, program variables, term variables, type variables, value variables
 - global, 151–152
 - logical, *see* logical variables
 - metavariables vs, 19
 - operational semantics
 - Impcore, 32
 - μ Scheme, 145
 - μ Smalltalk, 680
 - small-step semantics, 217
 - Smalltalk-80 meaning, 614
 - typing rules
 - nano-ML, 413 (nondeterministic), 422 (constraint-based)
 - Typed Impcore, 335
- variable(s) (continued)
 - typing rules (continued)
 - Typed μ Scheme, 363
 - value constructors vs, 468–471
 - variable capture, 373
 - in desugaring for ||, 165
 - of type variables, 373
 - type-lambda and, 365, 377–378
 - variadic functions, 169, 322 (exercise), S177
 - for extensible printers, S177
- verification
 - of invariants, 553
- visibility
 - abstract types vs objects, 626
 - instance variables, 624
 - μ Smalltalk, 631
 - to μ Smalltalk methods, 615
 - Molecule, 631
 - objects vs abstract types, 626
- visualizations
 - backtracking, 139
 - list operations, 129
- weakest preconditions, 246
- wedge (\wedge , type intersection), 564
- while
 - operational semantics
 - Impcore, 35
 - μ Scheme, 149
 - typing rules
 - Typed Impcore, 336
 - Typed μ Scheme, 363
- WHILEX vs WHILE, 42
- white objects, 261
 - in copying collection, 273
 - in mark-sweep collection, 269
- wholemeal programming, 172
- wildcard patterns
 - in μ ML, 461
 - in ML, 307
- write barrier, 286
- wrong, *see* going wrong
- Xerox PARC, 711
- zippers, 510–512 (exercise)

Concept index

775