The Racket Guide

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This guide is intended for programmers who are new to Racket or new to some part of Racket. It assumes programming experience, so if you are new to programming, consider instead reading *How to Design Programs*. If you want an especially quick introduction to Racket, start with Quick: An Introduction to Racket with Pictures.

Chapter 2 provides a brief introduction to Racket. From Chapter 3 on, this guide dives into details—covering much of the Racket toolbox, but leaving precise details to *The Racket Reference* and other reference manuals.

The source of this manual is available on GitHub.

Contents

1 Welcome to Racket **16**

1.1 Interacting with Racket 17

1.2 Definitions and Interactions 17

1.3 Creating Executables 18

1.4 A Note to Readers with Lisp/Scheme Experience 19

2 Racket Essentials **20**

2.1 Simple Values 20

2.2 Simple Definitions and Expressions 21

2.2.1 Definitions 21

2.2.2 An Aside on Indenting Code 22

2.2.3 Identifiers 23

2.2.4 Function Calls (Procedure Applications) 23

2.2.5 Conditionals with `if`, `and`, `or`, and `cond` 25

2.2.6 Function Calls, Again 28

2.2.7 Anonymous Functions with `lambda` 28

2.2.8 Local Binding with `define`, `let`, and `let*` 30

2.3 Lists, Iteration, and Recursion 32

2.3.1 Predefined List Loops 33

2.3.2 List Iteration from Scratch 34

2.3.3 Tail Recursion 35

2.3.4 Recursion versus Iteration 37

2.4 Pairs, Lists, and Racket Syntax 38

2.4.1 Quoting Pairs and Symbols with `quote` 39

2.4.2 Abbreviating quote with ' . . . 41
2.4.3 Lists and Racket Syntax . . . 42

3 Built-In Datatypes 44

3.1 Booleans . . . 44
3.2 Numbers . . . 44
3.3 Characters . . . 47
3.4 Strings (Unicode) . . . 49
3.5 Bytes and Byte Strings . . . 50
3.6 Symbols . . . 52
3.7 Keywords . . . 54
3.8 Pairs and Lists . . . 55
3.9 Vectors . . . 58
3.10 Hash Tables . . . 59
3.11 Boxes . . . 61
3.12 Void and Undefined . . . 61

4 Expressions and Definitions 63

4.1 Notation . . . 63
4.2 Identifiers and Binding . . . 64
4.3 Function Calls (Procedure Applications) . . . 65
4.3.1 Evaluation Order and Arity . . . 66
4.3.2 Keyword Arguments . . . 66
4.3.3 The apply Function . . . 67
4.4 Functions (Procedures): lambda . . . 68
4.4.1 Declaring a Rest Argument . . . 69

4.4.2 Declaring Optional Arguments . . . 70
4.4.3 Declaring Keyword Arguments . . . 71
4.4.4 Arity-Sensitive Functions: `case-lambda` . . . 73
4.5 Definitions: `define` . . . 74
4.5.1 Function Shorthand . . . 74
4.5.2 Curried Function Shorthand . . . 75
4.5.3 Multiple Values and `define-values` . . . 76
4.5.4 Internal Definitions . . . 78
4.6 Local Binding . . . 79
4.6.1 Parallel Binding: `let` . . . 79
4.6.2 Sequential Binding: `let*` . . . 80
4.6.3 Recursive Binding: `letrec` . . . 81
4.6.4 Named `let` . . . 82
4.6.5 Multiple Values: `let-values`, `let*-values`, `letrec-values` . . . 83
4.7 Conditionals . . . 84
4.7.1 Simple Branching: `if` . . . 84
4.7.2 Combining Tests: `and` and `or` . . . 85
4.7.3 Chaining Tests: `cond` . . . 85
4.8 Sequencing . . . 87
4.8.1 Effects Before: `begin` . . . 87
4.8.2 Effects After: `begin0` . . . 88
4.8.3 Effects If...: `when` and `unless` . . . 89
4.9 Assignment: `set!` . . . 90
4.9.1 Guidelines for Using Assignment . . . 91
4.9.2 Multiple Values: `set!-values` . . . 93

4.10 Quoting: `quote` and `'` . . . 94
4.11 Quasiquoting: `quasiquote` and `` ` `` . . . 96
4.12 Simple Dispatch: `case` . . . 98
4.13 Dynamic Binding: `parameterize` . . . 99

5 Programmer-Defined Datatypes **103**

5.1 Simple Structure Types: `struct` . . . 103
5.2 Copying and Update . . . 104
5.3 Structure Subtypes . . . 104
5.4 Opaque versus Transparent Structure Types . . . 105
5.5 Structure Comparisons . . . 106
5.6 Structure Type Generativity . . . 107
5.7 Prefab Structure Types . . . 108
5.8 More Structure Type Options . . . 110

6 Modules **115**

6.1 Module Basics . . . 115
6.1.1 Organizing Modules . . . 116
6.1.2 Library Collections . . . 117
6.1.3 Packages and Collections . . . 118
6.1.4 Adding Collections . . . 119
6.1.5 Module References Within a Collection . . . 120
6.2 Module Syntax . . . 121
6.2.1 The `module` Form . . . 121
6.2.2 The `#lang` Shorthand . . . 123
6.2.3 Submodules . . . 123

6.2.4 Main and Test Submodules . . . 125
6.3 Module Paths . . . 127
6.4 Imports: `require` . . . 132
6.5 Exports: `provide` . . . 134
6.6 Assignment and Redefinition . . . 136
6.7 Modules and Macros . . . 137
6.8 Protected Exports . . . 139

7 Contracts 140

7.1 Contracts and Boundaries . . . 140
7.1.1 Contract Violations . . . 140
7.1.2 Experimenting with Contracts and Modules . . . 141
7.1.3 Experimenting with Nested Contract Boundaries . . . 142
7.2 Simple Contracts on Functions . . . 142
7.2.1 Styles of `->` . . . 143
7.2.2 Using `define/contract` and `->` . . . 144
7.2.3 `any` and `any/c` . . . 144
7.2.4 Rolling Your Own Contracts . . . 145
7.2.5 Contracts on Higher-order Functions . . . 148
7.2.6 Contract Messages with "???" . . . 148
7.2.7 Dissecting a contract error message . . . 150
7.3 Contracts on Functions in General . . . 151
7.3.1 Optional Arguments . . . 151
7.3.2 Rest Arguments . . . 152
7.3.3 Keyword Arguments . . . 152
7.3.4 Optional Keyword Arguments . . . 153

7.3.5 Contracts for `case-lambda` . . . 154
7.3.6 Argument and Result Dependencies . . . 155
7.3.7 Checking State Changes . . . 158
7.3.8 Multiple Result Values . . . 159
7.3.9 Fixed but Statically Unknown Arities . . . 160
7.4 Contracts: A Thorough Example . . . 162
7.5 Contracts on Structures . . . 167
7.5.1 Guarantees for a Specific Value . . . 167
7.5.2 Guarantees for All Values . . . 167
7.5.3 Checking Properties of Data Structures . . . 169
7.6 Abstract Contracts using `#:exists` and `#:∃` . . . 171
7.7 Additional Examples . . . 173
7.7.1 A Customer-Manager Component . . . 174
7.7.2 A Parameteric (Simple) Stack . . . 176
7.7.3 A Dictionary . . . 178
7.7.4 A Queue . . . 180
7.8 Building New Contracts . . . 183
7.8.1 Contract Struct Properties . . . 188
7.8.2 With all the Bells and Whistles . . . 190
7.9 Gotchas . . . 194
7.9.1 Contracts and `eq?` . . . 194
7.9.2 Contract boundaries and `define/contract` . . . 195
7.9.3 Exists Contracts and Predicates . . . 196
7.9.4 Defining Recursive Contracts . . . 196
7.9.5 Mixing `set!` and `contract-out` . . . 197

8 Input and Output **199**

8.1 Varieties of Ports . . . 199

8.2 Default Ports . . . 201

8.3 Reading and Writing Racket Data . . . 202

8.4 Datatypes and Serialization . . . 203

8.5 Bytes, Characters, and Encodings . . . 205

8.6 I/O Patterns . . . 205

9 Regular Expressions **208**

9.1 Writing Regexp Patterns . . . 208

9.2 Matching Regexp Patterns . . . 209

9.3 Basic Assertions . . . 211

9.4 Characters and Character Classes . . . 212

9.4.1 Some Frequently Used Character Classes . . . 213

9.4.2 POSIX character classes . . . 213

9.5 Quantifiers . . . 214

9.6 Clusters . . . 215

9.6.1 Backreferences . . . 216

9.6.2 Non-capturing Clusters . . . 218

9.6.3 Cloisters . . . 218

9.7 Alternation . . . 219

9.8 Backtracking . . . 220

9.9 Looking Ahead and Behind . . . 220

9.9.1 Lookahead . . . 221

9.9.2 Lookbehind . . . 221

9.10 An Extended Example . . . 222

10 Exceptions and Control **224**

10.1 Exceptions 224

10.2 Prompts and Aborts 226

10.3 Continuations 227

11 Iterations and Comprehensions **230**

11.1 Sequence Constructors 231

11.2 `for` and `for*` 232

11.3 `for/list` and `for*/list` 234

11.4 `for/vector` and `for*/vector` 235

11.5 `for/and` and `for/or` 236

11.6 `for/first` and `for/last` 236

11.7 `for/fold` and `for*/fold` 237

11.8 Multiple-Valued Sequences 238

11.9 Breaking an Iteration 238

11.10 Iteration Performance 240

12 Pattern Matching **243**

13 Classes and Objects **247**

13.1 Methods 248

13.2 Initialization Arguments 250

13.3 Internal and External Names 251

13.4 Interfaces 251

13.5 Final, Augment, and Inner 252

13.6 Controlling the Scope of External Names 252

13.7 Mixins 254

13.7.1 Mixins and Interfaces . . . 255
13.7.2 The `mixin` Form . . . 255
13.7.3 Parameterized Mixins . . . 257
13.8 Traits . . . 257
13.8.1 Traits as Sets of Mixins . . . 258
13.8.2 Inherit and Super in Traits . . . 259
13.8.3 The `trait` Form . . . 260
13.9 Class Contracts . . . 261
13.9.1 External Class Contracts . . . 261
13.9.2 Internal Class Contracts . . . 264

14 Units (Components) 267

14.1 Signatures and Units . . . 267
14.2 Invoking Units . . . 269
14.3 Linking Units . . . 270
14.4 First-Class Units . . . 271
14.5 Whole-`module` Signatures and Units . . . 274
14.6 Contracts for Units . . . 275
14.6.1 Adding Contracts to Signatures . . . 275
14.6.2 Adding Contracts to Units . . . 276
14.7 `unit` versus `module` . . . 278

15 Reflection and Dynamic Evaluation 280

15.1 `eval` . . . 280
15.1.1 Local Scopes . . . 281
15.1.2 Namespaces . . . 281

15.1.3 Namespaces and Modules 282
15.2 Manipulating Namespaces 283
15.2.1 Creating and Installing Namespaces 284
15.2.2 Sharing Data and Code Across Namespaces 285
15.3 Scripting Evaluation and Using `load` 286
15.4 Code Inspectors for Trusted and Untrusted Code 288

16 Macros **290**

16.1 Pattern-Based Macros 290
16.1.1 `define-syntax-rule` 290
16.1.2 Lexical Scope 291
16.1.3 `define-syntax` and `syntax-rules` 292
16.1.4 Matching Sequences 293
16.1.5 Identifier Macros 294
16.1.6 `set!` Transformers 295
16.1.7 Macro-Generating Macros 295
16.1.8 Extended Example: Call-by-Reference Functions 296
16.2 General Macro Transformers 299
16.2.1 Syntax Objects 299
16.2.2 Macro Transformer Procedures 300
16.2.3 Mixing Patterns and Expressions: `syntax-case` 301
16.2.4 `with-syntax` and `generate-temporaries` 303
16.2.5 Compile and Run-Time Phases 304
16.2.6 General Phase Levels 309
16.2.7 Tainted Syntax 317
16.3 Module Instantiations and Visits 318

16.3.1 Declaration versus Instantiation 318
16.3.2 Compile-Time Instantiation 319
16.3.3 Visiting Modules 321
16.3.4 Lazy Visits via Available Modules 323

17 Creating Languages **326**

17.1 Module Languages 326
17.1.1 Implicit Form Bindings 327
17.1.2 Using `#lang s-exp` 329
17.2 Reader Extensions 330
17.2.1 Source Locations 331
17.2.2 Readtables 333
17.3 Defining new `#lang` Languages 335
17.3.1 Designating a `#lang` Language 335
17.3.2 Using `#lang reader` 336
17.3.3 Using `#lang s-exp syntax/module-reader` 337
17.3.4 Installing a Language 339
17.3.5 Source-Handling Configuration 340
17.3.6 Module-Handling Configuration 342

18 Concurrency and Synchronization **346**

18.1 Threads 346
18.2 Thread Mailboxes 347
18.3 Semaphores 348
18.4 Channels 349
18.5 Buffered Asynchronous Channels 350

18.6 Synchronizable Events and sync . . . 351
18.7 Building Your Own Synchronization Patterns . . . 355

19 Performance **359**

19.1 Performance in DrRacket . . . 359
19.2 Racket Virtual Machine Implementations . . . 359
19.3 Bytecode, Machine Code, and Just-in-Time (JIT) Compilers . . . 360
19.4 Modules and Performance . . . 361
19.5 Function-Call Optimizations . . . 362
19.6 Mutation and Performance . . . 363
19.7 letrec Performance . . . 364
19.8 Fixnum and Flonum Optimizations . . . 364
19.9 Unchecked, Unsafe Operations . . . 366
19.10 Foreign Pointers . . . 366
19.11 Regular Expression Performance . . . 366
19.12 Memory Management . . . 367
19.13 Reachability and Garbage Collection . . . 368
19.14 Weak Boxes and Testing . . . 369
19.15 Reducing Garbage Collection Pauses . . . 370

20 Parallelism **372**

20.1 Parallel Threads . . . 372
20.2 Parallelism with Futures . . . 373
20.3 Parallelism with Places . . . 378
20.4 Distributed Places . . . 380

21 Running and Creating Executables **384**

21.1 Running `racket` and `gracket` . . . 384
21.1.1 Interactive Mode . . . 384
21.1.2 Module Mode . . . 385
21.1.3 Load Mode . . . 386
21.2 Scripts . . . 386
21.2.1 Unix Scripts . . . 386
21.2.2 Windows Batch Files . . . 388
21.3 Creating Stand-Alone Executables . . . 389

22 More Libraries **390**
22.1 Graphics and GUIs . . . 390
22.2 The Web Server . . . 390
22.3 Using Foreign Libraries . . . 391
22.4 And More . . . 391

23 Dialects of Racket and Scheme **392**
23.1 More Rackets . . . 392
23.2 Standards . . . 393
23.2.1 R^{5}RS . . . 393
23.2.2 R^{6}RS . . . 393
23.3 Teaching . . . 394

24 Command-Line Tools and Your Editor of Choice **395**
24.1 Command-Line Tools . . . 395
24.1.1 Compilation and Configuration: `raco` . . . 395
24.1.2 Interactive evaluation . . . 396
24.1.3 Shell completion . . . 396

24.2 Emacs . . . 396
24.2.1 Major Modes . . . 396
24.2.2 Minor Modes . . . 397
24.2.3 Packages specific to Evil Mode . . . 398
24.3 Vim . . . 398
24.3.1 Enhanced Racket Support . . . 398
24.3.2 Indentation . . . 399
24.3.3 Highlighting . . . 399
24.3.4 Structured Editing . . . 399
24.3.5 REPLs . . . 400
24.3.6 Scribble . . . 400
24.3.7 Miscellaneous . . . 400
24.3.8 Older Versions of Vim . . . 401
24.4 Sublime Text . . . 401
24.5 Visual Studio Code . . . 401

Bibliography **402**

Index **403**

Index **403**

1 Welcome to Racket

Depending on how you look at it, **Racket** is

- a *programming language*—a dialect of Lisp and a descendant of Scheme;
- a *family* of programming languages—variants of Racket, and more; or
- a set of *tools*—for using a family of programming languages.

See §23 "Dialects of Racket and Scheme" for more information on other dialects of Lisp and how they relate to Racket.

Where there is no room for confusion, we use simply *Racket*.

Racket's main tools are

- `racket`, the core compiler, interpreter, and run-time system;
- **DrRacket**, the programming environment; and
- `raco`, a command-line tool for executing **Ra**cket **co**mmands that install packages, build libraries, and more.

Most likely, you'll want to explore the Racket language using DrRacket, especially at the beginning. If you prefer, you can also work with the command-line `racket` interpreter (see §21.1 "Running `racket` and `gracket`") and your favorite text editor (see §24 "Command-Line Tools and Your Editor of Choice"). The rest of this guide presents the language mostly independent of your choice of editor.

If you're using DrRacket, you'll need to choose the proper language, because DrRacket accommodates many different variants of Racket, as well as other languages. Assuming that you've never used DrRacket before, start it up, type the line

```
#lang racket
```

in DrRacket's top text area, and then click the Run button that's above the text area. DrRacket then understands that you mean to work in the normal variant of Racket (as opposed to the smaller `racket/base` or many other possibilities).

§23.1 "More Rackets" describes some of the other possibilities.

If you've used DrRacket before with something other than a program that starts `#lang`, DrRacket will remember the last language that you used, instead of inferring the language from the `#lang` line. In that case, use the Language|Choose Language... menu item. In the dialog that appears, select the first item, which tells DrRacket to use the language that is declared in a source program via `#lang`. Put the `#lang` line above in the top text area, still.

1.1 Interacting with Racket

DrRacket's bottom text area and the `racket` command-line program (when started with no options) both act as a kind of calculator. You type a Racket expression, hit the Return key, and the answer is printed. In the terminology of Racket, this kind of calculator is called a *read-eval-print loop* or *REPL*.

A number by itself is an expression, and the answer is just the number:

```
> 5
5
```

A string is also an expression that evaluates to itself. A string is written with double quotes at the start and end of the string:

```
> "Hello, world!"
"Hello, world!"
```

Racket uses parentheses to wrap larger expressions—almost any kind of expression, other than simple constants. For example, a function call is written: open parenthesis, function name, argument expression, and closing parenthesis. The following expression calls the built-in function `substring` with the arguments `"the boy out of the country"`, `4`, and `7`:

```
> (substring "the boy out of the country" 4 7)
"boy"
```

1.2 Definitions and Interactions

You can define your own functions that work like `substring` by using the `define` form, like this:

```
(define (extract str)
  (substring str 4 7))

> (extract "the boy out of the country")
"boy"
> (extract "the country out of the boy")
"cou"
```

Although you can evaluate the `define` form in the REPL, definitions are normally a part of a program that you want to keep and use later. So, in DrRacket, you'd normally put the definition in the top text area—called the *definitions area*—along with the `#lang` prefix:

```
#lang racket

(define (extract str)
  (substring str 4 7))
```

If calling `(extract "the boy")` is part of the main action of your program, that would go in the definitions area, too. But if it was just an example expression that you were using to explore `extract`, then you'd more likely leave the definitions area as above, click Run, and then evaluate `(extract "the boy")` in the REPL.

When using command-line `racket` instead of DrRacket, you'd save the above text in a file using your favorite editor. If you save it as `"extract.rkt"`, then after starting `racket` in the same directory, you'd evaluate the following sequence:

If you use `xrepl`, you can use `,enter extract.rkt`.

```
> (enter! "extract.rkt")
> (extract "the gal out of the city")
"gal"
```

The `enter!` form both loads the code and switches the evaluation context to the inside of the module, just like DrRacket's Run button.

1.3 Creating Executables

If your file (or definitions area in DrRacket) contains

```
#lang racket

(define (extract str)
  (substring str 4 7))

(extract "the cat out of the bag")
```

then it is a complete program that prints "cat" when run. You can run the program within DrRacket or using `enter!` in `racket`, but if the program is saved in ⟨*src-filename*⟩, you can also run it from a command line with

`racket` ⟨*src-filename*⟩

To package the program as an executable, you have a few options:

- In DrRacket, you can select the Racket|Create Executable... menu item.
- From a command-line prompt, run `raco exe` ⟨*src-filename*⟩, where ⟨*src-filename*⟩ contains the program. See §2 "`raco exe`: Creating Stand-Alone Executables" for more information.

- With Unix or Mac OS, you can turn the program file into an executable script by inserting the line

  ```
  #! /usr/bin/env racket
  ```

  at the very beginning of the file. Also, change the file permissions to executable using `chmod +x` ⟨*filename*⟩ on the command line.

  The script works as long as `racket` is in the user's executable search path. Alternately, use a full path to `racket` after `#!` (with a space between `#!` and the path), in which case the user's executable search path does not matter.

See §21.2 "Scripts" for more information on script files.

1.4 A Note to Readers with Lisp/Scheme Experience

If you already know something about Scheme or Lisp, you might be tempted to put just

```
(define (extract str)
  (substring str 4 7))
```

into `"extract.rktl"` and run `racket` with

```
> (load "extract.rktl")
> (extract "the dog out")
"dog"
```

That will work, because `racket` is willing to imitate a traditional Lisp environment, but we strongly recommend against using `load` or writing programs outside of a module.

Writing definitions outside of a module leads to bad error messages, bad performance, and awkward scripting to combine and run programs. The problems are not specific to `racket`; they're fundamental limitations of the traditional top-level environment, which Scheme and Lisp implementations have historically fought with ad hoc command-line flags, compiler directives, and build tools. The module system is designed to avoid these problems, so start with `#lang`, and you'll be happier with Racket in the long run.

2 Racket Essentials

This chapter provides a quick introduction to Racket as background for the rest of the guide. Readers with some Racket experience can safely skip to §3 “Built-In Datatypes”.

2.1 Simple Values

Racket values include numbers, booleans, strings, and byte strings. In DrRacket and documentation examples (when you read the documentation in color), value expressions are shown in green.

Numbers are written in the usual way, including fractions and imaginary numbers:

§3.2 “Numbers” (later in this guide) explains more about numbers.

```
1       3.14
1/2     6.02e+23
1+2i    99999999999999999999
```

Booleans are `#t` for true and `#f` for false. In conditionals, however, all non-`#f` values are treated as true.

§3.1 “Booleans” (later in this guide) explains more about booleans.

Strings are written between doublequotes. Within a string, backslash is an escaping character; for example, a backslash followed by a doublequote includes a literal doublequote in the string. Except for an unescaped doublequote or backslash, any Unicode character can appear in a string constant.

§3.4 “Strings (Unicode)” (later in this guide) explains more about strings.

```
"Hello, world!"
"Benjamin \"Bugsy\" Siegel"
"λx:(μα.α→α).xx"
```

When a constant is evaluated in the REPL, it typically prints the same as its input syntax. In some cases, the printed form is a normalized version of the input syntax. In documentation and in DrRacket’s REPL, results are printed in blue instead of green to highlight the difference between an input expression and a printed result.

Examples:

```
> 1.0000
1.0
> "Bugs \u0022Figaro\u0022 Bunny"
"Bugs \"Figaro\" Bunny"
```

2.2 Simple Definitions and Expressions

A program module is written as

`#lang` ⟨*langname*⟩ ⟨*topform*⟩*

where a ⟨*topform*⟩ is either a ⟨*definition*⟩ or an ⟨*expr*⟩. The REPL also evaluates ⟨*topform*⟩s.

In syntax specifications, text with a gray background, such as `#lang`, represents literal text. Whitespace must appear between such literals and nonterminals like ⟨*id*⟩, except that whitespace is not required before or after `(`, `)`, `[`, or `]`. A comment, which starts with `;` and runs until the end of the line, is treated the same as whitespace.

§1.3.9 "Reading Comments" in *The Racket Reference* provides more on different forms of comments.

Following the usual conventions, * in a grammar means zero or more repetitions of the preceding element, + means one or more repetitions of the preceding element, and { } groups a sequence as an element for repetition.

2.2.1 Definitions

A definition of the form

`(` `define` ⟨*id*⟩ ⟨*expr*⟩ `)`

§4.5 "Definitions: `define`" (later in this guide) explains more about definitions.

binds ⟨*id*⟩ to the result of ⟨*expr*⟩, while

`(` `define` `(` ⟨*id*⟩ ⟨*id*⟩* `)` ⟨*expr*⟩+ `)`

binds the first ⟨*id*⟩ to a function (also called a *procedure*) that takes arguments as named by the remaining ⟨*id*⟩s. In the function case, the ⟨*expr*⟩s are the body of the function. When the function is called, it returns the result of the last ⟨*expr*⟩.

Examples:

```
(define pie 3)             ; defines pie to be 3
(define (piece str)        ; defines piece as a function
  (substring str 0 pie))   ;  of one argument
> pie
3
> (piece "key lime")
"key"
```

Under the hood, a function definition is really the same as a non-function definition, and a function name does not have to be used in a function call. A function is just another kind of

value, though the printed form is necessarily less complete than the printed form of a number or string.

Examples:

```
> piece
#<procedure:piece>
> substring
#<procedure:substring>
```

A function definition can include multiple expressions for the function's body. In that case, only the value of the last expression is returned when the function is called. The other expressions are evaluated only for some side-effect, such as printing.

Examples:

```
(define (bake flavor)
  (printf "preheating oven...\n")
  (string-append flavor " pie"))
> (bake "apple")
preheating oven...
"apple pie"
```

Racket programmers prefer to avoid side-effects, so a definition usually has just one expression in its body. It's important, though, to understand that multiple expressions are allowed in a definition body, because it explains why the following `nobake` function fails to include its argument in its result:

```
(define (nobake flavor)
  string-append flavor "jello")

> (nobake "green")
"jello"
```

Within `nobake`, there are no parentheses around `string-append flavor "jello"`, so they are three separate expressions instead of one function-call expression. The expressions `string-append` and `flavor` are evaluated, but the results are never used. Instead, the result of the function is just the result of the final expression, `"jello"`.

2.2.2 An Aside on Indenting Code

Line breaks and indentation are not significant for parsing Racket programs, but most Racket programmers use a standard set of conventions to make code more readable. For example, the body of a definition is typically indented under the first line of the definition. Identifiers

are written immediately after an open parenthesis with no extra space, and closing parentheses never go on their own line.

DrRacket automatically indents according to the standard style when you type Enter in a program or REPL expression. For example, if you hit Enter after typing `(define (greet name)`, then DrRacket automatically inserts two spaces for the next line. If you change a region of code, you can select it in DrRacket and hit Tab, and DrRacket will re-indent the code (without inserting any line breaks). Editors like Emacs offer a Racket or Scheme mode with similar indentation support.

Re-indenting not only makes the code easier to read, it gives you extra feedback that your parentheses match in the way that you intended. For example, if you leave out a closing parenthesis after the last argument to a function, automatic indentation starts the next line under the first argument, instead of under the `define` keyword:

```
(define (halfbake flavor
                  (string-append flavor " creme brulee")))
```

In this case, indentation helps highlight the mistake. In other cases, where the indentation may be normal while an open parenthesis has no matching close parenthesis, both `racket` and DrRacket use the source's indentation to suggest where a parenthesis might be missing.

2.2.3 Identifiers

Racket's syntax for identifiers is especially liberal. Excluding the special characters

```
( ) [ ] { } " , ' ` ; # | \
```

and except for the sequences of characters that make number constants, almost any sequence of non-whitespace characters forms an ⟨*id*⟩. For example `substring` is an identifier. Also, `string-append` and `a+b` are identifiers, as opposed to arithmetic expressions. Here are several more examples:

```
+
integer?
pass/fail
Hfuhruhurr&Uumellmahaye
john-jacob-jingleheimer-schmidt
a-b-c+1-2-3
```

§4.2 "Identifiers and Binding" (later in this guide) explains more about identifiers.

2.2.4 Function Calls (Procedure Applications)

We have already seen many function calls, which are called *procedure applications* in more traditional terminology. The syntax of a function call is

§4.3 "Function Calls" (later in this guide) explains more about function calls.

(⟨*id*⟩ ⟨*expr*⟩*)

where the number of ⟨*expr*⟩s determines the number of arguments supplied to the function named by ⟨*id*⟩.

The `racket` language pre-defines many function identifiers, such as `substring` and `string-append`. More examples are below.

In example Racket code throughout the documentation, uses of pre-defined names are hyperlinked to the reference manual. So, you can click on an identifier to get full details about its use.

```
> (string-append "rope" "twine" "yarn")  ; append strings
"ropetwineyarn"
> (substring "corduroys" 0 4)            ; extract a substring
"cord"
> (string-prefix? "shoelace" "shoe")     ; recognize string pre-
fix/suffix
#t
> (string-suffix? "shoelace" "shoe")
#f
> (string? "Ceci n'est pas une string.") ; recognize strings
#t
> (string? 1)
#f
> (sqrt 16)                              ; find a square root
4
> (sqrt -16)
0+4i
> (+ 1 2)                                ; add numbers
3
> (- 2 1)                                ; subtract numbers
1
> (< 2 1)                                ; compare numbers
#f
> (>= 2 1)
#t
> (number? "c'est une number")           ; recognize numbers
#f
> (number? 1)
#t
> (equal? 6 "half dozen")                ; compare anything
#f
> (equal? 6 6)
#t
> (equal? "half dozen" "half dozen")
```

```
#t
```

2.2.5 Conditionals with `if`, `and`, `or`, and `cond`

The next simplest kind of expression is an `if` conditional:

```
( if ⟨expr⟩ ⟨expr⟩ ⟨expr⟩ )
```

§4.7 "Conditionals" (later in this guide) explains more about conditionals.

The first ⟨*expr*⟩ is always evaluated. If it produces a non-`#f` value, then the second ⟨*expr*⟩ is evaluated for the result of the whole `if` expression, otherwise the third ⟨*expr*⟩ is evaluated for the result.

Example:

```
> (if (> 2 3)
      "2 is bigger than 3"
      "2 is smaller than 3")
"2 is smaller than 3"


(define (reply s)
  (if (string-prefix? s "hello ")
      "hi!"
      "huh?"))

> (reply "hello racket")
"hi!"
> (reply "λx:(μα.α→α).xx")
"huh?"
```

Complex conditionals can be formed by nesting `if` expressions. For example, in the previous `reply` example, the input must be a string because `string-prefix?` would error when given non-strings. You can remove this restriction by adding another `if` to check first if the input is a string:

```
(define (reply-non-string s)
  (if (string? s)
      (if (string-prefix? s "hello ")
          "hi!"
          "huh?")
      "huh?"))
```

Instead of duplicating the `"huh?"` case, this function is better written as

```
(define (reply-non-string s)
  (if (if (string? s)
          (string-prefix? s "hello ")
          #f)
      "hi!"
      "huh?"))
```

but these kinds of nested `if`s are difficult to read. Racket provides more readable shortcuts through the `and` and `or` forms:

§4.7.2 “Combining Tests: `and` and `or`” (later in this guide) explains more about `and` and `or`.

```
( and ⟨expr⟩* )
( or ⟨expr⟩* )
```

The `and` form short-circuits: it stops and returns `#f` when an expression produces `#f`, otherwise it keeps going. The `or` form similarly short-circuits when it encounters a true result.

Examples:

```
(define (reply-non-string s)
  (if (and (string? s) (string-prefix? s "hello "))
      "hi!"
      "huh?"))
> (reply-non-string "hello racket")
"hi!"
> (reply-non-string 17)
"huh?"
```

Note that in the above grammar, the `and` and `or` forms work with any number of expressions.

Examples:

```
(define (reply-only-enthusiastic s)
  (if (and (string? s)
           (string-prefix? s "hello ")
           (string-suffix? s "!"))
      "hi!"
      "huh?"))
> (reply-only-enthusiastic "hello racket!")
"hi!"
> (reply-only-enthusiastic "hello racket")
"huh?"
```

Another common pattern of nested `if`s involves a sequence of tests, each with its own result:

```
(define (reply-more s)
```

```
(if (string-prefix? s "hello ")
    "hi!"
    (if (string-prefix? s "goodbye ")
        "bye!"
        (if (string-suffix? s "?")
            "I don't know"
            "huh?"))))
```

The shorthand for a sequence of tests is the `cond` form:

```
( cond {[ ⟨expr⟩ ⟨expr⟩* ]}* )
```

§4.7.3 “Chaining Tests: `cond`” (later in this guide) explains more about `cond`.

A `cond` form contains a sequence of clauses between square brackets. In each clause, the first ⟨*expr*⟩ is a test expression. If it produces true, then the clause's remaining ⟨*expr*⟩s are evaluated, and the last one in the clause provides the answer for the entire `cond` expression; the rest of the clauses are ignored. If the test ⟨*expr*⟩ produces `#f`, then the clause's remaining ⟨*expr*⟩s are ignored, and evaluation continues with the next clause. The last clause can use `else` as a synonym for a `#t` test expression.

Using `cond`, the `reply-more` function can be more clearly written as follows:

```
(define (reply-more s)
  (cond
   [(string-prefix? s "hello ")
    "hi!"]
   [(string-prefix? s "goodbye ")
    "bye!"]
   [(string-suffix? s "?")
    "I don't know"]
   [else "huh?"]))

> (reply-more "hello racket")
"hi!"
> (reply-more "goodbye cruel world")
"bye!"
> (reply-more "what is your favorite color?")
"I don't know"
> (reply-more "mine is lime green")
"huh?"
```

The use of square brackets for `cond` clauses is a convention. In Racket, parentheses and square brackets are actually interchangeable, as long as `(` is matched with `)` and `[` is matched with `]`. Using square brackets in a few key places makes Racket code even more readable.

2.2.6 Function Calls, Again

In our earlier grammar of function calls, we oversimplified. The actual syntax of a function call allows an arbitrary expression for the function, instead of just an ⟨*id*⟩:

§4.3 "Function Calls" (later in this guide) explains more about function calls.

```
( ⟨expr⟩ ⟨expr⟩* )
```

The first ⟨*expr*⟩ is often an ⟨*id*⟩, such as `string-append` or `+`, but it can be anything that evaluates to a function. For example, it can be a conditional expression:

```
(define (double v)
  ((if (string? v) string-append +) v v))

> (double "mnah")
"mnahmnah"
> (double 5)
10
```

Syntactically, the first expression in a function call could even be a number—but that leads to an error, since a number is not a function.

```
> (1 2 3 4)
application: not a procedure;
 expected a procedure that can be applied to arguments
  given: 1
```

When you accidentally omit a function name or when you use extra parentheses around an expression, you'll most often get an "expected a procedure" error like this one.

2.2.7 Anonymous Functions with `lambda`

Programming in Racket would be tedious if you had to name all of your numbers. Instead of writing `(+ 1 2)`, you'd have to write

§4.4 "Functions: `lambda`" (later in this guide) explains more about `lambda`.

```
> (define a 1)
> (define b 2)
> (+ a b)
3
```

It turns out that having to name all your functions can be tedious, too. For example, you might have a function `twice` that takes a function and an argument. Using `twice` is convenient if you already have a name for the function, such as `sqrt`:

```
(define (twice f v)
  (f (f v)))

> (twice sqrt 16)
2
```

If you want to call a function that is not yet defined, you could define it, and then pass it to `twice`:

```
(define (louder s)
  (string-append s "!"))

> (twice louder "hello")
"hello!!"
```

But if the call to `twice` is the only place where `louder` is used, it's a shame to have to write a whole definition. In Racket, you can use a `lambda` expression to produce a function directly. The `lambda` form is followed by identifiers for the function's arguments, and then the function's body expressions:

`(` `lambda` `(` ⟨*id*⟩* `)` ⟨*expr*⟩+ `)`

Evaluating a `lambda` form by itself produces a function:

```
> (lambda (s) (string-append s "!"))
#<procedure>
```

Using `lambda`, the above call to `twice` can be re-written as

```
> (twice (lambda (s) (string-append s "!"))
         "hello")
"hello!!"
> (twice (lambda (s) (string-append s "?!"))
         "hello")
"hello?!?!"
```

Another use of `lambda` is as a result for a function that generates functions:

```
(define (make-add-suffix s2)
  (lambda (s) (string-append s s2)))

> (twice (make-add-suffix "!") "hello")
"hello!!"
> (twice (make-add-suffix "?!") "hello")
```

```
"hello?!?!"
> (twice (make-add-suffix "...") "hello")
"hello......"
```

Racket is a *lexically scoped* language, which means that `s2` in the function returned by `make-add-suffix` always refers to the argument for the call that created the function. In other words, the `lambda`-generated function "remembers" the right `s2`:

```
> (define louder (make-add-suffix "!"))
> (define less-sure (make-add-suffix "?"))
> (twice less-sure "really")
"really??"
> (twice louder "really")
"really!!"
```

We have so far referred to definitions of the form `(define` ⟨*id*⟩ ⟨*expr*⟩`)` as "non-function definitions." This characterization is misleading, because the ⟨*expr*⟩ could be a `lambda` form, in which case the definition is equivalent to using the "function" definition form. For example, the following two definitions of `louder` are equivalent:

```
(define (louder s)
  (string-append s "!"))

(define louder
  (lambda (s)
    (string-append s "!")))

> louder
#<procedure:louder>
```

Note that the expression for `louder` in the second case is an "anonymous" function written with `lambda`, but, if possible, the compiler infers a name, anyway, to make printing and error reporting as informative as possible.

2.2.8 Local Binding with `define`, `let`, and `let*`

It's time to retract another simplification in our grammar of Racket. In the body of a function, definitions can appear before the body expressions:

`(` `define` `(` ⟨*id*⟩ ⟨*id*⟩`*` `)` ⟨*definition*⟩`*` ⟨*expr*⟩$^{+}$ `)`
`(` `lambda` `(` ⟨*id*⟩`*` `)` ⟨*definition*⟩`*` ⟨*expr*⟩$^{+}$ `)`

§4.5.4 "Internal Definitions" (later in this guide) explains more about local (internal) definitions.

Definitions at the start of a function body are local to the function body.

Examples:

```
(define (converse s)
  (define (starts? s2) ; local to converse
    (define spaced-s2 (string-append s2 " ")) ; local to starts?
    (string-prefix? s spaced-s2))
  (cond
    [(starts? "hello") "hi!"]
    [(starts? "goodbye") "bye!"]
    [else "huh?"]))
> (converse "hello world")
"hi!"
> (converse "hellonearth")
"huh?"
> (converse "goodbye friends")
"bye!"
> (converse "urp")
"huh?"
> starts? ; outside of converse, so...
starts?: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

Another way to create local bindings is the `let` form. An advantage of `let` is that it can be used in any expression position. Also, `let` binds many identifiers at once, instead of requiring a separate `define` for each identifier.

§4.5.4 “Internal Definitions” (later in this guide) explains more about `let` and `let*`.

`(` `let` `(` {`[` ⟨*id*⟩ ⟨*expr*⟩ `]`}* `)` ⟨*expr*⟩+ `)`

Each binding clause is an ⟨*id*⟩ and an ⟨*expr*⟩ surrounded by square brackets, and the expressions after the clauses are the body of the `let`. In each clause, the ⟨*id*⟩ is bound to the result of the ⟨*expr*⟩ for use in the body.

```
> (let ([x (random 4)]
        [o (random 4)])
    (cond
      [(> x o) "X wins"]
      [(> o x) "O wins"]
      [else "cat's game"]))
"cat's game"
```

The bindings of a `let` form are available only in the body of the `let`, so the binding clauses cannot refer to each other. The `let*` form, in contrast, allows later clauses to use earlier bindings:

```
> (let* ([x (random 4)]
         [o (random 4)]
         [diff (number->string (abs (- x o)))])
    (cond
      [(> x o) (string-append "X wins by " diff)]
      [(> o x) (string-append "O wins by " diff)]
      [else "cat's game"]))
"X wins by 1"
```

2.3 Lists, Iteration, and Recursion

Racket is a dialect of the language Lisp, whose name originally stood for "LISt Processor." The built-in list datatype remains a prominent feature of the language.

The `list` function takes any number of values and returns a list containing the values:

```
> (list "red" "green" "blue")
'("red" "green" "blue")
> (list 1 2 3 4 5)
'(1 2 3 4 5)
```

A list usually prints with `'`, but the printed form of a list depends on its content. See §3.8 "Pairs and Lists" for more information.

As you can see, a list result prints in the REPL as a quote `'` and then a pair of parentheses wrapped around the printed form of the list elements. There's an opportunity for confusion here, because parentheses are used for both expressions, such as `(list "red" "green" "blue")`, and printed results, such as `'("red" "green" "blue")`. In addition to the quote, parentheses for results are printed in blue in the documentation and in DrRacket, whereas parentheses for expressions are brown.

Many predefined functions operate on lists. Here are a few examples:

```
> (length (list "hop" "skip" "jump"))        ; count the elements
3
> (list-ref (list "hop" "skip" "jump") 0)    ; extract by position
"hop"
> (list-ref (list "hop" "skip" "jump") 1)
"skip"
> (append (list "hop" "skip") (list "jump")) ; combine lists
'("hop" "skip" "jump")
> (reverse (list "hop" "skip" "jump"))       ; reverse order
'("jump" "skip" "hop")
> (member "fall" (list "hop" "skip" "jump")) ; check for an ele-
ment
#f
```

2.3.1 Predefined List Loops

In addition to simple operations like `append`, Racket includes functions that iterate over the elements of a list. These iteration functions play a role similar to `for` in Java, Racket, and other languages. The body of a Racket iteration is packaged into a function to be applied to each element, so the `lambda` form becomes particularly handy in combination with iteration functions.

Different list-iteration functions combine iteration results in different ways. The `map` function uses the per-element results to create a new list:

```
> (map sqrt (list 1 4 9 16))
'(1 2 3 4)
> (map (lambda (i)
         (string-append i "!"))
       (list "peanuts" "popcorn" "crackerjack"))
'("peanuts!" "popcorn!" "crackerjack!")
```

The `andmap` and `ormap` functions combine the results by `and`ing or `or`ing:

```
> (andmap string? (list "a" "b" "c"))
#t
> (andmap string? (list "a" "b" 6))
#f
> (ormap number? (list "a" "b" 6))
#t
```

The `map`, `andmap`, and `ormap` functions can all handle multiple lists, instead of just a single list. The lists must all have the same length, and the given function must accept one argument for each list:

```
> (map (lambda (s n) (substring s 0 n))
       (list "peanuts" "popcorn" "crackerjack")
       (list 6 3 7))
'("peanut" "pop" "cracker")
```

The `filter` function keeps elements for which the body result is true, and discards elements for which it is `#f`:

```
> (filter string? (list "a" "b" 6))
'("a" "b")
> (filter positive? (list 1 -2 6 7 0))
'(1 6 7)
```

The `foldl` function generalizes some iteration functions. It uses the per-element function to both process an element and combine it with the "current" value, so the per-element function

takes an extra first argument. Also, a starting "current" value must be provided before the lists:

```
> (foldl (lambda (elem v)
           (+ v (* elem elem)))
         0
         '(1 2 3))
14
```

Despite its generality, `foldl` is not as popular as the other functions. One reason is that `map`, `ormap`, `andmap`, and `filter` cover the most common kinds of list loops.

Racket provides a general *list comprehension* form `for/list`, which builds a list by iterating through *sequences*. List comprehensions and related iteration forms are described in §11 "Iterations and Comprehensions".

2.3.2 List Iteration from Scratch

Although `map` and other iteration functions are predefined, they are not primitive in any interesting sense. You can write equivalent iterations using a handful of list primitives.

Since a Racket list is a linked list, the two core operations on a non-empty list are

- `first`: get the first thing in the list; and
- `rest`: get the rest of the list.

Examples:

```
> (first (list 1 2 3))
1
> (rest (list 1 2 3))
'(2 3)
```

To create a new node for a linked list—that is, to add to the front of the list—use the `cons` function, which is short for "construct." To get an empty list to start with, use the `empty` constant:

```
> empty
'()
> (cons "head" empty)
'("head")
> (cons "dead" (cons "head" empty))
'("dead" "head")
```

To process a list, you need to be able to distinguish empty lists from non-empty lists, because `first` and `rest` work only on non-empty lists. The `empty?` function detects empty lists, and `cons?` detects non-empty lists:

```
> (empty? empty)
#t
> (empty? (cons "head" empty))
#f
> (cons? empty)
#f
> (cons? (cons "head" empty))
#t
```

With these pieces, you can write your own versions of the `length` function, `map` function, and more.

Examples:

```
(define (my-length lst)
  (cond
    [(empty? lst) 0]
    [else (+ 1 (my-length (rest lst)))]))
> (my-length empty)
0
> (my-length (list "a" "b" "c"))
3
```

```
(define (my-map f lst)
  (cond
    [(empty? lst) empty]
    [else (cons (f (first lst))
                (my-map f (rest lst)))]))

> (my-map string-upcase (list "ready" "set" "go"))
'("READY" "SET" "GO")
```

If the derivation of the above definitions is mysterious to you, consider reading *How to Design Programs*. If you are merely suspicious of the use of recursive calls instead of a looping construct, then read on.

2.3.3 Tail Recursion

Both the `my-length` and `my-map` functions run in $O(n)$ space for a list of length n. This is easy to see by imagining how `(my-length (list "a" "b" "c"))` must evaluate:

```
(my-length (list "a" "b" "c"))
= (+ 1 (my-length (list "b" "c")))
= (+ 1 (+ 1 (my-length (list "c"))))
= (+ 1 (+ 1 (+ 1 (my-length (list)))))
= (+ 1 (+ 1 (+ 1 0)))
= (+ 1 (+ 1 1))
= (+ 1 2)
= 3
```

For a list with n elements, evaluation will stack up n `(+ 1 ...)` additions, and then finally add them up when the list is exhausted.

You can avoid piling up additions by adding along the way. To accumulate a length this way, we need a function that takes both a list and the length of the list seen so far; the code below uses a local function `iter` that accumulates the length in an argument `len`:

```
(define (my-length lst)
  ; local function iter:
  (define (iter lst len)
    (cond
      [(empty? lst) len]
      [else (iter (rest lst) (+ len 1))]))
  ; body of my-length calls iter:
  (iter lst 0))
```

Now evaluation looks like this:

```
(my-length (list "a" "b" "c"))
= (iter (list "a" "b" "c") 0)
= (iter (list "b" "c") 1)
= (iter (list "c") 2)
= (iter (list) 3)
3
```

The revised `my-length` runs in constant space, just as the evaluation steps above suggest. That is, when the result of a function call, like `(iter (list "b" "c") 1)`, is exactly the result of some other function call, like `(iter (list "c") 2)`, then the first one doesn't have to wait around for the second one, because that takes up space for no good reason.

This evaluation behavior is sometimes called *tail-call optimization*, but it's not merely an "optimization" in Racket; it's a guarantee about the way the code will run. More precisely, an expression in *tail position* with respect to another expression does not take extra computation space over the other expression.

In the case of `my-map`, $O(n)$ space complexity is reasonable, since it has to generate a result of size $O(n)$. Nevertheless, you can reduce the constant factor by accumulating the result

list. The only catch is that the accumulated list will be backwards, so you'll have to reverse it at the very end:

Attempting to reduce a constant factor like this is usually not worthwhile, as discussed below.

```
(define (my-map f lst)
  (define (iter lst backward-result)
    (cond
      [(empty? lst) (reverse backward-result)]
      [else (iter (rest lst)
                  (cons (f (first lst))
                        backward-result))]))
  (iter lst empty))
```

It turns out that if you write

```
(define (my-map f lst)
  (for/list ([i lst])
    (f i)))
```

then the `for/list` form in the function is expanded to essentially the same code as the `iter` local definition and use. The difference is merely syntactic convenience.

2.3.4 Recursion versus Iteration

The `my-length` and `my-map` examples demonstrate that iteration is just a special case of recursion. In many languages, it's important to try to fit as many computations as possible into iteration form. Otherwise, performance will be bad, and moderately large inputs can lead to stack overflow. Similarly, in Racket, it is sometimes important to make sure that tail recursion is used to avoid $O(n)$ space consumption when the computation is easily performed in constant space.

At the same time, recursion does not lead to particularly bad performance in Racket, and there is no such thing as stack overflow; you can run out of memory if a computation involves too much context, but exhausting memory typically requires orders of magnitude deeper recursion than would trigger a stack overflow in other languages. These considerations, combined with the fact that tail-recursive programs automatically run the same as a loop, lead Racket programmers to embrace recursive forms rather than avoid them.

Suppose, for example, that you want to remove consecutive duplicates from a list. While such a function can be written as a loop that remembers the previous element for each iteration, a Racket programmer would more likely just write the following:

```
(define (remove-dups l)
  (cond
    [(empty? l) empty]
```

```
    [(empty? (rest l)) l]
    [else
     (let ([i (first l)])
       (if (equal? i (first (rest l)))
           (remove-dups (rest l))
           (cons i (remove-dups (rest l)))))]))

> (remove-dups (list "a" "b" "b" "b" "c" "c"))
'("a" "b" "c")
```

In general, this function consumes $O(n)$ space for an input list of length n, but that's fine, since it produces an $O(n)$ result. If the input list happens to be mostly consecutive duplicates, then the resulting list can be much smaller than $O(n)$—and `remove-dups` will also use much less than $O(n)$ space! The reason is that when the function discards duplicates, it returns the result of a `remove-dups` call directly, so the tail-call "optimization" kicks in:

```
(remove-dups (list "a" "b" "b" "b" "b" "b"))
= (cons "a" (remove-dups (list "b" "b" "b" "b" "b")))
= (cons "a" (remove-dups (list "b" "b" "b" "b")))
= (cons "a" (remove-dups (list "b" "b" "b")))
= (cons "a" (remove-dups (list "b" "b")))
= (cons "a" (remove-dups (list "b")))
= (cons "a" (list "b"))
= (list "a" "b")
```

2.4 Pairs, Lists, and Racket Syntax

The `cons` function actually accepts any two values, not just a list for the second argument. When the second argument is not `empty` and not itself produced by `cons`, the result prints in a special way. The two values joined with `cons` are printed between parentheses, but with a dot (i.e., a period surrounded by whitespace) in between:

```
> (cons 1 2)
'(1 . 2)
> (cons "banana" "split")
'("banana" . "split")
```

Thus, a value produced by `cons` is not always a list. In general, the result of `cons` is a *pair*. The more traditional name for the `cons?` function is `pair?`, and we'll use the traditional name from now on.

The name `rest` also makes less sense for non-list pairs; the more traditional names for `first` and `rest` are `car` and `cdr`, respectively. (Granted, the traditional names are also nonsense. Just remember that "a" comes before "d," and `cdr` is pronounced "could-er.")

Examples:

```
> (car (cons 1 2))
1
> (cdr (cons 1 2))
2
> (pair? empty)
#f
> (pair? (cons 1 2))
#t
> (pair? (list 1 2 3))
#t
```

Racket's pair datatype and its relation to lists is essentially a historical curiosity, along with the dot notation for printing and the funny names `car` and `cdr`. Pairs are deeply wired into the culture, specification, and implementation of Racket, however, so they survive in the language.

You are perhaps most likely to encounter a non-list pair when making a mistake, such as accidentally reversing the arguments to `cons`:

```
> (cons (list 2 3) 1)
'((2 3) . 1)
> (cons 1 (list 2 3))
'(1 2 3)
```

Non-list pairs are used intentionally, sometimes. For example, the `make-hash` function takes a list of pairs, where the `car` of each pair is a key and the `cdr` is an arbitrary value.

The only thing more confusing to new Racketeers than non-list pairs is the printing convention for pairs where the second element *is* a pair, but *is not* a list:

```
> (cons 0 (cons 1 2))
'(0 1 . 2)
```

In general, the rule for printing a pair is as follows: use the dot notation unless the dot is immediately followed by an open parenthesis. In that case, remove the dot, the open parenthesis, and the matching close parenthesis. Thus, `'(0 . (1 . 2))` becomes `'(0 1 . 2)`, and `'(1 . (2 . (3 . ())))` becomes `'(1 2 3)`.

2.4.1 Quoting Pairs and Symbols with `quote`

A list prints with a quote mark before it, but if an element of a list is itself a list, then no quote mark is printed for the inner list:

```
> (list (list 1) (list 2 3) (list 4))
'((1) (2 3) (4))
```

For nested lists, especially, the `quote` form lets you write a list as an expression in essentially the same way that the list prints:

```
> (quote ("red" "green" "blue"))
'("red" "green" "blue")
> (quote ((1) (2 3) (4)))
'((1) (2 3) (4))
> (quote ())
'()
```

The `quote` form works with the dot notation, too, whether the quoted form is normalized by the dot-parenthesis elimination rule or not:

```
> (quote (1 . 2))
'(1 . 2)
> (quote (0 . (1 . 2)))
'(0 1 . 2)
```

Naturally, lists of any kind can be nested:

```
> (list (list 1 2 3) 5 (list "a" "b" "c"))
'((1 2 3) 5 ("a" "b" "c"))
> (quote ((1 2 3) 5 ("a" "b" "c")))
'((1 2 3) 5 ("a" "b" "c"))
```

If you wrap an identifier with `quote`, then you get output that looks like an identifier, but with a `'` prefix:

```
> (quote jane-doe)
'jane-doe
```

A value that prints like a quoted identifier is a *symbol*. In the same way that parenthesized output should not be confused with expressions, a printed symbol should not be confused with an identifier. In particular, the symbol `(quote map)` has nothing to do with the `map` identifier or the predefined function that is bound to `map`, except that the symbol and the identifier happen to be made up of the same letters.

Indeed, the intrinsic value of a symbol is nothing more than its character content. In this sense, symbols and strings are almost the same thing, and the main difference is how they print. The functions `symbol->string` and `string->symbol` convert between them.

Examples:

```
> map
#<procedure:map>
> (quote map)
'map
> (symbol? (quote map))
#t
> (symbol? map)
#f
> (procedure? map)
#t
> (string->symbol "map")
'map
> (symbol->string (quote map))
"map"
```

In the same way that `quote` for a list automatically applies itself to nested lists, `quote` on a parenthesized sequence of identifiers automatically applies itself to the identifiers to create a list of symbols:

```
> (car (quote (road map)))
'road
> (symbol? (car (quote (road map))))
#t
```

When a symbol is inside a list that is printed with `'`, the `'` on the symbol is omitted, since `'` is doing the job already:

```
> (quote (road map))
'(road map)
```

The `quote` form has no effect on a literal expression such as a number or string:

```
> (quote 42)
42
> (quote "on the record")
"on the record"
```

2.4.2 Abbreviating `quote` with `'`

As you may have guessed, you can abbreviate a use of `quote` by just putting `'` in front of a form to quote:

```
> '(1 2 3)
```

```
'(1 2 3)
> 'road
'road
> '((1 2 3) road ("a" "b" "c"))
'((1 2 3) road ("a" "b" "c"))
```

In the documentation, `'` within an expression is printed in green along with the form after it, since the combination is an expression that is a constant. In DrRacket, only the `'` is colored green. DrRacket is more precisely correct, because the meaning of `quote` can vary depending on the context of an expression. In the documentation, however, we routinely assume that standard bindings are in scope, and so we paint quoted forms in green for extra clarity.

A `'` expands to a `quote` form in quite a literal way. You can see this if you put a `'` in front of a form that has a `'`:

```
> (car ''road)
'quote
> (car '(quote road))
'quote
```

The `'` abbreviation works in output as well as input. The REPL's printer recognizes the symbol `'quote` as the first element of a two-element list when printing output, in which case it uses `'` to print the output:

```
> (quote (quote road))
''road
> '(quote road)
''road
> ''road
''road
```

2.4.3 Lists and Racket Syntax

Now that you know the truth about pairs and lists, and now that you've seen `quote`, you're ready to understand the main way in which we have been simplifying Racket's true syntax.

The syntax of Racket is not defined directly in terms of character streams. Instead, the syntax is determined by two layers:

- a *reader* layer, which turns a sequence of characters into lists, symbols, and other constants; and
- an *expander* layer, which processes the lists, symbols, and other constants to parse them as an expression.

The rules for printing and reading go together. For example, a list is printed with parentheses, and reading a pair of parentheses produces a list. Similarly, a non-list pair is printed with the dot notation, and a dot on input effectively runs the dot-notation rules in reverse to obtain a pair.

One consequence of the read layer for expressions is that you can use the dot notation in expressions that are not quoted forms:

```
> (+ 1 . (2))
3
```

This works because `(+ 1 . (2))` is just another way of writing `(+ 1 2)`. It is practically never a good idea to write application expressions using this dot notation; it's just a consequence of the way Racket's syntax is defined.

Normally, `.` is allowed by the reader only with a parenthesized sequence, and only before the last element of the sequence. However, a pair of `.`s can also appear around a single element in a parenthesized sequence, as long as the element is not first or last. Such a pair triggers a reader conversion that moves the element between `.`s to the front of the list. The conversion enables a kind of general infix notation:

```
> (1 . < . 2)
#t
> '(1 . < . 2)
'(< 1 2)
```

This two-dot convention is non-traditional, and it has essentially nothing to do with the dot notation for non-list pairs. Racket programmers use the infix convention sparingly—mostly for asymmetric binary operators such as `<` and `is-a?`.

3 Built-In Datatypes

The previous chapter introduced some of Racket's built-in datatypes: numbers, booleans, strings, lists, and procedures. This section provides a more complete coverage of the built-in datatypes for simple forms of data.

3.1 Booleans

Racket has two distinguished constants to represent boolean values: `#t` for true and `#f` for false. Uppercase `#T` and `#F` are parsed as the same values, but the lowercase forms are preferred.

The `boolean?` procedure recognizes the two boolean constants. In the result of a test expression for `if`, `cond`, `and`, `or`, etc., however, any value other than `#f` counts as true.

Examples:

```
> (= 2 (+ 1 1))
#t
> (boolean? #t)
#t
> (boolean? #f)
#t
> (boolean? "no")
#f
> (if "no" 1 0)
1
```

3.2 Numbers

A Racket *number* is either exact or inexact:

- An *exact* number is either
  - an arbitrarily large or small integer, such as `5`, `99999999999999999`, or `-17`;
  - a rational that is exactly the ratio of two arbitrarily small or large integers, such as `1/2`, `9999999999999999/2`, or `-3/4`; or
  - a complex number with exact real and imaginary parts (where the imaginary part is not zero), such as `1+2i` or `1/2+3/4i`.
- An *inexact* number is either

- an IEEE floating-point representation of a number, such as `2.0` or `3.14e+87`, where the IEEE infinities and not-a-number are written `+inf.0`, `-inf.0`, and `+nan.0` (or `-nan.0`); or
- a complex number with real and imaginary parts that are IEEE floating-point representations, such as `2.0+3.0i` or `-inf.0+nan.0i`; as a special case, an inexact complex number can have an exact zero real part with an inexact imaginary part.

Inexact numbers print with a decimal point or exponent specifier, and exact numbers print as integers and fractions. The same conventions apply for reading number constants, but `#e` or `#i` can prefix a number to force its parsing as an exact or inexact number. The prefixes `#b`, `#o`, and `#x` specify binary, octal, and hexadecimal interpretation of digits.

§1.3.3 "Reading Numbers" in *The Racket Reference* documents the fine points of the syntax of numbers.

Examples:

```
> 0.5
0.5
> #e0.5
1/2
> #x03BB
955
```

Computations that involve an inexact number produce inexact results, so that inexactness acts as a kind of taint on numbers. Beware, however, that Racket offers no "inexact booleans," so computations that branch on the comparison of inexact numbers can nevertheless produce exact results. The procedures `exact->inexact` and `inexact->exact` convert between the two types of numbers.

Examples:

```
> (/ 1 2)
1/2
> (/ 1 2.0)
0.5
> (if (= 3.0 2.999) 1 2)
2
> (inexact->exact 0.1)
3602879701896397/36028797018963968
```

Inexact results are also produced by procedures such as `sqrt`, `log`, and `sin` when an exact result would require representing real numbers that are not rational. Racket can represent only rational numbers and complex numbers with rational parts.

Examples:

```
> (sin 0)   ; rational...
0
> (sin 1/2) ; not rational...
0.479425538604203
```

In terms of performance, computations with small integers are typically the fastest, where "small" means that the number fits into one bit less than the machine's word-sized representation for signed numbers. Computation with very large exact integers or with non-integer exact numbers can be much more expensive than computation with inexact numbers.

```
(define (sigma f a b)
  (if (= a b)
      0
      (+ (f a) (sigma f (+ a 1) b))))

> (time (round (sigma (lambda (x) (/ 1 x)) 1 2000)))
cpu time: 26 real time: 3 gc time: 0
8
> (time (round (sigma (lambda (x) (/ 1.0 x)) 1 2000)))
cpu time: 0 real time: 0 gc time: 0
8.0
```

The number categories *integer*, *rational*, *real* (always rational), and *complex* are defined in the usual way, and are recognized by the procedures `integer?`, `rational?`, `real?`, and `complex?`, in addition to the generic `number?`. A few mathematical procedures accept only real numbers, but most implement standard extensions to complex numbers.

Examples:

```
> (integer? 5)
#t
> (complex? 5)
#t
> (integer? 5.0)
#t
> (integer? 1+2i)
#f
> (complex? 1+2i)
#t
> (complex? 1.0+2.0i)
#t
> (abs -5)
5
> (abs -5+2i)
abs: contract violation
```

```
  expected: real?
  given: -5+2i
> (sin -5+2i)
3.6076607742131563+1.0288031496599335i
```

The = procedure compares numbers for numerical equality. If it is given both inexact and exact numbers to compare, it essentially converts the inexact numbers to exact before comparing. The eqv? (and therefore equal?) procedure, in contrast, compares numbers considering both exactness and numerical equality.

Examples:

```
> (= 1 1.0)
#t
> (eqv? 1 1.0)
#f
```

Beware of comparisons involving inexact numbers, which by their nature can have surprising behavior. Even apparently simple inexact numbers may not mean what you think they mean; for example, while a base-2 IEEE floating-point number can represent 1/2 exactly, it can only approximate 1/10:

Examples:

```
> (= 1/2 0.5)
#t
> (= 1/10 0.1)
#f
> (inexact->exact 0.1)
3602879701896397/36028797018963968
```

§4.3 “Numbers” in *The Racket Reference* provides more on numbers and number procedures.

3.3 Characters

A Racket *character* corresponds to a Unicode *scalar value*. Roughly, a scalar value is an unsigned integer whose representation fits into 21 bits, and that maps to some notion of a natural-language character or piece of a character. Technically, a scalar value is a simpler notion than the concept called a “character” in the Unicode standard, but it’s an approximation that works well for many purposes. For example, any accented Roman letter can be represented as a scalar value, as can any common Chinese character.

Although each Racket character corresponds to an integer, the character datatype is separate from numbers. The char->integer and integer->char procedures convert between scalar-value numbers and the corresponding character.

A printable character normally prints as `#\` followed by the represented character. An unprintable character normally prints as `#\u` followed by the scalar value as hexadecimal number. A few characters are printed specially; for example, the space and linefeed characters print as `#\space` and `#\newline`, respectively.

§1.3.14 “Reading Characters” in *The Racket Reference* documents the fine points of the syntax of characters.

Examples:

```
> (integer->char 65)
#\A
> (char->integer #\A)
65
> #\λ
#\λ
> #\u03BB
#\λ
> (integer->char 17)
#\u0011
> (char->integer #\space)
32
```

The `display` procedure directly writes a character to the current output port (see §8 “Input and Output”), in contrast to the character-constant syntax used to print a character result.

Examples:

```
> #\A
#\A
> (display #\A)
A
```

Racket provides several classification and conversion procedures on characters. Beware, however, that conversions on some Unicode characters work as a human would expect only when they are in a string (e.g., upcasing “ß” or downcasing “Σ”).

Examples:

```
> (char-alphabetic? #\A)
#t
> (char-numeric? #\0)
#t
> (char-whitespace? #\newline)
#t
> (char-downcase #\A)
#\a
> (char-upcase #\ß)
#\ß
```

The `char=?` procedure compares two or more characters, and `char-ci=?` compares characters ignoring case. The `eqv?` and `equal?` procedures behave the same as `char=?` on characters; use `char=?` when you want to more specifically declare that the values being compared are characters.

Examples:

```
> (char=? #\a #\A)
#f
> (char-ci=? #\a #\A)
#t
> (eqv? #\a #\A)
#f
```

§4.6 "Characters" in *The Racket Reference* provides more on characters and character procedures.

3.4 Strings (Unicode)

A *string* is a fixed-length array of characters. It prints using double quotes, where double quote and backslash characters within the string are escaped with backslashes. Other common string escapes are supported, including `\n` for a linefeed, `\r` for a carriage return, octal escapes using `\` followed by up to three octal digits, and hexadecimal escapes with `\u` (up to four digits). Unprintable characters in a string are normally shown with `\u` when the string is printed.

§1.3.7 "Reading Strings" in *The Racket Reference* documents the fine points of the syntax of strings.

The `display` procedure directly writes the characters of a string to the current output port (see §8 "Input and Output"), in contrast to the string-constant syntax used to print a string result.

Examples:

```
> "Apple"
"Apple"
> "\u03BB"
"λ"
> (display "Apple")
Apple
> (display "a \"quoted\" thing")
a "quoted" thing
> (display "two\nlines")
two
lines
> (display "\u03BB")
λ
```

A string can be mutable or immutable; strings written directly as expressions are immutable, but most other strings are mutable. The `make-string` procedure creates a mutable string

given a length and optional fill character. The `string-ref` procedure accesses a character from a string (with 0-based indexing); the `string-set!` procedure changes a character in a mutable string.

Examples:

```
> (string-ref "Apple" 0)
#\A
> (define s (make-string 5 #\.))
> s
"....."
> (string-set! s 2 #\λ)
> s
"..λ.."
```

String ordering and case operations are generally *locale-independent*; that is, they work the same for all users. A few *locale-dependent* operations are provided that allow the way that strings are case-folded and sorted to depend on the end-user's locale. If you're sorting strings, for example, use `string<?` or `string-ci<?` if the sort result should be consistent across machines and users, but use `string-locale<?` or `string-locale-ci<?` if the sort is purely to order strings for an end user.

Examples:

```
> (string<? "apple" "Banana")
#f
> (string-ci<? "apple" "Banana")
#t
> (string-upcase "Straße")
"STRASSE"
> (parameterize ([current-locale "C"])
    (string-locale-upcase "Straße"))
"STRAßE"
```

For working with plain ASCII, working with raw bytes, or encoding/decoding Unicode strings as bytes, use byte strings.

§4.4 "Strings" in *The Racket Reference* provides more on strings and string procedures.

3.5 Bytes and Byte Strings

A *byte* is an exact integer between `0` and `255`, inclusive. The `byte?` predicate recognizes numbers that represent bytes.

Examples:

```
> (byte? 0)
#t
> (byte? 256)
#f
```

A *byte string* is similar to a string—see §3.4 “Strings (Unicode)”—but its content is a sequence of bytes instead of characters. Byte strings can be used in applications that process pure ASCII instead of Unicode text. The printed form of a byte string supports such uses in particular, because a byte string prints like the ASCII decoding of the byte string, but prefixed with a `#`. Unprintable ASCII characters or non-ASCII bytes in the byte string are written with octal notation.

§1.3.7 “Reading Strings” in *The Racket Reference* documents the fine points of the syntax of byte strings.

Examples:

```
> #"Apple"
#"Apple"
> (bytes-ref #"Apple" 0)
65
> (make-bytes 3 65)
#"AAA"
> (define b (make-bytes 2 0))
> b
#"\0\0"
> (bytes-set! b 0 1)
> (bytes-set! b 1 255)
> b
#"\1\377"
```

The `display` form of a byte string writes its raw bytes to the current output port (see §8 “Input and Output”). Technically, `display` of a normal (i.e,. character) string prints the UTF-8 encoding of the string to the current output port, since output is ultimately defined in terms of bytes; `display` of a byte string, however, writes the raw bytes with no encoding. Along the same lines, when this documentation shows output, it technically shows the UTF-8-decoded form of the output.

Examples:

```
> (display #"Apple")
Apple
> (display "\316\273")  ; same as "Î»"
Î»
> (display #"\316\273") ; UTF-8 encoding of λ
λ
```

For explicitly converting between strings and byte strings, Racket supports three kinds of encodings directly: UTF-8, Latin-1, and the current locale’s encoding. General facilities

for byte-to-byte conversions (especially to and from UTF-8) fill the gap to support arbitrary string encodings.

Examples:

```
> (bytes->string/utf-8 #"\316\273")
"λ"
> (bytes->string/latin-1 #"\316\273")
"Î»"
> (parameterize ([current-locale "C"])  ; C locale supports ASCII,
    (bytes->string/locale #"\316\273")) ; only, so...
bytes->string/locale: byte string is not a valid encoding
for the current locale
  byte string: #"\316\273"
> (let ([cvt (bytes-open-converter "cp1253" ; Greek code page
                                   "UTF-8")]
        [dest (make-bytes 2)])
    (bytes-convert cvt #"\353" 0 1 dest)
    (bytes-close-converter cvt)
    (bytes->string/utf-8 dest))
"λ"
```

§4.5 “Byte Strings” in *The Racket Reference* provides more on byte strings and byte-string procedures.

3.6 Symbols

A *symbol* is an atomic value that prints like an identifier preceded with `'`. An expression that starts with `'` and continues with an identifier produces a symbol value.

Examples:

```
> 'a
'a
> (symbol? 'a)
#t
```

For any sequence of characters, exactly one corresponding symbol is *interned*; calling the `string->symbol` procedure, or `read`ing a syntactic identifier, produces an interned symbol. Since interned symbols can be cheaply compared with `eq?` (and thus `eqv?` or `equal?`), they serve as a convenient values to use for tags and enumerations.

Symbols are case-sensitive. By using a `#ci` prefix or in other ways, the reader can be made to case-fold character sequences to arrive at a symbol, but the reader preserves case by default.

Examples:

```
> (eq? 'a 'a)
#t
> (eq? 'a (string->symbol "a"))
#t
> (eq? 'a 'b)
#f
> (eq? 'a 'A)
#f
> #ci'A
'a
```

Any string (i.e., any character sequence) can be supplied to `string->symbol` to obtain the corresponding symbol. For reader input, any character can appear directly in an identifier, except for whitespace and the following special characters:

```
( ) [ ] { } " , ' ` ; # | \
```

Actually, `#` is disallowed only at the beginning of a symbol, and then only if not followed by `%`; otherwise, `#` is allowed, too. Also, `.` by itself is not a symbol.

Whitespace or special characters can be included in an identifier by quoting them with `|` or `\`. These quoting mechanisms are used in the printed form of identifiers that contain special characters or that might otherwise look like numbers.

Examples:

```
> (string->symbol "one, two")
'|one, two|
> (string->symbol "6")
'|6|
```

§1.3.2 “Reading Symbols” in *The Racket Reference* documents the fine points of the syntax of symbols.

The `write` function prints a symbol without a `'` prefix. The `display` form of a symbol is the same as the corresponding string.

Examples:

```
> (write 'Apple)
Apple
> (display 'Apple)
Apple
> (write '|6|)
|6|
> (display '|6|)
6
```

The `gensym` and `string->uninterned-symbol` procedures generate fresh *uninterned*

symbols that are not equal (according to eq?) to any previously interned or uninterned symbol. Uninterned symbols are useful as fresh tags that cannot be confused with any other value.

Examples:

```
> (define s (gensym))
> s
'g42
> (eq? s 'g42)
#f
> (eq? 'a (string->uninterned-symbol "a"))
#f
```

§4.7 “Symbols” in *The Racket Reference* provides more on symbols.

3.7 Keywords

A *keyword* value is similar to a symbol (see §3.6 “Symbols”), but its printed form is prefixed with `#:`.

§1.3.15 “Reading Keywords” in *The Racket Reference* documents the fine points of the syntax of keywords.

Examples:

```
> (string->keyword "apple")
'#:apple
> '#:apple
'#:apple
> (eq? '#:apple (string->keyword "apple"))
#t
```

More precisely, a keyword is analogous to an identifier; in the same way that an identifier can be quoted to produce a symbol, a keyword can be quoted to produce a value. The same term “keyword” is used in both cases, but we sometimes use *keyword value* to refer more specifically to the result of a quote-keyword expression or of string->keyword. An unquoted keyword is not an expression, just as an unquoted identifier does not produce a symbol:

Examples:

```
> not-a-symbol-expression
not-a-symbol-expression: undefined;
 cannot reference an identifier before its definition
  in module: top-level
> #:not-a-keyword-expression
eval:2:0: #%datum: keyword misused as an expression
  at: #:not-a-keyword-expression
```

Despite their similarities, keywords are used in a different way than identifiers or symbols. Keywords are intended for use (unquoted) as special markers in argument lists and in certain syntactic forms. For run-time flags and enumerations, use symbols instead of keywords. The example below illustrates the distinct roles of keywords and symbols.

Examples:

```
> (define dir (find-system-path 'temp-dir)) ; not '#:temp-dir
> (with-output-to-file (build-path dir "stuff.txt")
    (lambda () (printf "example\n"))
    ; optional #:mode argument can be 'text or 'binary
    #:mode 'text
    ; optional #:exists argument can be 'replace, 'truncate, ...
    #:exists 'truncate)
```

3.8 Pairs and Lists

A *pair* joins two arbitrary values. The `cons` procedure constructs pairs, and the `car` and `cdr` procedures extract the first and second elements of the pair, respectively. The `pair?` predicate recognizes pairs.

Some pairs print by wrapping parentheses around the printed forms of the two pair elements, putting a `'` at the beginning and a `.` between the elements.

Examples:

```
> (cons 1 2)
'(1 . 2)
> (cons (cons 1 2) 3)
'((1 . 2) . 3)
> (car (cons 1 2))
1
> (cdr (cons 1 2))
2
> (pair? (cons 1 2))
#t
```

A *list* is a combination of pairs that creates a linked list. More precisely, a list is either the empty list `null`, or it is a pair whose first element is a list element and whose second element is a list. The `list?` predicate recognizes lists. The `null?` predicate recognizes the empty list.

A list normally prints as a `'` followed by a pair of parentheses wrapped around the list elements.

Examples:

```
> null
'()
> (cons 0 (cons 1 (cons 2 null)))
'(0 1 2)
> (list? null)
#t
> (list? (cons 1 (cons 2 null)))
#t
> (list? (cons 1 2))
#f
```

A list or pair prints using `list` or `cons` when one of its elements cannot be written as a `quoted` value. For example, a value constructed with `srcloc` cannot be written using `quote`, and it prints using `srcloc`:

```
> (srcloc "file.rkt" 1 0 1 (+ 4 4))
(srcloc "file.rkt" 1 0 1 8)
> (list 'here (srcloc "file.rkt" 1 0 1 8) 'there)
(list 'here (srcloc "file.rkt" 1 0 1 8) 'there)
> (cons 1 (srcloc "file.rkt" 1 0 1 8))
(cons 1 (srcloc "file.rkt" 1 0 1 8))
> (cons 1 (cons 2 (srcloc "file.rkt" 1 0 1 8)))
(list* 1 2 (srcloc "file.rkt" 1 0 1 8))
```

See also `list*`.

As shown in the last example, `list*` is used to abbreviate a series of `cons`es that cannot be abbreviated using `list`.

The `write` and `display` functions print a pair or list without a leading `'`, `cons`, `list`, or `list*`. There is no difference between `write` and `display` for a pair or list, except as they apply to elements of the list:

Examples:

```
> (write (cons 1 2))
(1 . 2)
> (display (cons 1 2))
(1 . 2)
> (write null)
()
> (display null)
()
> (write (list 1 2 "3"))
(1 2 "3")
> (display (list 1 2 "3"))
(1 2 3)
```

Among the most important predefined procedures on lists are those that iterate through the list's elements:

```
> (map (lambda (i) (/ 1 i))
       '(1 2 3))
'(1 1/2 1/3)
> (andmap (lambda (i) (i . < . 3))
          '(1 2 3))
#f
> (ormap (lambda (i) (i . < . 3))
          '(1 2 3))
#t
> (filter (lambda (i) (i . < . 3))
           '(1 2 3))
'(1 2)
> (foldl (lambda (v i) (+ v i))
         10
         '(1 2 3))
16
> (for-each (lambda (i) (display i))
            '(1 2 3))
123
> (member "Keys"
          '("Florida" "Keys" "U.S.A."))
'("Keys" "U.S.A.")
> (assoc 'where
         '((when "3:30") (where "Florida") (who "Mickey")))
'(where "Florida")
```

§4.10 "Pairs and Lists" in *The Racket Reference* provides more on pairs and lists.

Pairs are immutable (contrary to Lisp tradition), and `pair?` and `list?` recognize immutable pairs and lists, only. The `mcons` procedure creates a *mutable pair*, which works with `set-mcar!` and `set-mcdr!`, as well as `mcar` and `mcdr`. A mutable pair prints using `mcons`, while `write` and `display` print mutable pairs with `{` and `}`:

Examples:

```
> (define p (mcons 1 2))
> p
(mcons 1 2)
> (pair? p)
#f
> (mpair? p)
#t
> (set-mcar! p 0)
> p
(mcons 0 2)
```

```
> (write p)
{0 . 2}
```

3.9 Vectors

§4.11 “Mutable Pairs and Lists” in *The Racket Reference* provides more on mutable pairs.

A *vector* is a fixed-length array of arbitrary values. Unlike a list, a vector supports constant-time access and update of its elements.

A vector prints similar to a list—as a parenthesized sequence of its elements—but a vector is prefixed with `#` after `'`, or it uses `vector` if one of its elements cannot be expressed with `quote`.

For a vector as an expression, an optional length can be supplied. Also, a vector as an expression implicitly `quote`s the forms for its content, which means that identifiers and parenthesized forms in a vector constant represent symbols and lists.

§1.3.10 “Reading Vectors” in *The Racket Reference* documents the fine points of the syntax of vectors.

Examples:

```
> #("a" "b" "c")
'#("a" "b" "c")
> #(name (that tune))
'#(name (that tune))
> #4(baldwin bruce)
'#(baldwin bruce bruce bruce)
> (vector-ref #("a" "b" "c") 1)
"b"
> (vector-ref #(name (that tune)) 1)
'(that tune)
```

Like strings, a vector is either mutable or immutable, and vectors written directly as expressions are immutable.

Vectors can be converted to lists and vice versa via `vector->list` and `list->vector`; such conversions are particularly useful in combination with predefined procedures on lists. When allocating extra lists seems too expensive, consider using looping forms like `for/fold`, which recognize vectors as well as lists.

Example:

```
> (list->vector (map string-titlecase
                     (vector->list #("three" "blind" "mice"))))
'#("Three" "Blind" "Mice")
```

§4.12 “Vectors” in *The Racket Reference* provides more on vectors and vector procedures.

3.10 Hash Tables

A *hash table* implements a mapping from keys to values, where both keys and values can be arbitrary Racket values, and access and update to the table are normally constant-time operations. Keys are compared using `equal?`, `eqv?`, or `eq?`, depending on whether the hash table is created with `make-hash`, `make-hasheqv`, or `make-hasheq`.

Examples:

```
> (define ht (make-hash))
> (hash-set! ht "apple" '(red round))
> (hash-set! ht "banana" '(yellow long))
> (hash-ref ht "apple")
'(red round)
> (hash-ref ht "coconut")
hash-ref: no value found for key
  key: "coconut"
> (hash-ref ht "coconut" "not there")
"not there"
```

The `hash`, `hasheqv`, and `hasheq` functions create immutable hash tables from an initial set of keys and values, in which each value is provided as an argument after its key. Immutable hash tables can be extended with `hash-set`, which produces a new immutable hash table in constant time.

Examples:

```
> (define ht (hash "apple" 'red "banana" 'yellow))
> (hash-ref ht "apple")
'red
> (define ht2 (hash-set ht "coconut" 'brown))
> (hash-ref ht "coconut")
hash-ref: no value found for key
  key: "coconut"
> (hash-ref ht2 "coconut")
'brown
```

A literal immutable hash table can be written as an expression by using `#hash` (for an `equal?`-based table), `#hasheqv` (for an `eqv?`-based table), or `#hasheq` (for an `eq?`-based table). A parenthesized sequence must immediately follow `#hash`, `#hasheq`, or `#hasheqv`, where each element is a dotted key–value pair. The `#hash`, etc. forms implicitly `quote` their key and value sub-forms.

Examples:

```
> (define ht #hash(("apple" . red)
```

```
                    ("banana" . yellow)))
> (hash-ref ht "apple")
'red
```

§1.3.12 “Reading Hash Tables” in *The Racket Reference* documents the fine points of the syntax of hash table literals.

Both mutable and immutable hash tables print like immutable hash tables, using a quoted `#hash`, `#hasheqv`, or `#hasheq` form if all keys and values can be expressed with `quote` or using `hash`, `hasheq`, or `hasheqv` otherwise:

Examples:

```
> #hash(("apple" . red)
        ("banana" . yellow))
'#hash(("apple" . red) ("banana" . yellow))
> (hash 1 (srcloc "file.rkt" 1 0 1 (+ 4 4)))
(hash 1 (srcloc "file.rkt" 1 0 1 8))
```

A mutable hash table can optionally retain its keys *weakly*, so each mapping is retained only so long as the key is retained elsewhere.

Examples:

```
> (define ht (make-weak-hasheq))
> (hash-set! ht (gensym) "can you see me?")
> (collect-garbage)
> (hash-count ht)
0
```

Beware that even a weak hash table retains its values strongly, as long as the corresponding key is accessible. This creates a catch-22 dependency when a value refers back to its key, so that the mapping is retained permanently. To break the cycle, map the key to an *ephemeron* that pairs the value with its key (in addition to the implicit pairing of the hash table).

§16.2 “Ephemerons” in *The Racket Reference* documents the fine points of using ephemerons.

Examples:

```
> (define ht (make-weak-hasheq))
> (let ([g (gensym)])
    (hash-set! ht g (list g)))
> (collect-garbage)
> (hash-count ht)
1

> (define ht (make-weak-hasheq))
> (let ([g (gensym)])
    (hash-set! ht g (make-ephemeron g (list g))))
> (collect-garbage)
> (hash-count ht)
0
```

§4.15 “Hash Tables” in *The Racket Reference* provides more on hash tables and hash-table procedures.

3.11 Boxes

A *box* is like a single-element vector. It can print as a quoted `#&` followed by the printed form of the boxed value. A `#&` form can also be used as an expression, but since the resulting box is constant, it has practically no use.

Examples:

```
> (define b (box "apple"))
> b
'#&"apple"
> (unbox b)
"apple"
> (set-box! b '(banana boat))
> b
'#&(banana boat)
```

§4.14 “Boxes” in *The Racket Reference* provides more on boxes and box procedures.

3.12 Void and Undefined

Some procedures or expression forms have no need for a result value. For example, the `display` procedure is called only for the side-effect of writing output. In such cases the result value is normally a special constant that prints as `#<void>`. When the result of an expression is simply `#<void>`, the REPL does not print anything.

The `void` procedure takes any number of arguments and returns `#<void>`. (That is, the identifier `void` is bound to a procedure that returns `#<void>`, instead of being bound directly to `#<void>`.)

Examples:

```
> (void)
> (void 1 2 3)
> (list (void))
'(#<void>)
```

The `undefined` constant, which prints as `#<undefined>`, is sometimes used as the result of a reference whose value is not yet available. In previous versions of Racket (before version 6.1), referencing a local binding too early produced `#<undefined>`; too-early references now raise an exception, instead.

```
(define (fails)
  (define x x)
  x)
```

The `undefined` result can still be produced in some cases by the `shared` form.

```
> (fails)
x: undefined;
  cannot use before initialization
```

4 Expressions and Definitions

The §2 “Racket Essentials” chapter introduced some of Racket’s syntactic forms: definitions, procedure applications, conditionals, and so on. This section provides more details on those forms, plus a few additional basic forms.

4.1 Notation

This chapter (and the rest of the documentation) uses a slightly different notation than the character-based grammars of the §2 “Racket Essentials” chapter. The grammar for a use of a syntactic form `something` is shown like this:

```
(something [id ...+] an-expr ...)
```

The italicized meta-variables in this specification, such as *id* and *an-expr*, use the syntax of Racket identifiers, so *an-expr* is one meta-variable. A naming convention implicitly defines the meaning of many meta-variables:

- A meta-variable that ends in *id* stands for an identifier, such as `x` or `my-favorite-martian`.
- A meta-identifier that ends in *keyword* stands for a keyword, such as `#:tag`.
- A meta-identifier that ends with *expr* stands for any sub-form, and it will be parsed as an expression.
- A meta-identifier that ends with *body* stands for any sub-form; it will be parsed as either a local definition or an expression. The last *body* must be an expression; see also §4.5.4 “Internal Definitions”.

Square brackets in the grammar indicate a parenthesized sequence of forms, where square brackets are normally used (by convention). That is, square brackets *do not* mean optional parts of the syntactic form.

A `...` indicates zero or more repetitions of the preceding form, and `...+` indicates one or more repetitions of the preceding datum. Otherwise, non-italicized identifiers stand for themselves.

Based on the above grammar, then, here are a few conforming uses of `something`:

```
(something [x])
(something [x] (+ 1 2))
(something [x my-favorite-martian x] (+ 1 2) #f)
```

Some syntactic-form specifications refer to meta-variables that are not implicitly defined and not previously defined. Such meta-variables are defined after the main form, using a BNF-like format for alternatives:

```
(something-else [thing ...+] an-expr ...)

thing = thing-id
      | thing-keyword
```

The above example says that, within a `something-else` form, a *thing* is either an identifier or a keyword.

4.2 Identifiers and Binding

The context of an expression determines the meaning of identifiers that appear in the expression. In particular, starting a module with the language `racket`, as in

```
#lang racket
```

means that, within the module, the identifiers described in this guide start with the meaning described here: `cons` refers to the function that creates a pair, `car` refers to the function that extracts the first element of a pair, and so on.

§3.6 “Symbols” introduces the syntax of identifiers.

Forms like `define`, `lambda`, and `let` associate a meaning with one or more identifiers; that is, they *bind* identifiers. The part of the program for which the binding applies is the *scope* of the binding. The set of bindings in effect for a given expression is the expression’s *environment*.

For example, in

```
#lang racket

(define f
  (lambda (x)
    (let ([y 5])
      (+ x y))))

(f 10)
```

the `define` is a binding of `f`, the `lambda` has a binding for `x`, and the `let` has a binding for `y`. The scope of the binding for `f` is the entire module; the scope of the `x` binding is `(let ([y 5]) (+ x y))`; and the scope of the `y` binding is just `(+ x y)`. The environment of `(+ x y)` includes bindings for `y`, `x`, and `f`, as well as everything in `racket`.

A module-level `define` can bind only identifiers that are not already defined or `required` into the module. A local `define` or other binding forms, however, can give a new local binding for an identifier that already has a binding; such a binding *shadows* the existing binding.

Examples:

```
(define f
  (lambda (append)
    (define cons (append "ugly" "confusing"))
    (let ([append 'this-was])
      (list append cons))))
> (f list)
'(this-was ("ugly" "confusing"))
```

Similarly, a module-level `define` can shadow a binding from the module's language. For example, `(define cons 1)` in a `racket` module shadows the `cons` that is provided by `racket`. Intentionally shadowing a language binding is rarely a good idea—especially for widely used bindings like `cons`—but shadowing relieves a programmer from having to avoid every obscure binding that is provided by a language.

Even identifiers like `define` and `lambda` get their meanings from bindings, though they have *transformer* bindings (which means that they indicate syntactic forms) instead of value bindings. Since `define` has a transformer binding, the identifier `define` cannot be used by itself to get a value. However, the normal binding for `define` can be shadowed.

Examples:

```
> define
eval:1:0: define: bad syntax
  in: define
> (let ([define 5]) define)
5
```

Again, shadowing standard bindings in this way is rarely a good idea, but the possibility is an inherent part of Racket's flexibility.

4.3 Function Calls (Procedure Applications)

An expression of the form

```
(proc-expr arg-expr ...)
```

is a function call—also known as a *procedure application*—when *proc-expr* is not an identifier that is bound as a syntax transformer (such as `if` or `define`).

4.3.1 Evaluation Order and Arity

A function call is evaluated by first evaluating the *proc-expr* and all *arg-expr*s in order (left to right). Then, if *proc-expr* produces a function that accepts as many arguments as supplied *arg-expr*s, the function is called. Otherwise, an exception is raised.

Examples:

```
> (cons 1 null)
'(1)
> (+ 1 2 3)
6
> (cons 1 2 3)
cons: arity mismatch;
 the expected number of arguments does not match the given
number
  expected: 2
  given: 3
> (1 2 3)
application: not a procedure;
 expected a procedure that can be applied to arguments
  given: 1
```

Some functions, such as `cons`, accept a fixed number of arguments. Some functions, such as `+` or `list`, accept any number of arguments. Some functions accept a range of argument counts; for example `substring` accepts either two or three arguments. A function's *arity* is the number of arguments that it accepts.

4.3.2 Keyword Arguments

Some functions accept *keyword arguments* in addition to by-position arguments. For that case, an *arg* can be an *arg-keyword arg-expr* sequence instead of just a *arg-expr*:

§3.7 "Keywords" introduces keywords.

```
(proc-expr arg ...)

arg = arg-expr
    | arg-keyword arg-expr
```

For example,

```
(go "super.rkt" #:mode 'fast)
```

calls the function bound to `go` with `"super.rkt"` as a by-position argument, and with `'fast` as an argument associated with the `#:mode` keyword. A keyword is implicitly paired with the expression that follows it.

Since a keyword by itself is not an expression, then

```
(go "super.rkt" #:mode #:fast)
```

is a syntax error. The `#:mode` keyword must be followed by an expression to produce an argument value, and `#:fast` is not an expression.

The order of keyword *arg*s determines the order in which *arg-expr*s are evaluated, but a function accepts keyword arguments independent of their position in the argument list. The above call to `go` can be equivalently written

```
(go #:mode 'fast "super.rkt")
```

§3.7 "Procedure Applications and `#%app`" in *The Racket Reference* provides more on procedure applications.

4.3.3 The `apply` Function

The syntax for function calls supports any number of arguments, but a specific call always specifies a fixed number of arguments. As a result, a function that takes a list of arguments cannot directly apply a function like `+` to all of the items in a list:

```
(define (avg lst) ; doesn't work...
  (/ (+ lst) (length lst)))

> (avg '(1 2 3))
+: contract violation
  expected: number?
  given: '(1 2 3)


(define (avg lst) ; doesn't always work...
  (/ (+ (list-ref lst 0) (list-ref lst 1) (list-ref lst 2))
     (length lst)))

> (avg '(1 2 3))
2
> (avg '(1 2))
list-ref: index too large for list
  index: 2
  in: '(1 2)
```

The apply function offers a way around this restriction. It takes a function and a *list* argument, and it applies the function to the values in the list:

```
(define (avg lst)
  (/ (apply + lst) (length lst)))
```

```
> (avg '(1 2 3))
2
> (avg '(1 2))
3/2
> (avg '(1 2 3 4))
5/2
```

As a convenience, the apply function accepts additional arguments between the function and the list. The additional arguments are effectively consed onto the argument list:

```
(define (anti-sum lst)
  (apply - 0 lst))
```

```
> (anti-sum '(1 2 3))
-6
```

The apply function accepts keyword arguments, too, and it passes them along to the called function:

```
(apply go #:mode 'fast '("super.rkt"))
(apply go '("super.rkt") #:mode 'fast)
```

Keywords that are included in apply's list argument do not count as keyword arguments for the called function; instead, all arguments in this list are treated as by-position arguments. To pass a list of keyword arguments to a function, use the keyword-apply function, which accepts a function to apply and three lists. The first two lists are in parallel, where the first list contains keywords (sorted by keyword<?), and the second list contains a corresponding argument for each keyword. The third list contains by-position function arguments, as for apply.

```
(keyword-apply go
               '(#:mode)
               '(fast)
               '("super.rkt"))
```

4.4 Functions (Procedures): lambda

A lambda expression creates a function. In the simplest case, a lambda expression has the form

```
(lambda (arg-id ...)
  body ...+)
```

A `lambda` form with *n* `arg-id`s accepts *n* arguments:

```
> ((lambda (x) x)
   1)
1
> ((lambda (x y) (+ x y))
   1 2)
3
> ((lambda (x y) (+ x y))
   1)
arity mismatch;
 the expected number of arguments does not match the given
number
  expected: 2
  given: 1
```

4.4.1 Declaring a Rest Argument

A `lambda` expression can also have the form

```
(lambda rest-id
  body ...+)
```

That is, a `lambda` expression can have a single `rest-id` that is not surrounded by parentheses. The resulting function accepts any number of arguments, and the arguments are put into a list bound to `rest-id`.

Examples:

```
> ((lambda x x)
   1 2 3)
'(1 2 3)
> ((lambda x x))
'()
> ((lambda x (car x))
   1 2 3)
1
```

Functions with a `rest-id` often use `apply` to call another function that accepts any number of arguments.

§4.3.3 “The `apply` Function” describes `apply`.

Examples:

```
(define max-mag
  (lambda nums
    (apply max (map magnitude nums))))
> (max 1 -2 0)
1
> (max-mag 1 -2 0)
2
```

The `lambda` form also supports required arguments combined with a *`rest-id`*:

```
(lambda (arg-id ...+ . rest-id)
  body ...+)
```

The result of this form is a function that requires at least as many arguments as *`arg-id`*s, and also accepts any number of additional arguments.

Examples:

```
(define max-mag
  (lambda (num . nums)
    (apply max (map magnitude (cons num nums)))))
> (max-mag 1 -2 0)
2
> (max-mag)
max-mag: arity mismatch;
 the expected number of arguments does not match the given
number
  expected: at least 1
  given: 0
```

A *`rest-id`* variable is sometimes called a *rest argument*, because it accepts the "rest" of the function arguments. A function with a rest argument is sometimes called a *variadic* function, with elements in the rest argument called variadic arguments.

4.4.2 Declaring Optional Arguments

Instead of just an identifier, an argument (other than a rest argument) in a `lambda` form can be specified with an identifier and a default value:

```
(lambda gen-formals
  body ...+)

gen-formals = (arg ...)
            | rest-id
            | (arg ...+ . rest-id)

        arg = arg-id
            | [arg-id default-expr]
```

An argument of the form `[arg-id default-expr]` is optional. When the argument is not supplied in an application, *default-expr* produces the default value. The *default-expr* can refer to any preceding *arg-id*, and every following *arg-id* must have a default as well.

Examples:

```
(define greet
  (lambda (given [surname "Smith"])
    (string-append "Hello, " given " " surname)))
> (greet "John")
"Hello, John Smith"
> (greet "John" "Doe")
"Hello, John Doe"
```

```
(define greet
  (lambda (given [surname (if (equal? given "John")
                              "Doe"
                              "Smith")])
    (string-append "Hello, " given " " surname)))

> (greet "John")
"Hello, John Doe"
> (greet "Adam")
"Hello, Adam Smith"
```

4.4.3 Declaring Keyword Arguments

A `lambda` form can declare an argument to be passed by keyword, instead of position. Keyword arguments can be mixed with by-position arguments, and default-value expressions can be supplied for either kind of argument:

§4.3.2 “Keyword Arguments” introduces function calls with keywords.

```
(lambda gen-formals
  body ...+)
```

```
gen-formals = (arg ...)
            | rest-id
            | (arg ...+ . rest-id)

        arg = arg-id
            | [arg-id default-expr]
            | arg-keyword arg-id
            | arg-keyword [arg-id default-expr]
```

An argument specified as *arg-keyword arg-id* is supplied by an application using the same *arg-keyword*. The position of the keyword–identifier pair in the argument list does not matter for matching with arguments in an application, because it will be matched to an argument value by keyword instead of by position.

```
(define greet
  (lambda (given #:last surname)
    (string-append "Hello, " given " " surname)))

> (greet "John" #:last "Smith")
"Hello, John Smith"
> (greet #:last "Doe" "John")
"Hello, John Doe"
```

An *arg-keyword* [*arg-id default-expr*] argument specifies a keyword-based argument with a default value.

Examples:

```
(define greet
  (lambda (#:hi [hi "Hello"] given #:last [surname "Smith"])
    (string-append hi ", " given " " surname)))
> (greet "John")
"Hello, John Smith"
> (greet "Karl" #:last "Marx")
"Hello, Karl Marx"
> (greet "John" #:hi "Howdy")
"Howdy, John Smith"
> (greet "Karl" #:last "Marx" #:hi "Guten Tag")
"Guten Tag, Karl Marx"
```

The `lambda` form does not directly support the creation of a function that accepts "rest" keywords. To construct a function that accepts all keyword arguments, use `make-keyword-procedure`. The function supplied to `make-keyword-procedure` receives keyword arguments through parallel lists in the first two (by-position) arguments, and then all by-position arguments from an application as the remaining by-position arguments.

§4.3.3 "The `apply` Function" introduces `keyword-apply`.

Examples:

```
(define (trace-wrap f)
  (make-keyword-procedure
   (lambda (kws kw-args . rest)
     (printf "Called with ~s ~s ~s\n" kws kw-args rest)
     (keyword-apply f kws kw-args rest))))
> ((trace-wrap greet) "John" #:hi "Howdy")
Called with (#:hi) ("Howdy") ("John")
"Howdy, John Smith"
```

§3.8 “Procedure Expressions: `lambda` and `case-lambda`” in *The Racket Reference* provides more on function expressions.

4.4.4 Arity-Sensitive Functions: `case-lambda`

The `case-lambda` form creates a function that can have completely different behaviors depending on the number of arguments that are supplied. A case-lambda expression has the form

```
(case-lambda
  [formals body ...+]
  ...)

formals = (arg-id ...)
        | rest-id
        | (arg-id ...+ . rest-id)
```

where each `[formals body ...+]` is analogous to `(lambda formals body ...+)`. Applying a function produced by `case-lambda` is like applying a `lambda` for the first case that matches the number of given arguments.

Examples:

```
(define greet
  (case-lambda
    [(name) (string-append "Hello, " name)]
    [(given surname) (string-append "Hello, " given "
" surname)]))
> (greet "John")
"Hello, John"
> (greet "John" "Smith")
"Hello, John Smith"
> (greet)
greet: arity mismatch;
 the expected number of arguments does not match the given
```

number
given: 0

A `case-lambda` function cannot directly support optional or keyword arguments.

4.5 Definitions: `define`

A basic definition has the form

```
(define id expr)
```

in which case *id* is bound to the result of *expr*.

Examples:

```
(define salutation (list-ref '("Hi" "Hello") (random 2)))
> salutation
"Hi"
```

4.5.1 Function Shorthand

The `define` form also supports a shorthand for function definitions:

```
(define (id arg ...) body ...+)
```

which is a shorthand for

```
(define id (lambda (arg ...) body ...+))
```

Examples:

```
(define (greet name)
  (string-append salutation ", " name))
> (greet "John")
"Hi, John"
```

```
(define (greet first [surname "Smith"] #:hi [hi salutation])
  (string-append hi ", " first " " surname))
```

```
> (greet "John")
"Hi, John Smith"
> (greet "John" #:hi "Hey")
"Hey, John Smith"
> (greet "John" "Doe")
"Hi, John Doe"
```

The function shorthand via `define` also supports a rest argument (i.e., a final argument to collect extra arguments in a list):

```
(define (id arg ... . rest-id) body ...+)
```

which is a shorthand

```
(define id (lambda (arg ... . rest-id) body ...+))
```

Examples:

```
(define (avg . l)
  (/ (apply + l) (length l)))
> (avg 1 2 3)
2
```

4.5.2 Curried Function Shorthand

Consider the following `make-add-suffix` function that takes a string and returns another function that takes a string:

```
(define make-add-suffix
  (lambda (s2)
    (lambda (s) (string-append s s2))))
```

Although it's not common, the result of `make-add-suffix` could be called directly, like this:

```
> ((make-add-suffix "!") "hello")
"hello!"
```

In a sense, `make-add-suffix` is a function that takes two arguments, but it takes them one at a time. A function that takes some of its arguments and returns a function to consume more is sometimes called a *curried function*.

Using the function-shorthand form of `define`, `make-add-suffix` can be written equivalently as

```
(define (make-add-suffix s2)
  (lambda (s) (string-append s s2)))
```

This shorthand reflects the shape of the function call `(make-add-suffix "!")`. The `define` form further supports a shorthand for defining curried functions that reflects nested function calls:

```
(define ((make-add-suffix s2) s)
  (string-append s s2))

> ((make-add-suffix "!") "hello")
"hello!"


(define louder (make-add-suffix "!"))
(define less-sure (make-add-suffix "?"))

> (less-sure "really")
"really?"
> (louder "really")
"really!"
```

The full syntax of the function shorthand for `define` is as follows:

```
(define (head args) body ...+)

head = id
     | (head args)

args = arg ...
     | arg ... . rest-id
```

The expansion of this shorthand has one nested `lambda` form for each *head* in the definition, where the innermost *head* corresponds to the outermost `lambda`.

4.5.3 Multiple Values and `define-values`

A Racket expression normally produces a single result, but some expressions can produce multiple results. For example, `quotient` and `remainder` each produce a single value, but `quotient/remainder` produces the same two values at once:

```
> (quotient 13 3)
4
> (remainder 13 3)
1
> (quotient/remainder 13 3)
4
1
```

As shown above, the REPL prints each result value on its own line.

Multiple-valued functions can be implemented in terms of the `values` function, which takes any number of values and returns them as the results:

```
> (values 1 2 3)
1
2
3
```

```
(define (split-name name)
  (let ([parts (regexp-split " " name)])
    (if (= (length parts) 2)
        (values (list-ref parts 0) (list-ref parts 1))
        (error "not a <first> <last> name"))))
```

```
> (split-name "Adam Smith")
"Adam"
"Smith"
```

The `define-values` form binds multiple identifiers at once to multiple results produced from a single expression:

```
(define-values (id ...) expr)
```

The number of results produced by the *expr* must match the number of *id*s.

Examples:

```
(define-values (given surname) (split-name "Adam Smith"))
> given
"Adam"
> surname
"Smith"
```

A `define` form (that is not a function shorthand) is equivalent to a `define-values` form with a single *id*.

§3.14 “Definitions: `define`, `define-syntax`, ...” in *The Racket Reference* provides more on definitions.

4.5.4 Internal Definitions

When the grammar for a syntactic form specifies *body*, then the corresponding form can be either a definition or an expression. A definition as a *body* is an *internal definition*.

Expressions and internal definitions in a *body* sequence can be mixed, as long as the last *body* is an expression.

For example, the syntax of `lambda` is

```
(lambda gen-formals
  body ...+)
```

so the following are valid instances of the grammar:

```
(lambda (f)                ; no definitions
  (printf "running\n")
  (f 0))

(lambda (f)                ; one definition
  (define (log-it what)
    (printf "~a\n" what))
  (log-it "running")
  (f 0)
  (log-it "done"))

(lambda (f n)              ; two definitions
  (define (call n)
    (if (zero? n)
        (log-it "done")
        (begin
          (log-it "running")
          (f n)
          (call (- n 1)))))
  (define (log-it what)
    (printf "~a\n" what))
  (call n))
```

Internal definitions in a particular *body* sequence are mutually recursive; that is, any definition can refer to any other definition—as long as the reference isn't actually evaluated before its definition takes place. If a definition is referenced too early, an error occurs.

Examples:

```
(define (weird)
```

```
  (define x x)
  x)
> (weird)
x: undefined;
 cannot use before initialization
```

A sequence of internal definitions using just `define` is easily translated to an equivalent `letrec` form (as introduced in the next section). However, other definition forms can appear as a *body*, including `define-values`, `struct` (see §5 “Programmer-Defined Datatypes”) or `define-syntax` (see §16 “Macros”).

§1.2.3.8 “Internal Definitions” in *The Racket Reference* documents the fine points of internal definitions.

4.6 Local Binding

Although internal `define`s can be used for local binding, Racket provides three forms that give the programmer more control over bindings: `let`, `let*`, and `letrec`.

4.6.1 Parallel Binding: `let`

§3.9 “Local Binding: `let`, `let*`, `letrec`, ...” in *The Racket Reference* also documents `let`.

A `let` form binds a set of identifiers, each to the result of some expression, for use in the `let` body:

```
(let ([id expr] ...) body ...+)
```

The *id*s are bound “in parallel.” That is, no *id* is bound in the right-hand side *expr* for any *id*, but all are available in the *body*. The *id*s must be different from each other.

Examples:

```
> (let ([me "Bob"])
    me)
"Bob"
> (let ([me "Bob"]
        [myself "Robert"]
        [I "Bobby"])
    (list me myself I))
'("Bob" "Robert" "Bobby")
> (let ([me "Bob"]
        [me "Robert"])
    me)
eval:3:0: let: duplicate identifier
  at: me
  in: (let ((me "Bob") (me "Robert")) me)
```

The fact that an *id*'s *expr* does not see its own binding is often useful for wrappers that must refer back to the old value:

```
> (let ([+ (lambda (x y)
             (if (string? x)
                 (string-append x y)
                 (+ x y)))]) ; use original +
    (list (+ 1 2)
          (+ "see" "saw")))
'(3 "seesaw")
```

Occasionally, the parallel nature of `let` bindings is convenient for swapping or rearranging a set of bindings:

```
> (let ([me "Tarzan"]
        [you "Jane"])
    (let ([me you]
          [you me])
      (list me you)))
'("Jane" "Tarzan")
```

The characterization of `let` bindings as "parallel" is not meant to imply concurrent evaluation. The *expr*s are evaluated in order, even though the bindings are delayed until all *expr*s are evaluated.

4.6.2 Sequential Binding: `let*`

§3.9 "Local Binding: `let`, `let*`, `letrec`, ..." in *The Racket Reference* also documents `let*`.

The syntax of `let*` is the same as `let`:

```
(let* ([id expr] ...) body ...+)
```

The difference is that each *id* is available for use in later *expr*s, as well as in the *body*. Furthermore, the *id*s need not be distinct, and the most recent binding is the visible one.

Examples:

```
> (let* ([x (list "Burroughs")]
         [y (cons "Rice" x)]
         [z (cons "Edgar" y)])
    (list x y z))
'(("Burroughs") ("Rice" "Burroughs") ("Edgar" "Rice" "Burroughs"))
```

```
> (let* ([name (list "Burroughs")]
         [name (cons "Rice" name)]
         [name (cons "Edgar" name)])
    name)
'("Edgar" "Rice" "Burroughs")
```

In other words, a `let*` form is equivalent to nested `let` forms, each with a single binding:

```
> (let ([name (list "Burroughs")])
    (let ([name (cons "Rice" name)])
      (let ([name (cons "Edgar" name)])
        name)))
'("Edgar" "Rice" "Burroughs")
```

4.6.3 Recursive Binding: `letrec`

§3.9 "Local Binding: `let`, `let*`, `letrec`, ..." in *The Racket Reference* also documents `letrec`.

The syntax of `letrec` is also the same as `let`:

```
(letrec ([id expr] ...) body ...+)
```

While `let` makes its bindings available only in the *body*s, and `let*` makes its bindings available to any later binding *expr*, `letrec` makes its bindings available to all other *expr*s—even earlier ones. In other words, `letrec` bindings are recursive.

The *expr*s in a `letrec` form are most often `lambda` forms for recursive and mutually recursive functions:

```
> (letrec ([swing
            (lambda (t)
              (if (eq? (car t) 'tarzan)
                  (cons 'vine
                        (cons 'tarzan (cddr t)))
                  (cons (car t)
                        (swing (cdr t))))))])
    (swing '(vine tarzan vine vine)))
'(vine vine tarzan vine)
```

```
> (letrec ([tarzan-near-top-of-tree?
            (lambda (name path depth)
              (or (equal? name "tarzan")
                  (and (directory-exists? path)
                       (tarzan-in-directory? path depth))))])
```

```
            [tarzan-in-directory?
             (lambda (dir depth)
               (cond
                 [(zero? depth) #f]
                 [else
                  (ormap
                   (λ (elem)
                     (tarzan-near-top-of-tree? (path-element-
>string elem)
                                               (build-
path dir elem)
                                               (- depth 1)))
                   (directory-list dir))]))])
    (tarzan-near-top-of-tree? "tmp"
                              (find-system-path 'temp-dir)
                              4))
directory-list: could not open directory
  path: /var/folders/7y/jrt5816d25l9tflxsrp3w_6c0000gn/T/Tem
poraryItems
  system error: Operation not permitted; errno=1
```

While the *expr*s of a `letrec` form are typically `lambda` expressions, they can be any expression. The expressions are evaluated in order, and after each value is obtained, it is immediately associated with its corresponding *id*. If an *id* is referenced before its value is ready, an error is raised, just as for internal definitions.

```
> (letrec ([quicksand quicksand])
    quicksand)
quicksand: undefined;
 cannot use before initialization
```

4.6.4 Named `let`

A named `let` is an iteration and recursion form. It uses the same syntactic keyword `let` as for local binding, but an identifier after the `let` (instead of an immediate open parenthesis) triggers a different parsing.

```
(let proc-id ([arg-id init-expr] ...)
  body ...+)
```

A named `let` form is equivalent to

```
((letrec ([proc-id (lambda (arg-id ...)
```

```
                      body ...+)])
  proc-id)
 init-expr ...)
```

That is, a named `let` binds a function identifier that is visible only in the function's body, and it implicitly calls the function with the values of some initial expressions.

Examples:

```
(define (duplicate pos lst)
  (let dup ([i 0]
            [lst lst])
    (cond
      [(= i pos) (cons (car lst) lst)]
      [else (cons (car lst) (dup (+ i 1) (cdr lst)))])))
> (duplicate 1 (list "apple" "cheese burger!" "banana"))
'("apple" "cheese burger!" "cheese burger!" "banana")
```

4.6.5 Multiple Values: `let-values`, `let*-values`, `letrec-values`

§3.9 "Local Binding: `let`, `let*`, `letrec`, ..." in *The Racket Reference* also documents multiple-value binding forms.

In the same way that `define-values` binds multiple results in a definition (see §4.5.3 "Multiple Values and `define-values`"), `let-values`, `let*-values`, and `letrec-values` bind multiple results locally.

```
(let-values ([(id ...) expr] ...)
  body ...+)
```

```
(let*-values ([(id ...) expr] ...)
  body ...+)
```

```
(letrec-values ([(id ...) expr] ...)
  body ...+)
```

Each *expr* must produce as many values as corresponding *id*s. The binding rules are the same for the forms without `-values` forms: the *id*s of `let-values` are bound only in the *body*s, the *id*s of `let*-valuess` are bound in *expr*s of later clauses, and the *id*s of `letrec-value`s are bound for all *expr*s.

Example:

```
> (let-values ([(q r) (quotient/remainder 14 3)])
    (list q r))
'(4 2)
```

4.7 Conditionals

Most functions used for branching, such as `<` and `string?`, produce either `#t` or `#f`. Racket's branching forms, however, treat any value other than `#f` as true. We say a *true value* to mean any value other than `#f`.

This convention for "true value" meshes well with protocols where `#f` can serve as failure or to indicate that an optional value is not supplied. (Beware of overusing this trick, and remember that an exception is usually a better mechanism to report failure.)

For example, the `member` function serves double duty; it can be used to find the tail of a list that starts with a particular item, or it can be used to simply check whether an item is present in a list:

```
> (member "Groucho" '("Harpo" "Zeppo"))
#f
> (member "Groucho" '("Harpo" "Groucho" "Zeppo"))
'("Groucho" "Zeppo")
> (if (member "Groucho" '("Harpo" "Zeppo"))
      'yep
      'nope)
'nope
> (if (member "Groucho" '("Harpo" "Groucho" "Zeppo"))
      'yep
      'nope)
'yep
```

4.7.1 Simple Branching: `if`

§3.12 "Conditionals: `if`, `cond`, `and`, and `or`" in *The Racket Reference* also documents `if`.

In an `if` form,

```
(if test-expr then-expr else-expr)
```

the *`test-expr`* is always evaluated. If it produces any value other than `#f`, then *`then-expr`* is evaluated. Otherwise, *`else-expr`* is evaluated.

An `if` form must have both a *`then-expr`* and an *`else-expr`*; the latter is not optional. To perform (or skip) side-effects based on a *`test-expr`*, use `when` or `unless`, which we describe later in §4.8 "Sequencing".

4.7.2 Combining Tests: `and` and `or`

§3.12 "Conditionals: `if`, `cond`, `and`, and `or`" in *The Racket Reference* also documents `and` and `or`.

Racket's `and` and `or` are syntactic forms, rather than functions. Unlike a function, the `and` and `or` forms can skip evaluation of later expressions if an earlier one determines the answer.

```
(and expr ...)
```

An `and` form produces `#f` if any of its *expr*s produces `#f`. Otherwise, it produces the value of its last *expr*. As a special case, `(and)` produces `#t`.

```
(or expr ...)
```

The `or` form produces `#f` if all of its *expr*s produce `#f`. Otherwise, it produces the first non-`#f` value from its *expr*s. As a special case, `(or)` produces `#f`.

Examples:

```
> (define (got-milk? lst)
    (and (not (null? lst))
         (or (eq? 'milk (car lst))
             (got-milk? (cdr lst))))) ; recurs only if needed
> (got-milk? '(apple banana))
#f
> (got-milk? '(apple milk banana))
#t
```

If evaluation reaches the last *expr* of an `and` or `or` form, then the *expr*'s value directly determines the `and` or `or` result. Therefore, the last *expr* is in tail position, which means that the above `got-milk?` function runs in constant space.

§2.3.3 "Tail Recursion" introduces tail calls and tail positions.

4.7.3 Chaining Tests: `cond`

The `cond` form chains a series of tests to select a result expression. To a first approximation, the syntax of `cond` is as follows:

§3.12 "Conditionals: `if`, `cond`, `and`, and `or`" in *The Racket Reference* also documents `cond`.

```
(cond [test-expr body ...+]
      ...)
```

Each *test-expr* is evaluated in order. If it produces `#f`, the corresponding *body*s are ignored, and evaluation proceeds to the next *test-expr*. As soon as a *test-expr* produces

a true value, the associated *body*s are evaluated to produce the result for the `cond` form, and no further *test-expr*s are evaluated.

The last *test-expr* in a `cond` can be replaced by `else`. In terms of evaluation, `else` serves as a synonym for `#t`, but it clarifies that the last clause is meant to catch all remaining cases. If `else` is not used, then it is possible that no *test-expr*s produce a true value; in that case, the result of the `cond` expression is `#<void>`.

Examples:

```
> (cond
    [(= 2 3) (error "wrong!")]
    [(= 2 2) 'ok])
'ok
> (cond
    [(= 2 3) (error "wrong!")])
> (cond
    [(= 2 3) (error "wrong!")]
    [else 'ok])
'ok

(define (got-milk? lst)
  (cond
    [(null? lst) #f]
    [(eq? 'milk (car lst)) #t]
    [else (got-milk? (cdr lst))]))

> (got-milk? '(apple banana))
#f
> (got-milk? '(apple milk banana))
#t
```

The full syntax of `cond` includes two more kinds of clauses:

```
(cond cond-clause ...)

cond-clause = [test-expr then-body ...+]
            | [else then-body ...+]
            | [test-expr => proc-expr]
            | [test-expr]
```

The `=>` variant captures the true result of its *test-expr* and passes it to the result of the *proc-expr*, which must be a function of one argument.

Examples:

```
> (define (after-groucho lst)
    (cond
      [(member "Groucho" lst) => cdr]
      [else (error "not there")]))
> (after-groucho '("Harpo" "Groucho" "Zeppo"))
'("Zeppo")
> (after-groucho '("Harpo" "Zeppo"))
not there
```

A clause that includes only a *test-expr* is rarely used. It captures the true result of the *test-expr*, and simply returns the result for the whole `cond` expression.

4.8 Sequencing

Racket programmers prefer to write programs with as few side-effects as possible, since purely functional code is more easily tested and composed into larger programs. Interaction with the external environment, however, requires sequencing, such as when writing to a display, opening a graphical window, or manipulating a file on disk.

4.8.1 Effects Before: `begin`

§3.15 "Sequencing: `begin`, `begin0`, and `begin-for-syntax`" in *The Racket Reference* also documents `begin`.

A `begin` expression sequences expressions:

```
(begin expr ...+)
```

The *expr*s are evaluated in order, and the result of all but the last *expr* is ignored. The result from the last *expr* is the result of the `begin` form, and it is in tail position with respect to the `begin` form.

Examples:

```
(define (print-triangle height)
  (if (zero? height)
      (void)
      (begin
        (display (make-string height #\*))
        (newline)
        (print-triangle (sub1 height)))))
> (print-triangle 4)
****
***
```

```
**
*
```

Many forms, such as `lambda` or `cond` support a sequence of expressions even without a `begin`. Such positions are sometimes said to have an *implicit begin*.

Examples:

```
(define (print-triangle height)
  (cond
    [(positive? height)
     (display (make-string height #\*))
     (newline)
     (print-triangle (sub1 height))]))
> (print-triangle 4)
****
***
**
*
```

The `begin` form is special at the top level, at module level, or as a `body` after only internal definitions. In those positions, instead of forming an expression, the content of `begin` is spliced into the surrounding context.

Example:

```
> (let ([curly 0])
    (begin
      (define moe (+ 1 curly))
      (define larry (+ 1 moe)))
    (list larry curly moe))
'(2 0 1)
```

This splicing behavior is mainly useful for macros, as we discuss later in §16 “Macros”.

4.8.2 Effects After: `begin0`

§3.15 “Sequencing: `begin`, `begin0`, and `begin-for-syntax`” in *The Racket Reference* also documents `begin0`.

A `begin0` expression has the same syntax as a `begin` expression:

```
(begin0 expr ...+)
```

The difference is that `begin0` returns the result of the first `expr`, instead of the result of the last `expr`. The `begin0` form is useful for implementing side-effects that happen after a

computation, especially in the case where the computation produces an unknown number of results.

Examples:

```
(define (log-times thunk)
  (printf "Start: ~s\n" (current-inexact-milliseconds))
  (begin0
    (thunk)
    (printf "End..: ~s\n" (current-inexact-milliseconds))))
> (log-times (lambda () (sleep 0.1) 0))
Start: 1793458739137.199
End..: 1793458739253.704
0
> (log-times (lambda () (values 1 2)))
Start: 1793458739254.759
End..: 1793458739254.765
1
2
```

4.8.3 Effects If...: `when` and `unless`

§3.16 "Guarded Evaluation: `when` and `unless`" in *The Racket Reference* also documents `when` and `unless`.

The `when` form combines an `if`-style conditional with sequencing for the "then" clause and no "else" clause:

```
(when test-expr then-body ...+)
```

If *test-expr* produces a true value, then all of the *then-body*s are evaluated. The result of the last *then-body* is the result of the `when` form. Otherwise, no *then-body*s are evaluated and the result is `#<void>`.

The `unless` form is similar:

```
(unless test-expr then-body ...+)
```

The difference is that the *test-expr* result is inverted: the *then-body*s are evaluated only if the *test-expr* result is `#f`.

Examples:

```
(define (enumerate lst)
  (if (null? (cdr lst))
```

```
      (printf "~a.\n" (car lst))
      (begin
        (printf "~a, " (car lst))
        (when (null? (cdr (cdr lst)))
          (printf "and "))
        (enumerate (cdr lst)))))
> (enumerate '("Larry" "Curly" "Moe"))
Larry, Curly, and Moe.

(define (print-triangle height)
  (unless (zero? height)
    (display (make-string height #\*))
    (newline)
    (print-triangle (sub1 height))))

> (print-triangle 4)
****
***
**
*
```

4.9 Assignment: `set!`

§3.17 "Assignment: `set!` and `set!-values`" in *The Racket Reference* also documents `set!`.

Assign to a variable using `set!`:

```
(set! id expr)
```

A `set!` expression evaluates *expr* and changes *id* (which must be bound in the enclosing environment) to the resulting value. The result of the `set!` expression itself is `#<void>`.

Examples:

```
(define greeted null)
(define (greet name)
  (set! greeted (cons name greeted))
  (string-append "Hello, " name))
> (greet "Athos")
"Hello, Athos"
> (greet "Porthos")
"Hello, Porthos"
> (greet "Aramis")
"Hello, Aramis"
> greeted
'("Aramis" "Porthos" "Athos")
```

```
(define (make-running-total)
  (let ([n 0])
    (lambda ()
      (set! n (+ n 1))
      n)))
(define win (make-running-total))
(define lose (make-running-total))

> (win)
1
> (win)
2
> (lose)
1
> (win)
3
```

4.9.1 Guidelines for Using Assignment

Although using `set!` is sometimes appropriate, Racket style generally discourages the use of `set!`. The following guidelines may help explain when using `set!` is appropriate.

- As in any modern language, assigning to a shared identifier is no substitute for passing an argument to a procedure or getting its result.

  Really awful example:

  ```
  (define name "unknown")
  (define result "unknown")
  (define (greet)
    (set! result (string-append "Hello, " name)))

  > (set! name "John")
  > (greet)
  > result
  "Hello, John"
  ```

  Ok example:

  ```
  (define (greet name)
    (string-append "Hello, " name))

  > (greet "John")
  "Hello, John"
  > (greet "Anna")
  "Hello, Anna"
  ```

- A sequence of assignments to a local variable is far inferior to nested bindings.

  Bad example:

```
> (let ([tree 0])
    (set! tree (list tree 1 tree))
    (set! tree (list tree 2 tree))
    (set! tree (list tree 3 tree))
    tree)
'(((0 1 0) 2 (0 1 0)) 3 ((0 1 0) 2 (0 1 0)))
```

  Ok example:

```
> (let* ([tree 0]
         [tree (list tree 1 tree)]
         [tree (list tree 2 tree)]
         [tree (list tree 3 tree)])
    tree)
'(((0 1 0) 2 (0 1 0)) 3 ((0 1 0) 2 (0 1 0)))
```

- Using assignment to accumulate results from an iteration is bad style. Accumulating through a loop argument is better.

  Somewhat bad example:

```
(define (sum lst)
  (let ([s 0])
    (for-each (lambda (i) (set! s (+ i s)))
              lst)
    s))

> (sum '(1 2 3))
6
```

  Ok example:

```
(define (sum lst)
  (let loop ([lst lst] [s 0])
    (if (null? lst)
        s
        (loop (cdr lst) (+ s (car lst))))))

> (sum '(1 2 3))
6
```

  Better (use an existing function) example:

```
(define (sum lst)
  (apply + lst))

> (sum '(1 2 3))
6
```

Good (a general approach) example:

```
(define (sum lst)
  (for/fold ([s 0])
            ([i (in-list lst)])
    (+ s i)))

> (sum '(1 2 3))
6
```

- For cases where stateful objects are necessary or appropriate, then implementing the object's state with `set!` is fine.

  Ok example:

```
(define next-number!
  (let ([n 0])
    (lambda ()
      (set! n (add1 n))
      n)))

> (next-number!)
1
> (next-number!)
2
> (next-number!)
3
```

All else being equal, a program that uses no assignments or mutation is always preferable to one that uses assignments or mutation. While side effects are to be avoided, however, they should be used if the resulting code is significantly more readable or if it implements a significantly better algorithm.

The use of mutable values, such as vectors and hash tables, raises fewer suspicions about the style of a program than using `set!` directly. Nevertheless, simply replacing `set!`s in a program with `vector-set!`s obviously does not improve the style of the program.

4.9.2 Multiple Values: `set!-values`

§3.17 "Assignment: `set!` and `set!-values`" in *The Racket Reference* also documents `set!-values`.

The `set!-values` form assigns to multiple variables at once, given an expression that produces an appropriate number of values:

```
(set!-values (id ...) expr)
```

This form is equivalent to using `let-values` to receive multiple results from *expr*, and then assigning the results individually to the *id*s using `set!`.

Examples:

```
(define game
  (let ([w 0]
        [l 0])
    (lambda (win?)
      (if win?
          (set! w (+ w 1))
          (set! l (+ l 1)))
      (begin0
        (values w l)
        ; swap sides...
        (set!-values (w l) (values l w))))))
> (game #t)
1
0
> (game #t)
1
1
> (game #f)
1
2
```

4.10 Quoting: `quote` and `'`

§3.3 "Literals: `quote` and `#%datum`" in *The Racket Reference* also documents `quote`.

The `quote` form produces a constant:

```
(quote datum)
```

The syntax of a `datum` is technically specified as anything that the `read` function parses as a single element. The value of the `quote` form is the same value that `read` would produce given *datum*.

The *datum* can be a symbol, a boolean, a number, a (character or byte) string, a character, a keyword, an empty list, a pair (or list) containing more such values, a vector containing more such values, a hash table containing more such values, or a box containing another such value.

Examples:

```
> (quote apple)
'apple
> (quote #t)
#t
> (quote 42)
42
> (quote "hello")
"hello"
> (quote ())
'()
> (quote ((1 2 3) #("z" x) . the-end))
'((1 2 3) #("z" x) . the-end)
> (quote (1 2 . (3)))
'(1 2 3)
```

As the last example above shows, the *datum* does not have to match the normalized printed form of a value. A *datum* cannot be a printed representation that starts with `#<`, so it cannot be `#<void>`, `#<undefined>`, or a procedure.

The `quote` form is rarely used for a *datum* that is a boolean, number, or string by itself, since the printed forms of those values can already be used as constants. The `quote` form is more typically used for symbols and lists, which have other meanings (identifiers, function calls, etc.) when not quoted.

An expression

```
'datum
```

is a shorthand for

```
(quote datum)
```

and this shorthand is almost always used instead of `quote`. The shorthand applies even within the *datum*, so it can produce a list containing `quote`.

§1.3.8 “Reading Quotes” in *The Racket Reference* provides more on the `'` shorthand.

Examples:

```
> 'apple
'apple
> '"hello"
"hello"
> '(1 2 3)
'(1 2 3)
> (display '(you can 'me))
(you can (quote me))
```

4.11 Quasiquoting: `quasiquote` and `‘`

§3.20 “Quasiquoting: `quasiquote`, `unquote`, and `unquote-splicing`” in *The Racket Reference* also documents `quasiquote`.

The `quasiquote` form is similar to `quote`:

```
(quasiquote datum)
```

However, for each `(unquote expr)` that appears within the *datum*, the *expr* is evaluated to produce a value that takes the place of the `unquote` sub-form.

Example:

```
> (quasiquote (1 2 (unquote (+ 1 2)) (unquote (- 5 1))))
'(1 2 3 4)
```

This form can be used to write functions that build lists according to certain patterns.

Examples:

```
> (define (deep n)
    (cond
      [(zero? n) 0]
      [else
       (quasiquote ((unquote n) (unquote (deep (- n 1)))))]))
> (deep 8)
'(8 (7 (6 (5 (4 (3 (2 (1 0))))))))
```

Or even to cheaply construct expressions programmatically. (Of course, 9 times out of 10, you should be using a macro to do this (the 10th time being when you’re working through a textbook like PLAI).)

Examples:

```
> (define (build-exp n)
    (add-lets n (make-sum n)))
> (define (add-lets n body)
    (cond
      [(zero? n) body]
      [else
       (quasiquote
        (let ([(unquote (n->var n)) (unquote n)])
          (unquote (add-lets (- n 1) body))))]))
> (define (make-sum n)
    (cond
      [(= n 1) (n->var 1)]
```

```
      [else
       (quasiquote (+ (unquote (n->var n))
                      (unquote (make-sum (- n 1)))))]))
> (define (n->var n) (string->symbol (format "x~a" n)))
> (build-exp 3)
'(let ((x3 3)) (let ((x2 2)) (let ((x1 1)) (+ x3 (+ x2 x1)))))
```

The `unquote-splicing` form is similar to `unquote`, but its *expr* must produce a list, and the `unquote-splicing` form must appear in a context that produces either a list or a vector. As the name suggests, the resulting list is spliced into the context of its use.

Example:

```
> (quasiquote (1 2 (unquote-splicing (list (+ 1 2) (- 5 1))) 5))
'(1 2 3 4 5)
```

Using splicing we can revise the construction of our example expressions above to have just a single `let` expression and a single `+` expression.

Examples:

```
> (define (build-exp n)
    (add-lets
     n
     (quasiquote (+ (unquote-splicing
                     (build-list
                      n
                      (λ (x) (n->var (+ x 1)))))))))
> (define (add-lets n body)
    (quasiquote
     (let (unquote
           (build-list
            n
            (λ (n)
              (quasiquote
               [(unquote (n->var (+ n 1))) (unquote (+ n 1))]))))
       (unquote body))))
> (define (n->var n) (string->symbol (format "x~a" n)))
> (build-exp 3)
'(let ((x1 1) (x2 2) (x3 3)) (+ x1 x2 x3))
```

If a `quasiquote` form appears within an enclosing `quasiquote` form, then the inner `quasiquote` effectively cancels one layer of `unquote` and `unquote-splicing` forms, so that a second `unquote` or `unquote-splicing` is needed.

Examples:

```
> (quasiquote (1 2 (quasiquote (unquote (+ 1 2)))))
'(1 2 (quasiquote (unquote (+ 1 2))))
> (quasiquote (1 2 (quasiquote (unquote (unquote (+ 1 2))))))
'(1 2 (quasiquote (unquote 3)))
> (quasiquote (1 2 (quasiquote ((unquote (+ 1 2)) (unquote (unquote (- 5 1)))))))
'(1 2 (quasiquote ((unquote (+ 1 2)) (unquote 4))))
```

The evaluations above will not actually print as shown. Instead, the shorthand form of `quasiquote` and `unquote` will be used: `` ` `` (i.e., a backquote) and `,` (i.e., a comma). The same shorthands can be used in expressions:

Example:

```
> `(1 2 `(,(+ 1 2) ,,(- 5 1)))
'(1 2 `(,(+ 1 2) ,4))
```

The shorthand form of `unquote-splicing` is `,@`:

Example:

```
> `(1 2 ,@(list (+ 1 2) (- 5 1)))
'(1 2 3 4)
```

4.12 Simple Dispatch: `case`

The `case` form dispatches to a clause by matching the result of an expression to the values for the clause:

```
(case expr
  [(datum ...+) body ...+]
  ...)
```

Each *datum* will be compared to the result of *expr* using `equal?`, and then the corresponding `body`s are evaluated. The `case` form can dispatch to the correct clause in $O(\log N)$ time for N `datum`s.

Multiple *datum*s can be supplied for each clause, and the corresponding *body*s are evaluated if any of the *datum*s match.

Example:

```
> (let ([v (random 6)])
    (printf "~a\n" v)
```

```
    (case v
      [(0) 'zero]
      [(1) 'one]
      [(2) 'two]
      [(3 4 5) 'many]))
1
'one
```

The last clause of a `case` form can use `else`, just like `cond`:

Example:

```
> (case (random 6)
    [(0) 'zero]
    [(1) 'one]
    [(2) 'two]
    [else 'many])
'many
```

For more general pattern matching (but without the dispatch-time guarantee), use `match`, which is introduced in §12 “Pattern Matching”.

4.13 Dynamic Binding: `parameterize`

§11.3.2 “Parameters” in *The Racket Reference* also documents `parameterize`.

The `parameterize` form associates a new value with a *parameter* during the evaluation of *body* expressions:

```
(parameterize ([parameter-expr value-expr] ...)
  body ...+)
```

The term “parameter” is sometimes used to refer to the arguments of a function, but “parameter” in Racket has the more specific meaning described here.

For example, the `error-print-width` parameter controls how many characters of a value are printed in an error message:

```
> (parameterize ([error-print-width 5])
    (car (expt 10 1024)))
car: contract violation
  expected: pair?
  given: 10...
> (parameterize ([error-print-width 10])
    (car (expt 10 1024)))
car: contract violation
  expected: pair?
  given: 1000000...
```

More generally, parameters implement a kind of dynamic binding. The `make-parameter` function takes any value and returns a new parameter that is initialized to the given value. Applying the parameter as a function returns its current value:

```
> (define location (make-parameter "here"))
> (location)
"here"
```

In a `parameterize` form, each *`parameter-expr`* must produce a parameter. During the evaluation of the `body`s, each specified parameter is given the result of the corresponding *`value-expr`*. When control leaves the `parameterize` form—either through a normal return, an exception, or some other escape—the parameter reverts to its earlier value:

```
> (parameterize ([location "there"])
    (location))
"there"
> (location)
"here"
> (parameterize ([location "in a house"])
    (list (location)
          (parameterize ([location "with a mouse"])
            (location))
          (location)))
'("in a house" "with a mouse" "in a house")
> (parameterize ([location "in a box"])
    (car (location)))
car: contract violation
  expected: pair?
  given: "in a box"
> (location)
"here"
```

The `parameterize` form is not a binding form like `let`; each use of `location` above refers directly to the original definition. A `parameterize` form adjusts the value of a parameter during the whole time that the `parameterize` body is evaluated, even for uses of the parameter that are textually outside of the `parameterize` body:

```
> (define (would-you-could-you?)
    (and (not (equal? (location) "here"))
         (not (equal? (location) "there"))))
> (would-you-could-you?)
#f
> (parameterize ([location "on a bus"])
    (would-you-could-you?))
#t
```

If a use of a parameter is textually inside the body of a `parameterize` but not evaluated before the `parameterize` form produces a value, then the use does not see the value installed by the `parameterize` form:

```
> (let ([get (parameterize ([location "with a fox"])
               (lambda () (location)))])
    (get))
"here"
```

The current binding of a parameter can be adjusted imperatively by calling the parameter as a function with a value. If a `parameterize` has adjusted the value of the parameter, then directly applying the parameter procedure affects only the value associated with the active `parameterize`:

```
> (define (try-again! where)
    (location where))
> (location)
"here"
> (parameterize ([location "on a train"])
    (list (location)
          (begin (try-again! "in a boat")
                 (location))))
'("on a train" "in a boat")
> (location)
"here"
```

Using `parameterize` is generally preferable to updating a parameter value imperatively—for much the same reasons that binding a fresh variable with `let` is preferable to using `set!` (see §4.9 “Assignment: `set!`”).

It may seem that variables and `set!` can solve many of the same problems that parameters solve. For example, `lokation` could be defined as a string, and `set!` could be used to adjust its value:

```
> (define lokation "here")
> (define (would-ya-could-ya?)
    (and (not (equal? lokation "here"))
         (not (equal? lokation "there"))))
> (set! lokation "on a bus")
> (would-ya-could-ya?)
#t
```

Parameters, however, offer several crucial advantages over `set!`:

- The `parameterize` form helps automatically reset the value of a parameter when control escapes due to an exception. Adding exception handlers and other forms to rewind a `set!` is relatively tedious.

- Parameters work nicely with tail calls (see §2.3.3 “Tail Recursion”). The last *body* in a `parameterize` form is in tail position with respect to the `parameterize` form.
- Parameters work properly with threads (see §11.1 “Threads”). The `parameterize` form adjusts the value of a parameter only for evaluation in the current thread, which avoids race conditions with other threads.

5 Programmer-Defined Datatypes

§5 “Structures” in *The Racket Reference* also documents structure types.

New datatypes are normally created with the `struct` form, which is the topic of this chapter. The class-based object system, which we defer to §13 “Classes and Objects”, offers an alternate mechanism for creating new datatypes, but even classes and objects are implemented in terms of structure types.

5.1 Simple Structure Types: `struct`

§5.1 “Defining Structure Types: `struct`” in *The Racket Reference* also documents `struct`.

To a first approximation, the syntax of `struct` is

```
(struct struct-id (field-id ...))
```

Examples:

```
(struct posn (x y))
```

The `struct` form binds *`struct-id`* and a number of identifiers that are built from *`struct-id`* and the *`field-id`*s:

- *`struct-id`* : a *constructor* function that takes as many arguments as the number of *`field-id`*s, and returns an instance of the structure type.

  Example:

  ```
  > (posn 1 2)
  #<posn>
  ```

- *`struct-id?`* : a *predicate* function that takes a single argument and returns `#t` if it is an instance of the structure type, `#f` otherwise.

  Examples:

  ```
  > (posn? 3)
  #f
  > (posn? (posn 1 2))
  #t
  ```

- *`struct-id-field-id`* : for each *`field-id`*, an *accessor* that extracts the value of the corresponding field from an instance of the structure type.

  Examples:

```
> (posn-x (posn 1 2))
1
> (posn-y (posn 1 2))
2
```

- `struct:`*`struct-id`* : a *structure type descriptor*, which is a value that represents the structure type as a first-class value (with `#:super`, as discussed later in §5.8 “More Structure Type Options”).

A `struct` form places no constraints on the kinds of values that can appear for fields in an instance of the structure type. For example, `(posn "apple" #f)` produces an instance of `posn`, even though `"apple"` and `#f` are not valid coordinates for the obvious uses of `posn` instances. Enforcing constraints on field values, such as requiring them to be numbers, is normally the job of a contract, as discussed later in §7 “Contracts”.

5.2 Copying and Update

The `struct-copy` form clones a structure and optionally updates specified fields in the clone. This process is sometimes called a *functional update*, because the result is a structure with updated field values. but the original structure is not modified.

```
(struct-copy struct-id struct-expr [field-id expr] ...)
```

The *`struct-id`* that appears after `struct-copy` must be a structure type name bound by `struct`. The *`struct-expr`* must produce an instance of the structure type. The result is a new instance of the structure type that is like the old one, except that the field indicated by each *`field-id`* gets the value of the corresponding *`expr`*.

Examples:

```
> (define p1 (posn 1 2))
> (define p2 (struct-copy posn p1 [x 3]))
> (list (posn-x p2) (posn-y p2))
'(3 2)
> (list (posn-x p1) (posn-y p1))
'(1 2)
```

5.3 Structure Subtypes

An extended form of `struct` can be used to define a *structure subtype*, which is a structure type that extends an existing structure type:

```
(struct struct-id super-id (field-id ...))
```

The *super-id* must be a structure type name bound by `struct` (i.e., the name that cannot be used directly as an expression).

Examples:

```
(struct posn (x y))
(struct 3d-posn posn (z))
```

A structure subtype inherits the fields of its supertype, and the subtype constructor accepts the values for the subtype fields after values for the supertype fields. An instance of a structure subtype can be used with the predicate and accessors of the supertype.

Examples:

```
> (define p (3d-posn 1 2 3))
> p
#<3d-posn>
> (posn? p)
#t
> (3d-posn-z p)
3
; a 3d-posn has an x field, but there is no 3d-posn-x selector:
> (3d-posn-x p)
3d-posn-x: undefined;
 cannot reference an identifier before its definition
  in module: top-level
; use the supertype's posn-x selector to access the x field:
> (posn-x p)
1
```

5.4 Opaque versus Transparent Structure Types

With a structure type definition like

```
(struct posn (x y))
```

an instance of the structure type prints in a way that does not show any information about the fields' values. That is, structure types by default are *opaque*. If the accessors and mutators of a structure type are kept private to a module, then no other module can rely on the representation of the type's instances.

To make a structure type *transparent*, use the `#:transparent` keyword after the field-name sequence:

```
(struct posn (x y)
        #:transparent)

> (posn 1 2)
(posn 1 2)
```

An instance of a transparent structure type prints like a call to the constructor, so that it shows the structures field values. A transparent structure type also allows reflective operations, such as `struct?` and `struct-info`, to be used on its instances (see §15 “Reflection and Dynamic Evaluation”).

Structure types are opaque by default, because opaque structure instances provide more encapsulation guarantees. That is, a library can use an opaque structure to encapsulate data, and clients of the library cannot manipulate the data in the structure except as allowed by the library.

5.5 Structure Comparisons

A generic `equal?` comparison automatically recurs on the fields of a transparent structure type, but `equal?` defaults to mere instance identity for opaque structure types:

```
(struct glass (width height) #:transparent)

> (equal? (glass 1 2) (glass 1 2))
#t


(struct lead (width height))

> (define slab (lead 1 2))
> (equal? slab slab)
#t
> (equal? slab (lead 1 2))
#f
```

To support instances comparisons via `equal?` without making the structure type transparent, you can use the `#:methods` keyword, `gen:equal+hash`, and implement three methods:

```
(struct lead (width height)
  #:methods
  gen:equal+hash
```

```
 [(define (equal-proc a b equal?-recur)
    ; compare a and b
    (and (equal?-recur (lead-width a) (lead-width b))
         (equal?-recur (lead-height a) (lead-height b))))
  (define (hash-proc a hash-recur)
    ; compute primary hash code of a
    (+ (hash-recur (lead-width a))
       (* 3 (hash-recur (lead-height a)))))
  (define (hash2-proc a hash2-recur)
    ; compute secondary hash code of a
    (+ (hash2-recur (lead-width a))
            (hash2-recur (lead-height a)))))])

> (equal? (lead 1 2) (lead 1 2))
#t
```

The first function in the list implements the `equal?` test on two `lead`s; the third argument to the function is used instead of `equal?` for recursive equality testing, so that data cycles can be handled correctly. The other two functions compute primary and secondary hash codes for use with hash tables:

```
> (define h (make-hash))
> (hash-set! h (lead 1 2) 3)
> (hash-ref h (lead 1 2))
3
> (hash-ref h (lead 2 1))
hash-ref: no value found for key
  key: #<lead>
```

The first function provided with `gen:equal+hash` is not required to recursively compare the fields of the structure. For example, a structure type representing a set might implement equality by checking that the members of the set are the same, independent of the order of elements in the internal representation. Just take care that the hash functions produce the same value for any two structure types that are supposed to be equivalent.

5.6 Structure Type Generativity

Each time that a `struct` form is evaluated, it generates a structure type that is distinct from all existing structure types, even if some other structure type has the same name and fields.

This generativity is useful for enforcing abstractions and implementing programs such as interpreters, but beware of placing a `struct` form in positions that are evaluated multiple times.

Examples:

```
(define (add-bigger-fish lst)
  (struct fish (size) #:transparent) ; new every time
  (cond
   [(null? lst) (list (fish 1))]
   [else (cons (fish (* 2 (fish-size (car lst))))
               lst)]))
> (add-bigger-fish null)
(list (fish 1))
> (add-bigger-fish (add-bigger-fish null))
fish-size: contract violation
  expected: fish?
  given: (fish 1)
```

```
(struct fish (size) #:transparent)
(define (add-bigger-fish lst)
  (cond
   [(null? lst) (list (fish 1))]
   [else (cons (fish (* 2 (fish-size (car lst))))
               lst)]))

> (add-bigger-fish (add-bigger-fish null))
(list (fish 2) (fish 1))
```

5.7 Prefab Structure Types

Although a transparent structure type prints in a way that shows its content, the printed form of the structure cannot be used in an expression to get the structure back, unlike the printed form of a number, string, symbol, or list.

A *prefab* ("previously fabricated") structure type is a built-in type that is known to the Racket printer and expression reader. Infinitely many such types exist, and they are indexed by name, field count, supertype, and other such details. The printed form of a prefab structure is similar to a vector, but it starts `#s` instead of just `#`, and the first element in the printed form is the prefab structure type's name.

The following examples show instances of the `sprout` prefab structure type that has one field. The first instance has a field value `'bean`, and the second has field value `'alfalfa`:

```
> '#s(sprout bean)
'#s(sprout bean)
> '#s(sprout alfalfa)
'#s(sprout alfalfa)
```

Like numbers and strings, prefab structures are "self-quoting," so the quotes above are optional:

```
> #s(sprout bean)
'#s(sprout bean)
```

When you use the `#:prefab` keyword with `struct`, instead of generating a new structure type, you obtain bindings that work with the existing prefab structure type:

```
> (define lunch '#s(sprout bean))
> (struct sprout (kind) #:prefab)
> (sprout? lunch)
#t
> (sprout-kind lunch)
'bean
> (sprout 'garlic)
'#s(sprout garlic)
```

The field name `kind` above does not matter for finding the prefab structure type; only the name `sprout` and the number of fields matter. At the same time, the prefab structure type `sprout` with three fields is a different structure type than the one with a single field:

```
> (sprout? #s(sprout bean #f 17))
#f
> (struct sprout (kind yummy? count) #:prefab) ; redefine
> (sprout? #s(sprout bean #f 17))
#t
> (sprout? lunch)
#f
```

A prefab structure type can have another prefab structure type as its supertype, it can have mutable fields, and it can have auto fields. Variations in any of these dimensions correspond to different prefab structure types, and the printed form of the structure type's name encodes all of the relevant details.

```
> (struct building (rooms [location #:mutable]) #:prefab)
> (struct house building ([occupied #:auto]) #:prefab
    #:auto-value 'no)
> (house 5 'factory)
'#s((house (1 no) building 2 #(1)) 5 factory no)
```

Every prefab structure type is transparent—but even less abstract than a transparent type, because instances can be created without any access to a particular structure-type declaration or existing examples. Overall, the different options for structure types offer a spectrum of possibilities from more abstract to more convenient:

- Opaque (the default) : Instances cannot be inspected or forged without access to the structure-type declaration. As discussed in the next section, constructor guards and properties can be attached to the structure type to further protect or to specialize the behavior of its instances.
- Transparent : Anyone can inspect or create an instance without access to the structure-type declaration, which means that the value printer can show the content of an instance. All instance creation passes through a constructor guard, however, so that the content of an instance can be controlled, and the behavior of instances can be specialized through properties. Since the structure type is generated by its definition, instances cannot be manufactured simply through the name of the structure type, and therefore cannot be generated automatically by the expression reader.
- Prefab : Anyone can inspect or create an instance at any time, without prior access to a structure-type declaration or an example instance. Consequently, the expression reader can manufacture instances directly. The instance cannot have a constructor guard or properties.

Since the expression reader can generate prefab instances, they are useful when convenient serialization is more important than abstraction. Opaque and transparent structures also can be serialized, however, if they are defined with `serializable-struct` as described in §8.4 “Datatypes and Serialization”.

5.8 More Structure Type Options

The full syntax of `struct` supports many options, both at the structure-type level and at the level of individual fields:

```
(struct struct-id maybe-super (field ...)
        struct-option ...)

maybe-super =
            | super-id

      field = field-id
            | [field-id field-option ...]
```

A *struct-option* always starts with a keyword:

```
#:mutable
```

Causes all fields of the structure to be mutable, and introduces for each *field-id* a *mutator* `set-struct-id-field-id!` that sets

the value of the corresponding field in an instance of the structure type.

Examples:

```
> (struct dot (x y) #:mutable)
(define d (dot 1 2))
> (dot-x d)
1
> (set-dot-x! d 10)
> (dot-x d)
10
```

The `#:mutable` option can also be used as a *`field-option`*, in which case it makes an individual field mutable.

Examples:

```
> (struct person (name [age #:mutable]))
(define friend (person "Barney" 5))
> (set-person-age! friend 6)
> (set-person-name! friend "Mary")
set-person-name!: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

`#:transparent`

Controls reflective access to structure instances, as discussed in a previous section, §5.4 “Opaque versus Transparent Structure Types”.

`#:inspector` *`inspector-expr`*

Generalizes `#:transparent` to support more controlled access to reflective operations.

`#:prefab`

Accesses a built-in structure type, as discussed in a previous section, §5.7 “Prefab Structure Types”.

`#:auto-value` *`auto-expr`*

Specifies a value to be used for all automatic fields in the structure type, where an automatic field is indicated by the `#:auto` field option. The constructor procedure does not accept arguments for automatic fields. Automatic fields are implicitly mutable (via reflective operations), but mutator functions are bound only if `#:mutable` is also specified.

Examples:

```
> (struct posn (x y [z #:auto])
               #:transparent
               #:auto-value 0)
> (posn 1 2)
(posn 1 2 0)
```

`#:guard` *guard-expr*

Specifies a *constructor guard* procedure to be called whenever an instance of the structure type is created. The guard takes as many arguments as non-automatic fields in the structure type, plus one more for the name of the instantiated type (in case a sub-type is instantiated, in which case it's best to report an error using the sub-type's name). The guard should return the same number of values as given, minus the name argument. The guard can raise an exception if one of the given arguments is unacceptable, or it can convert an argument.

Examples:

```
> (struct thing (name)
          #:transparent
          #:guard (lambda (name type-name)
                    (cond
                      [(string? name) name]
                      [(symbol? name) (symbol-
>string name)]
                      [else (error type-name
                                   "bad name:
~e"
                                   name)])))
> (thing "apple")
(thing "apple")
> (thing 'apple)
(thing "apple")
> (thing 1/2)
thing: bad name: 1/2
```

The guard is called even when subtype instances are created. In that case, only the fields accepted by the constructor are provided to the

guard (but the subtype's guard gets both the original fields and fields added by the subtype).

Examples:

```
> (struct person thing (age)
          #:transparent
          #:guard (lambda (name age type-name)
                    (if (negative? age)
                        (error type-name "bad
age: ~e" age)
                        (values name age))))
> (person "John" 10)
(person "John" 10)
> (person "Mary" -1)
person: bad age: -1
> (person 10 10)
person: bad name: 10
```

`#:methods` *interface-expr* `[`*body* `...]`

Associates method definitions for the structure type that correspond to a *generic interface*. For example, implementing the methods for `gen:dict` allows instances of a structure type to be used as dictionaries. Implementing the methods for `gen:custom-write` allows the customization of how an instance of a structure type is `display`ed.

Examples:

```
> (struct cake (candles)
          #:methods gen:custom-write
          [(define (write-proc cake port mode)
             (define n (cake-candles cake))
             (show "   ~a   ~n" n #\. port)
             (show " .-~a-. ~n" n #\| port)
             (show " | ~a | ~n" n #\space port)
             (show "---~a---~n" n #\- port))
           (define (show fmt n ch port)
             (fprintf port fmt (make-
string n ch)))])
> (display (cake 5))
   .....
 .-|||||-.
 |       |
-----------
```

#:property *prop-expr val-expr*

Associates a *property* and value with the structure type. For example, the prop:procedure property allows a structure instance to be used as a function; the property value determines how a call is implemented when using the structure as a function.

Examples:

```
> (struct greeter (name)
          #:property prop:procedure
                     (lambda (self other)
                       (string-append
                        "Hi " other
                        ", I'm " (greeter-
name self))))
(define joe-greet (greeter "Joe"))
> (greeter-name joe-greet)
"Joe"
> (joe-greet "Mary")
"Hi Mary, I'm Joe"
> (joe-greet "John")
"Hi John, I'm Joe"
```

#:super *super-expr*

An alternative to supplying a super-id next to struct-id. Instead of the name of a structure type (which is not an expression), *super-expr* should produce a structure type descriptor value. An advantage of #:super is that structure type descriptors are values, so they can be passed to procedures.

Examples:

```
(define (raven-constructor super-type)
  (struct raven ()
          #:super super-type
          #:transparent
          #:property prop:procedure (lambda (self)
                                      'nevermore))
  raven)
> (let ([r ((raven-constructor struct:posn) 1 2)])
    (list r (r)))
(list (raven 1 2) 'nevermore)
> (let ([r ((raven-constructor struct:thing) "apple")])
    (list r (r)))
(list (raven "apple") 'nevermore)
```

§5 “Structures” in *The Racket Reference* provides more on structure types.

6 Modules

Modules let you organize Racket code into multiple files and reusable libraries.

6.1 Module Basics

Each Racket module typically resides in its own file. For example, suppose the file "cake.rkt" contains the following module:

"cake.rkt"

```
#lang racket

(provide print-cake)

; draws a cake with n candles
(define (print-cake n)
  (show "   ~a   " n #\.)
  (show " .-~a-. " n #\|)
  (show " | ~a | " n #\space)
  (show "---~a---" n #\-))

(define (show fmt n ch)
  (printf fmt (make-string n ch))
  (newline))
```

Then, other modules can import "cake.rkt" to use the print-cake function, since the provide line in "cake.rkt" explicitly exports the definition print-cake. The show function is private to "cake.rkt" (i.e., it cannot be used from other modules), since show is not exported.

The following "random-cake.rkt" module imports "cake.rkt":

"random-cake.rkt"

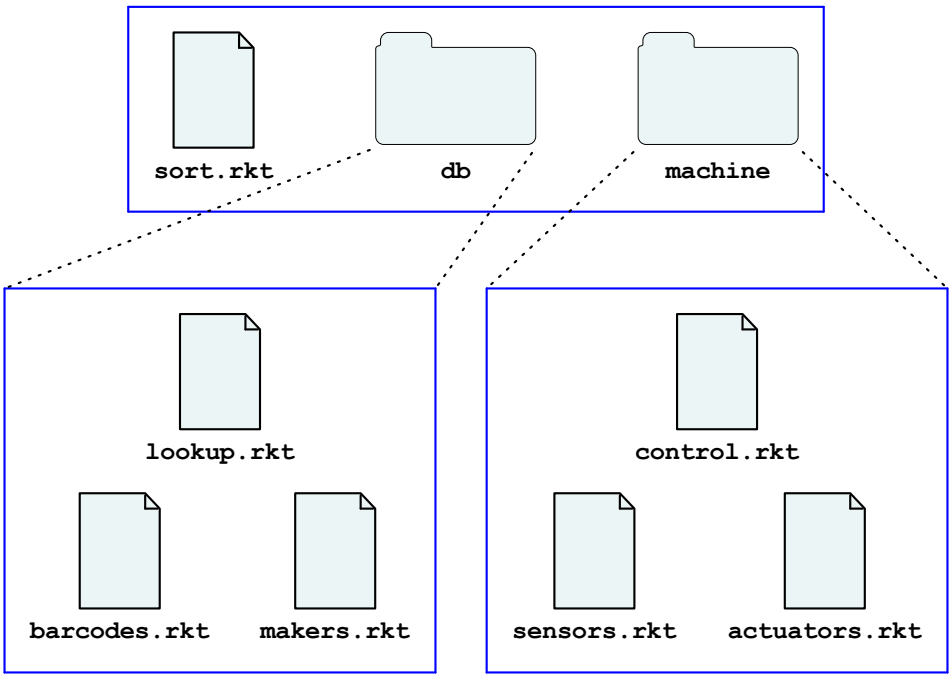
```
#lang racket

(require "cake.rkt")

(print-cake (random 30))
```

The relative reference "cake.rkt" in the import (require "cake.rkt") works if the "cake.rkt" and "random-cake.rkt" modules are in the same directory. Unix-style relative paths are used for relative module references on all platforms, much like relative URLs in HTML pages.

6.1.1 Organizing Modules

The "cake.rkt" and "random-cake.rkt" example demonstrates the most common way to organize a program into modules: put all module files in a single directory (perhaps with subdirectories), and then have the modules reference each other through relative paths. A directory of modules can act as a project, since it can be moved around on the filesystem or copied to other machines, and relative paths preserve the connections among modules.

As another example, if you are building a candy-sorting program, you might have a main "sort.rkt" module that uses other modules to access a candy database and a control sorting machine. If the candy-database module itself is organized into sub-modules that handle barcode and manufacturer information, then the database module could be "db/lookup.rkt" that uses helper modules "db/barcodes.rkt" and "db/makers.rkt". Similarly, the sorting-machine driver "machine/control.rkt" might use helper modules "machine/sensors.rkt" and "machine/actuators.rkt".



The "sort.rkt" module uses the relative paths "db/lookup.rkt" and "machine/control.rkt" to import from the database and machine-control libraries:

"sort.rkt"

```
#lang racket
(require "db/lookup.rkt" "machine/control.rkt")
....
```

The "db/lookup.rkt" module similarly uses paths relative to its own source to access the "db/barcodes.rkt" and "db/makers.rkt" modules:

"db/lookup.rkt"

```
#lang racket
(require "barcodes.rkt" "makers.rkt")
....
```

Ditto for "machine/control.rkt":

"machine/control.rkt"

```
#lang racket
(require "sensors.rkt" "actuators.rkt")
....
```

Racket tools all work automatically with relative paths. For example,

```
racket sort.rkt
```

on the command line runs the "sort.rkt" program and automatically loads and compiles required modules. With a large enough program, compilation from source can take too long, so use

```
raco make sort.rkt
```

to compile "sort.rkt" and all its dependencies to bytecode files. Running racket sort.rkt will automatically use bytecode files when they are present.

See §1 "raco make: Compiling Source to Bytecode" for more information on raco make.

6.1.2 Library Collections

A *collection* is a hierarchical grouping of installed library modules. A module in a collection is referenced through an unquoted, suffixless path. For example, the following module refers to the "date.rkt" library that is part of the "racket" collection:

```
#lang racket

(require racket/date)

(printf "Today is ~s\n"
        (date->string (seconds->date (current-seconds))))
```

When you search the online Racket documentation, the search results indicate the module that provides each binding. Alternatively, if you reach a binding's documentation by clicking on hyperlinks, you can hover over the binding name to find out which modules provide it.

A module reference like `racket/date` looks like an identifier, but it is not treated in the same way as `printf` or `date->string`. Instead, when `require` sees a module reference that is unquoted, it converts the reference to a collection-based module path:

- First, if the unquoted path contains no `/`, then `require` automatically adds a `"/main"` to the reference. For example, `(require slideshow)` is equivalent to `(require slideshow/main)`.
- Second, `require` implicitly adds a `".rkt"` suffix to the path.
- Finally, `require` resolves the path by searching among installed collections, instead of treating the path as relative to the enclosing module's path.

To a first approximation, a collection is implemented as a filesystem directory. For example, the `"racket"` collection is mostly located in a `"racket"` directory within the Racket installation's `"collects"` directory, as reported by

```
#lang racket

(require setup/dirs)

(build-path (find-collects-dir) ; main collection directory
            "racket")
```

The Racket installation's `"collects"` directory, however, is only one place that `require` looks for collection directories. Other places include the user-specific directory reported by `(find-user-collects-dir)` and directories configured through the `PLTCOLLECTS` search path. Finally, and most typically, collections are found through installed packages.

6.1.3 Packages and Collections

A *package* is a set of libraries that are installed through the Racket package manager (or included as pre-installed in a Racket distribution). For example, the `racket/gui` library is provided by the `"gui"` package, while `parser-tools/lex` is provided by the `"parser-tools"` library.

Racket programs do not refer to packages directly. Instead, programs refer to libraries via collections, and adding or removing a package changes the set of collection-based libraries that are available. A single package can supply libraries in multiple collections, and two different packages can supply libraries in the same collection (but not the same libraries, and the package manager ensures that installed packages do not conflict at that level).

For more information about packages, see *Package Management in Racket*.

More precisely, `racket/gui` is provided by `"gui-lib"`, `parser-tools/lex` is provided by `"parser-tools-lib"`, and the `"gui"` and `"parser-tools"` packages extend `"gui-lib"` and `"parser-tools-lib"` with documentation.

6.1.4 Adding Collections

Looking back at the candy-sorting example of §6.1.1 “Organizing Modules”, suppose that modules in `"db/"` and `"machine/"` need a common set of helper functions. Helper functions could be put in a `"utils/"` directory, and modules in `"db/"` or `"machine/"` could access utility modules with relative paths that start `"../utils/"`. As long as a set of modules work together in a single project, it’s best to stick with relative paths. A programmer can follow relative-path references without knowing about your Racket configuration.

Some libraries are meant to be used across multiple projects, so that keeping the library source in a directory with its uses does not make sense. In that case, the best option is to add a new collection. After the library is in a collection, it can be referenced with an unquoted path, just like libraries that are included with the Racket distribution.

You could add a new collection by placing files in the Racket installation or one of the directories reported by `(get-collects-search-dirs)`. Alternatively, you could add to the list of searched directories by setting the `PLTCOLLECTS` environment variable. The best option, however, is to add a package.

If you set `PLTCOLLECTS`, include an empty path in by starting the value with a colon (Unix and Mac OS) or semicolon (Windows) so that the original search paths are preserved.

Creating a package *does not* mean that you have to register with a package server or perform a bundling step that copies your source code into an archive format. Creating a package can simply mean using the package manager to make your libraries locally accessible as a collection from their current source locations.

For example, suppose you have a directory `"/usr/molly/bakery"` that contains the `"cake.rkt"` module (from the beginning of this section) and other related modules. To make the modules available as a `"bakery"` collection, either

- Use the `raco pkg` command-line tool:

  ```
  raco pkg install --link /usr/molly/bakery
  ```

  where the `--link` flag is not actually needed when the provided path includes a directory separator.

- Use DrRacket’s Package Manager item from the File menu. In the Do What I Mean panel, click Browse..., choose the `"/usr/molly/bakery"` directory, and click Install.

Afterward, `(require bakery/cake)` from any module will import the `print-cake` function from `"/usr/molly/bakery/cake.rkt"`.

By default, the name of the directory that you install is used both as the package name and as the collection that is provided by the package. Also, the package manager normally defaults to installation only for the current user, as opposed to all users of a Racket installation. See *Package Management in Racket* for more information.

If you intend to distribute your libraries to others, choose collection and package names carefully. The collection namespace is hierarchical, but top-level collection names are global,

and the package namespace is flat. Consider putting one-off libraries under some top-level name like "molly" that identifies the producer. Use a collection name like "bakery" when producing the definitive collection of baked-goods libraries.

After your libraries are put in a collection you can still use raco make to compile the library sources, but it's better and more convenient to use raco setup. The raco setup command takes a collection name (as opposed to a file name) and compiles all libraries within the collection. In addition, raco setup can build documentation for the collection and add it to the documentation index, as specified by a "info.rkt" module in the collection. See §6 "raco setup: Installation Management" for more information on raco setup.

6.1.5 Module References Within a Collection

When a module within a collection references another module within the same collection, either a relative path or a collection path could work. For example, a "sort.rkt" module that references "db/lookup.rkt" and "machine/control.rkt" modules within the same collection could be written with relative paths as in §6.1.1 "Organizing Modules":

"sort.rkt"

```
#lang racket
(require "db/lookup.rkt" "machine/control.rkt")
....
```

Alternatively, if the collection is named "candy", then "sort.rkt" could use collection paths to import the two modules:

"sort.rkt"

```
#lang racket
(require candy/db/lookup candy/machine/control)
....
```

For most purposes, these choices will work the same, but there are exceptions. When writing documentation with Scribble, you must use a collection path with defmodule and similar forms; that's partly because documentation is meant to be read by client programmers, and so the collection-based name should appear. Meanwhile, for require, using relative paths for references within a collection tends to be the most flexible approach, but with caveats.

Relative-path references work much like relative URL references: the reference is expanded based on the way the enclosing module is accessed. If the enclosing module is accessed through a filesystem path, then a relative path in require is combined with that filesystem path to form a new filesystem path. If the enclosing module is accessed through a collection path, then a relative path in require is combined with that collection path to form a new collection path. A collection path is, in turn, converted to a filesystem path, and so

the difference between starting with a filesystem or collection path does not usually matter. Unfortunately, inherent complexities of path resolution can create differences in some situations:

- Through soft links, multiple mount points, or case-insensitive filesystems (on an operating system that does not implicitly case-normalize paths), there may be multiple filesystem paths that refer to the same module file.

  For example, when the current directory is the `"candy"` collection's directory, the current-directory path that `racket` receives on startup may cause `racket sort.rkt` to use a different filesystem path than `racket -l candy/sort` finds through the library-collection search path. In that case, if `"sort.rkt"` leads to some modules through both relative-path references and collection-based references, it's possible that those resolve to difference instances of the same source module, creating confusion through multiple instantiations.

- When `raco exe` plus `raco distribute` are used to create an executable to run on a different machine, the paths of the current machine are likely unrelated to paths on the target machine. The `raco exe` tool treats modules that are referenced via filesystem paths differently than modules reference via collection paths, because only the latter make sense to access through reflective operations at run time.

  For example, if `raco exe sort.rkt` creates an executable that uses `(dynamic-require 'candy/db/lookup #f)` at run time, then that `dynamic-require` will fail in the case that `"db/lookup.rkt"` is resolved relative to the filesystem path `"sort.rkt"` at executable-creation time.

Using only collection-based paths (including using shell commands like `racket -l candy/sort` and not like `racket sort.rkt`) can avoid all problems, but then you must only develop modules within an installed collection, which is often inconvenient. Using relative-path references consistently tends to be the most convenient while still working in most circumstances.

6.2 Module Syntax

The `#lang` at the start of a module file begins a shorthand for a `module` form, much like `'` is a shorthand for a `quote` form. Unlike `'`, the `#lang` shorthand does not work well in a REPL, in part because it must be terminated by an end-of-file, but also because the longhand expansion of `#lang` depends on the name of the enclosing file.

6.2.1 The `module` Form

The longhand form of a module declaration, which works in a REPL as well as a file, is

```
(module name-id initial-module-path
  decl ...)
```

where the *name-id* is a name for the module, *initial-module-path* is an initial import, and each *decl* is an import, export, definition, or expression. In the case of a file, *name-id* normally matches the name of the containing file, minus its directory path or file extension, but *name-id* is ignored when the module is `required` through its file's path.

The *initial-module-path* is needed because even the `require` form must be imported for further use in the module body. In other words, the *initial-module-path* import bootstraps the syntax that is available in the body. The most commonly used *initial-module-path* is `racket`, which supplies most of the bindings described in this guide, including `require`, `define`, and `provide`. Another commonly used *initial-module-path* is `racket/base`, which provides less functionality, but still much of the most commonly needed functions and syntax.

For example, the `"cake.rkt"` example of the previous section could be written as

```
(module cake racket
  (provide print-cake)

  (define (print-cake n)
    (show "   ~a   " n #\.)
    (show " .-~a-. " n #\|)
    (show " | ~a | " n #\space)
    (show "---~a---" n #\-))

  (define (show fmt n ch)
    (printf fmt (make-string n ch))
    (newline)))
```

Furthermore, this `module` form can be evaluated in a REPL to declare a `cake` module that is not associated with any file. To refer to such an unassociated module, quote the module name:

Examples:

```
> (require 'cake)
> (print-cake 3)
   ...
 .-|||-.
 |     |
---------
```

Declaring a module does not immediately evaluate the body definitions and expressions of

the module. The module must be explicitly `required` at the top level to trigger evaluation. After evaluation is triggered once, later `requires` do not re-evaluate the module body.

Examples:

```
> (module hi racket
    (printf "Hello\n"))
> (require 'hi)
Hello
> (require 'hi)
```

6.2.2 The `#lang` Shorthand

The body of a `#lang` shorthand has no specific syntax, because the syntax is determined by the language name that follows `#lang`.

In the case of `#lang racket`, the syntax is

```
#lang racket
decl ...
```

which reads the same as

```
(module name racket
  decl ...)
```

where *name* is derived from the name of the file that contains the `#lang` form.

The `#lang racket/base` form has the same syntax as `#lang racket`, except that the longhand expansion uses `racket/base` instead of `racket`. The `#lang scribble/manual` form, in contrast, has a completely different syntax that doesn't even look like Racket, and which we do not attempt to describe in this guide.

Unless otherwise specified, a module that is documented as a "language" using the `#lang` notation will expand to `module` in the same way as `#lang racket`. The documented language name can be used directly with `module` or `require`, too.

6.2.3 Submodules

A `module` form can be nested within a module, in which case the nested `module` form declares a *submodule*. Submodules can be referenced directly by the enclosing module using a quoted name. The following example prints `"Tony"` by importing `tiger` from the `zoo` submodule:

"park.rkt"

```
#lang racket

(module zoo racket
  (provide tiger)
  (define tiger "Tony"))

(require 'zoo)

tiger
```

Running a module does not necessarily run its submodules. In the above example, running `"park.rkt"` runs its submodule `zoo` only because the `"park.rkt"` module `requires` the `zoo` submodule. Otherwise, a module and each of its submodules can be run independently. Furthermore, if `"park.rkt"` is compiled to a bytecode file (via `raco make`), then the code for `"park.rkt"` or the code for `zoo` can be loaded independently.

Submodules can be nested within submodules, and a submodule can be referenced directly by a module other than its enclosing module by using a submodule path.

A `module*` form is similar to a nested `module` form:

```
(module* name-id initial-module-path-or-#f
  decl ...)
```

The `module*` form differs from `module` in that it inverts the possibilities for reference between the submodule and enclosing module:

- A submodule declared with `module` can be `required` by its enclosing module, but the submodule cannot `require` the enclosing module or lexically reference the enclosing module's bindings.
- A submodule declared with `module*` can `require` its enclosing module, but the enclosing module cannot `require` the submodule.

In addition, a `module*` form can specify `#f` in place of an *`initial-module-path`*, in which case the submodule sees all of the enclosing module's bindings—including bindings that are not exported via `provide`.

One use of submodules declared with `module*` and `#f` is to export additional bindings through a submodule that are not normally exported from the module:

"cake.rkt"

```
#lang racket

(provide print-cake)

(define (print-cake n)
  (show "   ~a   " n #\.)
  (show " .-~a-. " n #\|)
  (show " | ~a | " n #\space)
  (show "---~a---" n #\-))

(define (show fmt n ch)
  (printf fmt (make-string n ch))
  (newline))

(module* extras #f
  (provide show))
```

In this revised `"cake.rkt"` module, `show` is not imported by a module that uses `(require "cake.rkt")`, since most clients of `"cake.rkt"` will not want the extra function. A module can require the `extra` submodule using `(require (submod "cake.rkt" extras))` to access the otherwise hidden `show` function.

See submodule paths for more information on `submod`.

6.2.4 Main and Test Submodules

The following variant of `"cake.rkt"` includes a `main` submodule that calls `print-cake`:

`"cake.rkt"`

```
#lang racket

(define (print-cake n)
  (show "   ~a   " n #\.)
  (show " .-~a-. " n #\|)
  (show " | ~a | " n #\space)
  (show "---~a---" n #\-))

(define (show fmt n ch)
  (printf fmt (make-string n ch))
  (newline))

(module* main #f
  (print-cake 10))
```

Running a module does not run its `module*`-defined submodules. Nevertheless, running

the above module via `racket` or DrRacket prints a cake with 10 candles, because the `main` submodule is a special case.

When a module is provided as a program name to the `racket` executable or run directly within DrRacket, if the module has a `main` submodule, the `main` submodule is run after its enclosing module. Declaring a `main` submodule thus specifies extra actions to be performed when a module is run directly, instead of `required` as a library within a larger program.

A `main` submodule does not have to be declared with `module*`. If the `main` module does not need to use bindings from its enclosing module, it can be declared with `module`. More commonly, `main` is declared using `module+`:

```
(module+ name-id
  decl ...)
```

A submodule declared with `module+` is like one declared with `module*` using `#f` as its *initial-module-path*. In addition, multiple `module+` forms can specify the same submodule name, in which case the bodies of the `module+` forms are combined to create a single submodule.

The combining behavior of `module+` is particularly useful for defining a `test` submodule, which can be conveniently run using `raco test` in much the same way that `main` is conveniently run with `racket`. For example, the following `"physics.rkt"` module exports `drop` and `to-energy` functions, and it defines a `test` module to hold unit tests:

`"physics.rkt"`

```
#lang racket
(module+ test
  (require rackunit)
  (define ε 1e-10))

(provide drop
         to-energy)

(define (drop t)
  (* 1/2 9.8 t t))

(module+ test
  (check-= (drop 0) 0 ε)
  (check-= (drop 10) 490 ε))

(define (to-energy m)
  (* m (expt 299792458.0 2)))

(module+ test
```

```
  (check-= (to-energy 0) 0 ε)
  (check-= (to-energy 1) 9e+16 1e+15))
```

Importing `"physics.rkt"` into a larger program does not run the `drop` and `to-energy` tests—or even trigger the loading of the test code, if the module is compiled—but running `raco test physics.rkt` at a command line runs the tests.

The above `"physics.rkt"` module is equivalent to using `module*`:

`"physics.rkt"`

```
#lang racket

(provide drop
         to-energy)

(define (drop t)
  (* 1/2 49/5 t t))

(define (to-energy m)
  (* m (expt 299792458 2)))

(module* test #f
  (require rackunit)
  (define ε 1e-10)
  (check-= (drop 0) 0 ε)
  (check-= (drop 10) 490 ε)
  (check-= (to-energy 0) 0 ε)
  (check-= (to-energy 1) 9e+16 1e+15))
```

Using `module+` instead of `module*` allows tests to be interleaved with function definitions.

The combining behavior of `module+` is also sometimes helpful for a `main` module. Even when combining is not needed, `(module+ main ....)` is preferred as it is more readable than `(module* main #f ....)`.

6.3 Module Paths

A *module path* is a reference to a module, as used with `require` or as the *`initial-module-path`* in a `module` form. It can be any of several forms:

```
(quote id)
```

A module path that is a quoted identifier refers to a non-file `module` declaration using the identifier. This form of module reference makes the most sense in a REPL.

Examples:

```
> (module m racket
    (provide color)
    (define color "blue"))
> (module n racket
    (require 'm)
    (printf "my favorite color is ~a\n" color))
> (require 'n)
my favorite color is blue
```

rel-string

A string module path is a relative path using Unix-style conventions: `/` is the path separator, `..` refers to the parent directory, and `.` refers to the same directory. The *rel-string* must not start or end with a path separator.

The path is relative to the enclosing file, if any, or it is relative to the current directory. (More precisely, the path is relative to the value of `(current-load-relative-directory)`, which is set while loading a file.)

§6.1 “Module Basics” shows examples using relative paths.

If a relative path ends with a `".ss"` suffix, it is converted to `".rkt"`. If the file that implements the referenced module actually ends in `".ss"`, the suffix will be changed back when attempting to load the file (but a `".rkt"` suffix takes precedence). This two-way conversion provides compatibility with older versions of Racket.

id

A module path that is an unquoted identifier refers to an installed library. The *id* is constrained to contain only ASCII letters, ASCII numbers, `+`, `-`, `_`, and `/`, where `/` separates path elements within the identifier. The elements refer to collections and sub-collections, instead of directories and sub-directories.

An example of this form is `racket/date`. It refers to the module whose source is the `"date.rkt"` file in the `"racket"` collection, which is installed as part of Racket. The `".rkt"` suffix is added automatically.

Another example of this form is `racket`, which is commonly used at the initial import. The path `racket` is shorthand for `racket/main`; when an *id* has no `/`, then `/main` is automatically added to the end. Thus, `racket` or `racket/main` refers to the module whose source is the `"main.rkt"` file in the `"racket"` collection.

Examples:

```
> (module m racket
    (require racket/date)

    (printf "Today is ~s\n"
            (date->string (seconds->date (current-
seconds)))))
> (require 'm)
Today is "Saturday, October 31st, 2026"
```

When the full path of a module ends with `".rkt"`, if no such file exists but one does exist with the `".ss"` suffix, then the `".ss"` suffix is substituted automatically. This transformation provides compatibility with older versions of Racket.

(lib *rel-string*)

Like an unquoted-identifier path, but expressed as a string instead of an identifier. Also, the *rel-string* can end with a file suffix, in which case `".rkt"` is not automatically added.

Example of this form include `(lib "racket/date.rkt")` and `(lib "racket/date")`, which are equivalent to `racket/date`. Other examples include `(lib "racket")`, `(lib "racket/main")`, and `(lib "racket/main.rkt")`, which are all equivalent to `racket`.

Examples:

```
> (module m (lib "racket")
    (require (lib "racket/date.rkt"))

    (printf "Today is ~s\n"
            (date->string (seconds->date (current-
seconds)))))
> (require 'm)
Today is "Saturday, October 31st, 2026"
```

(planet *id*)

Accesses a third-party library that is distributed through the PLaneT server. The library is downloaded the first time that it is needed, and then the local copy is used afterward.

The *id* encodes several pieces of information separated by a `/`: the package owner, then package name with optional version information, and an optional path to a specific library with the package. Like *id* as shorthand for a `lib` path, a `".rkt"` suffix is added automatically, and `/main` is used as the path if no sub-path element is supplied.

Examples:

```
> (module m (lib "racket")
    ; Use "schematics"'s "random.plt" 1.0, file
"random.rkt":
    (require (planet schematics/random:1/random))
    (display (random-gaussian)))
> (require 'm)
0.9050686838895684
```

As with other forms, an implementation file ending with `".ss"` can be substituted automatically if no implementation file ending with `".rkt"` exists.

```
(planet package-string)
```

Like the symbol form of a `planet`, but using a string instead of an identifier. Also, the *package-string* can end with a file suffix, in which case `".rkt"` is not added.

As with other forms, an `".ss"` extension is converted to `".rkt"`, while an implementation file ending with `".ss"` can be substituted automatically if no implementation file ending with `".rkt"` exists.

```
(planet rel-string (user-string pkg-string vers ...))

vers = nat
     | (nat nat)
     | (= nat)
     | (+ nat)
     | (- nat)
```

A more general form to access a library from the PLaneT server. In this general form, a PLaneT reference starts like a `lib` reference with a relative path, but the path is followed by information about the producer, package, and version of the library. The specified package is downloaded and installed on demand.

The *vers*es specify a constraint on the acceptable version of the package, where a version number is a sequence of non-negative integers, and the constraints determine the allowable values for each element in the sequence. If no constraint is provided for a particular element, then any version is allowed; in particular, omitting all *vers*es means that any version is acceptable. Specifying at least one *vers* is strongly recommended.

For a version constraint, a plain *nat* is the same as `(+ nat)`, which matches *nat* or higher for the corresponding element of the version number. A `(`*start-nat end-nat*`)` matches any number in the range *start-nat* to *end-nat*, inclusive. A `(= nat)` matches only exactly *nat*. A `(- nat)` matches *nat* or lower.

Examples:

```
> (module m (lib "racket")
    (require (planet "random.rkt" ("schematics" "random.plt" 1 0)))
    (display (random-gaussian)))
> (require 'm)
0.9050686838895684
```

The automatic `".ss"` and `".rkt"` conversions apply as with other forms.

```
(file string)
```

Refers to a file, where *string* is a relative or absolute path using the current platform's conventions. This form is not portable, and it should *not* be used when a plain, portable `rel-string` suffices.

The automatic `".ss"` and `".rkt"` conversions apply as with other forms.

```
(submod base element ...+)

   base = module-path
        | "."
        | ".."

element = id
        | ".."
```

Refers to a submodule of *base*. The sequence of *element*s within `submod` specify a path of submodule names to reach the final submodule.

Examples:

```
> (module zoo racket
    (module monkey-house racket
      (provide monkey)
      (define monkey "Curious George")))
> (require (submod 'zoo monkey-house))
> monkey
"Curious George"
```

Using `"."` as *base* within `submod` stands for the enclosing module. Using `".."` as *base* is equivalent to using `"."` followed by an extra `".."`. When a path of the form `(quote id)` refers to a submodule, it is equivalent to `(submod "." id)`.

Using `".."` as an *element* cancels one submodule step, effectively referring to the enclosing module. For example, `(submod "..")` refers to the enclosing module of the submodule in which the path appears.

Examples:

```
> (module zoo racket
    (module monkey-house racket
      (provide monkey)
      (define monkey "Curious George"))
    (module crocodile-house racket
      (require (submod ".." monkey-house))
      (provide dinner)
      (define dinner monkey)))
> (require (submod 'zoo crocodile-house))
> dinner
"Curious George"
```

6.4 Imports: `require`

The `require` form imports from another module. A `require` form can appear within a module, in which case it introduces bindings from the specified module into the importing module. A `require` form can also appear at the top level, in which case it both imports bindings and *instantiates* the specified module; that is, it evaluates the body definitions and expressions of the specified module, if they have not been evaluated already.

A single `require` can specify multiple imports at once:

```
(require require-spec ...)
```

Specifying multiple *require-spec*s in a single `require` is essentially the same as using multiple `require`s, each with a single *require-spec*. The difference is minor, and confined to the top-level: a single `require` can import a given identifier at most once, whereas a separate `require` can replace the bindings of a previous `require` (both only at the top level, outside of a module).

The allowed shape of a *require-spec* is defined recursively:

module-path

> In its simplest form, a *require-spec* is a *module-path* (as defined in the previous section, §6.3 “Module Paths”). In this case, the bindings introduced by `require` are determined by `provide` declarations within each module referenced by each *module-path*.
>
> Examples:
>
> ```
> > (module m racket
>     (provide color)
>     (define color "blue"))
> ```

```
> (module n racket
    (provide size)
    (define size 17))
> (require 'm 'n)
> (list color size)
'("blue" 17)
```

(only-in *require-spec id-maybe-renamed ...*)

id-maybe-renamed = *id*
| [*orig-id bind-id*]

An only-in form limits the set of bindings that would be introduced by a base *require-spec*. Also, only-in optionally renames each binding that is preserved: in a [*orig-id bind-id*] form, the *orig-id* refers to a binding implied by *require-spec*, and *bind-id* is the name that will be bound in the importing context instead of *orig-id*.

Examples:

```
> (module m (lib "racket")
    (provide tastes-great?
             less-filling?)
    (define tastes-great? #t)
    (define less-filling? #t))
> (require (only-in 'm tastes-great?))
> tastes-great?
#t
> less-filling?
less-filling?: undefined;
 cannot reference an identifier before its definition
  in module: top-level
> (require (only-in 'm [less-filling? lite?]))
> lite?
#t
```

(except-in *require-spec id ...*)

This form is the complement of only-in: it excludes specific bindings from the set specified by *require-spec*.

(rename-in *require-spec* [*orig-id bind-id*] ...)

This form supports renaming like only-in, but leaving alone identifiers from *require-spec* that are not mentioned as an *orig-id*.

(prefix-in *prefix-id require-spec*)

This is a shorthand for renaming, where *prefix-id* is added to the front of each identifier specified by *require-spec*.

The `only-in`, `except-in`, `rename-in`, and `prefix-in` forms can be nested to implement more complex manipulations of imported bindings. For example,

```
(require (prefix-in m: (except-in 'm ghost)))
```

imports all bindings that `m` exports, except for the `ghost` binding, and with local names that are prefixed with `m:`.

Equivalently, the `prefix-in` could be applied before `except-in`, as long as the omission with `except-in` is specified using the `m:` prefix:

```
(require (except-in (prefix-in m: 'm) m:ghost))
```

6.5 Exports: `provide`

By default, all of a module's definitions are private to the module. The `provide` form specifies definitions to be made available where the module is `required`.

(provide *provide-spec ...*)

A `provide` form can only appear at module level (i.e., in the immediate body of a `module`). Specifying multiple *provide-spec*s in a single `provide` is exactly the same as using multiple `provides` each with a single *provide-spec*.

Each identifier can be exported at most once from a module across all `provides` within the module. More precisely, the external name for each export must be distinct; the same internal binding can be exported multiple times with different external names.

The allowed shape of a *provide-spec* is defined recursively:

identifier

In its simplest form, a *provide-spec* indicates a binding within its module to be exported. The binding can be from either a local definition, or from an import.

(rename-out [*orig-id export-id*] ...)

A `rename-out` form is similar to just specifying an identifier, but the exported binding *orig-id* is given a different name, *export-id*, to importing modules.

(struct-out *struct-id*)

A `struct-out` form exports the bindings created by `(struct` *struct-id* `....)`.

See §5 “Programmer-Defined Datatypes” for information on `define-struct`.

(all-defined-out)

The `all-defined-out` shorthand exports all bindings that are defined within the exporting module (as opposed to imported).

Use of the `all-defined-out` shorthand is generally discouraged, because it makes less clear the actual exports for a module, and because Racket programmers get into the habit of thinking that definitions can be added freely to a module without affecting its public interface (which is not the case when `all-defined-out` is used).

(all-from-out *module-path*)

The `all-from-out` shorthand exports all bindings in the module that were imported using a *require-spec* that is based on *module-path*.

Although different *module-path*s could refer to the same file-based module, re-exporting with `all-from-out` is based specifically on the *module-path* reference, and not the module that is actually referenced.

(except-out *provide-spec id* ...)

Like *provide-spec*, but omitting the export of each *id*, where *id* is the external name of the binding to omit.

(prefix-out *prefix-id provide-spec*)

Like *provide-spec*, but adding *prefix-id* to the beginning of the external name for each exported binding.

6.6 Assignment and Redefinition

The use of `set!` on variables defined within a module is limited to the body of the defining module. That is, a module is allowed to change the value of its own definitions, and such changes are visible to importing modules. However, an importing context is not allowed to change the value of an imported binding.

Examples:

```
> (module m racket
    (provide counter increment!)
    (define counter 0)
    (define (increment!)
      (set! counter (add1 counter))))
> (require 'm)
> counter
0
> (increment!)
> counter
1
> (set! counter -1)
set!: cannot mutate module-required identifier
  at: counter
  in: (set! counter -1)
```

As the above example illustrates, a module can always grant others the ability to change its exports by providing a mutator function, such as `increment!`.

The prohibition on assignment of imported variables helps support modular reasoning about programs. For example, in the module,

```
(module m racket
  (provide rx:fish fishy-string?)
  (define rx:fish #rx"fish")
  (define (fishy-string? s)
    (regexp-match? rx:fish s)))
```

the function `fishy-string?` will always match strings that contain "fish", no matter how other modules use the `rx:fish` binding. For essentially the same reason that it helps programmers, the prohibition on assignment to imports also allows many programs to be executed more efficiently.

Along the same lines, when a module contains no `set!` of a particular identifier that is defined within the module, then the identifier is considered a *constant* that cannot be changed—not even by re-declaring the module.

Consequently, re-declaration of a module is not generally allowed. For file-based modules, simply changing the file does not lead to a re-declaration in any case, because file-based modules are loaded on demand, and the previously loaded declarations satisfy future requests. It is possible to use Racket's reflection support to re-declare a module, however, and non-file modules can be re-declared in the REPL; in such cases, the re-declaration may fail if it involves the re-definition of a previously constant binding.

```
> (module m racket
    (define pie 3.141597))
> (require 'm)
> (module m racket
    (define pie 3))
define-values: assignment disallowed;
 cannot re-define a constant
  constant: pie
  in module:'m
```

For exploration and debugging purposes, the Racket reflective layer provides a `compile-enforce-module-constants` parameter to disable the enforcement of constants.

```
> (compile-enforce-module-constants #f)
> (module m2 racket
    (provide pie)
    (define pie 3.141597))
> (require 'm2)
> (module m2 racket
    (provide pie)
    (define pie 3))
> (compile-enforce-module-constants #t)
> pie
3
```

6.7 Modules and Macros

Racket's module system cooperates closely with Racket's macro system for adding new syntactic forms to Racket. For example, in the same way that importing `racket/base` introduces syntax for `require` and `lambda`, importing other modules can introduce new syntactic forms (in addition to more traditional kinds of imports, such as functions or constants).

We introduce macros in more detail later, in §16 "Macros", but here's a simple example of a module that defines a pattern-based macro:

```
(module noisy racket
  (provide define-noisy)
```

```
(define-syntax-rule (define-noisy (id arg ...) body)
  (define (id arg ...)
    (show-arguments 'id  (list arg ...))
    body))

(define (show-arguments name args)
  (printf "calling ~s with arguments ~e" name args)))
```

The `define-noisy` binding provided by this module is a macro that acts like `define` for a function, but it causes each call to the function to print the arguments that are provided to the function:

```
> (require 'noisy)
> (define-noisy (f x y)
    (+ x y))
> (f 1 2)
calling f with arguments '(1 2)
3
```

Roughly, the `define-noisy` form works by replacing

```
(define-noisy (f x y)
  (+ x y))
```

with

```
(define (f x y)
  (show-arguments 'f (list x y))
  (+ x y))
```

Since `show-arguments` isn't provided by the `noisy` module, however, this literal textual replacement is not quite right. The actual replacement correctly tracks the origin of identifiers like `show-arguments`, so they can refer to other definitions in the place where the macro is defined—even if those identifiers are not available at the place where the macro is used.

There's more to the macro and module interaction than identifier binding. The `define-syntax-rule` form is itself a macro, and it expands to compile-time code that implements the transformation from `define-noisy` into `define`. The module system keeps track of which code needs to run at compile and which needs to run normally, as explained more in §16.2.5 "Compile and Run-Time Phases" and §16.3 "Module Instantiations and Visits".

6.8 Protected Exports

Sometimes, a module needs to export bindings to other modules that are at the same trust level as the exporting module, while at the same time preventing access from untrusted modules. Such exports should use the `protect-out` form in `provide`. For example, `ffi/unsafe` exports all of its unsafe bindings as *protected* in this sense.

Levels of trust are implemented with code inspectors (see §15.4 “Code Inspectors for Trusted and Untrusted Code”). Only modules loaded with an equally strong code inspector as an exporting module can use protected bindings from the exporting module. Operations like `dynamic-require` are granted access depending on the current code inspector as determined by `current-code-inspector`.

When a module re-exports a protected binding, it does not need to use `protect-out` again. Access is always determined by the code inspector of the module that originally defines a protected binding. When using a protected binding within a module, take care to either provide new bindings from the module with `protect-out` or ensure that no provided bindings expose functionality that was meant to be protected in the first place.

7 Contracts

This chapter provides a gentle introduction to Racket's contract system.

§8 "Contracts" in *The Racket Reference* provides more on contracts.

7.1 Contracts and Boundaries

Like a contract between two business partners, a software contract is an agreement between two parties. The agreement specifies obligations and guarantees for each "product" (or value) that is handed from one party to the other.

A contract thus establishes a boundary between the two parties. Whenever a value crosses this boundary, the contract monitoring system performs contract checks, making sure the partners abide by the established contract.

In this spirit, Racket encourages contracts mainly at module boundaries. Specifically, programmers may attach contracts to `provide` clauses and thus impose constraints and promises on the use of exported values. For example, the export specification

```
#lang racket

(provide (contract-out [amount positive?]))

(define amount ...)
```

promises to all clients of the above module that the value of `amount` will always be a positive number. The contract system monitors the module's obligation carefully. Every time a client refers to `amount`, the monitor checks that the value of `amount` is indeed a positive number.

The contracts library is built into the Racket language, but if you wish to use `racket/base`, you can explicitly require the contracts library like this:

```
#lang racket/base
(require racket/contract) ; now we can write contracts

(provide (contract-out [amount positive?]))

(define amount ...)
```

7.1.1 Contract Violations

If we bind `amount` to a number that is not positive,

```
#lang racket
```

```
(provide (contract-out [amount positive?]))

(define amount 0)
```

then, when the module is required, the monitoring system signals a violation of the contract and blames the module for breaking its promises.

An even bigger mistake would be to bind `amount` to a non-number value:

```
#lang racket

(provide (contract-out [amount positive?]))

(define amount 'amount)
```

In this case, the monitoring system will apply `positive?` to a symbol, but `positive?` reports an error, because its domain is only numbers. To make the contract capture our intentions for all Racket values, we can ensure that the value is both a number and is positive, combining the two contracts with `and/c`:

```
(provide (contract-out [amount (and/c number? positive?)]))
```

7.1.2 Experimenting with Contracts and Modules

All of the contracts and modules in this chapter (excluding those just following) are written using the standard `#lang` syntax for describing modules. Since modules serve as the boundary between parties in a contract, examples involve multiple modules.

To experiment with multiple modules within a single module or within DrRacket's definitions area, use Racket's submodules. For example, try the example earlier in this section like this:

```
#lang racket

(module+ server
  (provide (contract-out [amount (and/c number? positive?)]))
  (define amount 150))

(module+ main
  (require (submod ".." server))
  (+ amount 10))
```

Each of the modules and their contracts are wrapped in parentheses with the `module+` keyword at the front. The first form after `module` is the name of the module to be used in a

subsequent `require` statement (where each reference through a `require` prefixes the name with `".."`).

7.1.3 Experimenting with Nested Contract Boundaries

In many cases, it makes sense to attach contracts at module boundaries. It is often convenient, however, to be able to use contracts at a finer granularity than modules. The `define/contract` form enables this kind of use:

```
#lang racket

(define/contract amount
  (and/c number? positive?)
  150)

(+ amount 10)
```

In this example, the `define/contract` form establishes a contract boundary between the definition of `amount` and its surrounding context. In other words, the two parties here are the definition and the module that contains it.

Forms that create these *nested contract boundaries* can sometimes be subtle to use because they may have unexpected performance implications or blame a party that may seem unintuitive. These subtleties are explained in §7.2.2 “Using `define/contract` and `->`” and §7.9.2 “Contract boundaries and `define/contract`”.

7.2 Simple Contracts on Functions

A mathematical function has a *domain* and a *range*. The domain indicates the kind of values that the function can accept as arguments, and the range indicates the kind of values that it produces. The conventional notation for describing a function with its domain and range is

```
f : A -> B
```

where `A` is the domain of the function and `B` is the range.

Functions in a programming language have domains and ranges, too, and a contract can ensure that a function receives only values in its domain and produces only values in its range. A `->` creates such a contract for a function. The forms after a `->` specify contracts for the domains and finally a contract for the range.

Here is a module that might represent a bank account:

```
#lang racket

(provide (contract-out
          [deposit (-> number? any)]
          [balance (-> number?)]))

(define amount 0)
(define (deposit a) (set! amount (+ amount a)))
(define (balance) amount)
```

The module exports two functions:

- `deposit`, which accepts a number and returns some value that is not specified in the contract, and
- `balance`, which returns a number indicating the current balance of the account.

When a module exports a function, it establishes two channels of communication between itself as a "server" and the "client" module that imports the function. If the client module calls the function, it sends a value into the server module. Conversely, if such a function call ends and the function returns a value, the server module sends a value back to the client module. This client–server distinction is important, because when something goes wrong, one or the other of the parties is to blame.

If a client module were to apply `deposit` to `'millions`, it would violate the contract. The contract-monitoring system would catch this violation and blame the client for breaking the contract with the above module. In contrast, if the `balance` function were to return `'broke`, the contract-monitoring system would blame the server module.

A `->` by itself is not a contract; it is a *contract combinator*, which combines other contracts to form a contract.

7.2.1 Styles of `->`

If you are used to mathematical functions, you may prefer a contract arrow to appear between the domain and the range of a function, not at the beginning. If you have read *How to Design Programs*, you have seen this many times. Indeed, you may have seen contracts such as these in other people's code:

```
(provide (contract-out
          [deposit (number? . -> . any)]))
```

If a Racket S-expression contains two dots with a symbol in the middle, the reader re-arranges the S-expression and place the symbol at the front, as described in §2.4.3 "Lists and Racket Syntax". Thus,

```
(number? . -> . any)
```

is just another way of writing

```
(-> number? any)
```

7.2.2 Using `define/contract` and `->`

The `define/contract` form introduced in §7.1.3 "Experimenting with Nested Contract Boundaries" can also be used to define functions that come with a contract. For example,

```
(define/contract (deposit amount)
  (-> number? any)
  ; implementation goes here
  ....)
```

which defines the `deposit` function with the contract from earlier. Note that this has two potentially important impacts on the use of `deposit`:

1. The contract will be checked on any call to `deposit` that is outside of the definition of `deposit` – even those inside the module in which it is defined. Because there may be many calls inside the module, this checking may cause the contract to be checked too often, which could lead to a performance degradation. This is especially true if the function is called repeatedly from a loop.

2. In some situations, a function may be written to accept a more lax set of inputs when called by other code in the same module. For such use cases, the contract boundary established by `define/contract` is too strict.

7.2.3 `any` and `any/c`

The `any` contract used for `deposit` matches any kind of result, and it can only be used in the range position of a function contract. Instead of `any` above, we could use the more specific contract `void?`, which says that the function will always return the `(void)` value. The `void?` contract, however, would require the contract monitoring system to check the return value every time the function is called, even though the "client" module can't do much with the value. In contrast, `any` tells the monitoring system *not* to check the return value, it tells a potential client that the "server" module *makes no promises at all* about the function's return value, even whether it is a single value or multiple values.

The `any/c` contract is similar to `any`, in that it makes no demands on a value. Unlike `any`, `any/c` indicates a single value, and it is suitable for use as an argument contract. Using

any/c as a range contract imposes a check that the function produces a single value. That is,

```
(-> integer? any)
```

describes a function that accepts an integer and returns any number of values, while

```
(-> integer? any/c)
```

describes a function that accepts an integer and produces a single result (but does not say anything more about the result). The function

```
(define (f x) (values (+ x 1) (- x 1)))
```

matches (-> integer? any), but not (-> integer? any/c).

Use any/c as a result contract when it is particularly important to promise a single result from a function. Use any when you want to promise as little as possible (and incur as little checking as possible) for a function's result.

7.2.4 Rolling Your Own Contracts

The deposit function adds the given number to the value of amount. While the function's contract prevents clients from applying it to non-numbers, the contract still allows them to apply the function to complex numbers, negative numbers, or inexact numbers, none of which sensibly represent amounts of money.

The contract system allows programmers to define their own contracts as functions:

```
#lang racket

(define (amount? a)
  (and (number? a) (integer? a) (exact? a) (>= a 0)))

(provide (contract-out
          ; an amount is a natural number of cents
          ; is the given number an amount?
          [deposit (-> amount? any)]
          [amount? (-> any/c boolean?)]
          [balance (-> amount?)]))

(define amount 0)
(define (deposit a) (set! amount (+ amount a)))
(define (balance) amount)
```

This module defines an `amount?` function and uses it as a contract within `->` contracts. When a client calls the `deposit` function as exported with the contract `(-> amount? any)`, it must supply an exact, nonnegative integer, otherwise the `amount?` function applied to the argument will return `#f`, which will cause the contract-monitoring system to blame the client. Similarly, the server module must provide an exact, nonnegative integer as the result of `balance` to remain blameless.

Of course, it makes no sense to restrict a channel of communication to values that the client doesn't understand. Therefore the module also exports the `amount?` predicate itself, with a contract saying that it accepts an arbitrary value and returns a boolean.

In this case, we could also have used `natural-number/c` in place of `amount?`, since it implies exactly the same check:

```
(provide (contract-out
          [deposit (-> natural-number/c any)]
          [balance (-> natural-number/c)]))
```

Every function that accepts one argument can be treated as a predicate and thus used as a contract. For combining existing checks into a new one, however, contract combinators such as `and/c` and `or/c` are often useful. For example, here is yet another way to write the contracts above:

```
(define amount/c
  (and/c number? integer? exact? (or/c positive? zero?)))

(provide (contract-out
          [deposit (-> amount/c any)]
          [balance (-> amount/c)]))
```

Other values also serve double duty as contracts. For example, if a function accepts a number or `#f`, `(or/c number? #f)` suffices. Similarly, the `amount/c` contract could have been written with a `0` in place of `zero?`. If you use a regular expression as a contract, the contract accepts strings and byte strings that match the regular expression.

Naturally, you can mix your own contract-implementing functions with combinators like `and/c`. Here is a module for creating strings from banking records:

```
#lang racket

(define (has-decimal? str)
  (define L (string-length str))
  (and (>= L 3)
       (char=? #\. (string-ref str (- L 3)))))

(provide (contract-out
```

```
          ; convert a random number to a string
          [format-number (-> number? string?)]

          ; convert an amount into a string with a decimal
          ; point, as in an amount of US currency
          [format-nat (-> natural-number/c
                          (and/c string? has-decimal?))]))
```

The contract of the exported function `format-number` specifies that the function consumes a number and produces a string. The contract of the exported function `format-nat` is more interesting than the one of `format-number`. It consumes only natural numbers. Its range contract promises a string that has a `.` in the third position from the right.

If we want to strengthen the promise of the range contract for `format-nat` so that it admits only strings with digits and a single dot, we could write it like this:

```
#lang racket

(define (digit-char? x)
  (member x '(#\1 #\2 #\3 #\4 #\5 #\6 #\7 #\8 #\9 #\0)))

(define (has-decimal? str)
  (define L (string-length str))
  (and (>= L 3)
       (char=? #\. (string-ref str (- L 3)))))

(define (is-decimal-string? str)
  (define L (string-length str))
  (and (has-decimal? str)
       (andmap digit-char?
               (string->list (substring str 0 (- L 3))))
       (andmap digit-char?
               (string->list (substring str (- L 2) L)))))

....

(provide (contract-out
          ....
          ; convert an amount (natural number) of cents
          ; into a dollar-based string
          [format-nat (-> natural-number/c
                          (and/c string?
                                 is-decimal-string?))]))
```

Alternately, in this case, we could use a regular expression as a contract:

```
#lang racket

(provide
 (contract-out
  ....
  ; convert an amount (natural number) of cents
  ; into a dollar-based string
  [format-nat (-> natural-number/c
                  (and/c string? #rx"[0-9]*\\.[0-9][0-9]"))]))
```

7.2.5 Contracts on Higher-order Functions

Function contracts are not just restricted to having simple predicates on their domains or ranges. Any of the contract combinators discussed here, including function contracts themselves, can be used as contracts on the arguments and results of a function.

For example,

```
(-> integer? (-> integer? integer?))
```

is a contract that describes a curried function. It matches functions that accept one argument and then return another function accepting a second argument before finally returning an integer. If a server exports a function `make-adder` with this contract, and if `make-adder` returns a value other than a function, then the server is to blame. If `make-adder` does return a function, but the resulting function is applied to a value other than an integer, then the client is to blame.

Similarly, the contract

```
(-> (-> integer? integer?) integer?)
```

describes functions that accept other functions as its input. If a server exports a function `twice` with this contract and the `twice` is applied to a value other than a function of one argument, then the client is to blame. If `twice` is applied to a function of one argument and `twice` calls the given function on a value other than an integer, then the server is to blame.

7.2.6 Contract Messages with "???"

You wrote your module. You added contracts. You put them into the interface so that client programmers have all the information from interfaces. It's a piece of art:

```
> (module bank-server racket
    (provide
```

```
 (contract-out
  [deposit (-> (λ (x)
                 (and (number? x) (integer? x) (>= x 0)))
               any)]))

(define total 0)
(define (deposit a) (set! total (+ a total))))
```

Several clients used your module. Others used their modules in turn. And all of a sudden one of them sees this error message:

```
> (require 'bank-server)
> (deposit -10)
deposit: contract violation
  expected: ???
  given: -10
  in: the 1st argument of
      (-> ??? any)
  contract from: bank-server
  blaming: top-level
   (assuming the contract is correct)
  at: eval:2:0
```

What is the *???* doing there? Wouldn't it be nice if we had a name for this class of data much like we have string, number, and so on?

For this situation, Racket provides *flat named contracts*. The use of "contract" in this term shows that contracts are first-class values. The "flat" means that the collection of data is a subset of the built-in atomic classes of data; they are described by a predicate that consumes all Racket values and produces a boolean. The "named" part says what we want to do, which is to name the contract so that error messages become intelligible:

```
> (module improved-bank-server racket
    (provide
     (contract-out
      [deposit (-> (flat-named-contract
                    'amount
                    (λ (x)
                      (and (number? x) (integer? x) (>= x 0))))
                   any)]))

    (define total 0)
    (define (deposit a) (set! total (+ a total))))
```

With this little change, the error message becomes quite readable:

```
> (require 'improved-bank-server)
> (deposit -10)
deposit: contract violation
  expected: amount
  given: -10
  in: the 1st argument of
        (-> amount any)
  contract from: improved-bank-server
  blaming: top-level
   (assuming the contract is correct)
  at: eval:5:0
```

7.2.7 Dissecting a contract error message

In general, each contract error message consists of six sections:

- a name for the function or method associated with the contract and either the phrase "contract violation" or "broke its contract" depending on whether the contract was violated by the client or the server; e.g. in the previous example:

  deposit: contract violation

- a description of the precise aspect of the contract that was violated,

  expected: amount
  given: -10

- the complete contract plus a path into it showing which aspect was violated,

  in: the 1st argument of
  (-> amount any)

- the module where the contract was put (or, more generally, the boundary that the contract mediates),

  contract from: improved-bank-server

- who was blamed,

  blaming: top-level
  (assuming the contract is correct)

- and the source location where the contract appears.

  at: eval:5:0

7.3 Contracts on Functions in General

The -> contract constructor works for functions that take a fixed number of arguments and where the result contract is independent of the input arguments. To support other kinds of functions, Racket supplies additional contract constructors, notably ->* and ->i.

7.3.1 Optional Arguments

Take a look at this excerpt from a string-processing module:

```
#lang racket

(provide
 (contract-out
  ; pad the given str left and right with
  ; the (optional) char so that it is centered
  [string-pad-center (->* (string? natural-number/c)
                          (char?)
                          string?)]))

(define (string-pad-center str width [pad #\space])
  (define field-width (min width (string-length str)))
  (define rmargin (ceiling (/ (- width field-width) 2)))
  (define lmargin (floor (/ (- width field-width) 2)))
  (string-append (build-string lmargin (λ (x) pad))
                 str
                 (build-string rmargin (λ (x) pad))))
```

The module exports string-pad-center, a function that creates a string of a given width with the given string in the center. The default fill character is #\space; if the client module wishes to use a different character, it may call string-pad-center with a third argument, a char, overwriting the default.

The function definition uses optional arguments, which is appropriate for this kind of functionality. The interesting point here is the formulation of the contract for the string-pad-center.

The contract combinator ->*, demands several groups of contracts:

- The first one is a parenthesized group of contracts for all required arguments. In this example, we see two: string? and natural-number/c.
- The second one is a parenthesized group of contracts for all optional arguments: char?.

- The last one is a single contract: the result of the function.

Note that if a default value does not satisfy a contract, you won't get a contract error for this interface. If you can't trust yourself to get the initial value right, you need to communicate the initial value across a boundary.

7.3.2 Rest Arguments

The `max` operator consumes at least one real number, but it accepts any number of additional arguments. You can write other such functions using a rest argument, such as in `max-abs`:

See §4.4.1 "Declaring a Rest Argument" for an introduction to rest arguments.

```
(define (max-abs n . rst)
  (foldr (lambda (n m) (max (abs n) m)) (abs n) rst))
```

To describe this function through a contract, you can use the `...` feature of `->`.

```
(provide
 (contract-out
  [max-abs (-> real? real? ... real?)]))
```

Alternatively, you can use `->*` with a `#:rest` keyword, which specifies a contract on a list of arguments after the required and optional arguments:

```
(provide
 (contract-out
  [max-abs (->* (real?) () #:rest (listof real?) real?)]))
```

As always for `->*`, the contracts for the required arguments are enclosed in the first pair of parentheses, which in this case is a single real number. The empty pair of parenthesis indicates that there are no optional arguments (not counting the rest arguments). The contract for the rest argument follows `#:rest`; since all additional arguments must be real numbers, the list of rest arguments must satisfy the contract `(listof real?)`.

7.3.3 Keyword Arguments

It turns out that the `->` contract constructor also contains support for keyword arguments. For example, consider this function, which creates a simple GUI and asks the user a yes-or-no question:

See §4.4.3 "Declaring Keyword Arguments" for an introduction to keyword arguments.

```
#lang racket/gui
```

```
(define (ask-yes-or-no-question question
                                #:default answer
                                #:title title
                                #:width w
                                #:height h)
  (define d (new dialog% [label title] [width w] [height h]))
  (define msg (new message% [label question] [parent d]))
  (define (yes) (set! answer #t) (send d show #f))
  (define (no) (set! answer #f) (send d show #f))
  (define yes-b (new button%
                     [label "Yes"] [parent d]
                     [callback (λ (x y) (yes))]
                     [style (if answer '(border) '())]))
  (define no-b (new button%
                    [label "No"] [parent d]
                    [callback (λ (x y) (no))]
                    [style (if answer '() '(border))]))
  (send d show #t)
  answer)

(provide (contract-out
          [ask-yes-or-no-question
           (-> string?
               #:default boolean?
               #:title string?
               #:width exact-integer?
               #:height exact-integer?
               boolean?)]))
```

If you really want to ask a yes-or-no question via a GUI, you should use `message-box/custom`. For that matter, it's usually better to provide buttons with more specific answers than "yes" and "no."

The contract for `ask-yes-or-no-question` uses `->`, and in the same way that `lambda` (or `define`-based functions) allows a keyword to precede a functions formal argument, `->` allows a keyword to precede a function contract's argument contract. In this case, the contract says that `ask-yes-or-no-question` must receive four keyword arguments, one for each of the keywords `#:default`, `#:title`, `#:width`, and `#:height`. As in a function definition, the order of the keywords in `->` relative to each other does not matter for clients of the function; only the relative order of argument contracts without keywords matters.

7.3.4 Optional Keyword Arguments

Of course, many of the parameters in `ask-yes-or-no-question` (from the previous question) have reasonable defaults and should be made optional:

```
(define (ask-yes-or-no-question question
                                #:default answer
```

```
                                  #:title [title "Yes or No?"]
                                  #:width [w 400]
                                  #:height [h 200])
  ...)
```

To specify this function's contract, we need to use `->*` again. It supports keywords just as you might expect in both the optional and mandatory argument sections. In this case, we have the mandatory keyword `#:default` and optional keywords `#:title`, `#:width`, and `#:height`. So, we write the contract like this:

```
(provide (contract-out
          [ask-yes-or-no-question
           (->* (string?
                 #:default boolean?)
                (#:title string?
                 #:width exact-integer?
                 #:height exact-integer?)

                boolean?)]))
```

That is, we put the mandatory keywords in the first section, and we put the optional ones in the second section.

7.3.5 Contracts for `case-lambda`

A function defined with `case-lambda` might impose different constraints on its arguments depending on how many are provided. For example, a `report-cost` function might convert either a pair of numbers or a string into a new string:

See §4.4.4 "Arity-Sensitive Functions: `case-lambda`" for an introduction to `case-lambda`.

```
(define report-cost
  (case-lambda
    [(lo hi) (format "between $~a and $~a" lo hi)]
    [(desc) (format "~a of dollars" desc)]))

> (report-cost 5 8)
"between $5 and $8"
> (report-cost "millions")
"millions of dollars"
```

The contract for such a function is formed with the `case->` combinator, which combines as many functional contracts as needed:

```
(provide (contract-out
```

```
[report-cost
 (case->
  (integer? integer? . -> . string?)
  (string? . -> . string?))]))
```

As you can see, the contract for `report-cost` combines two function contracts, which is just as many clauses as the explanation of its functionality required.

7.3.6 Argument and Result Dependencies

The following is an excerpt from an imaginary numerics module:

```
(provide
 (contract-out
  [real-sqrt (->i ([argument (>=/c 1)])
                  [result (argument) (<=/c argument)])]))
```

The word "indy" is meant to suggest that blame may be assigned to the contract itself, because the contract must be considered an independent component. The name was chosen in response to two existing labels—"lax" and "picky"—for different semantics of function contracts in the research literature.

The contract for the exported function `real-sqrt` uses the `->i` rather than `->*` function contract. The "i" stands for an *indy dependent* contract, meaning the contract for the function range depends on the value of the argument. The appearance of `argument` in the line for `result`'s contract means that the result depends on the argument. In this particular case, the argument of `real-sqrt` is greater or equal to 1, so a very basic correctness check is that the result is smaller than the argument.

In general, a dependent function contract looks just like the more general `->*` contract, but with names added that can be used elsewhere in the contract.

Going back to the bank-account example, suppose that we generalize the module to support multiple accounts and that we also include a withdrawal operation. The improved bank-account module includes an `account` structure type and the following functions:

```
(provide (contract-out
          [balance (-> account? amount/c)]
          [withdraw (-> account? amount/c account?)]
          [deposit (-> account? amount/c account?)]))
```

Besides requiring that a client provide a valid amount for a withdrawal, however, the amount should be less than or equal to the specified account's balance, and the resulting account will have less money than it started with. Similarly, the module might promise that a deposit produces an account with money added to the account. The following implementation enforces those constraints and guarantees through contracts:

```
#lang racket
```

```
; section 1: the contract definitions
(struct account (balance))
(define amount/c natural-number/c)

; section 2: the exports
(provide
 (contract-out
  [create   (amount/c . -> . account?)]
  [balance  (account? . -> . amount/c)]
  [withdraw (->i ([acc account?]
                  [amt (acc) (and/c amount/c (<=/c (balance acc)))])
                 [result (acc amt)
                         (and/c account?
                                (lambda (res)
                                  (>= (balance res)
                                      (- (balance acc) amt))))])]
  [deposit  (->i ([acc account?]
                  [amt amount/c])
                 [result (acc amt)
                         (and/c account?
                                (lambda (res)
                                  (>= (balance res)
                                      (+ (balance acc) amt))))])]))

; section 3: the function definitions
(define balance account-balance)

(define (create amt) (account amt))

(define (withdraw a amt)
  (account (- (account-balance a) amt)))

(define (deposit a amt)
  (account (+ (account-balance a) amt)))
```

The contracts in section 2 provide typical type-like guarantees for `create` and `balance`. For `withdraw` and `deposit`, however, the contracts check and guarantee the more complicated constraints on `balance` and `deposit`. The contract on the second argument to `withdraw` uses `(balance acc)` to check whether the supplied withdrawal amount is small enough, where `acc` is the name given within `->i` to the function's first argument. The contract on the result of `withdraw` uses both `acc` and `amt` to guarantee that no more than that requested amount was withdrawn. The contract on `deposit` similarly uses `acc` and `amount` in the result contract to guarantee that at least as much money as provided was deposited into the account.

As written above, when a contract check fails, the error message is not great. The following revision uses `flat-named-contract` within a helper function `mk-account-contract` to provide better error messages.

```
#lang racket

; section 1: the contract definitions
(struct account (balance))
(define amount/c natural-number/c)

(define msg> "account a with balance larger than ~a expected")
(define msg< "account a with balance less than ~a expected")

(define (mk-account-contract acc amt op msg)
  (define balance0 (balance acc))
  (define (ctr a)
    (and (account? a) (op balance0 (balance a))))
  (flat-named-contract (format msg balance0) ctr))

; section 2: the exports
(provide
 (contract-out
  [create   (amount/c . -> . account?)]
  [balance  (account? . -> . amount/c)]
  [withdraw (->i ([acc account?]
                  [amt (acc) (and/c amount/c (<=/c (balance acc)))])
                 [result (acc amt) (mk-account-
contract acc amt >= msg>)])]
  [deposit  (->i ([acc account?]
                  [amt amount/c])
                 [result (acc amt)
                         (mk-account-contract acc amt <= msg<)])]))

; section 3: the function definitions
(define balance account-balance)

(define (create amt) (account amt))

(define (withdraw a amt)
  (account (- (account-balance a) amt)))

(define (deposit a amt)
  (account (+ (account-balance a) amt)))
```

7.3.7 Checking State Changes

The `->i` contract combinator can also ensure that a function only modifies state according to certain constraints. For example, consider this contract (it is a slightly simplified version from the function `preferences:add-panel` in the framework):

```
(->i ([parent (is-a?/c area-container-window<%>)])
     [_ (parent)
      (let ([old-children (send parent get-children)])
        (λ (child)
          (andmap eq?
                  (append old-children (list child))
                  (send parent get-children))))])
```

It says that the function accepts a single argument, named `parent`, and that `parent` must be an object matching the interface `area-container-window<%>`.

The range contract ensures that the function only modifies the children of `parent` by adding a new child to the front of the list. It accomplishes this by using the `_` instead of a normal identifier, which tells the contract library that the range contract does not depend on the values of any of the results, and thus the contract library evaluates the expression following the `_` when the function is called, instead of when it returns. Therefore the call to the `get-children` method happens before the function under the contract is called. When the function under contract returns, its result is passed in as `child`, and the contract ensures that the children after the function return are the same as the children before the function called, but with one more child, at the front of the list.

To see the difference in a toy example that focuses on this point, consider this program

```
#lang racket
(define x '())
(define (get-x) x)
(define (f) (set! x (cons 'f x)))
(provide
 (contract-out
  [f (->i () [_ () (begin (set! x (cons 'ctc x)) any/c)])]
  [get-x (-> (listof symbol?))]))
```

If you were to require this module, call `f`, then the result of `get-x` would be `'(f ctc)`. In contrast, if the contract for `f` were

```
(->i () [res () (begin (set! x (cons 'ctc x)) any/c)])
```

(only changing the underscore to `res`), then the result of `get-x` would be `'(ctc f)`.

7.3.8 Multiple Result Values

The function `split` consumes a list of `char`s and delivers the string that occurs before the first occurrence of `#\newline` (if any) and the rest of the list:

```
(define (split l)
  (define (split l w)
    (cond
      [(null? l) (values (list->string (reverse w)) '())]
      [(char=? #\newline (car l))
       (values (list->string (reverse w)) (cdr l))]
      [else (split (cdr l) (cons (car l) w))]))
  (split l '()))
```

It is a typical multiple-value function, returning two values by traversing a single list.

The contract for such a function can use the ordinary function arrow `->`, since `->` treats `values` specially when it appears as the last result:

```
(provide (contract-out
          [split (-> (listof char?)
                     (values string? (listof char?)))]))
```

The contract for such a function can also be written using `->*`:

```
(provide (contract-out
          [split (->* ((listof char?))
                      ()
                      (values string? (listof char?)))]))
```

As before, the contract for the argument with `->*` is wrapped in an extra pair of parentheses (and must always be wrapped like that) and the empty pair of parentheses indicates that there are no optional arguments. The contracts for the results are inside `values`: a string and a list of characters.

Now, suppose that we also want to ensure that the first result of `split` is a prefix of the given word in list format. In that case, we need to use the `->i` contract combinator:

```
(define (substring-of? s)
  (flat-named-contract
    (format "substring of ~s" s)
    (lambda (s2)
      (and (string? s2)
           (<= (string-length s2) (string-length s))
           (equal? (substring s 0 (string-length s2)) s2)))))
```

```
(provide
 (contract-out
  [split (->i ([fl (listof char?)])
              (values [s (fl) (substring-of? (list->string fl))]
                      [c (listof char?)]))]))
```

Like `->*`, the `->i` combinator uses a function over the argument to create the range contracts. Yes, it doesn't just return one contract but as many as the function produces values: one contract per value. In this case, the second contract is the same as before, ensuring that the second result is a list of `char`s. In contrast, the first contract strengthens the old one so that the result is a prefix of the given word.

This contract is expensive to check, of course. Here is a cheaper, though less stringent, version:

```
(provide
 (contract-out
  [split (->i ([fl (listof char?)])
              (values [s (fl) (string-len/c (+ 1 (length fl)))]
                      [c (listof char?)]))]))
```

Stop! Why did we add `1` to the length of `fl`?

7.3.9 Fixed but Statically Unknown Arities

Imagine yourself writing a contract for a function that accepts some other function and a list of numbers that eventually applies the former to the latter. Unless the arity of the given function matches the length of the given list, your procedure is in trouble.

Consider this `n-step` function:

```
; (number ... -> (union #f number?)) (listof number) -> void
(define (n-step proc inits)
  (let ([inc (apply proc inits)])
    (when inc
      (n-step proc (map (λ (x) (+ x inc)) inits)))))
```

The argument of `n-step` is `proc`, a function `proc` whose results are either numbers or false, and a list. It then applies `proc` to the list `inits`. As long as `proc` returns a number, `n-step` treats that number as an increment for each of the numbers in `inits` and recurs. When `proc` returns `false`, the loop stops.

Here are two uses:

```
; nat -> nat
(define (f x)
  (printf "~s\n" x)
  (if (= x 0) #f -1))
(n-step f '(2))

; nat nat -> nat
(define (g x y)
  (define z (+ x y))
  (printf "~s\n" (list x y z))
  (if (= z 0) #f -1))

(n-step g '(1 1))
```

A contract for `n-step` must specify two aspects of `proc`'s behavior: its arity must include the number of elements in `inits`, and it must return either a number or `#f`. The latter is easy, the former is difficult. At first glance, this appears to suggest a contract that assigns a *variable-arity* to `proc`:

```
(->* ()
     #:rest (listof any/c)
     (or/c number? #f))
```

This contract, however, says that the function must accept *any* number of arguments, not a *specific* but *undetermined* number. Thus, applying `n-step` to `(lambda (x) x)` and `(list 1 2)` breaks the contract because the given function accepts only one argument.

The correct contract uses the `unconstrained-domain->` combinator, which specifies only the range of a function, not its domain. It is then possible to combine this contract with an arity test to specify the correct contract for `n-step`:

```
(provide
 (contract-out
  [n-step
   (->i ([proc (inits)
          (and/c (unconstrained-domain->
                  (or/c #f number?))
                 (λ (f) (procedure-arity-includes?
                         f
                         (length inits))))]
         [inits (listof number?)])
        ()
        any)]))
```

7.4 Contracts: A Thorough Example

This section develops several different flavors of contracts for one and the same example: Racket's `argmax` function. According to its Racket documentation, the function consumes a procedure `proc` and a non-empty list of values, `lst`. It

> returns the *first* element in the list `lst` that maximizes the result of `proc`.

The emphasis on *first* is ours.

Examples:

```
> (argmax add1 (list 1 2 3))
3
> (argmax sqrt (list 0.4 0.9 0.16))
0.9
> (argmax second '((a 2) (b 3) (c 4) (d 1) (e 4)))
'(c 4)
```

Here is the simplest possible contract for this function:

version 1

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax (-> (-> any/c real?) (and/c pair? list?) any/c)]))
```

This contract captures two essential conditions of the informal description of `argmax`:

- the given function must produce numbers that are comparable according to `<`. In particular, the contract `(-> any/c number?)` would not do, because `number?` also recognizes complex numbers in Racket.
- the given list must contain at least one item.

When combined with the name, the contract explains the behavior of `argmax` at the same level as an ML function type in a module signature (except for the non-empty list aspect).

Contracts may communicate significantly more than a type signature, however. Take a look at this second contract for `argmax`:

version 2

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (define f@r (f r))
              (for/and ([v lov]) (>= f@r (f v))))))]))
```

It is a *dependent* contract that names the two arguments and uses the names to impose a predicate on the result. This predicate computes `(f r)` – where `r` is the result of `argmax` – and then validates that this value is greater than or equal to all values of `f` on the items of `lov`.

Is it possible that `argmax` could cheat by returning a random value that accidentally maximizes `f` over all elements of `lov`? With a contract, it is possible to rule out this possibility:

version 2 rev. a

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (define f@r (f r))
              (and (memq r lov)
                   (for/and ([v lov]) (>= f@r (f v)))))))]))
```

The `memq` function ensures that `r` is *intensionally equal* to one of the members of `lov`. Of course, a moment's worth of reflection shows that it is impossible to make up such a value. Functions are opaque values in Racket and without applying a function, it is impossible to determine whether some random input value produces an output value or triggers some exception. So we ignore this possibility from here on.

That is, "pointer equality" for those who prefer to think at the hardware level.

Version 2 formulates the overall sentiment of `argmax`'s documentation, but it fails to bring across that the result is the *first* element of the given list that maximizes the given function `f`. Here is a version that communicates this second aspect of the informal documentation:

version 3

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (define f@r (f r))
              (and (for/and ([v lov]) (>= f@r (f v)))
                   (eq? (first (memf (lambda (v) (= (f v) f@r)) lov))
                        r))))))]))
```

That is, the `memf` function determines the first element of `lov` whose value under `f` is equal to `r`'s value under `f`. If this element is intensionally equal to `r`, the result of `argmax` is correct.

This second refinement step introduces two problems. First, both conditions recompute the values of `f` for all elements of `lov`. Second, the contract is now quite difficult to read. Contracts should have a concise formulation that a client can comprehend with a simple scan. Let us eliminate the readability problem with two auxiliary functions that have reasonably meaningful names:

version 3 rev. a

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (define f@r (f r))
              (and (is-first-max? r f@r f lov)
                   (dominates-all f@r f lov))))))]))

; where

; f@r is greater or equal to all (f v) for v in lov
(define (dominates-all f@r f lov)
  (for/and ([v lov]) (>= f@r (f v))))
```

```
; r is eq? to the first element v of lov for which (pred? v)
(define (is-first-max? r f@r f lov)
  (eq? (first (memf (lambda (v) (= (f v) f@r)) lov)) r))
```

The names of the two predicates express their functionality and, in principle, render it unnecessary to read their definitions.

This step leaves us with the problem of the newly introduced inefficiency. To avoid the recomputation of `(f v)` for all `v` on `lov`, we change the contract so that it computes these values and reuses them as needed:

version 3 rev. b

```
#lang racket

(define (argmax f lov) ...)

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (define f@r (f r))
              (define flov (map f lov))
              (and (is-first-max? r f@r (map list lov flov))
                   (dominates-all f@r flov))))))]))

; where

; f@r is greater or equal to all f@v in flov
(define (dominates-all f@r flov)
  (for/and ([f@v flov]) (>= f@r f@v)))

; r is (first x) for the first x in lov+flov s.t. (= (second x)
f@r)
(define (is-first-max? r f@r lov+flov)
  (define fst (first lov+flov))
  (if (= (second fst) f@r)
      (eq? (first fst) r)
      (is-first-max? r f@r (rest lov+flov))))
```

Now the predicate on the result once again computes all values of `f` for elements of `lov` once.

Version 3 may still be too eager when it comes to calling `f`. While Racket's `argmax` always

The word "eager" comes from the literature on the linguistics of contracts.

calls f no matter how many items lov contains, let us imagine for illustrative purposes that our own implementation first checks whether the list is a singleton. If so, the first element would be the only element of lov and in that case there would be no need to compute (f r). As a matter of fact, since f may diverge or raise an exception for some inputs, argmax should avoid calling f when possible.

The argmax of Racket implicitly argues that it not only promises the first value that maximizes f over lov but also that f produces/produced a value for the result.

The following contract demonstrates how a higher-order dependent contract needs to be adjusted so as to avoid being over-eager:

version 4

```
#lang racket

(define (argmax f lov)
  (if (empty? (rest lov))
      (first lov)
      ...))

(provide
 (contract-out
  [argmax
    (->i ([f (-> any/c real?)] [lov (and/c pair? list?)]) ()
         (r (f lov)
            (lambda (r)
              (cond
                [(empty? (rest lov)) (eq? (first lov) r)]
                [else
                 (define f@r (f r))
                 (define flov (map f lov))
                 (and (is-first-max? r f@r (map list lov flov))
                      (dominates-all f@r flov))])))))]))

; where

; f@r is greater or equal to all f@v in flov
(define (dominates-all f@r lov) ...)

; r is (first x) for the first x in lov+flov s.t. (= (second x)
f@r)
(define (is-first-max? r f@r lov+flov) ...)
```

Note that such considerations don't apply to the world of first-order contracts. Only a higher-order (or lazy) language forces the programmer to express contracts with such precision.

The problem of diverging or exception-raising functions should alert the reader to the even more general problem of functions with side-effects. If the given function f has visible effects – say it logs its calls to a file – then the clients of argmax will be able to observe

two sets of logs for each call to `argmax`. To be precise, if the list of values contains more than one element, the log will contain two calls of `f` per value on `lov`. If `f` is expensive to compute, doubling the calls imposes a high cost.

To avoid this cost and to signal problems with overly eager contracts, a contract system could record the i/o of contracted function arguments and use these hashtables in the dependency specification. This is a topic of on-going research in PLT. Stay tuned.

7.5 Contracts on Structures

Modules deal with structures in two ways. First they export `struct` definitions, i.e., the ability to create structs of a certain kind, to access their fields, to modify them, and to distinguish structs of this kind against every other kind of value in the world. Second, on occasion a module exports a specific struct and wishes to promise that its fields contain values of a certain kind. This section explains how to protect structs with contracts for both uses.

7.5.1 Guarantees for a Specific Value

If your module defines a variable to be a structure value, then you can specify the structure's shape using `struct/c`.

```
#lang racket

(struct posn [x y])

(define origin (posn 0 0))

(provide
  (contract-out
    [origin (struct/c posn zero? zero?)]))
```

In this example, the module defines a structure shape for representing 2-dimensional positions and then creates one specific instance: `origin`. The export of this instance guarantees that its fields are `0`, i.e., they represent `(0,0)`, on the Cartesian grid.

See also `vector/c` and similar contract combinators for (flat) compound data.

7.5.2 Guarantees for All Values

The book *How to Design Programs* teaches that `posn`s should contain only numbers in their two fields. With contracts we would enforce this informal data definition as follows:

```
#lang racket
```

```
(struct posn (x y))

(provide
  (contract-out
    [struct posn ((x number?) (y number?))]
    [p-okay posn?]
    [p-sick posn?]))

(define p-okay (posn 10 20))
(define p-sick (posn 'a 'b))
```

This module exports the entire structure definition: `posn`, `posn?`, `posn-x`, `posn-y`, `set-posn-x!`, and `set-posn-y!`. Each function enforces or promises that the two fields of a `posn` structure are numbers — when the values flow across the module boundary. Thus, if a client calls `posn` on `10` and `'a`, the contract system signals a contract violation.

The creation of `p-sick` inside of the `posn` module, however, does not violate the contracts. The function `posn` is used internally, so `'a` and `'b` don't cross the module boundary. Similarly, when `p-sick` crosses the boundary of `posn`, the contract promises a `posn?` and nothing else. In particular, this check does *not* require that the fields of `p-sick` are numbers.

The association of contract checking with module boundaries implies that `p-okay` and `p-sick` look alike from a client's perspective until the client extracts the pieces:

```
#lang racket
(require lang/posn)

... (posn-x p-sick) ...
```

Using `posn-x` is the only way the client can find out what a `posn` contains in the `x` field. The application of `posn-x` sends `p-sick` back into the `posn` module and the result value – `'a` here – back to the client, again across the module boundary. At this very point, the contract system discovers that a promise is broken. Specifically, `posn-x` doesn't return a number but a symbol and is therefore blamed.

This specific example shows that the explanation for a contract violation doesn't always pinpoint the source of the error. The good news is that the error is located in the `posn` module. The bad news is that the explanation is misleading. Although it is true that `posn-x` produced a symbol instead of a number, it is the fault of the programmer who created a `posn` from symbols, i.e., the programmer who added

```
(define p-sick (posn 'a 'b))
```

to the module. So, when you are looking for bugs based on contract violations, keep this example in mind.

If we want to fix the contract for `p-sick` so that the error is caught when `sick` is exported, a single change suffices:

```
(provide
 (contract-out
  ...
  [p-sick (struct/c posn number? number?)]))
```

That is, instead of exporting `p-sick` as a plain `posn?`, we use a `struct/c` contract to enforce constraints on its components.

7.5.3 Checking Properties of Data Structures

Contracts written using `struct/c` immediately check the fields of the data structure, but sometimes this can have disastrous effects on the performance of a program that does not, itself, inspect the entire data structure.

As an example, consider the binary search tree search algorithm. A binary search tree is like a binary tree, except that the numbers are organized in the tree to make searching the tree fast. In particular, for each interior node in the tree, all of the numbers in the left subtree are smaller than the number in the node, and all of the numbers in the right subtree are larger than the number in the node.

We can implement a search function `in?` that takes advantage of the structure of the binary search tree.

```
#lang racket

(struct node (val left right))

; determines if `n' is in the binary search tree `b',
; exploiting the binary search tree invariant
(define (in? n b)
  (cond
    [(null? b) #f]
    [else (cond
            [(= n (node-val b))
             #t]
            [(< n (node-val b))
             (in? n (node-left b))]
            [(> n (node-val b))
             (in? n (node-right b))])]))

; a predicate that identifies binary search trees
(define (bst-between? b low high)
```

```
  (or (null? b)
      (and (<= low (node-val b) high)
           (bst-between? (node-left b) low (node-val b))
           (bst-between? (node-right b) (node-val b) high))))

(define (bst? b) (bst-between? b -inf.0 +inf.0))

(provide (struct-out node))
(provide
  (contract-out
    [bst? (any/c . -> . boolean?)]
    [in? (number? bst? . -> . boolean?)]))
```

In a full binary search tree, this means that the `in?` function only has to explore a logarithmic number of nodes.

The contract on `in?` guarantees that its input is a binary search tree. But a little careful thought reveals that this contract defeats the purpose of the binary search tree algorithm. In particular, consider the inner `cond` in the `in?` function. This is where the `in?` function gets its speed: it avoids searching an entire subtree at each recursive call. Now compare that to the `bst-between?` function. In the case that it returns `#t`, it traverses the entire tree, meaning that the speedup of `in?` is lost.

In order to fix that, we can employ a new strategy for checking the binary search tree contract. In particular, if we only checked the contract on the nodes that `in?` looks at, we can still guarantee that the tree is at least partially well-formed, but without changing the complexity.

To do that, we need to use `struct/dc` to define `bst-between?`. Like `struct/c`, `struct/dc` defines a contract for a structure. Unlike `struct/c`, it allows fields to be marked as lazy, so that the contracts are only checked when the matching selector is called. Also, it does not allow mutable fields to be marked as lazy.

The `struct/dc` form accepts a contract for each field of the struct and returns a contract on the struct. More interestingly, `struct/dc` allows us to write dependent contracts, i.e., contracts where some of the contracts on the fields depend on the values of other fields. We can use this to define the binary search tree contract:

```
#lang racket

(struct node (val left right))

; determines if `n' is in the binary search tree `b'
(define (in? n b) ... as before ...)

; bst-between : number number -> contract
; builds a contract for binary search trees
```

```
; whose values are between low and high
(define (bst-between/c low high)
  (or/c null?
        (struct/dc node [val (between/c low high)]
                        [left (val) #:lazy (bst-
between/c low val)]
                        [right (val) #:lazy (bst-
between/c val high)])))

(define bst/c (bst-between/c -inf.0 +inf.0))

(provide (struct-out node))
(provide
  (contract-out
    [bst/c contract?]
    [in? (number? bst/c . -> . boolean?)]))
```

In general, each use of `struct/dc` must name the fields and then specify contracts for each field. In the above, the `val` field is a contract that accepts values between `low` and `high`. The `left` and `right` fields are dependent on the value of the `val` field, indicated by their second sub-expressions. They are also marked with the `#:lazy` keyword to indicate that they should be checked only when the appropriate accessor is called on the struct instance. Their contracts are built by recursive calls to the `bst-between/c` function. Taken together, this contract ensures the same thing that the `bst-between?` function checked in the original example, but here the checking only happens as `in?` explores the tree.

Although this contract improves the performance of `in?`, restoring it to the logarithmic behavior that the contract-less version had, it is still imposes a fairly large constant overhead. So, the contract library also provides `define-opt/c` that brings down that constant factor by optimizing its body. Its shape is just like the `define` above. It expects its body to be a contract and then optimizes that contract.

```
(define-opt/c (bst-between/c low high)
  (or/c null?
        (struct/dc node [val (between/c low high)]
                        [left (val) #:lazy (bst-
between/c low val)]
                        [right (val) #:lazy (bst-
between/c val high)])))
```

7.6 Abstract Contracts using `#:exists` and `#:∃`

The contract system provides existential contracts that can protect abstractions, ensuring that clients of your module cannot depend on the precise representation choices you make

for your data structures.

The `contract-out` form allows you to write

```
#:∃ name-of-a-new-contract
```

as one of its clauses. This declaration introduces the variable *name-of-a-new-contract*, binding it to a new contract that hides information about the values it protects.

You can type `#:exists` instead of `#:∃` if you cannot easily type unicode characters; in DrRacket, typing `\exists` followed by either alt-\ or control-\ (depending on your platform) will produce ∃.

As an example, consider this (simple) implementation of a queue data structure:

```
#lang racket
(define empty '())
(define (enq top queue) (append queue (list top)))
(define (next queue) (car queue))
(define (deq queue) (cdr queue))
(define (empty? queue) (null? queue))

(provide
 (contract-out
  [empty (listof integer?)]
  [enq (-> integer? (listof integer?) (listof integer?))]
  [next (-> (listof integer?) integer?)]
  [deq (-> (listof integer?) (listof integer?))]
  [empty? (-> (listof integer?) boolean?)]))
```

This code implements a queue purely in terms of lists, meaning that clients of this data structure might use `car` and `cdr` directly on the data structure (perhaps accidentally) and thus any change in the representation (say to a more efficient representation that supports amortized constant time enqueue and dequeue operations) might break client code.

To ensure that the queue representation is abstract, we can use `#:∃` in the `contract-out` expression, like this:

```
(provide
 (contract-out
  #:∃ queue
  [empty queue]
  [enq (-> integer? queue queue)]
  [next (-> queue integer?)]
  [deq (-> queue queue)]
  [empty? (-> queue boolean?)]))
```

Now, if clients of the data structure try to use `car` and `cdr`, they receive an error, rather than mucking about with the internals of the queues.

See also §7.9.3 “Exists Contracts and Predicates”.

7.7 Additional Examples

This section illustrates the current state of Racket's contract implementation with a series of examples from *Design by Contract, by Example* [Mitchell02].

Mitchell and McKim's principles for design by contract DbC are derived from the 1970s style algebraic specifications. The overall goal of DbC is to specify the constructors of an algebra in terms of its observers. While we reformulate Mitchell and McKim's terminology and we use a mostly applicative approach, we retain their terminology of "classes" and "objects":

- **Separate queries from commands.**

  A *query* returns a result but does not change the observable properties of an object. A *command* changes the visible properties of an object, but does not return a result. In applicative implementation a command typically returns an new object of the same class.

- **Separate basic queries from derived queries.**

  A *derived query* returns a result that is computable in terms of basic queries.

- **For each derived query, write a post-condition contract that specifies the result in terms of the basic queries.**

- **For each command, write a post-condition contract that specifies the changes to the observable properties in terms of the basic queries.**

- **For each query and command, decide on a suitable pre-condition contract.**

Each of the following sections corresponds to a chapter in Mitchell and McKim's book (but not all chapters show up here). We recommend that you read the contracts first (near the end of the first modules), then the implementation (in the first modules), and then the test module (at the end of each section).

Mitchell and McKim use Eiffel as the underlying programming language and employ a conventional imperative programming style. Our long-term goal is to transliterate their examples into applicative Racket, structure-oriented imperative Racket, and Racket's class system.

Note: To mimic Mitchell and McKim's informal notion of parametericity (parametric polymorphism), we use first-class contracts. At several places, this use of first-class contracts improves on Mitchell and McKim's design (see comments in interfaces).

7.7.1 A Customer-Manager Component

This first module contains some struct definitions in a separate module in order to better track bugs.

```
#lang racket
; data definitions

(define id? symbol?)
(define id-equal? eq?)
(define-struct basic-customer (id name address) #:mutable)

; interface
(provide
 (contract-out
  [id?                   (-> any/c boolean?)]
  [id-equal?             (-> id? id? boolean?)]
  [struct basic-customer ((id id?)
                          (name string?)
                          (address string?))]))
; end of interface
```

This module contains the program that uses the above.

```
#lang racket

(require "1.rkt") ; the module just above

; implementation
; [listof (list basic-customer? secret-info)]
(define all '())

(define (find c)
  (define (has-c-as-key p)
    (id-equal? (basic-customer-id (car p)) c))
  (define x (filter has-c-as-key all))
  (if (pair? x) (car x) x))

(define (active? c)
  (pair? (find c)))

(define not-active? (compose not active? basic-customer-id))

(define count 0)
(define (get-count) count)
```

```
(define (add c)
  (set! all (cons (list c 'secret) all))
  (set! count (+ count 1)))

(define (name id)
  (define bc-with-id (find id))
  (basic-customer-name (car bc-with-id)))

(define (set-name id name)
  (define bc-with-id (find id))
  (set-basic-customer-name! (car bc-with-id) name))

(define c0 0)
; end of implementation

(provide
 (contract-out
  ; how many customers are in the db?
  [get-count (-> natural-number/c)]
  ; is the customer with this id active?
  [active?   (-> id? boolean?)]
  ; what is the name of the customer with this id?
  [name      (-> (and/c id? active?) string?)]
  ; change the name of the customer with this id
  [set-name  (->i ([id id?] [nn string?])
                  [result any/c] ; result contract
                  #:post (id nn) (string=? (name id) nn))]

  [add       (->i ([bc (and/c basic-customer? not-active?)])
                  ; A pre-post condition contract must use
                  ; a side-effect to express this contract
                  ; via post-conditions
                  #:pre () (set! c0 count)
                  [result any/c] ; result contract
                  #:post () (> count c0))]))
```

The tests:

```
#lang racket
(require rackunit rackunit/text-ui "1.rkt" "1b.rkt")

(add (make-basic-customer 'mf "matthias" "brookstone"))
(add (make-basic-customer 'rf "robby" "beverly hills park"))
(add (make-basic-customer 'fl "matthew" "pepper clouds town"))
(add (make-basic-customer 'sk "shriram" "i city"))
```

```
(run-tests
 (test-suite
  "manager"
  (test-equal? "id lookup" "matthias" (name 'mf))
  (test-equal? "count" 4 (get-count))
  (test-true "active?" (active? 'mf))
  (test-false "active? 2" (active? 'kk))
  (test-true "set name" (void? (set-name 'mf "matt")))))
```

7.7.2 A Parameteric (Simple) Stack

```
#lang racket

; a contract utility
(define (eq/c x) (lambda (y) (eq? x y)))

(define-struct stack (list p? eq))

(define (initialize p? eq) (make-stack '() p? eq))
(define (push s x)
  (make-stack (cons x (stack-list s)) (stack-p? s) (stack-eq s)))
(define (item-at s i) (list-ref (reverse (stack-list s)) (- i 1)))
(define (count s) (length  (stack-list s)))
(define (is-empty? s) (null? (stack-list s)))
(define not-empty? (compose not is-empty?))
(define (pop s) (make-stack (cdr (stack-list s))
                            (stack-p? s)
                            (stack-eq s)))
(define (top s) (car (stack-list s)))

(provide
 (contract-out
  ; predicate
  [stack?     (-> any/c boolean?)]

  ; primitive queries
  ; how many items are on the stack?
  [count      (-> stack? natural-number/c)]

  ; which item is at the given position?
  [item-at
   (->d ([s stack?] [i (and/c positive? (<=/c (count s)))])
        ()
```

```
      [result (stack-p? s)])]

  ; derived queries
  ; is the stack empty?
  [is-empty?
   (->d ([s stack?])
        ()
        [result (eq/c (= (count s) 0))])]

  ; which item is at the top of the stack
  [top
   (->d ([s (and/c stack? not-empty?)])
        ()
        [t (stack-p? s)] ; a stack item, t is its name
        #:post-cond
        ([stack-eq s] t (item-at s (count s))))]

  ; creation
  [initialize
   (->d ([p contract?] [s (p p . -> . boolean?)])
        ()
        ; Mitchell and McKim use (= (count s) 0) here to express
        ; the post-condition in terms of a primitive query
        [result (and/c stack? is-empty?)])]

  ; commands
  ; add an item to the top of the stack
  [push
   (->d ([s stack?] [x (stack-p? s)])
        ()
        [sn stack?] ; result kind
        #:post-cond
        (and (= (+ (count s) 1) (count sn))
             ([stack-eq s] x (top sn))))]

  ; remove the item at the top of the stack
  [pop
   (->d ([s (and/c stack? not-empty?)])
        ()
        [sn stack?] ; result kind
        #:post-cond
        (= (- (count s) 1) (count sn))))]))
```

The tests:

```
#lang racket
```

```
(require rackunit rackunit/text-ui "2.rkt")

(define s0 (initialize (flat-contract integer?) =))
(define s2 (push (push s0 2) 1))

(run-tests
 (test-suite
  "stack"
  (test-true
   "empty"
   (is-empty? (initialize (flat-contract integer?) =)))
  (test-true "push" (stack? s2))
  (test-true
   "push exn"
   (with-handlers ([exn:fail:contract? (lambda _ #t)])
     (push (initialize (flat-contract integer?)) 'a)
     #f))
  (test-true "pop" (stack? (pop s2)))
  (test-equal? "top" (top s2) 1)
  (test-equal? "toppop" (top (pop s2)) 2)))
```

7.7.3 A Dictionary

```
#lang racket

; a shorthand for use below
(define-syntax ⇒
  (syntax-rules ()
    [(⇒ antecedent consequent) (if antecedent consequent #t)]))

; implementation
(define-struct dictionary (l value? eq?))
; the keys should probably be another parameter (exercise)

(define (initialize p eq) (make-dictionary '() p eq))
(define (put d k v)
  (make-dictionary (cons (cons k v) (dictionary-l d))
                   (dictionary-value? d)
                   (dictionary-eq? d)))
(define (rem d k)
  (make-dictionary
   (let loop ([l (dictionary-l d)])
     (cond
       [(null? l) l]
```

```
       [(eq? (caar l) k) (loop (cdr l))]
       [else (cons (car l) (loop (cdr l)))]))
   (dictionary-value? d)
   (dictionary-eq? d)))
(define (count d) (length (dictionary-l d)))
(define (value-for d k) (cdr (assq k (dictionary-l d))))
(define (has? d k) (pair? (assq k (dictionary-l d))))
(define (not-has? d) (lambda (k) (not (has? d k))))
; end of implementation

; interface
(provide
 (contract-out
  ; predicates
  [dictionary? (-> any/c boolean?)]
  ; basic queries
  ; how many items are in the dictionary?
  [count       (-> dictionary? natural-number/c)]
  ; does the dictionary define key k?
  [has?        (->d ([d dictionary?] [k symbol?])
                    ()
                    [result boolean?]
                    #:post-cond
                    ((zero? (count d)) . ⇒ . (not result)))]
  ; what is the value of key k in this dictionary?
  [value-for   (->d ([d dictionary?]
                     [k (and/c symbol? (lambda (k) (has? d k)))])
                    ()
                    [result (dictionary-value? d)])]
  ; initialization
  ; post condition: for all k in symbol, (has? d k) is false.
  [initialize  (->d ([p contract?] [eq (p p . -> . boolean?)])
                    ()
                    [result (and/c dictionary? (compose zero? count))])]
  ; commands
  ; Mitchell and McKim say that put shouldn't consume Void (null
ptr)
  ; for v. We allow the client to specify a contract for all val-
ues
  ; via initialize. We could do the same via a key? parameter
  ; (exercise). add key k with value v to this dictionary
  [put         (->d ([d dictionary?]
                     [k (and/c symbol? (not-has? d))]
                     [v (dictionary-value? d)])
                    ()
                    [result dictionary?]
```

```
                    #:post-cond
                    (and (has? result k)
                         (= (count d) (- (count result) 1))
                         ([dictionary-eq? d] (value-
for result k) v)))]
  ; remove key k from this dictionary
  [rem         (->d ([d dictionary?]
                     [k (and/c symbol? (lambda (k) (has? d k)))])
                    ()
                    [result (and/c dictionary? (lambda (d) ((not-
has? d) k)))]
                    #:post-cond
                    (= (count d) (+ (count result) 1)))]))
; end of interface
```

The tests:

```
#lang racket
(require rackunit rackunit/text-ui "3.rkt")

(define d0 (initialize (flat-contract integer?) =))
(define d (put (put (put d0 'a 2) 'b 2) 'c 1))

(run-tests
 (test-suite
  "dictionaries"
  (test-equal? "value for" 2 (value-for d 'b))
  (test-false "has?" (has? (rem d 'b) 'b))
  (test-equal? "count" 3 (count d))
  (test-case "contract check for put: symbol?"
             (define d0 (initialize (flat-contract integer?) =))
             (check-exn exn:fail:contract? (lambda () (put d0 "a" 2))))))
```

7.7.4 A Queue

```
#lang racket

; Note: this queue doesn't implement the capacity restriction
; of Mitchell and McKim's queue but this is easy to add.

; a contract utility
(define (all-but-last l) (reverse (cdr (reverse l))))
(define (eq/c x) (lambda (y) (eq? x y)))
```

```
; implementation
(define-struct queue (list p? eq))

(define (initialize p? eq) (make-queue '() p? eq))
(define items queue-list)
(define (put q x)
  (make-queue (append (queue-list q) (list x))
              (queue-p? q)
              (queue-eq q)))
(define (count s) (length  (queue-list s)))
(define (is-empty? s) (null? (queue-list s)))
(define not-empty? (compose not is-empty?))
(define (rem s)
  (make-queue (cdr (queue-list s))
              (queue-p? s)
              (queue-eq s)))
(define (head s) (car (queue-list s)))

; interface
(provide
 (contract-out
  ; predicate
  [queue?     (-> any/c boolean?)]

  ; primitive queries
  ; Imagine providing this 'query' for the interface of the module
  ; only. Then in Racket there is no reason to have count or is-
empty?
  ; around (other than providing it to clients). After all items
is
  ; exactly as cheap as count.
  [items      (->d ([q queue?]) () [result (listof (queue-
p? q))])]

  ; derived queries
  [count      (->d ([q queue?])
                   ; We could express this second part of the post
                   ; condition even if count were a module "at-
tribute"
                   ; in the language of Eiffel; indeed it would
use the
                   ; exact same syntax (minus the arrow and
domain).
                   ()
                   [result (and/c natural-number/c
                                  (=/c (length (items q))))])]
```

```
  [is-empty?  (->d ([q queue?])
                   ()
                   [result (and/c boolean?
                                  (eq/c (null? (items q))))])]

  [head       (->d ([q (and/c queue? (compose not is-empty?))])
                   ()
                   [result (and/c (queue-p? q)
                                  (eq/c (car (items q))))])]
  ; creation
  [initialize (-> contract?
                  (contract? contract? . -> . boolean?)
                  (and/c queue? (compose null? items)))]

  ; commands
  [put        (->d ([oldq queue?] [i (queue-p? oldq)])
                   ()
                   [result
                    (and/c
                     queue?
                     (lambda (q)
                       (define old-items (items oldq))
                       (equal? (items q) (append old-
items (list i))))))])]

  [rem        (->d ([oldq (and/c queue? (compose not is-empty?))])
                   ()
                   [result
                    (and/c queue?
                           (lambda (q)
                             (equal? (cdr (items oldq)) (items q))))])]))
; end of interface
```

The tests:

```
#lang racket
(require rackunit rackunit/text-ui "5.rkt")

(define s (put (put (initialize (flat-contract integer?) =) 2) 1))

(run-tests
 (test-suite
  "queue"
  (test-true
   "empty"
```

```
 (is-empty? (initialize (flat-contract integer?) =)))
(test-true "put" (queue? s))
(test-equal? "count" 2 (count s))
(test-true "put exn"
           (with-handlers ([exn:fail:contract? (lambda _ #t)])
             (put (initialize (flat-contract integer?)) 'a)
             #f))
(test-true "remove" (queue? (rem s)))
(test-equal? "head" 2 (head s))))
```

7.8 Building New Contracts

Contracts are represented internally as functions that accept information about the contract (who is to blame, source locations, etc.) and produce projections (in the spirit of Dana Scott) that enforce the contract.

In a general sense, a projection is a function that accepts an arbitrary value, and returns a value that satisfies the corresponding contract. For example, a projection that accepts only integers corresponds to the contract `(flat-contract integer?)`, and can be written like this:

```
(define int-proj
  (λ (x)
    (if (integer? x)
        x
        (signal-contract-violation))))
```

As a second example, a projection that accepts unary functions on integers looks like this:

```
(define int->int-proj
  (λ (f)
    (if (and (procedure? f)
             (procedure-arity-includes? f 1))
        (λ (x) (int-proj (f (int-proj x))))
        (signal-contract-violation))))
```

Although these projections have the right error behavior, they are not quite ready for use as contracts, because they do not accommodate blame and do not provide good error messages. In order to accommodate these, contracts do not just use simple projections, but use functions that accept a blame object encapsulating the names of two parties that are the candidates for blame, as well as a record of the source location where the contract was established and the name of the contract. They can then, in turn, pass that information to `raise-blame-error` to signal a good error message.

Here is the first of those two projections, rewritten for use in the contract system:

```
(define (int-proj blame)
  (λ (x)
    (if (integer? x)
        x
        (raise-blame-error
         blame
         x
         '(expected: "<integer>" given: "~e")
         x))))
```

The new argument specifies who is to be blamed for positive and negative contract violations.

Contracts, in this system, are always established between two parties. One party, called the server, provides some value according to the contract, and the other, the client, consumes the value, also according to the contract. The server is called the positive position and the client the negative position. So, in the case of just the integer contract, the only thing that can go wrong is that the value provided is not an integer. Thus, only the positive party (the server) can ever accrue blame. The `raise-blame-error` function always blames the positive party.

Compare that to the projection for our function contract:

```
(define (int->int-proj blame)
  (define dom (int-proj (blame-swap blame)))
  (define rng (int-proj blame))
  (λ (f)
    (if (and (procedure? f)
             (procedure-arity-includes? f 1))
        (λ (x) (rng (f (dom x))))
        (raise-blame-error
         blame
         f
         '(expected "a procedure of one argument" given: "~e")
         f))))
```

In this case, the only explicit blame covers the situation where either a non-procedure is supplied to the contract or the procedure does not accept one argument. As with the integer projection, the blame here also lies with the producer of the value, which is why `raise-blame-error` is passed `blame` unchanged.

The checking for the domain and range are delegated to the `int-proj` function, which is supplied its arguments in the first two lines of the `int->int-proj` function. The trick here is that, even though the `int->int-proj` function always blames what it sees as positive, we can swap the blame parties by calling `blame-swap` on the given blame object, replacing the positive party with the negative party and vice versa.

This technique is not merely a cheap trick to get the example to work, however. The reversal

of the positive and the negative is a natural consequence of the way functions behave. That is, imagine the flow of values in a program between two modules. First, one module (the server) defines a function, and then that module is required by another (the client). So far, the function itself has to go from the original, providing module to the requiring module. Now, imagine that the requiring module invokes the function, supplying it an argument. At this point, the flow of values reverses. The argument is traveling back from the requiring module to the providing module! The client is "serving" the argument to the server, and the server is receiving that value as a client. And finally, when the function produces a result, that result flows back in the original direction from server to client. Accordingly, the contract on the domain reverses the positive and the negative blame parties, just like the flow of values reverses.

We can use this insight to generalize the function contracts and build a function that accepts any two contracts and returns a contract for functions between them.

This projection also goes further and uses `blame-add-context` to improve the error messages when a contract violation is detected.

```
(define (make-simple-function-contract dom-proj range-proj)
  (λ (blame)
    (define dom (dom-proj (blame-add-context blame
                                             "the argument of"
                                             #:swap? #t)))
    (define rng (range-proj (blame-add-context blame
                                               "the range of")))
    (λ (f)
      (if (and (procedure? f)
               (procedure-arity-includes? f 1))
          (λ (x) (rng (f (dom x))))
          (raise-blame-error
           blame
           f
           '(expected "a procedure of one argument" given: "~e")
           f)))))
```

While these projections are supported by the contract library and can be used to build new contracts, the contract library also supports a different API for projections that can be more efficient. Specifically, a late neg projection accepts a blame object without the negative blame information and then returns a function that accepts both the value to be contracted and the name of the negative party, in that order. The returned function then in turn returns the value with the contract. Rewriting `int->int-proj` to use this API looks like this:

```
(define (int->int-proj blame)
  (define dom-blame (blame-add-context blame
                                       "the argument of"
                                       #:swap? #t))
```

```
  (define rng-blame (blame-add-context blame "the range of"))
  (define (check-int v to-blame neg-party)
    (unless (integer? v)
      (raise-blame-error
       to-blame #:missing-party neg-party
       v
       '(expected "an integer" given: "~e")
       v)))
  (λ (f neg-party)
    (if (and (procedure? f)
             (procedure-arity-includes? f 1))
        (λ (x)
          (check-int x dom-blame neg-party)
          (define ans (f x))
          (check-int ans rng-blame neg-party)
          ans)
        (raise-blame-error
         blame #:missing-party neg-party
         f
         '(expected "a procedure of one argument" given: "~e")
         f))))
```

The advantage of this style of contract is that the *blame* argument can be supplied on the server side of the contract boundary and the result can be used for each different client. With the simpler situation, a new blame object has to be created for each client.

One final problem remains before this contract can be used with the rest of the contract system. In the function above, the contract is implemented by creating a wrapper function for `f`, but this wrapper function does not cooperate with `equal?`, nor does it let the runtime system know that there is a relationship between the result function and `f`, the input function.

To remedy these two problems, we should use chaperones instead of just using λ to create the wrapper function. Here is the `int->int-proj` function rewritten to use a chaperone:

```
(define (int->int-proj blame)
  (define dom-blame (blame-add-context blame
                                       "the argument of"
                                       #:swap? #t))
  (define rng-blame (blame-add-context blame "the range of"))
  (define (check-int v to-blame neg-party)
    (unless (integer? v)
      (raise-blame-error
       to-blame #:missing-party neg-party
       v
       '(expected "an integer" given: "~e")
       v)))
```

```
(λ (f neg-party)
  (if (and (procedure? f)
           (procedure-arity-includes? f 1))
      (chaperone-procedure
       f
       (λ (x)
         (check-int x dom-blame neg-party)
         (values (λ (ans)
                   (check-int ans rng-blame neg-party)
                   ans)
                 x)))
      (raise-blame-error
       blame #:missing-party neg-party
       f
       '(expected "a procedure of one argument" given: "~e")
       f))))
```

Projections like the ones described above, but suited to other, new kinds of value you might make, can be used with the contract library primitives. Specifically, we can use make-chaperone-contract to build it:

```
(define int->int-contract
  (make-contract
   #:name 'int->int
   #:late-neg-projection int->int-proj))
```

and then combine it with a value and get some contract checking.

```
(define/contract (f x)
  int->int-contract
  "not an int")

> (f #f)
f: contract violation;
 expected an integer
  given: #f
  in: the argument of
      int->int
  contract from: (function f)
  blaming: top-level
   (assuming the contract is correct)
  at: eval:5:0
> (f 1)
f: broke its own contract;
 promised an integer
```

produced: "not an int"
in: the range of
int->int
contract from: (function f)
blaming: (function f)
(assuming the contract is correct)
at: eval:5:0

7.8.1 Contract Struct Properties

The `make-chaperone-contract` function is okay for one-off contracts, but often you want to make many different contracts that differ only in some pieces. The best way to do that is to use a `struct` with either `prop:contract`, `prop:chaperone-contract`, or `prop:flat-contract`.

For example, lets say we wanted to make a simple form of the `->` contract that accepts one contract for the range and one for the domain. We should define a struct with two fields and use `build-chaperone-contract-property` to construct the chaperone contract property we need.

```
(struct simple-arrow (dom rng)
  #:property prop:chaperone-contract
  (build-chaperone-contract-property
   #:name
   (λ (arr) (simple-arrow-name arr))
   #:late-neg-projection
   (λ (arr) (simple-arrow-late-neg-proj arr))))
```

To do the automatic coercion of values like `integer?` and `#f` into contracts, we need to call `coerce-chaperone-contract` (note that this rejects impersonator contracts and does not insist on flat contracts; to do either of those things, call `coerce-contract` or `coerce-flat-contract` instead).

```
(define (simple-arrow-contract dom rng)
  (simple-arrow (coerce-contract 'simple-arrow-contract dom)
                (coerce-contract 'simple-arrow-contract rng)))
```

To define *`simple-arrow-name`* is straight-forward; it needs to return an s-expression representing the contract:

```
(define (simple-arrow-name arr)
  `(-> ,(contract-name (simple-arrow-dom arr))
       ,(contract-name (simple-arrow-rng arr))))
```

And we can define the projection using a generalization of the projection we defined earlier, this time using chaperones:

```
(define (simple-arrow-late-neg-proj arr)
  (define dom-ctc (get/build-late-neg-projection (simple-arrow-
dom arr)))
  (define rng-ctc (get/build-late-neg-projection (simple-arrow-
rng arr)))
  (λ (blame)
    (define dom+blame (dom-ctc (blame-add-context blame
                                                  "the argument
of"
                                                  #:swap? #t)))
    (define rng+blame (rng-ctc (blame-add-context blame "the range
of")))
    (λ (f neg-party)
      (if (and (procedure? f)
               (procedure-arity-includes? f 1))
          (chaperone-procedure
           f
           (λ (arg)
             (values
              (λ (result) (rng+blame result neg-party))
              (dom+blame arg neg-party))))
          (raise-blame-error
           blame #:missing-party neg-party
           f
           '(expected "a procedure of one argument" given: "~e")
           f)))))


(define/contract (f x)
  (simple-arrow-contract integer? boolean?)
  "not a boolean")

> (f #f)
f: contract violation
  expected: integer?
  given: #f
  in: the argument of
      (-> integer? boolean?)
  contract from: (function f)
  blaming: top-level
   (assuming the contract is correct)
  at: eval:12:0
> (f 1)
f: broke its own contract
```

promised: boolean?
produced: "not a boolean"
in: the range of
(-> integer? boolean?)
contract from: (function f)
blaming: (function f)
(assuming the contract is correct)
at: eval:12:0

7.8.2 With all the Bells and Whistles

There are a number of optional pieces to a contract that `simple-arrow-contract` did not add. In this section, we walk through all of them to show examples of how they can be implemented.

The first is a first-order check. This is used by `or/c` in order to determine which of the higher-order argument contracts to use when it sees a value. Here's the function for our simple arrow contract.

```
(define (simple-arrow-first-order ctc)
  (λ (v) (and (procedure? v)
              (procedure-arity-includes? v 1))))
```

It accepts a value and returns `#f` if the value is guaranteed not to satisfy the contract, and `#t` if, as far as we can tell, the value satisfies the contract, just be inspecting first-order properties of the value.

The next is random generation. Random generation in the contract library consists of two pieces: the ability to randomly generate values satisfying the contract and the ability to exercise values that match the contract that are given, in the hopes of finding bugs in them (and also to try to get them to produce interesting values to be used elsewhere during generation).

To exercise contracts, we need to implement a function that is given a `arrow-contract` struct and some fuel. It should return two values: a function that accepts values of the contract and exercises them, plus a list of values that the exercising process will always produce. In the case of our simple contract, we know that we can always produce values of the range, as long as we can generate values of the domain (since we can just call the function). So, here's a function that matches the *exercise* argument of `build-chaperone-contract-property`'s contract:

```
(define (simple-arrow-contract-exercise arr)
  (define env (contract-random-generate-get-current-environment))
  (λ (fuel)
    (define dom-generate
```

```
      (contract-random-generate/choose (simple-arrow-
dom arr) fuel))
    (cond
      [dom-generate
       (values
        (λ (f) (contract-random-generate-stash
                env
                (simple-arrow-rng arr)
                (f (dom-generate))))
        (list (simple-arrow-rng arr)))]
      [else
       (values void '())])))
```

If the domain contract can be generated, then we know we can do some good via exercising. In that case, we return a procedure that calls `f` (the function matching the contract) with something that we generated from the domain, and we stash the result value in the environment too. We also return `(simple-arrow-rng arr)` to indicate that exercising will always produce something of that contract.

If we cannot, then we simply return a function that does no exercising (`void`) and the empty list (indicating that we won't generate any values).

Then, to generate values matching the contract, we define a function that when given the contract and some fuel, makes up a random function. To help make it a more effective testing function, we can exercise any arguments it receives, and also stash them into the generation environment, but only if we can generate values of the range contract.

```
(define (simple-arrow-contract-generate arr)
  (λ (fuel)
    (define env (contract-random-generate-get-current-
environment))
    (define rng-generate
      (contract-random-generate/choose (simple-arrow-
rng arr) fuel))
    (cond
      [rng-generate
       (λ ()
         (λ (arg)
           (contract-random-generate-stash env (simple-arrow-
dom arr) arg)
           (rng-generate)))]
      [else
       #f])))
```

When the random generation pulls something out of the environment, it needs to be able to tell if a value that has been passed to `contract-random-generate-stash` is a candidate

for the contract it is trying to generate. Of course, it the contract passed to contract-random-generate-stash is an exact match, then it can use it. But it can also use the value if the contract is stronger (in the sense that it accepts fewer values).

To provide that functionality, we implement this function:

```
(define (simple-arrow-first-stronger? this that)
  (and (simple-arrow? that)
       (contract-stronger? (simple-arrow-dom that)
                           (simple-arrow-dom this))
       (contract-stronger? (simple-arrow-rng this)
                           (simple-arrow-rng that))))
```

This function accepts *this* and *that*, two contracts. It is guaranteed that *this* will be one of our simple arrow contracts, since we're supplying this function together with the simple arrow implementation. But the *that* argument might be any contract. This function checks to see if *that* is also a simple arrow contract and, if so compares the domain and range. Of course, there are other contracts that we could also check for (e.g., contracts built using -> or ->*), but we do not need to. The stronger function is allowed to return #f if it doesn't know the answer but if it returns #t, then the contract really must be stronger.

Now that we have all of the pieces implemented, we need to pass them to build-chaperone-contract-property so the contract system starts using them:

```
(struct simple-arrow (dom rng)
  #:property prop:custom-write contract-custom-write-property-proc
  #:property prop:chaperone-contract
  (build-chaperone-contract-property
   #:name
   (λ (arr) (simple-arrow-name arr))
   #:late-neg-projection
   (λ (arr) (simple-arrow-late-neg-proj arr))
   #:first-order simple-arrow-first-order
   #:stronger simple-arrow-first-stronger?
   #:generate simple-arrow-contract-generate
   #:exercise simple-arrow-contract-exercise))
(define (simple-arrow-contract dom rng)
  (simple-arrow (coerce-contract 'simple-arrow-contract dom)
                (coerce-contract 'simple-arrow-contract rng)))
```

We also add a prop:custom-write property so that the contracts print properly, e.g.:

```
> (simple-arrow-contract integer? integer?)
(-> integer? integer?)
```

(We use prop:custom-write because the contract library can not depend on

```
#lang racket/generic
```

but yet still wants to provide some help to make it easy to use the right printer.)

Now that that's done, we can use the new functionality. Here's a random function, generated by the contract library, using our `simple-arrow-contract-generate` function:

```
(define a-random-function
  (contract-random-generate
   (simple-arrow-contract integer? integer?)))

> (a-random-function 0)
0
> (a-random-function 1)
1
```

Here's how the contract system can now automatically find bugs in functions that consume simple arrow contracts:

```
(define/contract (misbehaved-f f)
  (-> (simple-arrow-contract integer? boolean?) any)
  (f "not an integer"))

> (contract-exercise misbehaved-f)
misbehaved-f: broke its own contract
  promised: integer?
  produced: "not an integer"
  in: the argument of
      the 1st argument of
      (-> (-> integer? boolean?) any)
  contract from: (function misbehaved-f)
  blaming: (function misbehaved-f)
   (assuming the contract is correct)
  at: eval:25:0
```

And if we hadn't implemented `simple-arrow-first-order`, then `or/c` would not be able to tell which branch of the `or/c` to use in this program:

```
(define/contract (maybe-accepts-a-function f)
  (or/c (simple-arrow-contract real? real?)
        (-> real? real? real?)
        real?)
  (if (procedure? f)
      (if (procedure-arity-includes f 1)
          (f 1132)
```

```
          (f 11 2))
      f))

> (maybe-accepts-a-function sqrt)
maybe-accepts-a-function: contract violation
  expected: real?
  given: #<procedure:sqrt>
  in: the argument of
      a part of the or/c of
      (or/c
       (-> real? real?)
       (-> real? real? real?)
       real?)
  contract from:
      (function maybe-accepts-a-function)
  blaming: top-level
   (assuming the contract is correct)
  at: eval:27:0
> (maybe-accepts-a-function 123)
123
```

7.9 Gotchas

7.9.1 Contracts and eq?

As a general rule, adding a contract to a program should either leave the behavior of the program unchanged, or should signal a contract violation. And this is almost true for Racket contracts, with one exception: eq?.

The eq? procedure is designed to be fast and does not provide much in the way of guarantees, except that if it returns true, it means that the two values behave identically in all respects. Internally, this is implemented as pointer equality at a low-level so it exposes information about how Racket is implemented (and how contracts are implemented).

Contracts interact poorly with eq? because function contract checking is implemented internally as wrapper functions. For example, consider this module:

```
#lang racket

(define (make-adder x)
  (if (= 1 x)
      add1
      (lambda (y) (+ x y))))
(provide (contract-out
```

```
          [make-adder (-> number? (-> number? number?))]))
```

It exports the `make-adder` function that is the usual curried addition function, except that it returns Racket's `add1` when its input is `1`.

You might expect that

```
(eq? (make-adder 1)
     (make-adder 1))
```

would return `#t`, but it does not. If the contract were changed to `any/c` (or even `(-> number? any/c)`), then the `eq?` call would return `#t`.

Moral: Do not use `eq?` on values that have contracts.

7.9.2 Contract boundaries and `define/contract`

The contract boundaries established by `define/contract`, which creates a nested contract boundary, are sometimes unintuitive. This is especially true when multiple functions or other values with contracts interact. For example, consider these two interacting functions:

```
> (define/contract (f x)
    (-> integer? integer?)
    x)
> (define/contract (g)
    (-> string?)
    (f "not an integer"))
> (g)
f: contract violation
  expected: integer?
  given: "not an integer"
  in: the 1st argument of
        (-> integer? integer?)
  contract from: (function f)
  blaming: top-level
   (assuming the contract is correct)
  at: eval:2:0
```

One might expect that the function `g` will be blamed for breaking the terms of its contract with `f`. Blaming `g` would be right if `f` and `g` were directly establishing contracts with each other. They aren't, however. Instead, the access between `f` and `g` is mediated through the top-level of the enclosing module.

More precisely, `f` and the top-level of the module have the `(-> integer? integer?)` contract mediating their interaction; `g` and the top-level have `(-> string?)` mediating their

interaction, but there is no contract directly between `f` and `g`. This means that the reference to `f` in the body of `g` is really the top-level of the module's responsibility, not `g`'s. In other words, the function `f` has been given to `g` with no contract between `g` and the top-level and thus the top-level is blamed.

If we wanted to add a contract between `g` and the top-level, we can use `define/contract`'s `#:freevar` declaration and see the expected blame:

```
> (define/contract (f x)
    (-> integer? integer?)
    x)
> (define/contract (g)
    (-> string?)
    #:freevar f (-> integer? integer?)
    (f "not an integer"))
> (g)
f: contract violation
   expected: integer?
   given: "not an integer"
   in: the 1st argument of
         (-> integer? integer?)
   contract from: top-level
   blaming: (function g)
    (assuming the contract is correct)
   at: eval:6:0
```

Moral: if two values with contracts should interact, put them in separate modules with contracts at the module boundary or use `#:freevar`.

7.9.3 Exists Contracts and Predicates

Much like the `eq?` example above, `#:∃` contracts can change the behavior of a program.

Specifically, the `null?` predicate (and many other predicates) return `#f` for `#:∃` contracts, and changing one of those contracts to `any/c` means that `null?` might now return `#t` instead, resulting in arbitrarily different behavior depending on how this boolean might flow around in the program.

Moral: Do not use predicates on `#:∃` contracts.

7.9.4 Defining Recursive Contracts

When defining a self-referential contract, it is natural to use `define`. For example, one might try to write a contract on streams like this:

```
> (define stream/c
    (promise/c
     (or/c null?
           (cons/c number? stream/c))))
stream/c: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

Unfortunately, this does not work because the value of `stream/c` is needed before it is defined. Put another way, all of the combinators evaluate their arguments eagerly, even though the values that they accept do not.

Instead, use

```
(define stream/c
  (promise/c
   (or/c
    null?
    (cons/c number? (recursive-contract stream/c)))))
```

The use of `recursive-contract` delays the evaluation of the identifier `stream/c` until after the contract is first checked, long enough to ensure that `stream/c` is defined.

See also §7.5.3 “Checking Properties of Data Structures”.

7.9.5 Mixing `set!` and `contract-out`

The contract library assumes that variables exported via `contract-out` are not assigned to, but does not enforce it. Accordingly, if you try to `set!` those variables, you may be surprised. Consider the following example:

```
> (module server racket
    (define (inc-x!) (set! x (+ x 1)))
    (define x 0)
    (provide (contract-out [inc-x! (-> void?)]
                           [x integer?])))
> (module client racket
    (require 'server)

    (define (print-latest) (printf "x is ~s\n" x))

    (print-latest)
    (inc-x!)
    (print-latest))
```

```
> (require 'client)
x is 0
x is 0
```

Both calls to `print-latest` print `0`, even though the value of `x` has been incremented (and the change is visible inside the module `x`).

To work around this, export accessor functions, rather than exporting the variable directly, like this:

```
#lang racket

(define (get-x) x)
(define (inc-x!) (set! x (+ x 1)))
(define x 0)
(provide (contract-out [inc-x! (-> void?)]
                       [get-x (-> integer?)]))
```

Moral: This is a bug that we will address in a future release.

8 Input and Output

A Racket port corresponds to the Unix notion of a stream (not to be confused with racket/stream's streams).

A Racket *port* represents a source or sink of data, such as a file, a terminal, a TCP connection, or an in-memory string. Ports provide sequential access in which data can be read or written a piece at a time, without requiring the data to be consumed or produced all at once. More specifically, an *input port* represents a source from which a program can read data, and an *output port* represents a sink to which a program can write data.

8.1 Varieties of Ports

Various functions create various kinds of ports. Here are a few examples:

- **Files:** The open-output-file function opens a file for writing, and open-input-file opens a file for reading.

  Examples:

  ```
  > (define out (open-output-file "data"))
  > (display "hello" out)
  > (close-output-port out)
  > (define in (open-input-file "data"))
  > (read-line in)
  "hello"
  > (close-input-port in)
  ```

  If a file exists already, then open-output-file raises an exception by default. Supply an option like #:exists 'truncate or #:exists 'update to re-write or update the file:

  Examples:

  ```
  > (define out (open-output-file "data" #:exists 'truncate))
  > (display "howdy" out)
  > (close-output-port out)
  ```

  Instead of having to match the open calls with close calls, most Racket programmers will use the call-with-input-file and call-with-output-file functions which take a function to call to carry out the desired operation. This function gets as its only argument the port, which is automatically opened and closed for the operation.

  Examples:

  ```
  > (call-with-output-file "data"
                           #:exists 'truncate
                           (lambda (out)
                             (display "hello" out)))
  ```

```
> (call-with-input-file "data"
                        (lambda (in)
                          (read-line in)))
"hello"
```

- **Strings:** The `open-output-string` function creates a port that accumulates data into a string, and `get-output-string` extracts the accumulated string. The `open-input-string` function creates a port to read from a string.

  Examples:

```
> (define p (open-output-string))
> (display "hello" p)
> (get-output-string p)
"hello"
> (read-line (open-input-string "goodbye\nfarewell"))
"goodbye"
```

- **TCP Connections:** The `tcp-connect` function creates both an input port and an output port for the client side of a TCP communication. The `tcp-listen` function creates a server, which accepts connections via `tcp-accept`.

  Examples:

```
> (define server (tcp-listen 12345))
> (define-values (c-in c-out) (tcp-connect "localhost" 12345))
> (define-values (s-in s-out) (tcp-accept server))
> (display "hello\n" c-out)
> (close-output-port c-out)
> (read-line s-in)
"hello"
> (read-line s-in)
#<eof>
```

- **Process Pipes:** The `subprocess` function runs a new process at the OS level and returns ports that correspond to the subprocess's stdin, stdout, and stderr. (The first three arguments can be certain kinds of existing ports to connect directly to the subprocess, instead of creating new ports.)

  Examples:

```
> (define-values (p stdout stdin stderr)
    (subprocess #f #f #f "/usr/bin/wc" "-w"))
> (display "a b c\n" stdin)
> (close-output-port stdin)
> (read-line stdout)
"       3"
> (close-input-port stdout)
> (close-input-port stderr)
```

- **Internal Pipes:** The `make-pipe` function returns two ports that are ends of a pipe. This kind of pipe is internal to Racket, and not related to OS-level pipes for communicating between different processes.

  Examples:

```
> (define-values (in out) (make-pipe))
> (display "garbage" out)
> (close-output-port out)
> (read-line in)
"garbage"
```

8.2 Default Ports

For most simple I/O functions, the target port is an optional argument, and the default is the *current input port* or *current output port*. Furthermore, error messages are written to the *current error port*, which is an output port. The `current-input-port`, `current-output-port`, and `current-error-port` functions return the corresponding current ports.

Examples:

```
> (display "Hi")
Hi
> (display "Hi" (current-output-port)) ; the same
Hi
```

If you start the `racket` program in a terminal, then the current input, output, and error ports are all connected to the terminal. More generally, they are connected to the OS-level stdin, stdout, and stderr. In this guide, the examples show output written to stdout in purple, and output written to stderr in red italics.

Examples:

```
(define (swing-hammer)
  (display "Ouch!" (current-error-port)))
> (swing-hammer)
Ouch!
```

The current-port functions are actually parameters, which means that their values can be set with `parameterize`.

See §4.13 “Dynamic Binding: `parameterize`” for an introduction to parameters.

Example:

```
> (let ([s (open-output-string)])
    (parameterize ([current-error-port s])
```

```
      (swing-hammer)
      (swing-hammer)
      (swing-hammer))
    (get-output-string s))
"Ouch!Ouch!Ouch!"
```

8.3 Reading and Writing Racket Data

As noted throughout §3 “Built-In Datatypes”, Racket provides three ways to print an instance of a built-in value:

- `print`, which prints a value in the same way that is it printed for a REPL result; and
- `write`, which prints a value in such a way that `read` on the output produces the value back; and
- `display`, which tends to reduce a value to just its character or byte content—at least for those datatypes that are primarily about characters or bytes, otherwise it falls back to the same output as `write`.

Here are some examples using each:

```
> (print 1/2)
1/2
> (print #\x)
#\x
> (print "hello")
"hello"
> (print #"goodbye")
#"goodbye"
> (print '|pea pod|)
'|pea pod|
> (print '("i" pod))
'("i" pod)
> (print write)
#<procedure:write>
```

```
> (write 1/2)
1/2
> (write #\x)
#\x
> (write "hello")
"hello"
> (write #"goodbye")
#"goodbye"
> (write '|pea pod|)
|pea pod|
> (write '("i" pod))
("i" pod)
> (write write)
#<procedure:write>
```

```
> (display 1/2)
1/2
> (display #\x)
x
> (display "hello")
hello
> (display #"goodbye")
goodbye
> (display '|pea pod|)
pea pod
> (display '("i" pod))
(i pod)
> (display write)
#<procedure:write>
```

Overall, `print` corresponds to the expression layer of Racket syntax, `write` corresponds to the reader layer, and `display` roughly corresponds to the character layer.

The `printf` function supports simple formatting of data and text. In the format string supplied to `printf`, `~a` `display`s the next argument, `~s` `write`s the next argument, and `~v` `print`s the next argument.

Examples:

```
(define (deliver who when what)
  (printf "Items ~a for shopper ~s: ~v" who when what))
> (deliver '("list") '("John") '("milk"))
Items (list) for shopper ("John"): '("milk")
```

After using `write`, as opposed to `display` or `print`, many forms of data can be read back in using `read`. The same values `print`ed can also be parsed by `read`, but the result may have extra quote forms, since a `print`ed form is meant to be read like an expression.

Examples:

```
> (define-values (in out) (make-pipe))
> (write "hello" out)
> (read in)
"hello"
> (write '("alphabet" soup) out)
> (read in)
'("alphabet" soup)
> (write #hash((a . "apple") (b . "banana")) out)
> (read in)
'#hash((a . "apple") (b . "banana"))
> (print '("alphabet" soup) out)
> (read in)
''("alphabet" soup)
> (display '("alphabet" soup) out)
> (read in)
'(alphabet soup)
```

8.4 Datatypes and Serialization

Prefab structure types (see §5.7 “Prefab Structure Types”) automatically support *serialization*: they can be written to an output stream, and a copy can be read back in from an input stream:

```
> (define-values (in out) (make-pipe))
> (write #s(sprout bean) out)
> (read in)
'#s(sprout bean)
```

Other structure types created by `struct`, which offer more abstraction than prefab structure types, normally `write` either using `#<....>` notation (for opaque structure types) or using `#(....)` vector notation (for transparent structure types). In neither case can the result be read back in as an instance of the structure type:

```
> (struct posn (x y))
> (write (posn 1 2))
#<posn>
> (define-values (in out) (make-pipe))
> (write (posn 1 2) out)
> (read in)
pipe::1: read: bad syntax `#<`
```

```
> (struct posn (x y) #:transparent)
> (write (posn 1 2))
#(struct:posn 1 2)
> (define-values (in out) (make-pipe))
> (write (posn 1 2) out)
> (define v (read in))
> v
'#(struct:posn 1 2)
> (posn? v)
#f
> (vector? v)
#t
```

The `serializable-struct` form defines a structure type that can be `serialize`d to a value that can be printed using `write` and restored via `read`. The `serialize`d result can be `deserialize`d to get back an instance of the original structure type. The serialization form and functions are provided by the `racket/serialize` library.

Examples:

```
> (require racket/serialize)
> (serializable-struct posn (x y) #:transparent)
> (deserialize (serialize (posn 1 2)))
(posn 1 2)
> (write (serialize (posn 1 2)))
((3) 1 ((#f . deserialize-info:posn-v0)) 0 () () (0 1 2))
> (define-values (in out) (make-pipe))
> (write (serialize (posn 1 2)) out)
> (deserialize (read in))
(posn 1 2)
```

In addition to the names bound by `struct`, `serializable-struct` binds an identifier with deserialization information, and it automatically `provides` the deserialization identifier from a module context. This deserialization identifier is accessed reflectively when a value is deserialized.

8.5 Bytes, Characters, and Encodings

Functions like `read-line`, `read`, `display`, and `write` all work in terms of characters (which correspond to Unicode scalar values). Conceptually, they are implemented in terms of `read-char` and `write-char`.

More primitively, ports read and write bytes, instead of characters. The functions `read-byte` and `write-byte` read and write raw bytes. Other functions, such as `read-bytes-line`, build on top of byte operations instead of character operations.

In fact, the `read-char` and `write-char` functions are conceptually implemented in terms of `read-byte` and `write-byte`. When a single byte's value is less than 128, then it corresponds to an ASCII character. Any other byte is treated as part of a UTF-8 sequence, where UTF-8 is a particular standard way of encoding Unicode scalar values in bytes (which has the nice property that ASCII characters are encoded as themselves). Thus, a single `read-char` may call `read-byte` multiple times, and a single `write-char` may generate multiple output bytes.

The `read-char` and `write-char` operations *always* use a UTF-8 encoding. If you have a text stream that uses a different encoding, or if you want to generate a text stream in a different encoding, use `reencode-input-port` or `reencode-output-port`. The `reencode-input-port` function converts an input stream from an encoding that you specify into a UTF-8 stream; that way, `read-char` sees UTF-8 encodings, even though the original used a different encoding. Beware, however, that `read-byte` also sees the re-encoded data, instead of the original byte stream.

8.6 I/O Patterns

`(require racket/port)` is needed for `#lang racket/base`.

For these examples, say you have two files in the same directory as your program, `"oneline.txt"` and `"manylines.txt"`.

`"oneline.txt"`

```
I am one line, but there is an empty line after this one.
```

`"manylines.txt"`

```
I am
a message
split over a few lines.
```

If you have a file that is quite small, you can get away with reading in the file as a string:

Examples:

```
> (define file-contents
    (port->string (open-input-file "oneline.txt") #:close? #t))
> (string-suffix? file-contents "after this one.")
#f
> (string-suffix? file-contents "after this one.\n")
#t
> (string-suffix? (string-trim file-contents) "after this one.")
#t
```

We use `port->string` from `racket/port` to do the reading to a string: the `#:close? #t` keyword argument ensures that our file is closed after the read.

We use `string-trim` from `racket/string` to remove any extraneous whitespace at the very beginning and very end of our file. (Lots of formatters out there insist that text files end with a single blank line).

See also `read-line` if your file has one line of text.

If, instead, you want to process individual lines of a file, then you can use `for` with `in-lines`:

```
> (define (upcase-all in)
    (for ([l (in-lines in)])
      (display (string-upcase l))
      (newline)))
> (upcase-all (open-input-string
               (string-append
                "Hello, World!\n"
                "Can you hear me, now?")))
HELLO, WORLD!
CAN YOU HEAR ME, NOW?
```

You could also combine computations over each line. So if you want to know how many lines contain "m", you could do:

Example:

```
> (with-input-from-file "manylines.txt"
    (lambda ()
      (for/sum ([l (in-lines)]
                #:when (string-contains? l "m"))
        1)))
2
```

Here, `with-input-from-file` from `racket/port` sets the default input port to be the file `"manylines.txt"` inside the thunk. It also closes the file after the computation has been completed (and in a few other cases).

However, if you want to determine whether “hello” appears in a file, then you could search separate lines, but it’s even easier to simply apply a regular expression (see §9 “Regular Expressions”) to the stream:

```
> (define (has-hello? in)
    (regexp-match? #rx"hello" in))
> (has-hello? (open-input-string "hello"))
#t
> (has-hello? (open-input-string "goodbye"))
#f
```

If you want to copy one port into another, use `copy-port` from `racket/port`, which efficiently transfers large blocks when lots of data is available, but also transfers small blocks immediately if that’s all that is available:

```
> (define o (open-output-string))
> (copy-port (open-input-string "broom") o)
> (get-output-string o)
"broom"
```

9 Regular Expressions

This chapter is a modified version of [Sitaram05].

A *regexp* value encapsulates a pattern that is described by a string or byte string. The regexp matcher tries to match this pattern against (a portion of) another string or byte string, which we will call the *text string*, when you call functions like `regexp-match`. The text string is treated as raw text, and not as a pattern.

§4.8 "Regular Expressions" in *The Racket Reference* provides more on regexps.

9.1 Writing Regexp Patterns

A string or byte string can be used directly as a regexp pattern, or it can be prefixed with `#rx` to form a literal regexp value. For example, `#rx"abc"` is a string-based regexp value, and `#rx#"abc"` is a byte string-based regexp value. Alternately, a string or byte string can be prefixed with `#px`, as in `#px"abc"`, for a slightly extended syntax of patterns within the string.

Most of the characters in a regexp pattern are meant to match occurrences of themselves in the text string. Thus, the pattern `#rx"abc"` matches a string that contains the characters `a`, `b`, and `c` in succession. Other characters act as *metacharacters*, and some character sequences act as *metasequences*. That is, they specify something other than their literal selves. For example, in the pattern `#rx"a.c"`, the characters `a` and `c` stand for themselves, but the metacharacter `.` can match *any* character. Therefore, the pattern `#rx"a.c"` matches an `a`, any character, and `c` in succession.

When we want a literal `\` inside a Racket string or regexp literal, we must escape it so that it shows up in the string at all. Racket strings use `\` as the escape character, so we end up with two `\`s: one Racket-string `\` to escape the regexp `\`, which then escapes the `.`. Another character that would need escaping inside a Racket string is `"`.

If we needed to match the character `.` itself, we can escape it by preceding it with a `\`. The character sequence `\.` is thus a metasequence, since it doesn't match itself but rather just `.`. So, to match `a`, `.`, and `c` in succession, we use the regexp pattern `#rx"a\\.c"`; the double `\` is an artifact of Racket strings, not the regexp pattern itself.

The `regexp` function takes a string or byte string and produces a regexp value. Use `regexp` when you construct a pattern to be matched against multiple strings, since a pattern is compiled to a regexp value before it can be used in a match. The `pregexp` function is like `regexp`, but using the extended syntax. Regexp values as literals with `#rx` or `#px` are compiled once and for all when they are read.

The `regexp-quote` function takes an arbitrary string and returns a string for a pattern that matches exactly the original string. In particular, characters in the input string that could serve as regexp metacharacters are escaped with a backslash, so that they safely match only themselves.

```
> (regexp-quote "cons")
"cons"
> (regexp-quote "list?")
"list\\?"
```

The `regexp-quote` function is useful when building a composite regexp from a mix of regexp strings and verbatim strings.

9.2 Matching Regexp Patterns

The `regexp-match-positions` function takes a regexp pattern and a text string, and it returns a match if the regexp matches (some part of) the text string, or `#f` if the regexp did not match the string. A successful match produces a list of *index pairs*.

Examples:

```
> (regexp-match-positions #rx"brain" "bird")
#f
> (regexp-match-positions #rx"needle" "hay needle stack")
'((4 . 10))
```

In the second example, the integers `4` and `10` identify the substring that was matched. The `4` is the starting (inclusive) index, and `10` the ending (exclusive) index of the matching substring:

```
> (substring "hay needle stack" 4 10)
"needle"
```

In this first example, `regexp-match-positions`'s return list contains only one index pair, and that pair represents the entire substring matched by the regexp. When we discuss subpatterns later, we will see how a single match operation can yield a list of submatches.

The `regexp-match-positions` function takes optional third and fourth arguments that specify the indices of the text string within which the matching should take place.

```
> (regexp-match-positions
   #rx"needle"
   "his needle stack -- my needle stack -- her needle stack"
   20 39)
'((23 . 29))
```

Note that the returned indices are still reckoned relative to the full text string.

The `regexp-match` function is like `regexp-match-positions`, but instead of returning index pairs, it returns the matching substrings:

```
> (regexp-match #rx"brain" "bird")
#f
> (regexp-match #rx"needle" "hay needle stack")
'("needle")
```

When `regexp-match` is used with byte-string regexp, the result is a matching byte substring:

```
> (regexp-match #rx#"needle" #"hay needle stack")
'(#"needle")
```

A byte-string regexp can be applied to a string, and a string regexp can be applied to a byte string. In both cases, the result is a byte string. Internally, all regexp matching is in terms of bytes, and a string regexp is expanded to a regexp that matches UTF-8 encodings of characters. For maximum efficiency, use byte-string matching instead of string, since matching bytes directly avoids UTF-8 encodings.

If you have data that is in a port, there's no need to first read it into a string. Functions like `regexp-match` can match on the port directly:

```
> (define-values (i o) (make-pipe))
> (write "hay needle stack" o)
> (close-output-port o)
> (regexp-match #rx#"needle" i)
'(#"needle")
```

The `regexp-match?` function is like `regexp-match-positions`, but simply returns a boolean indicating whether the match succeeded:

```
> (regexp-match? #rx"brain" "bird")
#f
> (regexp-match? #rx"needle" "hay needle stack")
#t
```

The `regexp-split` function takes two arguments, a regexp pattern and a text string, and it returns a list of substrings of the text string; the pattern identifies the delimiter separating the substrings.

```
> (regexp-split #rx":" "/bin:/usr/bin:/usr/bin/X11:/usr/local/bin")
'("/bin" "/usr/bin" "/usr/bin/X11" "/usr/local/bin")
> (regexp-split #rx" " "pea soup")
'("pea" "soup")
```

If the first argument matches empty strings, then the list of all the single-character substrings is returned.

```
> (regexp-split #rx"" "smithereens")
'("" "s" "m" "i" "t" "h" "e" "r" "e" "e" "n" "s" "")
```

Thus, to identify one-or-more spaces as the delimiter, take care to use the regexp `#rx" +"`, not `#rx" *"`.

```
> (regexp-split #rx" +" "split pea     soup")
'("split" "pea" "soup")
> (regexp-split #rx" *" "split pea     soup")
'("" "s" "p" "l" "i" "t" "" "p" "e" "a" "" "s" "o" "u" "p" "")
```

The `regexp-replace` function replaces the matched portion of the text string by another string. The first argument is the pattern, the second the text string, and the third is either the string to be inserted or a procedure to convert matches to the insert string.

```
> (regexp-replace #rx"te" "liberte" "ty")
"liberty"
> (regexp-replace #rx"." "racket" string-upcase)
"Racket"
```

If the pattern doesn't occur in the text string, the returned string is identical to the text string.

The `regexp-replace*` function replaces *all* matches in the text string by the insert string:

```
> (regexp-replace* #rx"te" "liberte egalite fraternite" "ty")
"liberty egality fratyrnity"
> (regexp-replace* #rx"[ds]" "drracket" string-upcase)
"Drracket"
```

9.3 Basic Assertions

The *assertions* `^` and `$` identify the beginning and the end of the text string, respectively. They ensure that their adjoining regexps match at one or other end of the text string:

```
> (regexp-match-positions #rx"^contact" "first contact")
#f
```

The regexp above fails to match because `contact` does not occur at the beginning of the text string. In

```
> (regexp-match-positions #rx"laugh$" "laugh laugh laugh laugh")
'((18 . 23))
```

the regexp matches the *last* `laugh`.

The metasequence `\b` asserts that a word boundary exists, but this metasequence works only with `#px` syntax. In

```
> (regexp-match-positions #px"yack\\b" "yackety yack")
'((8 . 12))
```

the `yack` in `yackety` doesn't end at a word boundary so it isn't matched. The second `yack` does and is.

The metasequence `\B` (also `#px` only) has the opposite effect to `\b`; it asserts that a word boundary does not exist. In

```
> (regexp-match-positions #px"an\\B" "an analysis")
'((3 . 5))
```

the `an` that doesn't end in a word boundary is matched.

9.4 Characters and Character Classes

Typically, a character in the regexp matches the same character in the text string. Sometimes it is necessary or convenient to use a regexp metasequence to refer to a single character. For example, the metasequence `\.` matches the period character.

The metacharacter `.` matches *any* character (other than newline in multi-line mode; see §9.6.3 "Cloisters"):

```
> (regexp-match #rx"p.t" "pet")
'("pet")
```

The above pattern also matches `pat`, `pit`, `pot`, `put`, and `p8t`, but not `peat` or `pffft`.

A *character class* matches any one character from a set of characters. A typical format for this is the *bracketed character class* `[...]`, which matches any one character from the non-empty sequence of characters enclosed within the brackets. Thus, `#rx"p[aeiou]t"` matches `pat`, `pet`, `pit`, `pot`, `put`, and nothing else.

Inside the brackets, a `-` between two characters specifies the Unicode range between the characters. For example, `#rx"ta[b-dgn-p]"` matches `tab`, `tac`, `tad`, `tag`, `tan`, `tao`, and `tap`.

An initial `^` after the left bracket inverts the set specified by the rest of the contents; i.e., it specifies the set of characters *other than* those identified in the brackets. For example, `#rx"do[^g]"` matches all three-character sequences starting with `do` except `dog`.

Note that the metacharacter `^` inside brackets means something quite different from what it means outside. Most other metacharacters (`.`, `*`, `+`, `?`, etc.) cease to be metacharacters when inside brackets, although you may still escape them for peace of mind. A `-` is a metacharacter only when it's inside brackets, and when it is neither the first nor the last character between the brackets.

Bracketed character classes cannot contain other bracketed character classes (although they contain certain other types of character classes; see below). Thus, a `[` inside a bracketed character class doesn't have to be a metacharacter; it can stand for itself. For example, `#rx"[a[b]"` matches `a`, `[`, and `b`.

Furthermore, since empty bracketed character classes are disallowed, a `]` immediately occurring after the opening left bracket also doesn't need to be a metacharacter. For example,

`#rx"[]ab]"` matches `]`, `a`, and `b`.

9.4.1 Some Frequently Used Character Classes

In `#px` syntax, some standard character classes can be conveniently represented as metasequences instead of as explicit bracketed expressions: `\d` matches a digit (the same as `[0-9]`); `\s` matches an ASCII whitespace character; and `\w` matches a character that could be part of a "word".

Following regexp custom, we identify "word" characters as `[A-Za-z0-9_]`, although these are too restrictive for what a Racketeer might consider a "word."

The upper-case versions of these metasequences stand for the inversions of the corresponding character classes: `\D` matches a non-digit, `\S` a non-whitespace character, and `\W` a non-"word" character.

Remember to include a double backslash when putting these metasequences in a Racket string:

```
> (regexp-match #px"\\d\\d"
    "0 dear, 1 have 2 read catch 22 before 9")
'("22")
```

These character classes can be used inside a bracketed expression. For example, `#px"[a-z\\d]"` matches a lower-case letter or a digit.

9.4.2 POSIX character classes

A *POSIX character class* is a special metasequence of the form `[:...:]` that can be used only inside a bracketed expression in `#px` syntax. The POSIX classes supported are

- `[:alnum:]` — ASCII letters and digits
- `[:alpha:]` — ASCII letters
- `[:ascii:]` — ASCII characters
- `[:blank:]` — ASCII widthful whitespace: space and tab
- `[:cntrl:]` — "control" characters: ASCII 0 to 31
- `[:digit:]` — ASCII digits, same as `\d`
- `[:graph:]` — ASCII characters that use ink
- `[:lower:]` — ASCII lower-case letters
- `[:print:]` — ASCII ink-users plus widthful whitespace

- `[:space:]` — ASCII whitespace, same as `\s`
- `[:upper:]` — ASCII upper-case letters
- `[:word:]` — ASCII letters and _, same as `\w`
- `[:xdigit:]` — ASCII hex digits

For example, the `#px"[[:alpha:]_]"` matches a letter or underscore.

```
> (regexp-match #px"[[:alpha:]_]" "--x--")
'("x")
> (regexp-match #px"[[:alpha:]_]" "--_--")
'("_")
> (regexp-match #px"[[:alpha:]_]" "--:--")
#f
```

The POSIX class notation is valid *only* inside a bracketed expression. For instance, `[:alpha:]`, when not inside a bracketed expression, will not be read as the letter class. Rather, it is (from previous principles) the character class containing the characters `:`, `a`, `l`, `p`, `h`.

```
> (regexp-match #px"[:alpha:]" "--a--")
'("a")
> (regexp-match #px"[:alpha:]" "--x--")
#f
```

9.5 Quantifiers

The *quantifiers* `*`, `+`, and `?` match respectively: zero or more, one or more, and zero or one instances of the preceding subpattern.

```
> (regexp-match-positions #rx"c[ad]*r" "cadaddadddr")
'((0 . 11))
> (regexp-match-positions #rx"c[ad]*r" "cr")
'((0 . 2))
> (regexp-match-positions #rx"c[ad]+r" "cadaddadddr")
'((0 . 11))
> (regexp-match-positions #rx"c[ad]+r" "cr")
#f
> (regexp-match-positions #rx"c[ad]?r" "cadaddadddr")
#f
> (regexp-match-positions #rx"c[ad]?r" "cr")
'((0 . 2))
> (regexp-match-positions #rx"c[ad]?r" "car")
'((0 . 3))
```

In `#px` syntax, you can use braces to specify much finer-tuned quantification than is possible with `*`, `+`, `?`:

- The quantifier `{`*m*`}` matches *exactly* *m* instances of the preceding subpattern; *m* must be a nonnegative integer.
- The quantifier `{`*m*`,`*n*`}` matches at least *m* and at most *n* instances. `m` and `n` are nonnegative integers with *m* less or equal to *n*. You may omit either or both numbers, in which case *m* defaults to 0 and *n* to infinity.

It is evident that `+` and `?` are abbreviations for `{1,}` and `{0,1}` respectively, and `*` abbreviates `{,}`, which is the same as `{0,}`.

```
> (regexp-match #px"[aeiou]{3}" "vacuous")
'("uou")
> (regexp-match #px"[aeiou]{3}" "evolve")
#f
> (regexp-match #px"[aeiou]{2,3}" "evolve")
#f
> (regexp-match #px"[aeiou]{2,3}" "zeugma")
'("eu")
```

The quantifiers described so far are all *greedy*: they match the maximal number of instances that would still lead to an overall match for the full pattern.

```
> (regexp-match #rx"<.*>" "<tag1> <tag2> <tag3>")
'("<tag1> <tag2> <tag3>")
```

To make these quantifiers *non-greedy*, append a `?` to them. Non-greedy quantifiers match the minimal number of instances needed to ensure an overall match.

```
> (regexp-match #rx"<.*?>" "<tag1> <tag2> <tag3>")
'("<tag1>")
```

The non-greedy quantifiers are `*?`, `+?`, `??`, `{`*m*`}?`, and `{`*m*`,`*n*`}?`, although `{`*m*`}?` is always the same as `{`*m*`}`. Note that the metacharacter `?` has two different uses, and both uses are represented in `??`.

9.6 Clusters

Clustering—enclosure within parens `(...)`—identifies the enclosed *subpattern* as a single entity. It causes the matcher to capture the *submatch*, or the portion of the string matching the subpattern, in addition to the overall match:

```
> (regexp-match #rx"([a-z]+) ([0-9]+), ([0-9]+)" "jan 1, 1970")
'("jan 1, 1970" "jan" "1" "1970")
```

Clustering also causes a following quantifier to treat the entire enclosed subpattern as an entity:

```
> (regexp-match #rx"(pu )*" "pu pu platter")
'("pu pu " "pu ")
```

The number of submatches returned is always equal to the number of subpatterns specified in the regexp, even if a particular subpattern happens to match more than one substring or no substring at all.

```
> (regexp-match #rx"([a-z ]+;)*" "lather; rinse; repeat;")
'("lather; rinse; repeat;" " repeat;")
```

Here, the `*`-quantified subpattern matches three times, but it is the last submatch that is returned.

It is also possible for a quantified subpattern to fail to match, even if the overall pattern matches. In such cases, the failing submatch is represented by `#f`

```
> (define date-re
    ; match ‘month year' or ‘month day, year';
    ; subpattern matches day, if present
    #rx"([a-z]+) +([0-9]+,)? *([0-9]+)")
> (regexp-match date-re "jan 1, 1970")
'("jan 1, 1970" "jan" "1," "1970")
> (regexp-match date-re "jan 1970")
'("jan 1970" "jan" #f "1970")
```

9.6.1 Backreferences

Submatches can be used in the insert string argument of the procedures `regexp-replace` and `regexp-replace*`. The insert string can use `\`*n* as a *backreference* to refer back to the *n*th submatch, which is the substring that matched the *n*th subpattern. A `\0` refers to the entire match, and it can also be specified as `\&`.

```
> (regexp-replace #rx"_(.+?)_"
    "the _nina_, the _pinta_, and the _santa maria_"
    "*\\1*")
"the *nina*, the _pinta_, and the _santa maria_"
> (regexp-replace* #rx"_(.+?)_"
    "the _nina_, the _pinta_, and the _santa maria_"
    "*\\1*")
```

```
"the *nina*, the *pinta*, and the *santa maria*"
> (regexp-replace #px"(\\S+) (\\S+) (\\S+)"
    "eat to live"
    "\\3 \\2 \\1")
"live to eat"
```

Use `\\` in the insert string to specify a literal backslash. Also, `\$` stands for an empty string, and is useful for separating a backreference `\`*n* from an immediately following number.

Backreferences can also be used within a `#px` pattern to refer back to an already matched subpattern in the pattern. `\`*n* stands for an exact repeat of the *n*th submatch. Note that `\0`, which is useful in an insert string, makes no sense within the regexp pattern, because the entire regexp has not matched yet so you cannot refer back to it.}

```
> (regexp-match #px"([a-z]+) and \\1"
                "billions and billions")
'("billions and billions" "billions")
```

Note that the backreference is not simply a repeat of the previous subpattern. Rather it is a repeat of the particular substring already matched by the subpattern.

In the above example, the backreference can only match `billions`. It will not match `millions`, even though the subpattern it harks back to—`([a-z]+)`—would have had no problem doing so:

```
> (regexp-match #px"([a-z]+) and \\1"
                "billions and millions")
#f
```

The following example marks all immediately repeating patterns in a number string:

```
> (regexp-replace* #px"(\\d+)\\1"
    "12334098324243242098098234"
    "{\\1,\\1}")
"12{3,3}40983{24,24}3242{098,098}0234"
```

The following example corrects doubled words:

```
> (regexp-replace* #px"\\b(\\S+) \\1\\b"
    (string-append "now is the the time for all good men to "
                   "to come to the aid of of the party")
    "\\1")
"now is the time for all good men to come to the aid of the party"
```

9.6.2 Non-capturing Clusters

It is often required to specify a cluster (typically for quantification) but without triggering the capture of submatch information. Such clusters are called *non-capturing*. To create a non-capturing cluster, use `(?:` instead of `(` as the cluster opener.

In the following example, a non-capturing cluster eliminates the "directory" portion of a given Unix pathname, and a capturing cluster identifies the basename.

But don't parse paths with regexps. Use functions like `split-path`, instead.

```
> (regexp-match #rx"^(?:[a-z]*/)*([a-z]+)$"
                "/usr/local/bin/racket")
'("/usr/local/bin/racket" "racket")
```

9.6.3 Cloisters

The location between the `?` and the `:` of a non-capturing cluster is called a *cloister*. You can put modifiers there that will cause the enclustered subpattern to be treated specially. The modifier `i` causes the subpattern to match case-insensitively:

The term *cloister* is a useful, if terminally cute, coinage from the abbots of Perl.

```
> (regexp-match #rx"(?i:hearth)" "HeartH")
'("HeartH")
```

The modifier `m` causes the subpattern to match in *multi-line mode*, where `.` does not match a newline character, `^` can match just after a newline, and `$` can match just before a newline.

```
> (regexp-match #rx"." "\na\n")
'("\n")
> (regexp-match #rx"(?m:.)" "\na\n")
'("a")
> (regexp-match #rx"^A plan$" "A man\nA plan\nA canal")
#f
> (regexp-match #rx"(?m:^A plan$)" "A man\nA plan\nA canal")
'("A plan")
```

You can put more than one modifier in the cloister:

```
> (regexp-match #rx"(?mi:^A Plan$)" "a man\na plan\na canal")
'("a plan")
```

A minus sign before a modifier inverts its meaning. Thus, you can use `-i` in a *subcluster* to overturn the case-insensitivities caused by an enclosing cluster.

```
> (regexp-match #rx"(?i:the (?-i:TeX)book)"
                "The TeXbook")
'("The TeXbook")
```

The above regexp will allow any casing for `the` and `book`, but it insists that `TeX` not be differently cased.

9.7 Alternation

You can specify a list of *alternate* subpatterns by separating them by `|`. The `|` separates subpatterns in the nearest enclosing cluster (or in the entire pattern string if there are no enclosing parens).

```
> (regexp-match #rx"f(ee|i|o|um)" "a small, final fee")
'("fi" "i")
> (regexp-replace* #rx"([yi])s(e[sdr]?|ing|ation)"
                   (string-append
                    "analyse an energising organisation"
                    " pulsing with noisy organisms")
                   "\\1z\\2")
"analyze an energizing organization pulsing with noisy organisms"
```

Note again that if you wish to use clustering merely to specify a list of alternate subpatterns but do not want the submatch, use `(?:` instead of `(`.

```
> (regexp-match #rx"f(?:ee|i|o|um)" "fun for all")
'("fo")
```

An important thing to note about alternation is that the leftmost matching alternate is picked regardless of its length. Thus, if one of the alternates is a prefix of a later alternate, the latter may not have a chance to match.

```
> (regexp-match #rx"call|call-with-current-continuation"
                "call-with-current-continuation")
'("call")
```

To allow the longer alternate to have a shot at matching, place it before the shorter one:

```
> (regexp-match #rx"call-with-current-continuation|call"
                "call-with-current-continuation")
'("call-with-current-continuation")
```

In any case, an overall match for the entire regexp is always preferred to an overall non-match. In the following, the longer alternate still wins, because its preferred shorter prefix fails to yield an overall match.

```
> (regexp-match
   #rx"(?:call|call-with-current-continuation) constrained"
   "call-with-current-continuation constrained")
'("call-with-current-continuation constrained")
```

9.8 Backtracking

We've already seen that greedy quantifiers match the maximal number of times, but the overriding priority is that the overall match succeed. Consider

```
> (regexp-match #rx"a*a" "aaaa")
'("aaaa")
```

The regexp consists of two subregexps: `a*` followed by `a`. The subregexp `a*` cannot be allowed to match all four `a`'s in the text string `aaaa`, even though `*` is a greedy quantifier. It may match only the first three, leaving the last one for the second subregexp. This ensures that the full regexp matches successfully.

The regexp matcher accomplishes this via a process called *backtracking*. The matcher tentatively allows the greedy quantifier to match all four `a`'s, but then when it becomes clear that the overall match is in jeopardy, it *backtracks* to a less greedy match of three `a`'s. If even this fails, as in the call

```
> (regexp-match #rx"a*aa" "aaaa")
'("aaaa")
```

the matcher backtracks even further. Overall failure is conceded only when all possible backtracking has been tried with no success.

Backtracking is not restricted to greedy quantifiers. Nongreedy quantifiers match as few instances as possible, and progressively backtrack to more and more instances in order to attain an overall match. There is backtracking in alternation too, as the more rightward alternates are tried when locally successful leftward ones fail to yield an overall match.

Sometimes it is efficient to disable backtracking. For example, we may wish to commit to a choice, or we know that trying alternatives is fruitless. A nonbacktracking regexp is enclosed in `(?>...)`.

```
> (regexp-match #rx"(?>a+)." "aaaa")
#f
```

In this call, the subregexp `?>a+` greedily matches all four `a`'s, and is denied the opportunity to backtrack. So, the overall match is denied. The effect of the regexp is therefore to match one or more `a`'s followed by something that is definitely non-`a`.

9.9 Looking Ahead and Behind

You can have assertions in your pattern that look *ahead* or *behind* to ensure that a subpattern does or does not occur. These "look around" assertions are specified by putting the subpattern checked for in a cluster whose leading characters are: `?=` (for positive lookahead), `?!`

(negative lookahead), `?<=` (positive lookbehind), `?<!` (negative lookbehind). Note that the subpattern in the assertion does not generate a match in the final result; it merely allows or disallows the rest of the match.

9.9.1 Lookahead

Positive lookahead with `?=` peeks ahead to ensure that its subpattern *could* match.

```
> (regexp-match-positions #rx"grey(?=hound)"
    "i left my grey socks at the greyhound")
'((28 . 32))
```

The regexp `#rx"grey(?=hound)"` matches `grey`, but *only* if it is followed by `hound`. Thus, the first `grey` in the text string is not matched.

Negative lookahead with `?!` peeks ahead to ensure that its subpattern *could not* possibly match.

```
> (regexp-match-positions #rx"grey(?!hound)"
    "the gray greyhound ate the grey socks")
'((27 . 31))
```

The regexp `#rx"grey(?!hound)"` matches `grey`, but only if it is *not* followed by `hound`. Thus the `grey` just before `socks` is matched.

9.9.2 Lookbehind

Positive lookbehind with `?<=` checks that its subpattern *could* match immediately to the left of the current position in the text string.

```
> (regexp-match-positions #rx"(?<=grey)hound"
    "the hound in the picture is not a greyhound")
'((38 . 43))
```

The regexp `#rx"(?<=grey)hound"` matches `hound`, but only if it is preceded by `grey`.

Negative lookbehind with `?<!` checks that its subpattern could not possibly match immediately to the left.

```
> (regexp-match-positions #rx"(?<!grey)hound"
    "the greyhound in the picture is not a hound")
'((38 . 43))
```

The regexp `#rx"(?<!grey)hound"` matches `hound`, but only if it is *not* preceded by `grey`.

Lookaheads and lookbehinds can be convenient when they are not confusing.

9.10 An Extended Example

Here's an extended example from Friedl's *Mastering Regular Expressions*, page 189, that covers many of the features described in this chapter. The problem is to fashion a regexp that will match any and only IP addresses or *dotted quads*: four numbers separated by three dots, with each number between 0 and 255.

First, we define a subregexp `n0-255` that matches 0 through 255:

```
> (define n0-255
    (string-append
     "(?:"
     "\\d|"        ;  0 through 9
     "\\d\\d|"     ;  00 through 99
     "[01]\\d\\d|" ; 000 through 199
     "2[0-4]\\d|"  ; 200 through 249
     "25[0-5]"     ; 250 through 255
     ")"))
```

Note that `n0-255` lists prefixes as preferred alternates, which is something we cautioned against in §9.7 "Alternation". However, since we intend to anchor this subregexp explicitly to force an overall match, the order of the alternates does not matter.

The first two alternates simply get all single- and double-digit numbers. Since 0-padding is allowed, we need to match both 1 and 01. We need to be careful when getting 3-digit numbers, since numbers above 255 must be excluded. So we fashion alternates to get 000 through 199, then 200 through 249, and finally 250 through 255.

An IP-address is a string that consists of four `n0-255`s with three dots separating them.

```
> (define ip-re1
    (string-append
     "^"          ; nothing before
     n0-255       ; the first n0-255,
     "(?:"        ; then the subpattern of
     "\\."        ; a dot followed by
     n0-255       ; an n0-255,
     ")"          ; which is
     "{3}"        ; repeated exactly 3 times
     "$"))
; with nothing following
```

Let's try it out:

```
> (regexp-match (pregexp ip-re1) "1.2.3.4")
'("1.2.3.4")
> (regexp-match (pregexp ip-re1) "55.155.255.265")
#f
```

which is fine, except that we also have

```
> (regexp-match (pregexp ip-re1) "0.00.000.00")
'("0.00.000.00")
```

All-zero sequences are not valid IP addresses! Lookahead to the rescue. Before starting to match `ip-re1`, we look ahead to ensure we don't have all zeros. We could use positive lookahead to ensure there *is* a digit other than zero.

```
> (define ip-re
    (pregexp
     (string-append
       "(?=.*[1-9])" ; ensure there's a non-0 digit
       ip-re1)))
```

Or we could use negative lookahead to ensure that what's ahead isn't composed of *only* zeros and dots.

```
> (define ip-re
    (pregexp
     (string-append
       "(?![0.]*$)" ; not just zeros and dots
                    ; (note: . is not metachar inside [...])
       ip-re1)))
```

The regexp `ip-re` will match all and only valid IP addresses.

```
> (regexp-match ip-re "1.2.3.4")
'("1.2.3.4")
> (regexp-match ip-re "0.0.0.0")
#f
```

10 Exceptions and Control

Racket provides an especially rich set of control operations—not only operations for raising and catching exceptions, but also operations for grabbing and restoring portions of a computation.

10.1 Exceptions

Whenever a run-time error occurs, an *exception* is raised. Unless the exception is caught, then it is handled by printing a message associated with the exception, and then escaping from the computation.

```
> (/ 1 0)
/: division by zero
> (car 17)
car: contract violation
  expected: pair?
  given: 17
```

To catch an exception, use the `with-handlers` form:

```
(with-handlers ([predicate-expr handler-expr] ...)
  body ...+)
```

Each *predicate-expr* in a handler determines a kind of exception that is caught by the `with-handlers` form, and the value representing the exception is passed to the handler procedure produced by *handler-expr*. The result of the *handler-expr* is the result of the `with-handlers` expression.

For example, a divide-by-zero error raises an instance of the `exn:fail:contract:divide-by-zero` structure type:

```
> (with-handlers ([exn:fail:contract:divide-by-zero?
                   (lambda (exn) +inf.0)])
    (/ 1 0))
+inf.0
> (with-handlers ([exn:fail:contract:divide-by-zero?
                   (lambda (exn) +inf.0)])
    (car 17))
car: contract violation
  expected: pair?
  given: 17
```

The `error` function is one way to raise your own exception. It packages an error message and other information into an `exn:fail` structure:

```
> (error "crash!")
crash!
> (with-handlers ([exn:fail? (lambda (exn) 'air-bag)])
    (error "crash!"))
'air-bag
```

The `exn:fail:contract:divide-by-zero` and `exn:fail` structure types are sub-types of the `exn` structure type. Exceptions raised by core forms and functions always raise an instance of `exn` or one of its sub-types, but an exception does not have to be represented by a structure. The `raise` function lets you raise any value as an exception:

```
> (raise 2)
uncaught exception: 2
> (with-handlers ([(lambda (v) (equal? v 2)) (lambda (v) 'two)])
    (raise 2))
'two
> (with-handlers ([(lambda (v) (equal? v 2)) (lambda (v) 'two)])
    (/ 1 0))
/: division by zero
```

Multiple *predicate-expr*s in a `with-handlers` form let you handle different kinds of exceptions in different ways. The predicates are tried in order, and if none of them match, then the exception is propagated to enclosing contexts.

```
> (define (always-fail n)
    (with-handlers ([even? (lambda (v) 'even)]
                    [positive? (lambda (v) 'positive)])
      (raise n)))
> (always-fail 2)
'even
> (always-fail 3)
'positive
> (always-fail -3)
uncaught exception: -3
> (with-handlers ([negative? (lambda (v) 'negative)])
   (always-fail -3))
'negative
```

Using `(lambda (v) #t)` as a predicate captures all exceptions, of course:

```
> (with-handlers ([(lambda (v) #t) (lambda (v) 'oops)])
    (car 17))
'oops
```

Capturing all exceptions is usually a bad idea, however. If the user types Ctl-C in a terminal window or clicks the Stop button in DrRacket to interrupt a computation, then normally the `exn:break` exception should not be caught. To catch only exceptions that represent errors, use `exn:fail?` as the predicate:

```
> (with-handlers ([exn:fail? (lambda (v) 'oops)])
    (car 17))
'oops
> (with-handlers ([exn:fail? (lambda (v) 'oops)])
    (break-thread (current-thread)) ; simulate Ctl-C
    (car 17))
user break
```

Exceptions carry information about the error that occurred. The `exn-message` accessor provides a descriptive message for the exception. The `exn-continuation-marks` accessor provides information about the point where the exception was raised.

[1]

```
> (with-handlers ([exn:fail?
                   (lambda (v)
                     ((error-display-handler) (exn-
message v) v))])
    (car 17))
car: contract violation
  expected: pair?
  given: 17
  context...:
   /Users/robby/snapshot/racket/racket/collects/racket/private/more-
scheme.rkt:145:2: call-with-break-parameterization
   /Users/robby/snapshot/racket/build/docs/share/pkgs/sandbox-
lib/racket/sandbox.rkt:921:7
   /Users/robby/snapshot/racket/build/docs/share/pkgs/sandbox-
lib/racket/sandbox.rkt:891:2: user-process
```

10.2 Prompts and Aborts

When an exception is raised, control escapes out of an arbitrary deep evaluation context to the point where the exception is caught—or all the way out if the exception is never caught:

```
> (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (/ 1 0)))))))
/: division by zero
```

[1] The `continuation-mark-set->context` procedure provides best-effort structured backtrace information.

But if control escapes "all the way out," why does the REPL keep going after an error is printed? You might think that it's because the REPL wraps every interaction in a `with-handlers` form that catches all exceptions, but that's not quite the reason.

The actual reason is that the REPL wraps the interaction with a *prompt*, which effectively marks the evaluation context with an escape point. If an exception is not caught, then information about the exception is printed, and then evaluation *aborts* to the nearest enclosing prompt. More precisely, each prompt has a *prompt tag*, and there is a designated *default prompt tag* that the uncaught-exception handler uses to abort.

The `call-with-continuation-prompt` function installs a prompt with a given prompt tag, and then it evaluates a given thunk under the prompt. The `default-continuation-prompt-tag` function returns the default prompt tag. The `abort-current-continuation` function escapes to the nearest enclosing prompt that has a given prompt tag.

```
> (define (escape v)
    (abort-current-continuation
     (default-continuation-prompt-tag)
     (lambda () v)))
> (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (escape 0)))))))
0
> (+ 1
     (call-with-continuation-prompt
      (lambda ()
        (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (+ 1 (escape 0))))))))
      (default-continuation-prompt-tag)))
1
```

In `escape` above, the value `v` is wrapped in a procedure that is called after escaping to the enclosing prompt.

Prompts and aborts look very much like exception handling and raising. Indeed, prompts and aborts are essentially a more primitive form of exceptions, and `with-handlers` and `raise` are implemented in terms of prompts and aborts. The power of the more primitive forms is related to the word "continuation" in the operator names, as we discuss in the next section.

10.3 Continuations

A *continuation* is a value that encapsulates a piece of an expression's evaluation context. The `call-with-composable-continuation` function captures the *current continuation* starting outside the current function call and running up to the nearest enclosing prompt. (Keep in mind that each REPL interaction is implicitly wrapped in a prompt.)

For example, in

```
(+ 1 (+ 1 (+ 1 0)))
```

at the point where `0` is evaluated, the expression context includes three nested addition expressions. We can grab that context by changing `0` to grab the continuation before returning 0:

```
> (define saved-k #f)
> (define (save-comp!)
    (call-with-composable-continuation
     (lambda (k) ; k is the captured continuation
       (set! saved-k k)
       0)))
> (+ 1 (+ 1 (+ 1 (save-comp!))))
3
```

The continuation saved in `saved-k` encapsulates the program context `(+ 1 (+ 1 (+ 1 ?)))`, where `?` represents a place to plug in a result value—because that was the expression context when `save-comp!` was called. The continuation is encapsulated so that it behaves like the function `(lambda (v) (+ 1 (+ 1 (+ 1 v))))`:

```
> (saved-k 0)
3
> (saved-k 10)
13
> (saved-k (saved-k 0))
6
```

The continuation captured by `call-with-composable-continuation` is determined dynamically, not syntactically. For example, with

```
> (define (sum n)
    (if (zero? n)
        (save-comp!)
        (+ n (sum (sub1 n)))))
> (sum 5)
15
```

the continuation in `saved-k` becomes `(lambda (x) (+ 5 (+ 4 (+ 3 (+ 2 (+ 1 x))))))`:

```
> (saved-k 0)
15
> (saved-k 10)
25
```

A more traditional continuation operator in Racket (or Scheme) is `call-with-current-continuation`, which is usually abbreviated `call/cc`. It is like `call-with-composable-continuation`, but applying the captured continuation first aborts (to the current prompt) before restoring the saved continuation.

```
> (+ 1 (+ 1 (+ 1 (save-comp!))))
3
> (+ 1 (saved-k 0))
4
> (define (save-cc!)
    (call-with-current-continuation
     (lambda (k) ; k is the captured continuation
       (set! saved-k k)
       0)))
> (+ 1 (+ 1 (+ 1 (save-cc!))))
3
> (+ 1 (saved-k 0))
3
```

Other Scheme systems traditionally support a single prompt at the program start, instead of allowing new prompts via `call-with-continuation-prompt`.

Continuations as in Racket are sometimes called *delimited continuations*, since a program can introduce new delimiting prompts, and continuations as captured by `call-with-composable-continuation` are sometimes called *composable continuations*, because they do not have a built-in abort.

For an example of how continuations are useful, see *More: Systems Programming with Racket*. For specific control operators that have more convenient names than the primitives described here, see `racket/control`.

11 Iterations and Comprehensions

The `for` family of syntactic forms support iteration over *sequences*. Lists, vectors, strings, byte strings, input ports, and hash tables can all be used as sequences, and constructors like `in-range` offer even more kinds of sequences.

Variants of `for` accumulate iteration results in different ways, but they all have the same syntactic shape. Simplifying for now, the syntax of `for` is

```
(for ([id sequence-expr] ...)
  body ...+)
```

A `for` loop iterates through the sequence produced by the *sequence-expr*. For each element of the sequence, `for` binds the element to *id*, and then it evaluates the *body*s for side effects.

Examples:

```
> (for ([i '(1 2 3)])
    (display i))
123
> (for ([i "abc"])
    (printf "~a..." i))
a...b...c...
> (for ([i 4])
    (display i))
0123
```

The `for/list` variant of `for` is more Racket-like. It accumulates *body* results into a list, instead of evaluating *body* only for side effects. In more technical terms, `for/list` implements a *list comprehension*.

Examples:

```
> (for/list ([i '(1 2 3)])
    (* i i))
'(1 4 9)
> (for/list ([i "abc"])
    i)
'(#\a #\b #\c)
> (for/list ([i 4])
    i)
'(0 1 2 3)
```

The full syntax of `for` accommodates multiple sequences to iterate in parallel, and the `for*` variant nests the iterations instead of running them in parallel. More variants of `for` and `for*` accumulate *body* results in different ways. In all of these variants, predicates that prune iterations can be included along with bindings.

Before details on the variations of `for`, though, it's best to see the kinds of sequence generators that make interesting examples.

11.1 Sequence Constructors

The `in-range` function generates a sequence of numbers, given an optional starting number (which defaults to `0`), a number before which the sequence ends, and an optional step (which defaults to `1`). Using a non-negative integer *k* directly as a sequence is a shorthand for `(in-range k)`.

Examples:

```
> (for ([i 3])
    (display i))
012
> (for ([i (in-range 3)])
    (display i))
012
> (for ([i (in-range 1 4)])
    (display i))
123
> (for ([i (in-range 1 4 2)])
    (display i))
13
> (for ([i (in-range 4 1 -1)])
    (display i))
432
> (for ([i (in-range 1 4 1/2)])
    (printf " ~a " i))
 1  3/2  2  5/2  3  7/2
```

The `in-naturals` function is similar, except that the starting number must be an exact non-negative integer (which defaults to `0`), the step is always `1`, and there is no upper limit. A `for` loop using just `in-naturals` will never terminate unless a body expression raises an exception or otherwise escapes.

Example:

```
> (for ([i (in-naturals)])
    (if (= i 10)
```

```
        (error "too much!")
        (display i)))
0123456789
too much!
```

The `stop-before` and `stop-after` functions construct a new sequence given a sequence and a predicate. The new sequence is like the given sequence, but truncated either immediately before or immediately after the first element for which the predicate returns true.

Example:

```
> (for ([i (stop-before "abc def"
                        char-whitespace?)])
    (display i))
abc
```

Sequence constructors like `in-list`, `in-vector` and `in-string` simply make explicit the use of a list, vector, or string as a sequence. Along with `in-range`, these constructors raise an exception when given the wrong kind of value, and since they otherwise avoid a run-time dispatch to determine the sequence type, they enable more efficient code generation; see §11.10 “Iteration Performance” for more information.

Examples:

```
> (for ([i (in-string "abc")])
    (display i))
abc
> (for ([i (in-string '(1 2 3))])
    (display i))
in-string: contract violation
  expected: string?
  given: '(1 2 3)
```

§4.17.1 “Sequences” in *The Racket Reference* provides more on sequences.

11.2 `for` and `for*`

A more complete syntax of `for` is

```
(for (clause ...)
  body ...+)

clause = [id sequence-expr]
       | #:when boolean-expr
       | #:unless boolean-expr
```

When multiple [*id sequence-expr*] clauses are provided in a `for` form, the corresponding sequences are traversed in parallel:

```
> (for ([i (in-range 1 4)]
        [chapter '("Intro" "Details" "Conclusion")])
    (printf "Chapter ~a. ~a\n" i chapter))
Chapter 1. Intro
Chapter 2. Details
Chapter 3. Conclusion
```

With parallel sequences, the `for` expression stops iterating when any sequence ends. This behavior allows `in-naturals`, which creates an infinite sequence of numbers, to be used for indexing:

```
> (for ([i (in-naturals 1)]
        [chapter '("Intro" "Details" "Conclusion")])
    (printf "Chapter ~a. ~a\n" i chapter))
Chapter 1. Intro
Chapter 2. Details
Chapter 3. Conclusion
```

The `for*` form, which has the same syntax as `for`, nests multiple sequences instead of running them in parallel:

```
> (for* ([book '("Guide" "Reference")]
         [chapter '("Intro" "Details" "Conclusion")])
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
Reference Intro
Reference Details
Reference Conclusion
```

Thus, `for*` is a shorthand for nested `for`s in the same way that `let*` is a shorthand for nested `let`s.

The `#:when` *boolean-expr* form of a *clause* is another shorthand. It allows the *body*s to evaluate only when the *boolean-expr* produces a true value:

```
> (for* ([book '("Guide" "Reference")]
         [chapter '("Intro" "Details" "Conclusion")]
         #:when (not (equal? chapter "Details")))
    (printf "~a ~a\n" book chapter))
```

```
Guide Intro
Guide Conclusion
Reference Intro
Reference Conclusion
```

A *boolean-expr* with `#:when` can refer to any of the preceding iteration bindings. In a `for` form, this scoping makes sense only if the test is nested in the iteration of the preceding bindings; thus, bindings separated by `#:when` are mutually nested, instead of in parallel, even with `for`.

```
> (for ([book '("Guide" "Reference" "Notes")]
        #:when (not (equal? book "Notes"))
        [i (in-naturals 1)]
        [chapter '("Intro" "Details" "Conclusion" "Index")]
        #:when (not (equal? chapter "Index")))
    (printf "~a Chapter ~a. ~a\n" book i chapter))
Guide Chapter 1. Intro
Guide Chapter 2. Details
Guide Chapter 3. Conclusion
Reference Chapter 1. Intro
Reference Chapter 2. Details
Reference Chapter 3. Conclusion
```

An `#:unless` clause is analogous to a `#:when` clause, but the *body*s evaluate only when the *boolean-expr* produces a false value.

11.3 `for/list` and `for*/list`

The `for/list` form, which has the same syntax as `for`, evaluates the *body*s to obtain values that go into a newly constructed list:

```
> (for/list ([i (in-naturals 1)]
             [chapter '("Intro" "Details" "Conclusion")])
    (string-append (number->string i) ". " chapter))
'("1. Intro" "2. Details" "3. Conclusion")
```

A `#:when` clause in a `for-list` form prunes the result list along with evaluations of the *body*s:

```
> (for/list ([i (in-naturals 1)]
             [chapter '("Intro" "Details" "Conclusion")]
             #:when (odd? i))
    chapter)
'("Intro" "Conclusion")
```

This pruning behavior of `#:when` is more useful with `for/list` than `for`. Whereas a plain `when` form normally suffices with `for`, a `when` expression form in a `for/list` would cause the result list to contain `#<void>`s instead of omitting list elements.

The `for*/list` form is like `for*`, nesting multiple iterations:

```
> (for*/list ([book '("Guide" "Ref.")]
              [chapter '("Intro" "Details")])
    (string-append book " " chapter))
'("Guide Intro" "Guide Details" "Ref. Intro" "Ref. Details")
```

A `for*/list` form is not quite the same thing as nested `for/list` forms. Nested `for/list`s would produce a list of lists, instead of one flattened list. Much like `#:when`, then, the nesting of `for*/list` is more useful than the nesting of `for*`.

11.4 `for/vector` and `for*/vector`

The `for/vector` form can be used with the same syntax as the `for/list` form, but the evaluated *body*s go into a newly-constructed vector instead of a list:

```
> (for/vector ([i (in-naturals 1)]
               [chapter '("Intro" "Details" "Conclusion")])
    (string-append (number->string i) ". " chapter))
'#("1. Intro" "2. Details" "3. Conclusion")
```

The `for*/vector` form behaves similarly, but the iterations are nested as in `for*`.

The `for/vector` and `for*/vector` forms also allow the length of the vector to be constructed to be supplied in advance. The resulting iteration can be performed more efficiently than plain `for/vector` or `for*/vector`:

```
> (let ([chapters '("Intro" "Details" "Conclusion")])
    (for/vector #:length (length chapters) ([i (in-naturals 1)]
                                            [chapter chapters])
      (string-append (number->string i) ". " chapter)))
'#("1. Intro" "2. Details" "3. Conclusion")
```

If a length is provided, the iteration stops when the vector is filled or the requested iterations are complete, whichever comes first. If the provided length exceeds the requested number of iterations, then the remaining slots in the vector are initialized to the default argument of `make-vector`.

11.5 `for/and` and `for/or`

The `for/and` form combines iteration results with `and`, stopping as soon as it encounters `#f`:

```
> (for/and ([chapter '("Intro" "Details" "Conclusion")])
    (equal? chapter "Intro"))
#f
```

The `for/or` form combines iteration results with `or`, stopping as soon as it encounters a true value:

```
> (for/or ([chapter '("Intro" "Details" "Conclusion")])
    (equal? chapter "Intro"))
#t
```

As usual, the `for*/and` and `for*/or` forms provide the same facility with nested iterations.

11.6 `for/first` and `for/last`

The `for/first` form returns the result of the first time that the *body*s are evaluated, skipping further iterations. This form is most useful with a `#:when` clause.

```
> (for/first ([chapter '("Intro" "Details" "Conclusion" "Index")]
              #:when (not (equal? chapter "Intro")))
    chapter)
"Details"
```

If the *body*s are evaluated zero times, then the result is `#f`.

The `for/last` form runs all iterations, returning the value of the last iteration (or `#f` if no iterations are run):

```
> (for/last ([chapter '("Intro" "Details" "Conclusion" "Index")]
             #:when (not (equal? chapter "Index")))
    chapter)
"Conclusion"
```

As usual, the `for*/first` and `for*/last` forms provide the same facility with nested iterations:

```
> (for*/first ([book '("Guide" "Reference")]
```

```
               [chapter '("Intro" "Details" "Conclusion" "Index")]
               #:when (not (equal? chapter "Intro")))
    (list book chapter))
'("Guide" "Details")
> (for*/last ([book '("Guide" "Reference")]
              [chapter '("Intro" "Details" "Conclusion" "Index")]
              #:when (not (equal? chapter "Index")))
    (list book chapter))
'("Reference" "Conclusion")
```

11.7 `for/fold` and `for*/fold`

The `for/fold` form is a very general way to combine iteration results. Its syntax is slightly different than the syntax of `for`, because accumulation variables must be declared at the beginning:

```
(for/fold ([accum-id init-expr] ...)
          (clause ...)
  body ...+)
```

In the simple case, only one `[accum-id init-expr]` is provided, and the result of the `for/fold` is the final value for *accum-id*, which starts out with the value of *init-expr*. In the *clause*s and *body*s, *accum-id* can be referenced to get its current value, and the last *body* provides the value of *accum-id* for the next iteration.

Examples:

```
> (for/fold ([len 0])
            ([chapter '("Intro" "Conclusion")])
    (+ len (string-length chapter)))
15
> (for/fold ([prev #f])
            ([i (in-naturals 1)]
             [chapter '("Intro" "Details" "Details" "Conclusion")]
             #:when (not (equal? chapter prev)))
    (printf "~a. ~a\n" i chapter)
    chapter)
1. Intro
2. Details
4. Conclusion
"Conclusion"
```

When multiple *accum-id*s are specified, then the last *body* must produce multiple values, one for each *accum-id*. The `for/fold` expression itself produces multiple values for the results.

Example:

```
> (for/fold ([prev #f]
             [counter 1])
            ([chapter '("Intro" "Details" "Details" "Conclusion")]
             #:when (not (equal? chapter prev)))
    (printf "~a. ~a\n" counter chapter)
    (values chapter
            (add1 counter)))
1. Intro
2. Details
3. Conclusion
"Conclusion"
4
```

11.8 Multiple-Valued Sequences

In the same way that a function or expression can produce multiple values, individual iterations of a sequence can produce multiple elements. For example, a hash table as a sequence generates two values for each iteration: a key and a value.

In the same way that `let-values` binds multiple results to multiple identifiers, `for` can bind multiple sequence elements to multiple iteration identifiers:

While `let` must be changed to `let-values` to bind multiple identifiers, `for` simply allows a parenthesized list of identifiers instead of a single identifier in any clause.

```
> (for ([(k v) #hash(("apple" . 1) ("banana" . 3))])
    (printf "~a count: ~a\n" k v))
apple count: 1
banana count: 3
```

This extension to multiple-value bindings works for all `for` variants. For example, `for*/list` nests iterations, builds a list, and also works with multiple-valued sequences:

```
> (for*/list ([(k v) #hash(("apple" . 1) ("banana" . 3))]
              [(i) (in-range v)])
    k)
'("apple" "banana" "banana" "banana")
```

11.9 Breaking an Iteration

An even more complete syntax of `for` is

```
(for (clause ...)
  body-or-break ... body)

      clause = [id sequence-expr]
             | #:when boolean-expr
             | #:unless boolean-expr
             | break

body-or-break = body
              | break

       break = #:break boolean-expr
             | #:final boolean-expr
```

That is, a `#:break` or `#:final` clause can be included among the binding clauses and body of the iteration. Among the binding clauses, `#:break` is like `#:unless` but when its *boolean-expr* is true, all sequences within the `for` are stopped. Among the *body*s, `#:break` has the same effect on sequences when its *boolean-expr* is true, and it also prevents later *body*s from evaluation in the current iteration.

For example, while using `#:unless` between clauses effectively skips later sequences as well as the body,

```
> (for ([book '("Guide" "Story" "Reference")]
        #:unless (equal? book "Story")
        [chapter '("Intro" "Details" "Conclusion")])
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
Reference Intro
Reference Details
Reference Conclusion
```

using `#:break` causes the entire `for` iteration to terminate:

```
> (for ([book '("Guide" "Story" "Reference")]
        #:break (equal? book "Story")
        [chapter '("Intro" "Details" "Conclusion")])
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
> (for* ([book '("Guide" "Story" "Reference")]
         [chapter '("Intro" "Details" "Conclusion")])
    #:break (and (equal? book "Story")
```

```
                (equal? chapter "Conclusion"))
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
Story Intro
Story Details
```

A `#:final` clause is similar to `#:break`, but it does not immediately terminate the iteration. Instead, it allows at most one more element to be drawn for each sequence and at most one more evaluation of the *body*s.

```
> (for* ([book '("Guide" "Story" "Reference")]
         [chapter '("Intro" "Details" "Conclusion")])
    #:final (and (equal? book "Story")
                 (equal? chapter "Conclusion"))
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
Story Intro
Story Details
Story Conclusion
> (for ([book '("Guide" "Story" "Reference")]
        #:final (equal? book "Story")
        [chapter '("Intro" "Details" "Conclusion")])
    (printf "~a ~a\n" book chapter))
Guide Intro
Guide Details
Guide Conclusion
Story Intro
```

11.10 Iteration Performance

Ideally, a `for` iteration should run as fast as a loop that you write by hand as a recursive-function invocation. A hand-written loop, however, is normally specific to a particular kind of data, such as lists. In that case, the hand-written loop uses selectors like `car` and `cdr` directly, instead of handling all forms of sequences and dispatching to an appropriate iterator.

The `for` forms can provide the performance of hand-written loops when enough information is apparent about the sequences to iterate, specifically when the clause has one of the following *fast-clause* forms:

```
fast-clause = [id fast-seq]
```

```
              | [(id) fast-seq]
              | [(id id) fast-indexed-seq]
              | [(id ...) fast-parallel-seq]

fast-seq = literal
         | (in-range expr)
         | (in-range expr expr)
         | (in-range expr expr expr)
         | (in-inclusive-range expr expr)
         | (in-inclusive-range expr expr expr)
         | (in-naturals)
         | (in-naturals expr)
         | (in-list expr)
         | (in-mlist expr)
         | (in-vector expr)
         | (in-string expr)
         | (in-bytes expr)
         | (in-value expr)
         | (stop-before fast-seq predicate-expr)
         | (stop-after fast-seq predicate-expr)

fast-indexed-seq = (in-indexed fast-seq)
                 | (stop-before fast-indexed-seq predicate-expr)
                 | (stop-after fast-indexed-seq predicate-expr)

fast-parallel-seq = (in-parallel fast-seq ...)
                  | (stop-before fast-parallel-seq predicate-expr)
                  | (stop-after fast-parallel-seq predicate-expr)
```

Examples:

```
> (define lst '(a b c d e f g h))
> (time (for ([i (in-range 100000)])
          (for ([elem (in-list lst)])         ; fast
            (void))))
cpu time: 10 real time: 1 gc time: 0
> (time (for ([i (in-range 100000)])
          (for ([elem '(a b c d e f g h)])    ; also fast
            (void))))
cpu time: 12 real time: 1 gc time: 0
> (time (for ([i (in-range 100000)])
          (for ([elem lst])                   ; slower
            (void))))
cpu time: 37 real time: 5 gc time: 0
> (time (let ([seq (in-list lst)])
          (for ([i (in-range 100000)])
            (for ([elem seq])                 ; also slower
```

```
                (void)))))
cpu time: 64 real time: 9 gc time: 0
```

The grammars above are not complete, because the set of syntactic patterns that provide good performance is extensible, just like the set of sequence values. The documentation for a sequence constructor should indicate the performance benefits of using it directly in a `for` *clause*.

§3.18 “Iterations and Comprehensions: `for`, `for/list`, ...” in *The Racket Reference* provides more on iterations and comprehensions.

12 Pattern Matching

(require racket/match) is needed for #lang racket/base.

The match form supports pattern matching on arbitrary Racket values, as opposed to functions like regexp-match that compare regular expressions to byte and character sequences (see §9 “Regular Expressions”).

```
(match target-expr
  [pattern expr ...+] ...)
```

The match form takes the result of target-expr and tries to match each *pattern* in order. As soon as it finds a match, it evaluates the corresponding *expr* sequence to obtain the result for the match form. If *pattern* includes *pattern variables*, they are treated like wildcards, and each variable is bound in the *expr* to the input fragments that it matched.

Most Racket literal expressions can be used as patterns:

```
> (match 2
    [1 'one]
    [2 'two]
    [3 'three])
'two
> (match #f
    [#t 'yes]
    [#f 'no])
'no
> (match "apple"
    ['apple 'symbol]
    ["apple" 'string]
    [#f 'boolean])
'string
```

Constructors like cons, list, and vector can be used to create patterns that match pairs, lists, and vectors:

```
> (match '(1 2)
    [(list 0 1) 'one]
    [(list 1 2) 'two])
'two
> (match '(1 . 2)
    [(list 1 2) 'list]
    [(cons 1 2) 'pair])
'pair
> (match #(1 2)
    [(list 1 2) 'list]
    [(vector 1 2) 'vector])
```

```
'vector
```

A constructor bound with `struct` also can be used as a pattern constructor:

```
> (struct shoe (size color))
> (struct hat (size style))
> (match (hat 23 'bowler)
    [(shoe 10 'white) "bottom"]
    [(hat 23 'bowler) "top"])
"top"
```

Unquoted, non-constructor identifiers in a pattern are pattern variables that are bound in the result expressions, except `_`, which does not bind (and thus is usually used as a catch-all):

```
> (match '(1)
    [(list x) (+ x 1)]
    [(list x y) (+ x y)])
2
> (match '(1 2)
    [(list x) (+ x 1)]
    [(list x y) (+ x y)])
3
> (match (hat 23 'bowler)
    [(shoe sz col) sz]
    [(hat sz stl) sz])
23
> (match (hat 11 'cowboy)
    [(shoe sz 'black) 'a-good-shoe]
    [(hat sz 'bowler) 'a-good-hat]
    [_ 'something-else])
'something-else
```

Note that the identifier `else` is **not** a reserved catch-all (like `_`). If `else` appears in a pattern then its binding from `racket/base` may be shadowed, and this can cause problems with `cond` and `case`.

```
> (match 1
    [else
     (case 2
       [(a 1 b) 3]
       [else 4])])
eval:15:0: case: bad syntax (not a datum sequence)
  expected: a datum sequence or the binding 'else' from
racket/base
  given: a locally bound identifier
```

```
  at: else
  in: (case 2 ((a 1 b) 3) (else 4))
> (match #f
    [else
     (cond
       [#f 'not-evaluated]
       [else 'also-not-evaluated])])
```

To match against a value bound to an identifier, use ==.

```
> (define val 42)
> (match (list 42)
    [(list (== val)) 'matched])
'matched
> (match (list 43)
    [(list (== val)) 'not-matched]
    [_ 'this-branch-is-evaluated])
'this-branch-is-evaluated
> (match (list 43)
    [(list val)
     ; without ==, val is a pattern variable
     (format "match binds val to ~a" val)])
"match binds val to 43"
```

An ellipsis, written ..., acts like a Kleene star within a list or vector pattern: the preceding sub-pattern can be used to match any number of times for any number of consecutive elements of the list or vector. If a sub-pattern followed by an ellipsis includes a pattern variable, the variable matches multiple times, and it is bound in the result expression to a list of matches:

```
> (match '(1 1 1)
    [(list 1 ...) 'ones]
    [_ 'other])
'ones
> (match '(1 1 2)
    [(list 1 ...) 'ones]
    [_ 'other])
'other
> (match '(1 2 3 4)
    [(list 1 x ... 4) x])
'(2 3)
> (match (list (hat 23 'bowler) (hat 22 'pork-pie))
    [(list (hat sz styl) ...) (apply + sz)])
45
```

Ellipses can be nested to match nested repetitions, and in that case, pattern variables can be bound to lists of lists of matches:

```
> (match '((! 1) (! 2 2) (! 3 3 3))
    [(list (list '! x ...) ...) x])
'((1) (2 2) (3 3 3))
```

The `quasiquote` form (see §4.11 "Quasiquoting: `quasiquote` and `‘`" for more about it) can also be used to build patterns. While unquoted portions of a normal quasiquoted form mean regular racket evaluation, here unquoted portions mean go back to regular pattern matching.

So, in the example below, the with expression is the pattern and it gets rewritten into the application expression, using quasiquote as a pattern in the first instance and quasiquote to build an expression in the second.

```
> (match `{with {x 1} {+ x 1}}
    [`{with {,id ,rhs} ,body}
     `{{lambda {,id} ,body} ,rhs}])
'((lambda (x) (+ x 1)) 1)
```

For information on many more pattern forms, see `racket/match`.

Forms like `match-let` and `match-lambda` support patterns in positions that otherwise must be identifiers. For example, `match-let` generalizes `let` to a destructing bind:

```
> (match-let ([(list x y z) '(1 2 3)])
    (list z y x))
'(3 2 1)
```

For information on these additional forms, see `racket/match`.

§9 "Pattern Matching" in *The Racket Reference* provides more on pattern matching.

13 Classes and Objects

The chapter is based on a paper [Flatt06] for `#lang racket/base`.

A `class` expression denotes a first-class value, just like a `lambda` expression:

```
(class superclass-expr decl-or-expr ...)
```

The *superclass-expr* determines the superclass for the new class. Each *decl-or-expr* is either a declaration related to methods, fields, and initialization arguments, or it is an expression that is evaluated each time that the class is instantiated. In other words, instead of a method-like constructor, a class has initialization expressions interleaved with field and method declarations.

By convention, class names end with `%`. The built-in root class is `object%`. The following expression creates a class with public methods `get-size`, `grow`, and `eat`:

```
(class object%
  (init size)                ; initialization argument

  (define current-size size) ; field

  (super-new)                ; superclass initialization

  (define/public (get-size)
    current-size)

  (define/public (grow amt)
    (set! current-size (+ amt current-size)))

  (define/public (eat other-fish)
    (grow (send other-fish get-size))))
```

The `size` initialization argument must be supplied via a named argument when instantiating the class through the `new` form:

```
(new (class object% (init size) ....) [size 10])
```

Of course, we can also name the class and its instance:

```
(define fish% (class object% (init size) ....))
(define charlie (new fish% [size 10]))
```

In the definition of `fish%`, `current-size` is a private field that starts out with the value of the `size` initialization argument. Initialization arguments like `size` are available only during

class instantiation, so they cannot be referenced directly from a method. The `current-size` field, in contrast, is available to methods.

The `(super-new)` expression in `fish%` invokes the initialization of the superclass. In this case, the superclass is `object%`, which takes no initialization arguments and performs no work; `super-new` must be used, anyway, because a class must always invoke its superclass's initialization.

Initialization arguments, field declarations, and expressions such as `(super-new)` can appear in any order within a `class`, and they can be interleaved with method declarations. The relative order of expressions in the class determines the order of evaluation during instantiation. For example, if a field's initial value requires calling a method that works only after superclass initialization, then the field declaration must be placed after the `super-new` call. Ordering field and initialization declarations in this way helps avoid imperative assignment. The relative order of method declarations makes no difference for evaluation, because methods are fully defined before a class is instantiated.

13.1 Methods

Each of the three `define/public` declarations in `fish%` introduces a new method. The declaration uses the same syntax as a Racket function, but a method is not accessible as an independent function. A call to the `grow` method of a `fish%` object requires the `send` form:

```
> (send charlie grow 6)
> (send charlie get-size)
16
```

Within `fish%`, self methods can be called like functions, because the method names are in scope. For example, the `eat` method within `fish%` directly invokes the `grow` method. Within a class, attempting to use a method name in any way other than a method call results in a syntax error.

In some cases, a class must call methods that are supplied by the superclass but not overridden. In that case, the class can use `send` with `this` to access the method:

```
(define hungry-fish% (class fish% (super-new)
                       (define/public (eat-more fish1 fish2)
                         (send this eat fish1)
                         (send this eat fish2))))
```

Alternately, the class can declare the existence of a method using `inherit`, which brings the method name into scope for a direct call:

```
(define hungry-fish% (class fish% (super-new)
                       (inherit eat)
                       (define/public (eat-more fish1 fish2)
                         (eat fish1) (eat fish2))))
```

With the `inherit` declaration, if `fish%` had not provided an `eat` method, an error would be signaled in the evaluation of the `class` form for `hungry-fish%`. In contrast, with `(send this ....)`, an error would not be signaled until the `eat-more` method is called and the `send` form is evaluated. For this reason, `inherit` is preferred.

Another drawback of `send` is that it is less efficient than `inherit`. Invocation of a method via `send` involves finding a method in the target object's class at run time, making `send` comparable to an interface-based method call in Java. In contrast, `inherit`-based method invocations use an offset within the class's method table that is computed when the class is created.

To achieve performance similar to `inherit`-based method calls when invoking a method from outside the method's class, the programmer must use the `generic` form, which produces a class- and method-specific *generic method* to be invoked with `send-generic`:

```
(define get-fish-size (generic fish% get-size))

> (send-generic charlie get-fish-size)
16
> (send-generic (new hungry-fish% [size 32]) get-fish-size)
32
> (send-generic (new object%) get-fish-size)
generic:get-size: target is not an instance of the generic's
class
  target: (object)
  class name: fish%
```

Roughly speaking, the form translates the class and the external method name to a location in the class's method table. As illustrated by the last example, sending through a generic method checks that its argument is an instance of the generic's class.

Whether a method is called directly within a `class`, through a generic method, or through `send`, method overriding works in the usual way:

```
(define picky-fish% (class fish% (super-new)
                      (define/override (grow amt)

                        (super grow (* 3/4 amt)))))
(define daisy (new picky-fish% [size 20]))
```

```
> (send daisy eat charlie)
> (send daisy get-size)
32
```

The `grow` method in `picky-fish%` is declared with `define/override` instead of `define/public`, because `grow` is meant as an overriding declaration. If `grow` had been declared with `define/public`, an error would have been signaled when evaluating the `class` expression, because `fish%` already supplies `grow`.

Using `define/override` also allows the invocation of the overridden method via a `super` call. For example, the `grow` implementation in `picky-fish%` uses `super` to delegate to the superclass implementation.

13.2 Initialization Arguments

Since `picky-fish%` declares no initialization arguments, any initialization values supplied in `(new picky-fish% ....)` are propagated to the superclass initialization, i.e., to `fish%`. A subclass can supply additional initialization arguments for its superclass in a `super-new` call, and such initialization arguments take precedence over arguments supplied to `new`. For example, the following `size-10-fish%` class always generates fish of size 10:

```
(define size-10-fish% (class fish% (super-new [size 10])))

> (send (new size-10-fish%) get-size)
10
```

In the case of `size-10-fish%`, supplying a `size` initialization argument with `new` would result in an initialization error; because the `size` in `super-new` takes precedence, a `size` supplied to `new` would have no target declaration.

An initialization argument is optional if the `class` form declares a default value. For example, the following `default-10-fish%` class accepts a `size` initialization argument, but its value defaults to 10 if no value is supplied on instantiation:

```
(define default-10-fish% (class fish%
                           (init [size 10])
                           (super-new [size size])))

> (new default-10-fish%)
(object:default-10-fish% ...)
> (new default-10-fish% [size 20])
(object:default-10-fish% ...)
```

In this example, the `super-new` call propagates its own `size` value as the `size` initialization argument to the superclass.

13.3 Internal and External Names

The two uses of `size` in `default-10-fish%` expose the double life of class-member identifiers. When `size` is the first identifier of a bracketed pair in `new` or `super-new`, `size` is an *external name* that is symbolically matched to an initialization argument in a class. When `size` appears as an expression within `default-10-fish%`, `size` is an *internal name* that is lexically scoped. Similarly, a call to an inherited `eat` method uses `eat` as an internal name, whereas a `send` of `eat` uses `eat` as an external name.

The full syntax of the `class` form allows a programmer to specify distinct internal and external names for a class member. Since internal names are local, they can be renamed to avoid shadowing or conflicts. Such renaming is not frequently necessary, but workarounds in the absence of renaming can be especially cumbersome.

13.4 Interfaces

Interfaces are useful for checking that an object or a class implements a set of methods with a particular (implied) behavior. This use of interfaces is helpful even without a static type system (which is the main reason that Java has interfaces).

An interface in Racket is created using the `interface` form, which merely declares the method names required to implement the interface. An interface can extend other interfaces, which means that implementations of the interface automatically implement the extended interfaces.

```
(interface (superinterface-expr ...) id ...)
```

To declare that a class implements an interface, the `class*` form must be used instead of `class`:

```
(class* superclass-expr (interface-expr ...) decl-or-expr ...)
```

For example, instead of forcing all fish classes to be derived from `fish%`, we can define `fish-interface` and change the `fish%` class to declare that it implements `fish-interface`:

```
(define fish-interface (interface () get-size grow eat))
(define fish% (class* object% (fish-interface) ....))
```

If the definition of `fish%` does not include `get-size`, `grow`, and `eat` methods, then an error is signaled in the evaluation of the `class*` form, because implementing the `fish-interface` interface requires those methods.

The `is-a?` predicate accepts an object as its first argument and either a class or interface as its second argument. When given a class, `is-a?` checks whether the object is an instance of that class or a derived class. When given an interface, `is-a?` checks whether the object's class implements the interface. In addition, the `implementation?` predicate checks whether a given class implements a given interface.

13.5 Final, Augment, and Inner

As in Java, a method in a `class` form can be specified as *final*, which means that a subclass cannot override the method. A final method is declared using `public-final` or `override-final`, depending on whether the declaration is for a new method or an overriding implementation.

Between the extremes of allowing arbitrary overriding and disallowing overriding entirely, the class system also supports Beta-style *augmentable* methods [Goldberg04]. A method declared with `pubment` is like `public`, but the method cannot be overridden in subclasses; it can be augmented only. A `pubment` method must explicitly invoke an augmentation (if any) using `inner`; a subclass augments the method using `augment`, instead of `override`.

In general, a method can switch between augment and override modes in a class derivation. The `augride` method specification indicates an augmentation to a method where the augmentation is itself overrideable in subclasses (though the superclass's implementation cannot be overridden). Similarly, `overment` overrides a method and makes the overriding implementation augmentable.

13.6 Controlling the Scope of External Names

Java's access modifiers (like `protected`) play a role similar to `define-member-name`, but unlike in Java, Racket's mechanism for controlling access is based on lexical scope, not the inheritance hierarchy.

As noted in §13.3 "Internal and External Names", class members have both internal and external names. A member definition binds an internal name locally, and this binding can be locally renamed. External names, in contrast, have global scope by default, and a member definition does not bind an external name. Instead, a member definition refers to an existing binding for an external name, where the member name is bound to a *member key*; a class ultimately maps member keys to methods, fields, and initialization arguments.

Recall the `hungry-fish%` `class` expression:

```
(define hungry-fish% (class fish% ....
                       (inherit eat)
                       (define/public (eat-more fish1 fish2)
                         (eat fish1) (eat fish2))))
```

During its evaluation, the `hungry-fish%` and `fish%` classes refer to the same global binding of `eat`. At run time, calls to `eat` in `hungry-fish%` are matched with the `eat` method in `fish%` through the shared method key that is bound to `eat`.

The default binding for an external name is global, but a programmer can introduce an external-name binding with the `define-member-name` form.

```
(define-member-name id member-key-expr)
```

In particular, by using `(generate-member-key)` as the `member-key-expr`, an external name can be localized for a particular scope, because the generated member key is inaccessible outside the scope. In other words, `define-member-name` gives an external name a kind of package-private scope, but generalized from packages to arbitrary binding scopes in Racket.

For example, the following `fish%` and `pond%` classes cooperate via a `get-depth` method that is only accessible to the cooperating classes:

```
(define-values (fish% pond%) ; two mutually recursive classes
  (let ()
    (define-member-name get-depth (generate-member-key))
    (define fish%
      (class ....
        (define my-depth ....)
        (define my-pond ....)
        (define/public (dive amt)
        (set! my-depth
              (min (+ my-depth amt)
                   (send my-pond get-depth))))))
    (define pond%
      (class ....
        (define current-depth ....)
        (define/public (get-depth) current-depth)))
    (values fish% pond%)))
```

External names are in a namespace that separates them from other Racket names. This separate namespace is implicitly used for the method name in `send`, for initialization-argument names in `new`, or for the external name in a member definition. The special form `member-name-key` provides access to the binding of an external name in an arbitrary expression position: `(member-name-key id)` produces the member-key binding of `id` in the current scope.

A member-key value is primarily used with a `define-member-name` form. Normally, then, `(member-name-key id)` captures the method key of `id` so that it can be communicated to a use of `define-member-name` in a different scope. This capability turns out to be useful for generalizing mixins, as discussed next.

13.7 Mixins

Since `class` is an expression form instead of a top-level declaration as in Smalltalk and Java, a `class` form can be nested inside any lexical scope, including `lambda`. The result is a *mixin*, i.e., a class extension that is parameterized with respect to its superclass.

For example, we can parameterize the `picky-fish%` class over its superclass to define `picky-mixin`:

```
(define (picky-mixin %)
  (class % (super-new)
    (define/override (grow amt) (super grow (* 3/4 amt)))))
(define picky-fish% (picky-mixin fish%))
```

Many small differences between Smalltalk-style classes and Racket classes contribute to the effective use of mixins. In particular, the use of `define/override` makes explicit that `picky-mixin` expects a class with a `grow` method. If `picky-mixin` is applied to a class without a `grow` method, an error is signaled as soon as `picky-mixin` is applied.

Similarly, a use of `inherit` enforces a "method existence" requirement when the mixin is applied:

```
(define (hungry-mixin %)
  (class % (super-new)
    (inherit eat)
    (define/public (eat-more fish1 fish2)
      (eat fish1)
      (eat fish2))))
```

The advantage of mixins is that we can easily combine them to create new classes whose implementation sharing does not fit into a single-inheritance hierarchy—without the ambiguities associated with multiple inheritance. Equipped with `picky-mixin` and `hungry-mixin`, creating a class for a hungry, yet picky fish is straightforward:

```
(define picky-hungry-fish%
  (hungry-mixin (picky-mixin fish%)))
```

The use of keyword initialization arguments is critical for the easy use of mixins. For example, `picky-mixin` and `hungry-mixin` can augment any class with suitable `eat` and `grow` methods, because they do not specify initialization arguments and add none in their `super-new` expressions:

```
(define person%
  (class object%
    (init name age)
```

```
    ....
    (define/public (eat food) ....)
    (define/public (grow amt) ....)))
(define child% (hungry-mixin (picky-mixin person%)))
(define oliver (new child% [name "Oliver"] [age 6]))
```

Finally, the use of external names for class members (instead of lexically scoped identifiers) makes mixin use convenient. Applying `picky-mixin` to `person%` works because the names `eat` and `grow` match, without any a priori declaration that `eat` and `grow` should be the same method in `fish%` and `person%`. This feature is a potential drawback when member names collide accidentally; some accidental collisions can be corrected by limiting the scope external names, as discussed in §13.6 “Controlling the Scope of External Names”.

13.7.1 Mixins and Interfaces

Using `implementation?`, `picky-mixin` could require that its base class implements `grower-interface`, which could be implemented by both `fish%` and `person%`:

```
(define grower-interface (interface () grow))
(define (picky-mixin %)
  (unless (implementation? % grower-interface)
    (error "picky-mixin: not a grower-interface class"))
  (class % ....))
```

Another use of interfaces with a mixin is to tag classes generated by the mixin, so that instances of the mixin can be recognized. In other words, `is-a?` cannot work on a mixin represented as a function, but it can recognize an interface (somewhat like a *specialization interface*) that is consistently implemented by the mixin. For example, classes generated by `picky-mixin` could be tagged with `picky-interface`, enabling the `is-picky?` predicate:

```
(define picky-interface (interface ()))
(define (picky-mixin %)
  (unless (implementation? % grower-interface)
    (error "picky-mixin: not a grower-interface class"))
  (class* % (picky-interface) ....))
(define (is-picky? o)
  (is-a? o picky-interface))
```

13.7.2 The `mixin` Form

To codify the `lambda`-plus-`class` pattern for implementing mixins, including the use of interfaces for the domain and range of the mixin, the class system provides a `mixin` macro:

```
(mixin (interface-expr ...) (interface-expr ...)
  decl-or-expr ...)
```

The first set of `interface-expr`s determines the domain of the mixin, and the second set determines the range. That is, the expansion is a function that tests whether a given base class implements the first sequence of `interface-expr`s and produces a class that implements the second sequence of `interface-expr`s. Other requirements, such as the presence of `inherit`ed methods in the superclass, are then checked for the `class` expansion of the `mixin` form. For example:

```
> (define choosy-interface (interface () choose?))
> (define hungry-interface (interface () eat))
> (define choosy-eater-mixin
    (mixin (choosy-interface) (hungry-interface)
      (inherit choose?)
      (super-new)
      (define/public (eat x)
        (cond
          [(choose? x)
           (printf "chomp chomp chomp on ~a.\n" x)]
          [else
           (printf "I'm not crazy about ~a.\n" x)]))))
> (define herring-lover%
    (class* object% (choosy-interface)
      (super-new)
      (define/public (choose? x)
        (regexp-match #px"^herring" x))))
> (define herring-eater% (choosy-eater-mixin herring-lover%))
> (define eater (new herring-eater%))
> (send eater eat "elderberry")
I'm not crazy about elderberry.
> (send eater eat "herring")
chomp chomp chomp on herring.
> (send eater eat "herring ice cream")
chomp chomp chomp on herring ice cream.
```

Mixins not only override methods and introduce public methods, they can also augment methods, introduce augment-only methods, add an overrideable augmentation, and add an augmentable override — all of the things that a class can do (see §13.5 “Final, Augment, and Inner”).

13.7.3 Parameterized Mixins

As noted in §13.6 “Controlling the Scope of External Names”, external names can be bound with `define-member-name`. This facility allows a mixin to be generalized with respect to the methods that it defines and uses. For example, we can parameterize `hungry-mixin` with respect to the external member key for `eat`:

```
(define (make-hungry-mixin eat-method-key)
  (define-member-name eat eat-method-key)
  (mixin () () (super-new)
    (inherit eat)
    (define/public (eat-more x y) (eat x) (eat y))))
```

To obtain a particular hungry-mixin, we must apply this function to a member key that refers to a suitable `eat` method, which we can obtain using `member-name-key`:

```
((make-hungry-mixin (member-name-key eat))
 (class object% .... (define/public (eat x) 'yum)))
```

Above, we apply `hungry-mixin` to an anonymous class that provides `eat`, but we can also combine it with a class that provides `chomp`, instead:

```
((make-hungry-mixin (member-name-key chomp))
 (class object% .... (define/public (chomp x) 'yum)))
```

13.8 Traits

A *trait* is similar to a mixin, in that it encapsulates a set of methods to be added to a class. A trait is different from a mixin in that its individual methods can be manipulated with trait operators such as `trait-sum` (merge the methods of two traits), `trait-exclude` (remove a method from a trait), and `trait-alias` (add a copy of a method with a new name; do not redirect any calls to the old name).

The practical difference between mixins and traits is that two traits can be combined, even if they include a common method and even if neither method can sensibly override the other. In that case, the programmer must explicitly resolve the collision, usually by aliasing methods, excluding methods, and merging a new trait that uses the aliases.

Suppose our `fish%` programmer wants to define two class extensions, `spots` and `stripes`, each of which includes a `get-color` method. The fish’s spot color should not override the stripe color nor vice versa; instead, a `spots+stripes-fish%` should combine the two colors, which is not possible if `spots` and `stripes` are implemented as plain mixins. If, however, `spots` and `stripes` are implemented as traits, they can be combined. First, we alias `get-color` in each trait to a non-conflicting name. Second, the `get-color` methods

are removed from both and the traits with only aliases are merged. Finally, the new trait is used to create a class that introduces its own `get-color` method based on the two aliases, producing the desired `spots+stripes` extension.

13.8.1 Traits as Sets of Mixins

One natural approach to implementing traits in Racket is as a set of mixins, with one mixin per trait method. For example, we might attempt to define the spots and stripes traits as follows, using association lists to represent sets:

```
(define spots-trait
  (list (cons 'get-color
              (lambda (%) (class % (super-new)
                                 (define/public (get-color)
                                   'black))))))
(define stripes-trait
  (list (cons 'get-color
              (lambda (%) (class % (super-new)
                                 (define/public (get-color)
                                   'red))))))
```

A set representation, such as the above, allows `trait-sum` and `trait-exclude` as simple manipulations; unfortunately, it does not support the `trait-alias` operator. Although a mixin can be duplicated in the association list, the mixin has a fixed method name, e.g., `get-color`, and mixins do not support a method-rename operation. To support `trait-alias`, we must parameterize the mixins over the external method name in the same way that `eat` was parameterized in §13.7.3 “Parameterized Mixins”.

To support the `trait-alias` operation, `spots-trait` should be represented as:

```
(define spots-trait
  (list (cons (member-name-key get-color)
              (lambda (get-color-key %)
                (define-member-name get-color get-color-key)
                (class % (super-new)
                  (define/public (get-color) 'black))))))
```

When the `get-color` method in `spots-trait` is aliased to `get-trait-color` and the `get-color` method is removed, the resulting trait is the same as

```
(list (cons (member-name-key get-trait-color)
            (lambda (get-color-key %)
              (define-member-name get-color get-color-key)
              (class % (super-new)
                (define/public (get-color) 'black)))))
```

To apply a trait *T* to a class *C* and obtain a derived class, we use `((trait->mixin T) C)`. The `trait->mixin` function supplies each mixin of *T* with the key for the mixin's method and a partial extension of *C*:

```
(define ((trait->mixin T) C)
  (foldr (lambda (m %) ((cdr m) (car m) %)) C T))
```

Thus, when the trait above is combined with other traits and then applied to a class, the use of `get-color` becomes a reference to the external name `get-trait-color`.

13.8.2 Inherit and Super in Traits

This first implementation of traits supports `trait-alias`, and it supports a trait method that calls itself, but it does not support trait methods that call each other. In particular, suppose that a spot-fish's market value depends on the color of its spots:

```
(define spots-trait
  (list (cons (member-name-key get-color) ....)
        (cons (member-name-key get-price)
              (lambda (get-price %) ....
                (class % ....
                  (define/public (get-price)
                    .... (get-color) ....))))))
```

In this case, the definition of `spots-trait` fails, because `get-color` is not in scope for the `get-price` mixin. Indeed, depending on the order of mixin application when the trait is applied to a class, the `get-color` method may not be available when `get-price` mixin is applied to the class. Therefore adding an `(inherit get-color)` declaration to the `get-price` mixin does not solve the problem.

One solution is to require the use of `(send this get-color)` in methods such as `get-price`. This change works because `send` always delays the method lookup until the method call is evaluated. The delayed lookup is more expensive than a direct call, however. Worse, it also delays checking whether a `get-color` method even exists.

A second, effective, and efficient solution is to change the encoding of traits. Specifically, we represent each method as a pair of mixins: one that introduces the method and one that implements it. When a trait is applied to a class, all of the method-introducing mixins are applied first. Then the method-implementing mixins can use `inherit` to directly access any introduced method.

```
(define spots-trait
  (list (list (local-member-name-key get-color)
              (lambda (get-color get-price %) ....
```

```
          (class % ....
            (define/public (get-color) (void))))
        (lambda (get-color get-price %) ....
          (class % ....
            (define/override (get-color) 'black))))
  (list (local-member-name-key get-price)
        (lambda (get-color get-price %) ....
          (class % ....
            (define/public (get-price) (void))))
        (lambda (get-color get-price %) ....
          (class % ....
            (inherit get-color)
            (define/override (get-price)
              .... (get-color) ....))))))
```

With this trait encoding, `trait-alias` adds a new method with a new name, but it does not change any references to the old method.

13.8.3 The `trait` Form

`(require racket/trait)` is needed.

The general-purpose trait pattern is clearly too complex for a programmer to use directly, but it is easily codified in a `trait` macro:

```
(trait trait-clause ...)
```

The `id`s in the optional `inherit` clause are available for direct reference in the method `expr`s, and they must be supplied either by other traits or the base class to which the trait is ultimately applied.

Using this form in conjunction with trait operators such as `trait-sum`, `trait-exclude`, `trait-alias`, and `trait->mixin`, we can implement `spots-trait` and `stripes-trait` as desired.

```
(define spots-trait
  (trait
    (define/public (get-color) 'black)
    (define/public (get-price) ... (get-color) ...)))

(define stripes-trait
  (trait
    (define/public (get-color) 'red)))

(define spots+stripes-trait
```

```
(trait-sum
 (trait-exclude (trait-alias spots-trait
                             get-color get-spots-color)
                get-color)
 (trait-exclude (trait-alias stripes-trait
                             get-color get-stripes-color)
                get-color)
 (trait
   (inherit get-spots-color get-stripes-color)
   (define/public (get-color)
     .... (get-spots-color) .... (get-stripes-color) ....))))
```

13.9 Class Contracts

As classes are values, they can flow across contract boundaries, and we may wish to protect parts of a given class with contracts. For this, the `class/c` form is used. The `class/c` form has many subforms, which describe two types of contracts on fields and methods: those that affect uses via instantiated objects and those that affect subclasses.

13.9.1 External Class Contracts

In its simplest form, `class/c` protects the public fields and methods of objects instantiated from the contracted class. There is also an `object/c` form that can be used to similarly protect the public fields and methods of a particular object. Take the following definition of `animal%`, which uses a public field for its `size` attribute:

```
(define animal%
  (class object%
    (super-new)
    (field [size 10])
    (define/public (eat food)
      (set! size (+ size (get-field size food))))))
```

For any instantiated `animal%`, accessing the `size` field should return a positive number. Also, if the `size` field is set, it should be assigned a positive number. Finally, the `eat` method should receive an argument which is an object with a `size` field that contains a positive number. To ensure these conditions, we will define the `animal%` class with an appropriate contract:

```
(define positive/c (and/c number? positive?))
(define edible/c (object/c (field [size positive/c])))
(define/contract animal%
  (class/c (field [size positive/c])
```

```
          [eat (->m edible/c void?)])
  (class object%
    (super-new)
    (field [size 10])
    (define/public (eat food)
      (set! size (+ size (get-field size food))))))
```

Here we use `->m` to describe the behavior of `eat` since we do not need to describe any requirements for the `this` parameter. Now that we have our contracted class, we can see that the contracts on both `size` and `eat` are enforced:

```
> (define bob (new animal%))
> (set-field! size bob 3)
> (get-field size bob)
3
> (set-field! size bob 'large)
animal%: contract violation
  expected: positive/c
  given: 'large
  in: the size field in
      (class/c
       (eat
        (->m
         (object/c (field (size positive/c)))
         void?))
       (field (size positive/c)))
  contract from: (definition animal%)
  blaming: top-level
   (assuming the contract is correct)
  at: eval:31:0
> (define richie (new animal%))
> (send bob eat richie)
> (get-field size bob)
13
> (define rock (new object%))
> (send bob eat rock)
eat: contract violation
  expected: an object with the size field
  given: (object)
  fields: none
  in: the 1st argument of
      the eat method in
      (class/c
       (eat
        (->m
         (object/c (field (size positive/c)))
```

```
          void?))
        (field (size positive/c)))
  contract from: (definition animal%)
  contract on: animal%
  blaming: top-level
   (assuming the contract is correct)
  at: eval:31:0
> (define giant (new (class object% (super-
new) (field [size 'large]))))
> (send bob eat giant)
eat: contract violation
  expected: positive/c
  given: 'large
  in: the size field in
      the 1st argument of
      the eat method in
      (class/c
       (eat
        (->m
         (object/c (field (size positive/c)))
         void?))
       (field (size positive/c)))
  contract from: (definition animal%)
  contract on: animal%
  blaming: top-level
   (assuming the contract is correct)
  at: eval:31:0
```

There are two important caveats for external class contracts. First, external method contracts are only enforced when the target of dynamic dispatch is the method implementation of the contracted class, which lies within the contract boundary. Overriding that implementation, and thus changing the target of dynamic dispatch, will mean that the contract is no longer enforced for clients, since accessing the method no longer crosses the contract boundary. Unlike external method contracts, external field contracts are always enforced for clients of subclasses, since fields cannot be overridden or shadowed.

Second, these contracts do not restrict subclasses of `animal%` in any way. Fields and methods that are inherited and used by subclasses are not checked by these contracts, and uses of the superclass's methods via `super` are also unchecked. The following example illustrates both caveats:

```
(define large-animal%
  (class animal%
    (super-new)
    (inherit-field size)
    (set! size 'large)
```

```
    (define/override (eat food)
      (display "Nom nom nom") (newline))))

> (define elephant (new large-animal%))
> (send elephant eat (new object%))
Nom nom nom
> (get-field size elephant)
animal%: broke its own contract
  promised: positive/c
  produced: 'large
  in: the size field in
      (class/c
       (eat
        (->m
         (object/c (field (size positive/c)))
         void?))
       (field (size positive/c)))
  contract from: (definition animal%)
  blaming: (definition animal%)
   (assuming the contract is correct)
  at: eval:31:0
```

13.9.2 Internal Class Contracts

Notice that retrieving the `size` field from the object `elephant` blames `animal%` for the contract violation. This blame is correct, but unfair to the `animal%` class, as we have not yet provided it with a method for protecting itself from subclasses. To this end we add internal class contracts, which provide directives to subclasses for how they may access and override features of the superclass. This distinction between external and internal class contracts allows for weaker contracts within the class hierarchy, where invariants may be broken internally by subclasses but should be enforced for external uses via instantiated objects.

As a simple example of what kinds of protection are available, we provide an example aimed at the `animal%` class that uses all the applicable forms:

```
(class/c (field [size positive/c])
         (inherit-field [size positive/c])
         [eat (->m edible/c void?)]
         (inherit [eat (->m edible/c void?)])
         (super [eat (->m edible/c void?)])
         (override [eat (->m edible/c void?)]))
```

This class contract not only ensures that objects of class `animal%` are protected as before, but also ensure that subclasses of `animal%` only store appropriate values within the `size` field

and use the implementation of `size` from `animal%` appropriately. These contract forms only affect uses within the class hierarchy, and only for method calls that cross the contract boundary.

That means that `inherit` will only affect subclass uses of a method until a subclass overrides that method, and that `override` only affects calls from the superclass into a subclass's overriding implementation of that method. Since these only affect internal uses, the `override` form does not automatically enter subclasses into obligations when objects of those classes are used. Also, use of `override` only makes sense, and thus can only be used, for methods where no Beta-style augmentation has taken place. The following example shows this difference:

```
(define/contract glutton%
  (class/c (override [eat (->m edible/c void?)]))
  (class animal%
    (super-new)
    (inherit eat)
    (define/public (gulp food-list)
      (for ([f food-list])
        (eat f)))))
(define/contract sloppy-eater%
  (class/c [eat (->m edible/c edible/c)])
  (class glutton%
    (super-new)
    (inherit-field size)
    (define/override (eat f)
      (let ([food-size (get-field size f)])
        (set! size (/ food-size 2))
        (set-field! size f (/ food-size 2))
        f))))


> (define pig (new sloppy-eater%))
> (define slop1 (new animal%))
> (define slop2 (new animal%))
> (define slop3 (new animal%))
> (send pig eat slop1)
(object:animal% ...)
> (get-field size slop1)
5
> (send pig gulp (list slop1 slop2 slop3))
eat: contract violation
  expected: void?
  given: (object:animal% ...)
  in: the range of
      the eat method in
      (class/c
```

```
        (override (eat
                   (->m
                    (object/c
                     (field (size positive/c)))
                    void?))))
contract from: (definition glutton%)
contract on: glutton%
blaming: top-level
 (assuming the contract is correct)
at: eval:47:0
```

In addition to the internal class contract forms shown here, there are similar forms for Beta-style augmentable methods. The `inner` form describes to the subclass what is expected from augmentations of a given method. Both `augment` and `augride` tell the subclass that the given method is a method which has been augmented and that any calls to the method in the subclass will dynamically dispatch to the appropriate implementation in the superclass. Such calls will be checked according to the given contract. The two forms differ in that use of `augment` signifies that subclasses can augment the given method, whereas use of `augride` signifies that subclasses must override the current augmentation instead.

This means that not all forms can be used at the same time. Only one of the `override`, `augment`, and `augride` forms can be used for a given method, and none of these forms can be used if the given method has been finalized. In addition, `super` can be specified for a given method only if `augride` or `override` can be specified. Similarly, `inner` can be specified only if `augment` or `augride` can be specified.

14 Units (Components)

(require racket/unit) is needed for #lang racket/base.

Units organize a program into separately compilable and reusable *components*. A unit resembles a procedure in that both are first-class values that are used for abstraction. While procedures abstract over values in expressions, units abstract over names in collections of definitions. Just as a procedure is called to evaluate its expressions given actual arguments for its formal parameters, a unit is *invoked* to evaluate its definitions given actual references for its imported variables. Unlike a procedure, however, a unit's imported variables can be partially linked with the exported variables of another unit *prior to invocation*. Linking merges multiple units together into a single compound unit. The compound unit itself imports variables that will be propagated to unresolved imported variables in the linked units, and re-exports some variables from the linked units for further linking.

14.1 Signatures and Units

The interface of a unit is described in terms of *signatures*. Each signature is defined (normally within a module) using define-signature. For example, the following signature, placed in a "toy-factory-sig.rkt" file, describes the exports of a component that implements a toy factory:

By convention, signature names end with ^.

"toy-factory-sig.rkt"

```
#lang racket

(define-signature toy-factory^
  (build-toys  ; (integer? -> (listof toy?))
   repaint     ; (toy? symbol? -> toy?)
   toy?        ; (any/c -> boolean?)
   toy-color)) ; (toy? -> symbol?)

(provide toy-factory^)
```

An implementation of the toy-factory^ signature is written using define-unit with an export clause that names toy-factory^:

By convention, unit names end with @.

"simple-factory-unit.rkt"

```
#lang racket

(require "toy-factory-sig.rkt")

(define-unit simple-factory@
  (import)
  (export toy-factory^)
```

```
  (printf "Factory started.\n")

  (struct toy (color) #:transparent)

  (define (build-toys n)
    (for/list ([i (in-range n)])
      (toy 'blue)))

  (define (repaint t col)
    (toy col)))

(provide simple-factory@)
```

The `toy-factory^` signature also could be referenced by a unit that needs a toy factory to implement something else. In that case, `toy-factory^` would be named in an `import` clause. For example, a toy store would get toys from a toy factory. (Suppose, for the sake of an example with interesting features, that the store is willing to sell only toys in a particular color.)

"toy-store-sig.rkt"

```
#lang racket

(define-signature toy-store^
  (store-color     ; (-> symbol?)
   stock!          ; (integer? -> void?)
   get-inventory)) ; (-> (listof toy?))

(provide toy-store^)
```

"toy-store-unit.rkt"

```
#lang racket

(require "toy-store-sig.rkt"
         "toy-factory-sig.rkt")

(define-unit toy-store@
  (import toy-factory^)
  (export toy-store^)

  (define inventory null)

  (define (store-color) 'green)

  (define (maybe-repaint t)
    (if (eq? (toy-color t) (store-color))
```

```
        t
        (repaint t (store-color))))

  (define (stock! n)
    (set! inventory
          (append inventory
                  (map maybe-repaint
                       (build-toys n)))))

  (define (get-inventory) inventory))

(provide toy-store@)
```

Note that `"toy-store-unit.rkt"` imports `"toy-factory-sig.rkt"`, but not `"simple-factory-unit.rkt"`. Consequently, the `toy-store@` unit relies only on the specification of a toy factory, not on a specific implementation.

14.2 Invoking Units

The `simple-factory@` unit has no imports, so it can be invoked directly using `invoke-unit`:

```
> (require "simple-factory-unit.rkt")
> (invoke-unit simple-factory@)
Factory started.
```

The `invoke-unit` form does not make the body definitions available, however, so we cannot build any toys with this factory. The `define-values/invoke-unit` form binds the identifiers of a signature to the values supplied by a unit (to be invoked) that implements the signature:

```
> (define-values/invoke-unit/infer simple-factory@)
Factory started.
> (build-toys 3)
(list (toy 'blue) (toy 'blue) (toy 'blue))
```

Since `simple-factory@` exports the `toy-factory^` signature, each identifier in `toy-factory^` is defined by the `define-values/invoke-unit/infer` form. The `/infer` part of the form name indicates that the identifiers bound by the declaration are inferred from `simple-factory@`.

Now that the identifiers in `toy-factory^` are defined, we can also invoke `toy-store@`, which imports `toy-factory^` to produce `toy-store^`:

```
> (require "toy-store-unit.rkt")
> (define-values/invoke-unit/infer toy-store@)
> (get-inventory)
'()
> (stock! 2)
> (get-inventory)
(list (toy 'green) (toy 'green))
```

Again, the `/infer` part `define-values/invoke-unit/infer` determines that `toy-store@` imports `toy-factory^`, and so it supplies the top-level bindings that match the names in `toy-factory^` as imports to `toy-store@`.

14.3 Linking Units

We can make our toy economy more efficient by having toy factories that cooperate with stores, creating toys that do not have to be repainted. Instead, the toys are always created using the store's color, which the factory gets by importing `toy-store^`:

`"store-specific-factory-unit.rkt"`

```
#lang racket

(require "toy-store-sig.rkt"
         "toy-factory-sig.rkt")

(define-unit store-specific-factory@
  (import toy-store^)
  (export toy-factory^)

  (struct toy () #:transparent)

  (define (toy-color t) (store-color))

  (define (build-toys n)
    (for/list ([i (in-range n)])
      (toy)))

  (define (repaint t col)
    (error "cannot repaint")))

(provide store-specific-factory@)
```

To invoke `store-specific-factory@`, we need `toy-store^` bindings to supply to the unit. But to get `toy-store^` bindings by invoking `toy-store@`, we will need a toy factory!

The unit implementations are mutually dependent, and we cannot invoke either before the other.

The solution is to *link* the units together, and then we can invoke the combined units. The `define-compound-unit/infer` form links any number of units to form a combined unit. It can propagate imports and exports from the linked units, and it can satisfy each unit's imports using the exports of other linked units.

```
> (require "toy-factory-sig.rkt")
> (require "toy-store-sig.rkt")
> (require "toy-store-unit.rkt")
> (require "store-specific-factory-unit.rkt")
> (define-compound-unit/infer toy-store+factory@
    (import)
    (export toy-factory^ toy-store^)
    (link store-specific-factory@
          toy-store@))
```

The overall result above is a unit `toy-store+factory@` that exports both `toy-factory^` and `toy-store^`. The connection between `store-specific-factory@` and `toy-store@` is inferred from the signatures that each imports and exports.

This unit has no imports, so we can always invoke it:

```
> (define-values/invoke-unit/infer toy-store+factory@)
> (stock! 2)
> (get-inventory)
(list (toy) (toy))
> (map toy-color (get-inventory))
'(green green)
```

14.4 First-Class Units

The `define-unit` form combines `define` with a `unit` form, similar to the way that `(define (f x) ....)` combines `define` followed by an identifier with an implicit `lambda`.

Expanding the shorthand, the definition of `toy-store@` could almost be written as

```
(define toy-store@
  (unit
   (import toy-factory^)
   (export toy-store^)

   (define inventory null)
```

```
  (define (store-color) 'green)
  ....))
```

A difference between this expansion and `define-unit` is that the imports and exports of `toy-store@` cannot be inferred. That is, besides combining `define` and `unit`, `define-unit` attaches static information to the defined identifier so that its signature information is available statically to `define-values/invoke-unit/infer` and other forms.

Despite the drawback of losing static signature information, `unit` can be useful in combination with other forms that work with first-class values. For example, we could wrap a `unit` that creates a toy store in a `lambda` to supply the store's color:

`"toy-store-maker.rkt"`

```
#lang racket

(require "toy-store-sig.rkt"
         "toy-factory-sig.rkt")

(define toy-store@-maker
  (lambda (the-color)
    (unit
     (import toy-factory^)
     (export toy-store^)

     (define inventory null)

     (define (store-color) the-color)

     ; the rest is the same as before

     (define (maybe-repaint t)
       (if (eq? (toy-color t) (store-color))
           t
           (repaint t (store-color))))

     (define (stock! n)
       (set! inventory
             (append inventory
                     (map maybe-repaint
                          (build-toys n)))))

     (define (get-inventory) inventory))))

(provide toy-store@-maker)
```

To invoke a unit created by `toy-store@-maker`, we must use `define-values/invoke-`

unit, instead of the /infer variant:

```
> (require "simple-factory-unit.rkt")
> (define-values/invoke-unit/infer simple-factory@)
Factory started.
> (require "toy-store-maker.rkt")
> (define-values/invoke-unit (toy-store@-maker 'purple)
    (import toy-factory^)
    (export toy-store^))
> (stock! 2)
> (get-inventory)
(list (toy 'purple) (toy 'purple))
```

In the define-values/invoke-unit form, the (import toy-factory^) line takes bindings from the current context that match the names in toy-factory^ (the ones that we created by invoking simple-factory@), and it supplies them as imports to toy-store@. The (export toy-store^) clause indicates that the unit produced by toy-store@-maker will export toy-store^, and the names from that signature are defined after invoking the unit.

To link a unit from toy-store@-maker, we can use the compound-unit form:

```
> (require "store-specific-factory-unit.rkt")
> (define toy-store+factory@
    (compound-unit
     (import)
     (export TF TS)
     (link [((TF : toy-factory^)) store-specific-factory@ TS]
           [((TS : toy-store^)) toy-store@ TF])))
```

This compound-unit form packs a lot of information into one place. The left-hand-side TF and TS in the link clause are binding identifiers. The identifier TF is essentially bound to the elements of toy-factory^ as implemented by store-specific-factory@. The identifier TS is similarly bound to the elements of toy-store^ as implemented by toy-store@. Meanwhile, the elements bound to TS are supplied as imports for store-specific-factory@, since TS follows store-specific-factory@. The elements bound to TF are similarly supplied to toy-store@. Finally, (export TF TS) indicates that the elements bound to TF and TS are exported from the compound unit.

The above compound-unit form uses store-specific-factory@ as a first-class unit, even though its information could be inferred. Every unit can be used as a first-class unit, in addition to its use in inference contexts. Also, various forms let a programmer bridge the gap between inferred and first-class worlds. For example, define-unit-binding binds a new identifier to the unit produced by an arbitrary expression; it statically associates signature information to the identifier, and it dynamically checks the signatures against the first-class unit produced by the expression.

14.5 Whole-`module` Signatures and Units

In programs that use units, modules like `"toy-factory-sig.rkt"` and `"simple-factory-unit.rkt"` are common. The `racket/signature` and `racket/unit` module names can be used as languages to avoid much of the boilerplate module, signature, and unit declaration text.

For example, `"toy-factory-sig.rkt"` can be written as

```
#lang racket/signature

build-toys  ; (integer? -> (listof toy?))
repaint     ; (toy? symbol? -> toy?)
toy?        ; (any/c -> boolean?)
toy-color   ; (toy? -> symbol?)
```

The signature `toy-factory^` is automatically provided from the module, inferred from the filename `"toy-factory-sig.rkt"` by replacing the `"-sig.rkt"` suffix with `^`.

Similarly, `"simple-factory-unit.rkt"` module can be written

```
#lang racket/unit

(require "toy-factory-sig.rkt")

(import)
(export toy-factory^)

(printf "Factory started.\n")

(struct toy (color) #:transparent)

(define (build-toys n)
  (for/list ([i (in-range n)])
    (toy 'blue)))

(define (repaint t col)
  (toy col))
```

The unit `simple-factory@` is automatically provided from the module, inferred from the filename `"simple-factory-unit.rkt"` by replacing the `"-unit.rkt"` suffix with `@`.

14.6 Contracts for Units

There are a couple of ways of protecting units with contracts. One way is useful when writing new signatures, and the other handles the case when a unit must conform to an already existing signature.

14.6.1 Adding Contracts to Signatures

When contracts are added to a signature, then all units which implement that signature are protected by those contracts. The following version of the `toy-factory^` signature adds the contracts previously written in comments:

`"contracted-toy-factory-sig.rkt"`

```
#lang racket

(define-signature contracted-toy-factory^
  ((contracted
    [build-toys (-> integer? (listof toy?))]
    [repaint    (-> toy? symbol? toy?)]
    [toy?       (-> any/c boolean?)]
    [toy-color  (-> toy? symbol?)])))

(provide contracted-toy-factory^)
```

Now we take the previous implementation of `simple-factory@` and implement this version of `toy-factory^` instead:

`"contracted-simple-factory-unit.rkt"`

```
#lang racket

(require "contracted-toy-factory-sig.rkt")

(define-unit contracted-simple-factory@
  (import)
  (export contracted-toy-factory^)

  (printf "Factory started.\n")

  (struct toy (color) #:transparent)

  (define (build-toys n)
    (for/list ([i (in-range n)])
      (toy 'blue)))
```

```
  (define (repaint t col)
    (toy col)))

(provide contracted-simple-factory@)
```

As before, we can invoke our new unit and bind the exports so that we can use them. This time, however, misusing the exports causes the appropriate contract errors.

```
> (require "contracted-simple-factory-unit.rkt")
> (define-values/invoke-unit/infer contracted-simple-factory@)
Factory started.
> (build-toys 3)
(list (toy 'blue) (toy 'blue) (toy 'blue))
> (build-toys #f)
build-toys: contract violation
  expected: integer?
  given: #f
  in: the 1st argument of
      (-> integer? (listof toy?))
  contract from:
      (unit contracted-simple-factory@)
  blaming: top-level
   (assuming the contract is correct)
  at: <collects>/racket/private/unit/exptime/import-export.r
kt:498:23
> (repaint 3 'blue)
repaint: contract violation
  expected: toy?
  given: 3
  in: the 1st argument of
      (-> toy? symbol? toy?)
  contract from:
      (unit contracted-simple-factory@)
  blaming: top-level
   (assuming the contract is correct)
  at: <collects>/racket/private/unit/exptime/import-export.r
kt:498:23
```

14.6.2 Adding Contracts to Units

However, sometimes we may have a unit that must conform to an already existing signature that is not contracted. In this case, we can create a unit contract with `unit/c` or use the `define-unit/contract` form, which defines a unit which has been wrapped with a unit contract.

For example, here's a version of `toy-factory@` which still implements the regular `toy-factory^`, but whose exports have been protected with an appropriate unit contract.

`"wrapped-simple-factory-unit.rkt"`

```
#lang racket

(require "toy-factory-sig.rkt")

(define-unit/contract wrapped-simple-factory@
  (import)
  (export (toy-factory^
           [build-toys (-> integer? (listof toy?))]
           [repaint    (-> toy? symbol? toy?)]
           [toy?       (-> any/c boolean?)]
           [toy-color  (-> toy? symbol?)])))

  (printf "Factory started.\n")

  (struct toy (color) #:transparent)

  (define (build-toys n)
    (for/list ([i (in-range n)])
      (toy 'blue)))

  (define (repaint t col)
    (toy col)))

(provide wrapped-simple-factory@)
```

```
> (require "wrapped-simple-factory-unit.rkt")
> (define-values/invoke-unit/infer wrapped-simple-factory@)
Factory started.
toy?228: undefined;
 cannot use before initialization
> (build-toys 3)
(list (toy 'blue) (toy 'blue) (toy 'blue))
> (build-toys #f)
build-toys: contract violation
  expected: integer?
  given: #f
  in: the 1st argument of
      (-> integer? (listof toy?))
  contract from:
      (unit contracted-simple-factory@)
  blaming: top-level
   (assuming the contract is correct)
```

```
  at: <collects>/racket/private/unit/exptime/import-export.r
kt:498:23
> (repaint 3 'blue)
repaint: contract violation
  expected: toy?
  given: 3
  in: the 1st argument of
      (-> toy? symbol? toy?)
  contract from:
      (unit contracted-simple-factory@)
  blaming: top-level
   (assuming the contract is correct)
  at: <collects>/racket/private/unit/exptime/import-export.r
kt:498:23
```

14.7 `unit` versus `module`

As a form for modularity, `unit` complements `module`:

- The `module` form is primarily for managing a universal namespace. For example, it allows a code fragment to refer specifically to the `car` operation from `racket/base`—the one that extracts the first element of an instance of the built-in pair datatype—as opposed to any number of other functions with the name `car`. In other words, the `module` construct lets you refer to *the* binding that you want.

- The `unit` form is for parameterizing a code fragment with respect to most any kind of run-time value. For example, it allows a code fragment to work with a `car` function that accepts a single argument, where the specific function is determined later by linking the fragment to another. In other words, the `unit` construct lets you refer to *a* binding that meets some specification.

The `lambda` and `class` forms, among others, also allow parameterization of code with respect to values that are chosen later. In principle, any of those could be implemented in terms of any of the others. In practice, each form offers certain conveniences—such as allowing overriding of methods or especially simple application to values—that make them suitable for different purposes.

The `module` form is more fundamental than the others, in a sense. After all, a program fragment cannot reliably refer to a `lambda`, `class`, or `unit` form without the namespace management provided by `module`. At the same time, because namespace management is closely related to separate expansion and compilation, `module` boundaries end up as separate-compilation boundaries in a way that prohibits mutual dependencies among fragments. For similar reasons, `module` does not separate interface from implementation.

Use `unit` when `module` by itself almost works, but when separately compiled pieces must refer to each other, or when you want a stronger separation between *interface* (i.e., the parts that need to be known at expansion and compilation time) and *implementation* (i.e., the run-time parts). More generally, use `unit` when you need to parameterize code over functions, datatypes, and classes, and when the parameterized code itself provides definitions to be linked with other parameterized code.

15 Reflection and Dynamic Evaluation

Racket is a *dynamic* language. It offers numerous facilities for loading, compiling, and even constructing new code at run time.

15.1 `eval`

The `eval` function takes a representation of an expression or definition (as a "quoted" form or syntax object) and evaluates it:

```
> (eval '(+ 1 2))
3
```

This example will not work within a module or in DrRacket's definitions window, but it will work in the interactions window, for reasons that are explained by the end of §15.1.2 "Namespaces".

The power of `eval` is that an expression can be constructed dynamically:

```
> (define (eval-formula formula)
    (eval `(let ([x 2]
                 [y 3])
             ,formula)))
> (eval-formula '(+ x y))
5
> (eval-formula '(+ (* x y) y))
9
```

Of course, if we just wanted to evaluate expressions with given values for `x` and `y`, we do not need `eval`. A more direct approach is to use first-class functions:

```
> (define (apply-formula formula-proc)
    (formula-proc 2 3))
> (apply-formula (lambda (x y) (+ x y)))
5
> (apply-formula (lambda (x y) (+ (* x y) y)))
9
```

However, if expressions like `(+ x y)` and `(+ (* x y) y)` are read from a file supplied by a user, for example, then `eval` might be appropriate. Similarly, the REPL reads expressions that are typed by a user and uses `eval` to evaluate them.

Also, `eval` is often used directly or indirectly on whole modules. For example, a program might load a module on demand using `dynamic-require`, which is essentially a wrapper around `eval` to dynamically load the module code.

15.1.1 Local Scopes

The `eval` function cannot see local bindings in the context where it is called. For example, calling `eval` inside an unquoted `let` form to evaluate a formula does not make values visible for `x` and `y`:

```
> (define (broken-eval-formula formula)
    (let ([x 2]
          [y 3])
      (eval formula)))
> (broken-eval-formula '(+ x y))
x: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

The `eval` function cannot see the `x` and `y` bindings precisely because it is a function, and Racket is a lexically scoped language. Imagine if `eval` were implemented as

```
(define (eval x)
  (eval-expanded (macro-expand x)))
```

then at the point when `eval-expanded` is called, the most recent binding of `x` is to the expression to evaluate, not the `let` binding in `broken-eval-formula`. Lexical scope prevents such confusing and fragile behavior, and consequently prevents `eval` from seeing local bindings in the context where it is called.

You might imagine that even though `eval` cannot see the local bindings in `broken-eval-formula`, there must actually be a data structure mapping `x` to `2` and `y` to `3`, and you would like a way to get that data structure. In fact, no such data structure exists; the compiler is free to replace every use of `x` with `2` at compile time, so that the local binding of `x` does not exist in any concrete sense at run-time. Even when variables cannot be eliminated by constant-folding, normally the names of the variables can be eliminated, and the data structures that hold local values do not resemble a mapping from names to values.

15.1.2 Namespaces

Since `eval` cannot see the bindings from the context where it is called, another mechanism is needed to determine dynamically available bindings. A *namespace* is a first-class value that encapsulates the bindings available for dynamic evaluation.

Some functions, such as `eval`, accept an optional namespace argument. More often, the namespace used by a dynamic operation is the *current namespace* as determined by the `current-namespace` parameter.

Informally, the term *namespace* is sometimes used interchangeably with *environment* or *scope*. In Racket, the term *namespace* has the more specific, dynamic meaning given above, and it should not be confused with static lexical concepts.

When `eval` is used in a REPL, the current namespace is the one that the REPL uses for evaluating expressions. That's why the following interaction successfully accesses `x` via `eval`:

```
> (define x 3)
> (eval 'x)
3
```

In contrast, try the following simple module and running it directly in DrRacket or supplying the file as a command-line argument to `racket`:

```
#lang racket

(eval '(cons 1 2))
```

This fails because the initial current namespace is empty. When you run `racket` in interactive mode (see §21.1.1 "Interactive Mode"), the initial namespace is initialized with the exports of the `racket` module, but when you run a module directly, the initial namespace starts empty.

In general, it's a bad idea to use `eval` with whatever namespace happens to be installed. Instead, create a namespace explicitly and install it for the call to eval:

```
#lang racket

(define ns (make-base-namespace))
(eval '(cons 1 2) ns) ; works
```

The `make-base-namespace` function creates a namespace that is initialized with the exports of `racket/base`. The later section §15.2 "Manipulating Namespaces" provides more information on creating and configuring namespaces.

15.1.3 Namespaces and Modules

As with `let` bindings, lexical scope means that `eval` cannot automatically see the definitions of a `module` in which it is called. Unlike `let` bindings, however, Racket provides a way to reflect a module into a namespace.

The `module->namespace` function takes a quoted module path and produces a namespace for evaluating expressions and definitions as if they appeared in the `module` body:

```
> (module m racket/base
    (define x 11))
> (require 'm)
```

```
> (define ns (module->namespace ''m))
> (eval 'x ns)
11
```

The double quoting in `''m` is because `'m` is a module path that refers to an interactively declared module, and so `''m` is the quoted form of the path.

The `module->namespace` function is mostly useful from outside a module, where the module's full name is known. Inside a `module` form, however, the full name of a module may not be known, because it may depend on where the module source is located when it is eventually loaded.

From within a `module`, use `define-namespace-anchor` to declare a reflection hook on the module, and use `namespace-anchor->namespace` to reel in the module's namespace:

```
#lang racket

(define-namespace-anchor a)
(define ns (namespace-anchor->namespace a))

(define x 1)
(define y 2)

(eval '(cons x y) ns) ; produces (1 . 2)
```

15.2 Manipulating Namespaces

A namespace encapsulates two pieces of information:

- A mapping from identifiers to bindings. For example, a namespace might map the identifier `lambda` to the `lambda` form. An "empty" namespace is one that maps every identifier to an uninitialized top-level variable.
- A mapping from module names to module declarations and instances. (The distinction between declaration and instance is discussed in §16.3 "Module Instantiations and Visits".)

The first mapping is used for evaluating expressions in a top-level context, as in `(eval '(lambda (x) (+ x 1)))`. The second mapping is used, for example, by `dynamic-require` to locate a module. The call `(eval '(require racket/base))` normally uses both pieces: the identifier mapping determines the binding of `require`; if it turns out to mean `require`, then the module mapping is used to locate the `racket/base` module.

From the perspective of the core Racket run-time system, all evaluation is reflective. Execution starts with an initial namespace that contains a few primitive modules, and that is further populated by loading files and modules as specified on the command line or as supplied in the REPL. Top-level `require` and `define` forms adjusts the identifier mapping, and module declarations (typically loaded on demand for a `require` form) adjust the module mapping.

15.2.1 Creating and Installing Namespaces

The function make-empty-namespace creates a new, empty namespace. Since the namespace is truly empty, it cannot at first be used to evaluate any top-level expression—not even (require racket). In particular,

```
(parameterize ([current-namespace (make-empty-namespace)])
  (namespace-require 'racket))
```

fails, because the namespace does not include the primitive modules on which racket is built.

To make a namespace useful, some modules must be *attached* from an existing namespace. Attaching a module adjusts the mapping of module names to instances by transitively copying entries (the module and all its imports) from an existing namespace's mapping. Normally, instead of just attaching the primitive modules—whose names and organization are subject to change—a higher-level module is attached, such as racket or racket/base.

The make-base-empty-namespace function provides a namespace that is empty, except that racket/base is attached. The resulting namespace is still "empty" in the sense that the identifiers-to-bindings part of the namespace has no mappings; only the module mapping has been populated. Nevertheless, with an initial module mapping, further modules can be loaded.

A namespace created with make-base-empty-namespace is suitable for many basic dynamic tasks. For example, suppose that a my-dsl library implements a domain-specific language in which you want to execute commands from a user-specified file. A namespace created with make-base-empty-namespace is enough to get started:

```
(define (run-dsl file)
  (parameterize ([current-namespace (make-base-empty-namespace)])
    (namespace-require 'my-dsl)
    (load file)))
```

Note that the parameterize of current-namespace does not affect the meaning of identifiers like namespace-require within the parameterize body. Those identifiers obtain their meaning from the enclosing context (probably a module). Only expressions that are dynamic with respect to this code, such as the content of loaded files, are affected by the parameterize.

Another subtle point in the above example is the use of (namespace-require 'my-dsl) instead of (eval '(require my-dsl)). The latter would not work, because eval needs to obtain a meaning for require in the namespace, and the namespace's identifier mapping is initially empty. The namespace-require function, in contrast, directly imports the given module into the current namespace. Starting with (namespace-require 'racket/base)

would introduce a binding for `require` and make a subsequent `(eval '(require my-dsl))` work. The above is better, not only because it is more compact, but also because it avoids introducing bindings that are not part of the domain-specific languages.

15.2.2 Sharing Data and Code Across Namespaces

Modules not attached to a new namespace will be loaded and instantiated afresh if they are demanded by evaluation. For example, `racket/base` does not include `racket/class`, and loading `racket/class` again will create a distinct class datatype:

```
> (require racket/class)
> (class? object%)
#t
> (class?
   (parameterize ([current-namespace (make-base-empty-namespace)])
     (namespace-require 'racket/class) ; loads again
     (eval 'object%)))
#f
```

For cases when dynamically loaded code needs to share more code and data with its context, use the `namespace-attach-module` function. The first argument to `namespace-attach-module` is a source namespace from which to draw a module instance; in some cases, the current namespace is known to include the module that needs to be shared:

```
> (require racket/class)
> (class?
   (let ([ns (make-base-empty-namespace)])
     (namespace-attach-module (current-namespace)
                              'racket/class
                              ns)
     (parameterize ([current-namespace ns])
       (namespace-require 'racket/class) ; uses attached
       (eval 'object%))))
#t
```

Within a module, however, the combination of `define-namespace-anchor` and `namespace-anchor->empty-namespace` offers a more reliable method for obtaining a source namespace:

```
#lang racket/base

(require racket/class)

(define-namespace-anchor a)
```

```
(define (load-plug-in file)
  (let ([ns (make-base-empty-namespace)])
    (namespace-attach-module (namespace-anchor->empty-namespace a)
                             'racket/class
                             ns)
    (parameterize ([current-namespace ns])
      (dynamic-require file 'plug-in%))))
```

The anchor bound by `namespace-attach-module` connects the run time of a module with the namespace in which a module is loaded (which might differ from the current namespace). In the above example, since the enclosing module requires `racket/class`, the namespace produced by `namespace-anchor->empty-namespace` certainly contains an instance of `racket/class`. Moreover, that instance is the same as the one imported into the module, so the class datatype is shared.

15.3 Scripting Evaluation and Using `load`

Historically, Lisp implementations did not offer module systems. Instead, large programs were built by essentially scripting the REPL to evaluate program fragments in a particular order. While REPL scripting turns out to be a bad way to structure programs and libraries, it is still sometimes a useful capability.

Describing a program via `load` interacts especially badly with macro-defined language extensions [Flatt02].

The `load` function runs a REPL script by `read`ing S-expressions from a file, one by one, and passing them to `eval`. If a file `"place.rkts"` contains

```
(define city "Salt Lake City")
(define state "Utah")
(printf "~a, ~a\n" city state)
```

then it can be loaded in a REPL:

```
> (load "place.rkts")
Salt Lake City, Utah
> city
"Salt Lake City"
```

Since `load` uses `eval`, however, a module like the following generally will not work—for the same reasons described in §15.1.2 “Namespaces”:

```
#lang racket

(define there "Utopia")

(load "here.rkts")
```

The current namespace for evaluating the content of "here.rkts" is likely to be empty; in any case, you cannot get there from "here.rkts". Also, any definitions in "here.rkts" will not become visible for use within the module; after all, the load happens dynamically, while references to identifiers within the module are resolved lexically, and therefore statically.

Unlike eval, load does not accept a namespace argument. To supply a namespace to load, set the current-namespace parameter. The following example evaluates the expressions in "here.rkts" using the bindings of the racket/base module:

```
#lang racket

(parameterize ([current-namespace (make-base-namespace)])
  (load "here.rkts"))
```

You can even use namespace-anchor->namespace to make the bindings of the enclosing module accessible for dynamic evaluation. In the following example, when "here.rkts" is loaded, it can refer to there as well as the bindings of racket:

```
#lang racket

(define there "Utopia")

(define-namespace-anchor a)
(parameterize ([current-namespace (namespace-anchor-
>namespace a)])
  (load "here.rkts"))
```

Still, if "here.rkts" defines any identifiers, the definitions cannot be directly (i.e., statically) referenced by in the enclosing module.

The racket/load module language is different from racket or racket/base. A module using racket/load treats all of its content as dynamic, passing each form in the module body to eval (using a namespace that is initialized with racket). As a result, uses of eval and load in the module body see the same dynamic namespace as immediate body forms. For example, if "here.rkts" contains

```
(define here "Morporkia")
(define (go!) (set! here there))
```

then running

```
#lang racket/load

(define there "Utopia")
```

```
(load "here.rkts")

(go!)
(printf "~a\n" here)
```

prints “Utopia”.

Drawbacks of using `racket/load` include reduced error checking, tool support, and performance. For example, with the program

```
#lang racket/load

(define good 5)
(printf "running\n")
good
bad
```

DrRacket’s Check Syntax tool cannot tell that the second `good` is a reference to the first, and the unbound reference to `bad` is reported only at run time instead of rejected syntactically.

15.4 Code Inspectors for Trusted and Untrusted Code

Code inspectors provide the mechanism for determining which modules are trusted to use functions like `module->namespace` or unsafe modules like `ffi/unsafe`. When a module is declared, the value of `current-code-inspector` is associated to the module declaration. When a module is instantiated (i.e., when the body of the declaration is actually executed), a sub-inspector is created to guard the module’s exports. Access to the module’s protected exports requires a code inspector that is stronger (i.e., higher in the inspector hierarchy) than the module’s instantiation inspector; note that a module’s declaration inspector is always stronger than its instantiation inspector, so modules are declared with the same code inspector can access each other’s exports.

To distinguish between trusted and untrusted code, load trusted code first, then set `current-code-inspector` to the result of `(make-inspector (current-code-inspector))` to install a weaker inspector, and finally load untrusted code with the weaker inspector in place. The weaker inspector should stay in place when any untrusted code is run. If necessary, trusted code can restore the original inspector temporarily during the dynamic extent of trusted code (as long as it does not call back into untrusted code).

Syntax-object constants within a module, such as literal identifiers in a template, retain the inspector of their source module. In this way, a macro from a trusted module can be used within an untrusted module, and protected identifiers in the macro expansion still work, even through they ultimately appear in an untrusted module. To prevent abuse of identifiers

by extracting them from expanded code, functions like `local-expand` are protected, and functions like `expand` return tainted syntax if not given a sufficiently powerful inspector.

Compiled code from a `".zo"` file is inherently untrustworthy, unfortunately, since it can be synthesized by means other than `compile`. When compiled code is written to a `".zo"` file, syntax-object constants within the compiled code lose their inspectors. All syntax-object constants within compiled code acquire the enclosing module's declaration-time inspector when the code is loaded.

16 Macros

A *macro* is a syntactic form with an associated *transformer* that *expands* the original form into existing forms. To put it another way, a macro is an extension to the Racket compiler. Most of the syntactic forms of `racket/base` and `racket` are actually macros that expand into a small set of core constructs.

Like many languages, Racket provides pattern-based macros that make simple transformations easy to implement and reliable to use. Racket also supports arbitrary macro transformers that are implemented in Racket—or in a macro-extended variant of Racket.

This chapter provides an introduction to Racket macros, but see *Fear of Macros* for an introduction from a different perspective.

Racket includes additional support for macro development: A *macro debugger* to make it easier for experienced programmers to debug their macros and for novices to study their behavior, and of macros. And the *syntax/parse library* for writing macros and specifying syntax that automatically validates macro uses and reports syntax errors.

16.1 Pattern-Based Macros

A *pattern-based macro* replaces any code that matches a pattern to an expansion that uses parts of the original syntax that match parts of the pattern.

16.1.1 `define-syntax-rule`

The simplest way to create a macro is to use `define-syntax-rule`:

```
(define-syntax-rule pattern template)
```

As a running example, consider the `swap` macro, which swaps the values stored in two variables. It can be implemented using `define-syntax-rule` as follows:

```
(define-syntax-rule (swap x y)
  (let ([tmp x])
    (set! x y)
    (set! y tmp)))
```

The macro is "un-Rackety" in the sense that it involves side effects on variables—but the point of macros is to let you add syntactic forms that some other language designer might not approve.

The `define-syntax-rule` form binds a macro that matches a single pattern. The pattern must always start with an open parenthesis followed by an identifier, which is `swap` in this case. After the initial identifier, other identifiers are *macro pattern variables* that can match

anything in a use of the macro. Thus, this macro matches the form `(swap form1 form2)` for any *form1* and *form2*.

Macro pattern variables are similar to pattern variables for `match`. See §12 “Pattern Matching”.

After the pattern in `define-syntax-rule` is the *template*. The template is used in place of a form that matches the pattern, except that each instance of a pattern variable in the template is replaced with the part of the macro use the pattern variable matched. For example, in

```
(swap first last)
```

the pattern variable `x` matches `first` and `y` matches `last`, so that the expansion is

```
(let ([tmp first])
  (set! first last)
  (set! last tmp))
```

16.1.2 Lexical Scope

Suppose that we use the `swap` macro to swap variables named `tmp` and `other`:

```
(let ([tmp 5]
      [other 6])
  (swap tmp other)
  (list tmp other))
```

The result of the above expression should be `(6 5)`. The naive expansion of this use of `swap`, however, is

```
(let ([tmp 5]
      [other 6])
  (let ([tmp tmp])
    (set! tmp other)
    (set! other tmp))
  (list tmp other))
```

whose result is `(5 6)`. The problem is that the naive expansion confuses the `tmp` in the context where `swap` is used with the `tmp` that is in the macro template.

Racket doesn’t produce the naive expansion for the above use of `swap`. Instead, it produces

```
(let ([tmp 5]
      [other 6])
  (let ([tmp_1 tmp])
    (set! tmp other)
    (set! other tmp_1))
  (list tmp other))
```

with the correct result in `(6 5)`. Similarly, in the example

```
(let ([set! 5]
      [other 6])
  (swap set! other)
  (list set! other))
```

the expansion is

```
(let ([set!_1 5]
      [other 6])
  (let ([tmp set!_1])
    (set! set!_1 other)
    (set! other tmp))
  (list set!_1 other))
```

so that the local `set!` binding doesn't interfere with the assignments introduced by the macro template.

In other words, Racket's pattern-based macros automatically maintain lexical scope, so macro implementors can reason about variable reference in macros and macro uses in the same way as for functions and function calls.

16.1.3 `define-syntax` and `syntax-rules`

The `define-syntax-rule` form binds a macro that matches a single pattern, but Racket's macro system supports transformers that match multiple patterns starting with the same identifier. To write such macros, the programmer must use the more general `define-syntax` form along with the `syntax-rules` transformer form:

```
(define-syntax id
  (syntax-rules (literal-id ...)
    [pattern template]
    ...))
```

The `define-syntax-rule` form is itself a macro that expands into `define-syntax` with a `syntax-rules` form that contains only one pattern and template.

For example, suppose we would like a `rotate` macro that generalizes `swap` to work on either two or three identifiers, so that

```
(let ([red 1] [green 2] [blue 3])
  (rotate red green)      ; swaps
  (rotate red green blue) ; rotates left
  (list red green blue))
```

produces `(1 3 2)`. We can implement `rotate` using `syntax-rules`:

```
(define-syntax rotate
  (syntax-rules ()
    [(rotate a b) (swap a b)]
    [(rotate a b c) (begin
                      (swap a b)
                      (swap b c))]))
```

The expression `(rotate red green)` matches the first pattern in the `syntax-rules` form, so it expands to `(swap red green)`. The expression `(rotate red green blue)` matches the second pattern, so it expands to `(begin (swap red green) (swap green blue))`.

16.1.4 Matching Sequences

A better `rotate` macro would allow any number of identifiers, instead of just two or three. To match a use of `rotate` with any number of identifiers, we need a pattern form that has something like a Kleene star. In a Racket macro pattern, a star is written as `...`.

To implement `rotate` with `...`, we need a base case to handle a single identifier, and an inductive case to handle more than one identifier:

```
(define-syntax rotate
  (syntax-rules ()
    [(rotate a) (void)]
    [(rotate a b c ...) (begin
                          (swap a b)
                          (rotate b c ...))]))
```

When a pattern variable like `c` is followed by `...` in a pattern, then it must be followed by `...` in a template, too. The pattern variable effectively matches a sequence of zero or more forms, and it is replaced in the template by the same sequence.

Both versions of `rotate` so far are a bit inefficient, since pairwise swapping keeps moving the value from the first variable into every variable in the sequence until it arrives at the last one. A more efficient `rotate` would move the first value directly to the last variable. We can use `...` patterns to implement the more efficient variant using a helper macro:

```
(define-syntax rotate
  (syntax-rules ()
    [(rotate a c ...)
     (shift-to (c ... a) (a c ...))]))
```

```
(define-syntax shift-to
  (syntax-rules ()
    [(shift-to (from0 from ...) (to0 to ...))
     (let ([tmp from0])
       (set! to from) ...
       (set! to0 tmp))]))
```

In the `shift-to` macro, `...` in the template follows `(set! to from)`, which causes the `(set! to from)` expression to be duplicated as many times as necessary to use each identifier matched in the `to` and `from` sequences. (The number of `to` and `from` matches must be the same, otherwise the macro expansion fails with an error.)

16.1.5 Identifier Macros

Given our macro definitions, the `swap` or `rotate` identifiers must be used after an open parenthesis, otherwise a syntax error is reported:

```
> (+ swap 3)
eval:2:0: swap: bad syntax
  in: swap
```

An *identifier macro* is a pattern-matching macro that works when used by itself without parentheses. For example, we can define `val` as an identifier macro that expands to `(get-val)`, so `(+ val 3)` would expand to `(+ (get-val) 3)`.

```
> (define-syntax val
    (lambda (stx)
      (syntax-case stx ()
        [val (identifier? (syntax val)) (syntax (get-val))])))
> (define-values (get-val put-val!)
    (let ([private-val 0])
      (values (lambda () private-val)
              (lambda (v) (set! private-val v)))))
> val
0
> (+ val 3)
3
```

The `val` macro uses `syntax-case`, which enables defining more powerful macros and will be explained in the §16.2.3 “Mixing Patterns and Expressions: `syntax-case`” section. For now it is sufficient to know that to define a macro, `syntax-case` is used in a `lambda`, and its templates must be wrapped with an explicit `syntax` constructor. Finally, `syntax-case` clauses may specify additional guard conditions after the pattern.

Our `val` macro uses an `identifier?` condition to ensure that `val` *must not* be used with parentheses. Instead, the macro raises a syntax error:

```
> (val)
eval:8:0: val: bad syntax
  in: (val)
```

16.1.6 `set!` Transformers

With the above `val` macro, we still must call `put-val!` to change the stored value. It would be more convenient, however, to use `set!` directly on `val`. To invoke the macro when `val` is used with `set!`, we create an assignment transformer with `make-set!-transformer`. We must also declare `set!` as a literal in the `syntax-case` literal list.

```
> (define-syntax val2
    (make-set!-transformer
     (lambda (stx)
       (syntax-case stx (set!)
         [val2 (identifier? (syntax val2)) (syntax (get-val))]
         [(set! val2 e) (syntax (put-val! e))]))))
> val2
0
> (+ val2 3)
3
> (set! val2 10)
> val2
10
```

16.1.7 Macro-Generating Macros

Suppose that we have many identifiers like `val` and `val2` that we'd like to redirect to accessor and mutator functions like `get-val` and `put-val!`. We'd like to be able to just write:

```
(define-get/put-id val get-val put-val!)
```

Naturally, we can implement `define-get/put-id` as a macro:

```
> (define-syntax-rule (define-get/put-id id get put!)
    (define-syntax id
      (make-set!-transformer
       (lambda (stx)
         (syntax-case stx (set!)
           [id (identifier? (syntax id)) (syntax (get))]
```

```
            [(set! id e) (syntax (put! e))])))))
> (define-get/put-id val3 get-val put-val!)
> (set! val3 11)
> val3
11
```

The `define-get/put-id` macro is a *macro-generating macro*.

16.1.8 Extended Example: Call-by-Reference Functions

We can use pattern-matching macros to add a form to Racket for defining first-order *call-by-reference* functions. When a call-by-reference function body mutates its formal argument, the mutation applies to variables that are supplied as actual arguments in a call to the function.

For example, if `define-cbr` is like `define` except that it defines a call-by-reference function, then

```
(define-cbr (f a b)
  (swap a b))

(let ([x 1] [y 2])
  (f x y)
  (list x y))
```

produces `(2 1)`.

We will implement call-by-reference functions by having function calls supply accessor and mutators for the arguments, instead of supplying argument values directly. In particular, for the function `f` above, we'll generate

```
(define (do-f get-a get-b put-a! put-b!)
  (define-get/put-id a get-a put-a!)
  (define-get/put-id b get-b put-b!)
  (swap a b))
```

and redirect a function call `(f x y)` to

```
(do-f (lambda () x)
      (lambda () y)
      (lambda (v) (set! x v))
      (lambda (v) (set! y v)))
```

Clearly, then `define-cbr` is a macro-generating macro, which binds `f` to a macro that expands to a call of `do-f`. That is, `(define-cbr (f a b) (swap a b))` needs to generate the definition

```
(define-syntax f
  (syntax-rules ()
    [(id actual ...)
     (do-f (lambda () actual)
           ...
           (lambda (v)
             (set! actual v))
           ...)]))
```

At the same time, `define-cbr` needs to define `do-f` using the body of `f`, this second part is slightly more complex, so we defer most of it to a `define-for-cbr` helper module, which lets us write `define-cbr` easily enough:

```
(define-syntax-rule (define-cbr (id arg ...) body)
  (begin
    (define-syntax id
      (syntax-rules ()
        [(id actual (... ...))
         (do-f (lambda () actual)
               (... ...)
               (lambda (v)
                 (set! actual v))
               (... ...))]))
    (define-for-cbr do-f (arg ...)
      () ; explained below...
      body)))
```

Our remaining task is to define `define-for-cbr` so that it converts

```
(define-for-cbr do-f (a b) () (swap a b))
```

to the function definition `do-f` above. Most of the work is generating a `define-get/put-id` declaration for each argument, `a` and `b`, and putting them before the body. Normally, that's an easy task for `...` in a pattern and template, but this time there's a catch: we need to generate the names `get-a` and `put-a!` as well as `get-b` and `put-b!`, and the pattern language provides no way to synthesize identifiers based on existing identifiers.

As it turns out, lexical scope gives us a way around this problem. The trick is to iterate expansions of `define-for-cbr` once for each argument in the function, and that's why `define-for-cbr` starts with an apparently useless `()` after the argument list. We need to keep track of all the arguments seen so far and the `get` and `put` names generated for each,

in addition to the arguments left to process. After we've processed all the identifiers, then we have all the names we need.

Here is the definition of `define-for-cbr`:

```
(define-syntax define-for-cbr
  (syntax-rules ()
    [(define-for-cbr do-f (id0 id ...)
       (gens ...) body)
     (define-for-cbr do-f (id ...)
       (gens ... (id0 get put)) body)]
    [(define-for-cbr do-f ()
       ((id get put) ...) body)
     (define (do-f get ... put ...)
       (define-get/put-id id get put) ...
       body)]))
```

Step-by-step, expansion proceeds as follows:

```
(define-for-cbr do-f (a b)
  () (swap a b))
=> (define-for-cbr do-f (b)
     ([a get_1 put_1]) (swap a b))
=> (define-for-cbr do-f ()
     ([a get_1 put_1] [b get_2 put_2]) (swap a b))
=> (define (do-f get_1 get_2 put_1 put_2)
     (define-get/put-id a get_1 put_1)
     (define-get/put-id b get_2 put_2)
     (swap a b))
```

The "subscripts" on `get_1`, `get_2`, `put_1`, and `put_2` are inserted by the macro expander to preserve lexical scope, since the `get` generated by each iteration of `define-for-cbr` should not bind the `get` generated by a different iteration. In other words, we are essentially tricking the macro expander into generating fresh names for us, but the technique illustrates some of the surprising power of pattern-based macros with automatic lexical scope.

The last expression eventually expands to just

```
(define (do-f get_1 get_2 put_1 put_2)
  (let ([tmp (get_1)])
    (put_1 (get_2))
    (put_2 tmp)))
```

which implements the call-by-name function `f`.

To summarize, then, we can add call-by-reference functions to Racket with just three small pattern-based macros: `define-cbr`, `define-for-cbr`, and `define-get/put-id`.

16.2 General Macro Transformers

The `define-syntax` form creates a *transformer binding* for an identifier, which is a binding that can be used at compile time while expanding expressions to be evaluated at run time. The compile-time value associated with a transformer binding can be anything; if it is a procedure of one argument, then the binding is used as a macro, and the procedure is the *macro transformer*.

16.2.1 Syntax Objects

The input and output of a macro transformer (i.e., source and replacement forms) are represented as *syntax objects*. A syntax object contains symbols, lists, and constant values (such as numbers) that essentially correspond to the `quoted` form of the expression. For example, a representation of the expression `(+ 1 2)` contains the symbol `'+` and the numbers `1` and `2`, all in a list. In addition to this quoted content, a syntax object associates source-location and lexical-binding information with each part of the form. The source-location information is used when reporting syntax errors (for example), and the lexical-binding information allows the macro system to maintain lexical scope. To accommodate this extra information, the representation of the expression `(+ 1 2)` is not merely `'(+ 1 2)`, but a packaging of `'(+ 1 2)` into a syntax object.

To create a literal syntax object, use the `syntax` form:

```
> (syntax (+ 1 2))
#<syntax:eval:1:0 (+ 1 2)>
```

In the same way that `'` abbreviates `quote`, `#'` abbreviates `syntax`:

```
> #'(+ 1 2)
#<syntax:eval:1:0 (+ 1 2)>
```

A syntax object that contains just a symbol is an *identifier syntax object*. Racket provides some additional operations specific to identifier syntax objects, including the `identifier?` operation to detect identifiers. Most notably, `free-identifier=?` determines whether two identifiers refer to the same binding:

```
> (identifier? #'car)
#t
> (identifier? #'(+ 1 2))
#f
> (free-identifier=? #'car #'cdr)
#f
> (free-identifier=? #'car #'car)
#t
```

```
> (require (only-in racket/base [car also-car]))
> (free-identifier=? #'car #'also-car)
#t
```

To see the lists, symbols, numbers, etc. within a syntax object, use `syntax->datum`:

```
> (syntax->datum #'(+ 1 2))
'(+ 1 2)
```

The `syntax-e` function is similar to `syntax->datum`, but it unwraps a single layer of source-location and lexical-context information, leaving sub-forms that have their own information wrapped as syntax objects:

```
> (syntax-e #'(+ 1 2))
'(#<syntax:eval:1:0 +> #<syntax:eval:1:0 1> #<syntax:eval:1:0 2>)
```

The `syntax-e` function always leaves syntax-object wrappers around sub-forms that are represented via symbols, numbers, and other literal values. The only time it unwraps extra sub-forms is when unwrapping a pair, in which case the `cdr` of the pair may be recursively unwrapped, depending on how the syntax object was constructed.

The opposite of `syntax->datum` is, of course, `datum->syntax`. In addition to a datum like `'(+ 1 2)`, `datum->syntax` needs an existing syntax object to donate its lexical context, and optionally another syntax object to donate its source location:

```
> (datum->syntax #'lex
                 '(+ 1 2)
                 #'srcloc)
#<syntax:eval:1:0 (+ 1 2)>
```

In the above example, the lexical context of `#'lex` is used for the new syntax object, while the source location of `#'srcloc` is used.

When the second (i.e., the "datum") argument to `datum->syntax` includes syntax objects, those syntax objects are preserved intact in the result. That is, deconstructing the result with `syntax-e` eventually produces the syntax objects that were given to `datum->syntax`.

16.2.2 Macro Transformer Procedures

Any procedure of one argument can be a macro transformer. As it turns out, the `syntax-rules` form is a macro that expands to a procedure form. For example, if you evaluate a `syntax-rules` form directly (instead of placing on the right-hand of a `define-syntax` form), the result is a procedure:

```
> (syntax-rules () [(nothing) something])
#<procedure>
```

Instead of using `syntax-rules`, you can write your own macro transformer procedure directly using `lambda`. The argument to the procedure is a syntax object that represents the source form, and the result of the procedure must be a syntax object that represents the replacement form:

```
> (define-syntax self-as-string
    (lambda (stx)
      (datum->syntax stx
                     (format "~s" (syntax->datum stx)))))
> (self-as-string (+ 1 2))
"(self-as-string (+ 1 2))"
```

The source form passed to a macro transformer represents an expression in which its identifier is used in an application position (i.e., after a parenthesis that starts an expression), or it represents the identifier by itself if it is used as an expression position and not in an application position.

```
> (self-as-string (+ 1 2))
"(self-as-string (+ 1 2))"
> self-as-string
"self-as-string"
```

The procedure produced by `syntax-rules` raises a syntax error if its argument corresponds to a use of the identifier by itself, which is why `syntax-rules` does not implement an identifier macro.

The `define-syntax` form supports the same shortcut syntax for functions as `define`, so that the following `self-as-string` definition is equivalent to the one that uses `lambda` explicitly:

```
> (define-syntax (self-as-string stx)
    (datum->syntax stx
                   (format "~s" (syntax->datum stx))))
> (self-as-string (+ 1 2))
"(self-as-string (+ 1 2))"
```

16.2.3 Mixing Patterns and Expressions: `syntax-case`

The procedure generated by `syntax-rules` internally uses `syntax-e` to deconstruct the given syntax object, and it uses `datum->syntax` to construct the result. The `syntax-rules` form doesn't provide a way to escape from pattern-matching and template-construction mode into an arbitrary Racket expression.

The `syntax-case` form lets you mix pattern matching, template construction, and arbitrary expressions:

```
(syntax-case stx-expr (literal-id ...)
  [pattern expr]
  ...)
```

Unlike `syntax-rules`, the `syntax-case` form does not produce a procedure. Instead, it starts with a *stx-expr* expression that determines the syntax object to match against the *pattern*s. Also, each `syntax-case` clause has a *pattern* and *expr*, instead of a *pattern* and *template*. Within an *expr*, the `syntax` form—usually abbreviated with `#'`—shifts into template-construction mode; if the *expr* of a clause starts with `#'`, then we have something like a `syntax-rules` form:

```
> (syntax->datum
   (syntax-case #'(+ 1 2) ()
    [(op n1 n2) #'(- n1 n2)]))
'(- 1 2)
```

We could write the `swap` macro using `syntax-case` instead of `define-syntax-rule` or `syntax-rules`:

```
(define-syntax (swap stx)
  (syntax-case stx ()
    [(swap x y) #'(let ([tmp x])
                    (set! x y)
                    (set! y tmp))]))
```

One advantage of using `syntax-case` is that we can provide better error reporting for `swap`. For example, with the `define-syntax-rule` definition of `swap`, then `(swap x 2)` produces a syntax error in terms of `set!`, because `2` is not an identifier. We can refine our `syntax-case` implementation of `swap` to explicitly check the sub-forms:

```
(define-syntax (swap stx)
  (syntax-case stx ()
    [(swap x y)
     (if (and (identifier? #'x)
              (identifier? #'y))
         #'(let ([tmp x])
             (set! x y)
             (set! y tmp))
         (raise-syntax-error #f
                             "not an identifier"
                             stx
                             (if (identifier? #'x)
                                 #'y
                                 #'x)))]))
```

With this definition, `(swap x 2)` provides a syntax error originating from `swap` instead of `set!`.

In the above definition of `swap`, `#'x` and `#'y` are templates, even though they are not used as the result of the macro transformer. This example illustrates how templates can be used to access pieces of the input syntax, in this case for checking the form of the pieces. Also, the match for `#'x` or `#'y` is used in the call to `raise-syntax-error`, so that the syntax-error message can point directly to the source location of the non-identifier.

16.2.4 `with-syntax` and `generate-temporaries`

Since `syntax-case` lets us compute with arbitrary Racket expressions, we can more simply solve a problem that we had in writing `define-for-cbr` (see §16.1.8 "Extended Example: Call-by-Reference Functions"), where we needed to generate a set of names based on a sequence `id ...`:

```
(define-syntax (define-for-cbr stx)
  (syntax-case stx ()
    [(_ do-f (id ...) body)
     ....
       #'(define (do-f get ... put ...)
           (define-get/put-id id get put) ...
           body) ....]))
```

In place of the `....`s above, we need to bind `get ...` and `put ...` to lists of generated identifiers. We cannot use `let` to bind `get` and `put`, because we need bindings that count as pattern variables, instead of normal local variables. The `with-syntax` form lets us bind pattern variables:

```
(define-syntax (define-for-cbr stx)
  (syntax-case stx ()
    [(_ do-f (id ...) body)
     (with-syntax ([(get ...) ....]
                   [(put ...) ....])
       #'(define (do-f get ... put ...)
           (define-get/put-id id get put) ...
           body))]))
```

Now we need an expression in place of `....` that generates as many identifiers as there are `id` matches in the original pattern. Since this is a common task, Racket provides a helper function, `generate-temporaries`, that takes a sequence of identifiers and returns a sequence of generated identifiers:

```
(define-syntax (define-for-cbr stx)
```

```
  (syntax-case stx ()
    [(_ do-f (id ...) body)
     (with-syntax ([(get ...) (generate-temporaries #'(id ...))]
                   [(put ...) (generate-temporaries #'(id ...))])
       #'(define (do-f get ... put ...)
           (define-get/put-id id get put) ...
           body))]))
```

This way of generating identifiers is normally easier to think about than tricking the macro expander into generating names with purely pattern-based macros.

In general, the left-hand side of a `with-syntax` binding is a pattern, just like in `syntax-case`. In fact, a `with-syntax` form is just a `syntax-case` form turned partially inside-out.

16.2.5 Compile and Run-Time Phases

As sets of macros get more complicated, you might want to write your own helper functions, like `generate-temporaries`. For example, to provide good syntax error messages, `swap`, `rotate`, and `define-cbr` all should check that certain sub-forms in the source form are identifiers. We could use a `check-ids` function to perform this checking everywhere:

```
(define-syntax (swap stx)
  (syntax-case stx ()
    [(swap x y) (begin
                  (check-ids stx #'(x y))
                  #'(let ([tmp x])
                      (set! x y)
                      (set! y tmp)))]))

(define-syntax (rotate stx)
  (syntax-case stx ()
    [(rotate a c ...)
     (begin
       (check-ids stx #'(a c ...))
       #'(shift-to (c ... a) (a c ...)))]))
```

The `check-ids` function can use the `syntax->list` function to convert a syntax-object wrapping a list into a list of syntax objects:

```
(define (check-ids stx forms)
  (for-each
   (lambda (form)
     (unless (identifier? form)
       (raise-syntax-error #f
```

```
                          "not an identifier"
                          stx
                          form)))
    (syntax->list forms)))
```

If you define `swap` and `check-ids` in this way, however, it doesn't work:

```
> (let ([a 1] [b 2]) (swap a b))
check-ids: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

The problem is that `check-ids` is defined as a run-time expression, but `swap` is trying to use it at compile time. In interactive mode, compile time and run time are interleaved, but they are not interleaved within the body of a module, and they are not interleaved across modules that are compiled ahead-of-time. To help make all of these modes treat code consistently, Racket separates the binding spaces for different phases.

To define a `check-ids` function that can be referenced at compile time, use `begin-for-syntax`:

```
(begin-for-syntax
  (define (check-ids stx forms)
    (for-each
     (lambda (form)
       (unless (identifier? form)
         (raise-syntax-error #f
                             "not an identifier"
                             stx
                             form)))
     (syntax->list forms))))
```

With this for-syntax definition, then `swap` works:

```
> (let ([a 1] [b 2]) (swap a b) (list a b))
'(2 1)
> (swap a 1)
eval:13:0: swap: not an identifier
  at: 1
  in: (swap a 1)
```

When organizing a program into modules, you may want to put helper functions in one module to be used by macros that reside on other modules. In that case, you can write the helper function using `define`:

"utils.rkt"

```
#lang racket

(provide check-ids)

(define (check-ids stx forms)
  (for-each
   (lambda (form)
     (unless (identifier? form)
       (raise-syntax-error #f
                           "not an identifier"
                           stx
                           form)))
   (syntax->list forms)))
```

Then, in the module that implements macros, import the helper function using `(require (for-syntax "utils.rkt"))` instead of `(require "utils.rkt")`:

```
#lang racket

(require (for-syntax "utils.rkt"))

(define-syntax (swap stx)
  (syntax-case stx ()
    [(swap x y) (begin
                  (check-ids stx #'(x y))
                  #'(let ([tmp x])
                      (set! x y)
                      (set! y tmp)))]))
```

Since modules are separately compiled and cannot have circular dependencies, the `"utils.rkt"` module's run-time body can be compiled before compiling the module that implements `swap`. Thus, the run-time definitions in `"utils.rkt"` can be used to implement `swap`, as long as they are explicitly shifted into compile time by `(require (for-syntax ....))`.

The `racket` module provides `syntax-case`, `generate-temporaries`, `lambda`, `if`, and more for use in both the run-time and compile-time phases. That is why we can use `syntax-case` in the `racket` REPL both directly and in the right-hand side of a `define-syntax` form.

The `racket/base` module, in contrast, exports those bindings only in the run-time phase. If you change the module above that defines `swap` so that it uses the `racket/base` language instead of `racket`, then it no longer works. Adding `(require (for-syntax racket/base))` imports `syntax-case` and more into the compile-time phase, so that the module works again.

Suppose that `define-syntax` is used to define a local macro in the right-hand side of a `define-syntax` form. In that case, the right-hand side of the inner `define-syntax` is in the *meta-compile phase level*, also known as *phase level 2*. To import `syntax-case` into that phase level, you would have to use `(require (for-syntax (for-syntax racket/base)))` or, equivalently, `(require (for-meta 2 racket/base))`. For example,

```
#lang racket/base
(require  ;; This provides the bindings for the definition
          ;; of shell-game.
          (for-syntax racket/base)

          ;; And this for the definition of
          ;; swap.
          (for-syntax (for-syntax racket/base)))

(define-syntax (shell-game stx)

  (define-syntax (swap stx)
    (syntax-case stx ()
      [(_ a b)
       #'(let ([tmp a])
           (set! a b)
           (set! b tmp))]))

  (syntax-case stx ()
    [(_ a b c)
     (let ([a #'a] [b #'b] [c #'c])
       (when (= 0 (random 2)) (swap a b))
       (when (= 0 (random 2)) (swap b c))
       (when (= 0 (random 2)) (swap a c))
       #`(list #,a #,b #,c))]))

(shell-game 3 4 5)
(shell-game 3 4 5)
(shell-game 3 4 5)
```

Negative phase levels also exist. If a macro uses a helper function that is imported `for-syntax`, and if the helper function returns syntax-object constants generated by `syntax`, then identifiers in the syntax will need bindings at *phase level -1*, also known as the *template phase level*, to have any binding at the run-time phase level relative to the module that defines the macro.

For instance, the `swap-stx` helper function in the example below is not a syntax transformer—it's just an ordinary function—but it produces syntax objects that get spliced into the result of `shell-game`. Therefore, its containing `helper` submodule needs to be

imported at `shell-game`'s phase 1 with `(require (for-syntax 'helper))`.

But from the perspective of `swap-stx`, its results will ultimately be evaluated at phase level -1, when the syntax returned by `shell-game` is evaluated. In other words, a negative phase level is a positive phase level from the opposite direction: `shell-game`'s phase 1 is `swap-stx`'s phase 0, so `shell-game`'s phase 0 is `swap-stx`'s phase -1. And that's why this example won't work—the `'helper` submodule has no bindings at phase -1.

```
#lang racket/base
(require (for-syntax racket/base))

(module helper racket/base
  (provide swap-stx)
  (define (swap-stx a-stx b-stx)
    #`(let ([tmp #,a-stx])
        (set! #,a-stx #,b-stx)
        (set! #,b-stx tmp))))

(require (for-syntax 'helper))

(define-syntax (shell-game stx)
  (syntax-case stx ()
    [(_ a b c)
     #`(begin
         #,(swap-stx #'a #'b)
         #,(swap-stx #'b #'c)
         #,(swap-stx #'a #'c)
         (list a b c))]))

(define x 3)
(define y 4)
(define z 5)
(shell-game x y z)
```

To repair this example, we add `(require (for-template racket/base))` to the `'helper` submodule.

```
#lang racket/base
(require (for-syntax racket/base))

(module helper racket/base
  (require (for-template racket/base)) ; binds `let` and `set!` at phase -
1
  (provide swap-stx)
  (define (swap-stx a-stx b-stx)
    #`(let ([tmp #,a-stx])
```

```
          (set! #,a-stx #,b-stx)
          (set! #,b-stx tmp))))

(require (for-syntax 'helper))

(define-syntax (shell-game stx)
  (syntax-case stx ()
    [(_ a b c)
     #`(begin
         #,(swap-stx #'a #'b)
         #,(swap-stx #'b #'c)
         #,(swap-stx #'a #'c)
         (list a b c))]))

(define x 3)
(define y 4)
(define z 5)
(shell-game x y z)
(shell-game x y z)
(shell-game x y z)
```

16.2.6 General Phase Levels

A *phase* can be thought of as a way to separate computations in a pipeline of processes where one produces code that is used by the next. (E.g., a pipeline that consists of a preprocessor process, a compiler, and an assembler.)

Imagine starting two Racket processes for this purpose. If you ignore inter-process communication channels like sockets and files, the processes will have no way to share anything other than the text that is piped from the standard output of one process into the standard input of the other. Similarly, Racket effectively allows multiple invocations of a module to exist in the same process but separated by phase. Racket enforces *separation* of such phases, where different phases cannot communicate in any way other than via the protocol of macro expansion, where the output of one phase is the code used in the next.

Phases and Bindings

Every binding of an identifier exists in a particular phase. The link between a binding and its phase is represented by an integer *phase level*. Phase level 0 is the phase used for "plain" (or "runtime") definitions, so

```
(define age 5)
```

adds a binding for `age` into phase level 0. The identifier `age` can be defined at a higher phase level using `begin-for-syntax`:

```
(begin-for-syntax
  (define age 5))
```

With a single `begin-for-syntax` wrapper, `age` is defined at phase level 1. We can easily mix these two definitions in the same module or in a top-level namespace, and there is no clash between the two `age`s that are defined at different phase levels:

```
> (define age 3)
> (begin-for-syntax
    (define age 9))
```

The `age` binding at phase level 0 has a value of 3, and the `age` binding at phase level 1 has a value of 9.

Syntax objects capture binding information as a first-class value. Thus,

```
#'age
```

is a syntax object that represents the `age` binding—but since there are two `age`s (one at phase level 0 and one at phase level 1), which one does it capture? In fact, Racket imbues `#'age` with lexical information for all phase levels, so the answer is that `#'age` captures both.

The relevant binding of `age` captured by `#'age` is determined when `#'age` is eventually used. As an example, we bind `#'age` to a pattern variable so we can use it in a template, and then we `eval`uate the template:

We use `eval` here to demonstrate phases, but see §15 “Reflection and Dynamic Evaluation” for caveats about `eval`.

```
> (eval (with-syntax ([age #'age])
          #'(displayln age)))
3
```

The result is `3` because `age` is used at phase 0 level. We can try again with the use of `age` inside `begin-for-syntax`:

```
> (eval (with-syntax ([age #'age])
          #'(begin-for-syntax
              (displayln age))))
9
```

In this case, the answer is `9`, because we are using `age` at phase level 1 instead of 0 (i.e., `begin-for-syntax` evaluates its expressions at phase level 1). So, you can see that we started with the same syntax object, `#'age`, and we were able to use it in two different ways: at phase level 0 and at phase level 1.

A syntax object has a lexical context from the moment it first exists. A syntax object that is provided from a module retains its lexical context, and so it references bindings in the

context of its source module, not the context of its use. The following example defines `button` at phase level 0 and binds it to `0`, while `see-button` binds the syntax object for `button` in module `a`:

```
> (module a racket
    (define button 0)
    (provide (for-syntax see-button))
    ; Why not (define see-button #'button)? We explain later.
    (define-for-syntax see-button #'button))
> (module b racket
    (require 'a)
    (define button 8)
    (define-syntax (m stx)
      see-button)
    (m))
> (require 'b)
0
```

The result of the `m` macro is the value of `see-button`, which is `#'button` with the lexical context of the `a` module. Even though there is another `button` in `b`, the second `button` will not confuse Racket, because the lexical context of `#'button` (the value bound to `see-button`) is `a`.

Note that `see-button` is bound at phase level 1 by virtue of defining it with `define-for-syntax`. Phase level 1 is needed because `m` is a macro, so its body executes at one phase higher than the context of its definition. Since `m` is defined at phase level 0, its body is at phase level 1, so any bindings referenced by the body must be at phase level 1.

Phases and Modules

A phase level is a module-relative concept. When importing from another module via `require`, Racket lets us shift imported bindings to a phase level that is different from the original one:

```
(require "a.rkt")                ; import with no phase shift
(require (for-syntax "a.rkt"))   ; shift phase by +1
(require (for-template "a.rkt")) ; shift phase by -1
(require (for-meta 5 "a.rkt"))   ; shift phase by +5
```

That is, using `for-syntax` in `require` means that all of the bindings from that module will have their phase levels increased by one. A binding that is `defined` at phase level 0 and imported with `for-syntax` becomes a phase-level 1 binding:

```
> (module c racket
    (define x 0) ; defined at phase level 0
    (provide x))
```

```
> (module d racket
    (require (for-syntax 'c))
    ; has a binding at phase level 1, not 0:
    #'x)
```

Let's see what happens if we try to create a binding for the `#'button` syntax object at phase level 0:

```
> (define button 0)
> (define see-button #'button)
```

Now both `button` and `see-button` are defined at phase 0. The lexical context of `#'button` will know that there is a binding for `button` at phase 0. In fact, it seems like things are working just fine if we try to `eval` `see-button`:

```
> (eval see-button)
0
```

Now, let's use `see-button` in a macro:

```
> (define-syntax (m stx)
    see-button)
> (m)
see-button: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

Clearly, `see-button` is not defined at phase level 1, so we cannot refer to it inside the macro body. Let's try to use `see-button` in another module by putting the button definitions in a module and importing it at phase level 1. Then, we will get `see-button` at phase level 1:

```
> (module a racket
    (define button 0)
    (define see-button #'button)
    (provide see-button))
> (module b racket
    (require (for-syntax 'a)) ; gets see-button at phase level 1
    (define-syntax (m stx)
      see-button)
    (m))
eval:1:0: button: unbound identifier;
 also, no #%top syntax transformer is bound
  in: button
```

Racket says that `button` is unbound now! When `a` is imported at phase level 1, we have the following bindings:

```
button      at phase level 1
see-button  at phase level 1
```

So the macro `m` can see a binding for `see-button` at phase level 1 and will return the `#'button` syntax object, which refers to `button` binding at phase level 1. But the use of `m` is at phase level 0, and there is no `button` at phase level 0 in `b`. That is why `see-button` needs to be bound at phase level 1, as in the original `a`. In the original `b`, then, we have the following bindings:

```
button      at phase level 0
see-button  at phase level 1
```

In this scenario, we can use `see-button` in the macro, since `see-button` is bound at phase level 1. When the macro expands, it will refer to a `button` binding at phase level 0.

Defining `see-button` with `(define see-button #'button)` isn't inherently wrong; it depends on how we intend to use `see-button`. For example, we can arrange for `m` to sensibly use `see-button` because it puts it in a phase level 1 context using `begin-for-syntax`:

```
> (module a racket
    (define button 0)
    (define see-button #'button)
    (provide see-button))
> (module b racket
    (require (for-syntax 'a))
    (define-syntax (m stx)
      (with-syntax ([x see-button])
        #'(begin-for-syntax
            (displayln x))))
    (m))
0
```

In this case, module `b` has both `button` and `see-button` bound at phase level 1. The expansion of the macro is

```
(begin-for-syntax
  (displayln button))
```

which works, because `button` is bound at phase level 1.

Now, you might try to cheat the phase system by importing `a` at both phase level 0 and phase level 1. Then you would have the following bindings

```
button      at phase level 0
```

```
see-button  at phase level 0
button      at phase level 1
see-button  at phase level 1
```

You might expect now that `see-button` in a macro would work, but it doesn't:

```
> (module a racket
    (define button 0)
    (define see-button #'button)
    (provide see-button))
> (module b racket
    (require 'a
             (for-syntax 'a))
    (define-syntax (m stx)
      see-button)
    (m))
eval:1:0: button: unbound identifier;
 also, no #%top syntax transformer is bound
  in: button
```

In the definition of module `a`, the variable `see-button` is at phase 0, and its value is the syntax object for `button`, which shows the only visible `button` binding is at the same phase. (That is the key detail.) As discussed, the `for-syntax` import shifts the phase level of *both* up one, so the phase 1 binding of `see-button` used in module `b` is the binding from the module `a` that is shifted into phase 1, which refers to `button` in `a` at phase 1. The fact that in module `b` there is also a phase 0 variable `button` from a different instantiation of module `a` does not matter, because there is no way to reach it from the (shifted) `see-button` from `a`.

This kind of phase-level mismatch between instantiations can be repaired with `syntax-shift-phase-level`. Recall that a syntax object like `#'button` captures lexical information at *all* phase levels. The problem here is that `see-button` is invoked at phase 1, but needs to return a syntax object that can be evaluated at phase 0. By default, `see-button` is bound to `#'button` at the same phase level. But with `syntax-shift-phase-level`, we can make `see-button` refer to `#'button` at a different relative phase level. In this case, we use a phase shift of `-1` to make `see-button` at phase 1 refer to `#'button` at phase 0. (Because the phase shift happens at every level, it will also make `see-button` at phase 0 refer to `#'button` at phase -1.)

Note that `syntax-shift-phase-level` merely creates a reference across phases. To make that reference work, we still need to instantiate our module at both phases so the reference and its target have their bindings available. Thus, in module `'b`, we still import module `'a` at both phase 0 and phase 1—using `(require 'a (for-syntax 'a))`—so we have a phase-1 binding for `see-button` and a phase-0 binding for `button`. Now macro `m` will work.

```
> (module a racket
    (define button 0)
    (define see-button (syntax-shift-phase-level #'button -1))
    (provide see-button))
> (module b racket
    (require 'a (for-syntax 'a))
    (define-syntax (m stx)
      see-button)
    (m))
> (require 'b)
0
```

By the way, what happens to the `see-button` that's bound at phase 0? Its `#'button` binding has likewise been shifted, but to phase -1. Since `button` itself isn't bound at phase -1, if we try to evaluate `see-button` at phase 0, we get an error. In other words, we haven't permanently cured our mismatch problem—we've just shifted it to a less bothersome location.

```
> (module a racket
    (define button 0)
    (define see-button (syntax-shift-phase-level #'button -1))
    (provide see-button))
> (module b racket
    (require 'a (for-syntax 'a))
    (define-syntax (m stx)
      see-button)
    (m))
> (module b2 racket
    (require 'a)
    (eval see-button))
> (require 'b2)
button: undefined;
 cannot reference an identifier before its definition
  in module: top-level
```

Mismatches like the one above can also arise when a macro tries to match literal bindings—using `syntax-case` or `syntax-parse`.

```
> (module x racket
    (require (for-syntax syntax/parse)
             (for-template racket/base))

    (provide (all-defined-out))

    (define button 0)
    (define (make) #'button)
```

```
    (define-syntax (process stx)
      (define-literal-set locals (button))
      (syntax-parse stx
        [(_ (n (~literal button))) #'#''ok])))
> (module y racket
    (require (for-meta 1 'x)
             (for-meta 2 'x racket/base))

    (begin-for-syntax
      (define-syntax (m stx)
        (with-syntax ([out (make)])
          #'(process (0 out)))))

    (define-syntax (p stx)
      (m))

    (p))
eval:2:0: process: expected the identifier `button'
  at: button
  in: (process (0 button))
```

In this example, `make` is being used in `y` at phase level 2, and it returns the `#'button` syntax object—which refers to `button` bound at phase level 0 inside `x` and at phase level 2 in `y` from `(for-meta 2 'x)`. The `process` macro is imported at phase level 1 from `(for-meta 1 'x)`, and it knows that `button` should be bound at phase level 1. When the `syntax-parse` is executed inside `process`, it is looking for `button` bound at phase level 1 but it sees only a phase level 2 binding and doesn't match.

To fix the example, we can provide `make` at phase level 1 relative to `x`, and then we import it at phase level 1 in `y`:

```
> (module x racket
    (require (for-syntax syntax/parse)
             (for-template racket/base))

    (provide (all-defined-out))

    (define button 0)

    (provide (for-syntax make))
    (define-for-syntax (make) #'button)
    (define-syntax (process stx)
      (define-literal-set locals (button))
      (syntax-parse stx
        [(_ (n (~literal button))) #'#''ok])))
> (module y racket
```

```
    (require (for-meta 1 'x)
             (for-meta 2 racket/base))

    (begin-for-syntax
      (define-syntax (m stx)
        (with-syntax ([out (make)])
          #'(process (0 out)))))

    (define-syntax (p stx)
      (m))

    (p))
> (require 'y)
'ok
```

16.2.7 Tainted Syntax

Modules often contain definitions that are meant only for use within the same module and not exported with `provide`. Still, a use of a macro defined in the module can expand into a reference of an unexported identifier. In general, such an identifier must not be extracted from the expanded expression and used in a different context, because using the identifier in a different context may break invariants of the macro's module.

For example, the following module exports a macro `go` that expands to a use of `unchecked-go`:

"m.rkt"

```
#lang racket
(provide go)

(define (unchecked-go n x)
  ; to avoid disaster, n must be a number
  (+ n 17))

(define-syntax (go stx)
  (syntax-case stx ()
    [(_ x)
     #'(unchecked-go 8 x)]))
```

If the reference to `unchecked-go` is extracted from the expansion of `(go 'a)`, then it might be inserted into a new expression, `(unchecked-go #f 'a)`, leading to disaster. The `datum->syntax` procedure can be used similarly to construct references to an unexported identifier, even when no macro expansion includes a reference to the identifier.

Ultimately, protection of a module's private bindings depends on changing the current

code inspector by setting the current-code-inspector parameter. That's because a code inspector controls access to a module's internal state through functions like module->namespace. The current code inspector also gates access to the protected exports of unsafe modules like racket/unsafe/ops.

See also §15.4 "Code Inspectors for Trusted and Untrusted Code".

Since the result of macro expansion can be abused to gain access to protected bindings, macro functions like local-expand are also protected: references to local-expand and similar are allowed only within modules that are declared while the original code inspector is the current code inspector. Functions like expand, which are not used to implement macros but are used to inspect the result of macro expansion, are protected in a different way: the expansion result is *tainted* so that it cannot be compiled or expanded again. More precisely, functions like expand accept an optional inspector argument that determines whether the result is tainted, but the default value of the argument is (current-code-inspector).

In previous versions of Racket, a macro was responsible for protecting expansion using syntax-protect. The use of syntax-protect is no longer required or recommended.

16.3 Module Instantiations and Visits

Modules often contain just function and structure-type definitions, in which case the module itself behaves in a purely functional way, and the time when the functions are created is not observable. If a module's top-level expressions include side effects, however, then the timing of the effects can matter. The distinction between module declaration and instantiation provides some control over that timing. The concept of module visits further explains the interaction of effects with macro implementations.

16.3.1 Declaration versus Instantiation

Declaring a module does not immediately evaluate expressions in the module's body. For example, evaluating

```
> (module number-n racket/base
    (provide n)
    (define n (random 10))
    (printf "picked ~a\n" n))
```

declares the module number-n, but it doesn't immediately pick a random number for n or display the number. A require of number-n causes the module to be *instantiated* (i.e., it triggers an *instantiation*), which implies that the expressions in the body of the module are evaluated:

```
> (require 'number-n)
picked 5
> n
5
```

After a module is instantiated in a particular namespace, further `requires` of the module use the same instance, as opposed to instantiating the module again:

```
> (require 'number-n)
> n
5
> (module use-n racket/base
    (require 'number-n)
    (printf "still ~a\n" n))
> (require 'use-n)
still 5
```

The `dynamic-require` function, like `require`, triggers instantiation of a module if it is not already instantiated, so `dynamic-require` with `#f` as a second argument is useful to just trigger the instantiation effects of a module:

```
> (module use-n-again racket/base
    (require 'number-n)
    (printf "also still ~a\n" n))
> (dynamic-require ''use-n-again #f)
also still 5
```

Instantiation of modules by `require` is transitive. That is, if `require` of a module instantiates it, then any module `required` by that one is also instantiated (if it's not instantiated already):

```
> (module number-m racket/base
    (provide m)
    (define m (random 10))
    (printf "picked ~a\n" m))
> (module use-m racket/base
    (require 'number-m)
    (printf "still ~a\n" m))
> (require 'use-m)
picked 0
still 0
```

16.3.2 Compile-Time Instantiation

In the same way that declaring a module does not by itself instantiate a module, declaring a module that `requires` another module does not by itself instantiate the `required` module, as illustrated in the preceding example. However, declaring a module *does* expand and compile the module. If a module imports another with `(require (for-syntax ....))`, then module that is imported `for-syntax` must be instantiated during expansion:

```
> (module number-p racket/base
    (provide p)
    (define p (random 10))
    (printf "picked ~a\n" p))
> (module use-p-at-compile-time racket/base
    (require (for-syntax racket/base
                         'number-p))
    (define-syntax (pm stx)
      #`#,p)
    (printf "was ~a at compile time\n" (pm)))
picked 1
```

Unlike run-time instantiation in a namespace, when a module is used `for-syntax` for another module expansion in the same namespace, the `for-syntax`ed module is instantiated separately for each expansion. Continuing the previous example, if `number-p` is used a second time `for-syntax`, then a second random number is selected for a new `p`:

```
> (module use-p-again-at-compile-time racket/base
    (require (for-syntax racket/base
                         'number-p))
    (define-syntax (pm stx)
      #`#,p)
    (printf "was ~a at second compile time\n" (pm)))
picked 3
```

Separate compile-time instantiations of `number-p` helps prevent accidental propagation of effects from one module's compilation to another module's compilation. Preventing those effects make compilation reliably separate and more deterministic.

The expanded forms of `use-p-at-compile-time` and `use-p-again-at-compile-time` record the number that was selected each time, so those two different numbers are printed when the modules are instantiated:

```
> (dynamic-require ''use-p-at-compile-time #f)
was 1 at compile time
> (dynamic-require ''use-p-again-at-compile-time #f)
was 3 at second compile time
```

A namespace's top level behaves like a separate module, where multiple interactions in the top level conceptually extend a single expansion of the module. So, when using `(require (for-syntax ....))` twice in the top level, the second use does not trigger a new compile-time instance:

```
> (begin (require (for-syntax 'number-p)) 'done)
picked 4
```

```
'done
> (begin (require (for-syntax 'number-p)) 'done-again)
'done-again
```

However, a run-time instance of a module is kept separate from all compile-time instances, including at the top level, so a non-`for-syntax` use of `number-p` will pick another random number:

```
> (require 'number-p)
picked 5
```

16.3.3 Visiting Modules

When a module `provide`s a macro for use by other modules, the other modules use the macro by directly `require`ing the macro provider—i.e., without `for-syntax`. That's because the macro is being imported for use in a run-time position (even though the macro's implementation lives at compile time), while `for-syntax` would import a binding for use in compile-time position.

The module implementing a macro, meanwhile, might `require` another module `for-syntax` to implement the macro. The `for-syntax` module needs a compile-time instantiation during any module expansion that might use the macro. That requirement sets up a kind of transitivity through `require` that is similar to instantiation transitivity, but "off by one" at the point where the `for-syntax` shift occurs in the chain.

Here's an example to make that scenario concrete:

```
> (module number-q racket/base
    (provide q)
    (define q (random 10))
    (printf "picked ~a\n" q))
> (module use-q-at-compile-time racket/base
    (require (for-syntax racket/base
                         'number-q))
    (provide qm)
    (define-syntax (qm stx)
      #`#,q)
    (printf "was ~a at compile time\n" (qm)))
picked 7
> (module use-qm racket/base
    (require 'use-q-at-compile-time)
    (printf "was ~a at second compile time\n" (qm)))
picked 4
> (dynamic-require ''use-qm #f)
```

```
was 7 at compile time
was 4 at second compile time
```

In this example, when `use-q-at-compile-time` is expanded and compiled, `number-q` is instantiated once. In this case, that instantiation is needed to expand the `(qm)` macro, but the module system would proactively create a compile-time instantiation of `number-q` even if the `qm` macro turned out not to be used.

Then, as `use-qm` is expanded and compiled, a second compile-time instantiation of `number-q` is created. That compile-time instantiation is needed to expand the `(qm)` form within `use-qm`.

Instantiating `use-qm` correctly reports the number that was picked during that second module's compilation. First, though, the `require` of `use-q-at-compile-time` in `use-qm` triggers a transitive instantiation of `use-q-at-compile-time`, which correctly reports the number that was picked in its compilation.

Overall, the example illustrates a transitive effect of `require` that we had already seen:

- When a module is instantiated, the run-time expressions in its body are evaluated.
- When a module is instantiated, then any module that it `require`s (without `for-syntax`) is also instantiated.

This rule does not explain the compile-time instantiations of `number-q`, however. To explain that, we need a new word, *visit*, for the concept that we saw in §16.3.2 "Compile-Time Instantiation":

- When a module is visited, the compile-time expressions (such as macro definition) in its body are evaluated.
- As a module is expanded, it is visited.
- When a module is visited, then any module that it `require`s (without `for-syntax`) is also visited.
- When a module is visited, then any module that it `require`s `for-syntax` is instantiated at compile time.

Note that when visiting one module causes a compile-time instantiation of another module, the transitiveness of instantiation through regular `require`s can trigger more compile-time instantiations. Instantiation itself won't trigger further visits, however, because any instantiated module has already been expanded and compiled.

The compile-time expressions of a module that are evaluated by visiting include both the right-hand sides of `define-syntax` forms and the body of `begin-for-syntax` forms. That's why a randomly selected number is printed immediately in the following example:

```
> (module compile-time-number racket/base
    (require (for-syntax racket/base))
    (begin-for-syntax
      (printf "picked ~a\n" (random)))
    (printf "running\n"))
picked 0.25549265186825576
```

Instantiating the module evaluates only the run-time expressions, which prints “running” but not a new random number:

```
> (dynamic-require ''compile-time-number #f)
running
```

The description of instantiates and visit above is phrased in terms of normal `require`s and `for-syntax` `require`s, but a more precise specification is in terms of module phases. For example, if module *A* has `(require (for-syntax` *B*`))` and module *B* has `(require (for-template` *C*`))`, then module *C* is instantiated when module *A* is instantiated, because the `for-syntax` and `for-template` shifts cancel. We have not yet specified what happens with `for-meta 2` for when `for-syntax`es combine; we leave that to the next section, §16.3.4 “Lazy Visits via Available Modules”.

If you think of the top-level as a kind of module that is continuously expanded, the above rules imply that `require` of another module at the top level both instantiates and visits the other module (if it is not already instantiated and visited). That’s roughly true, but the visit is made lazy in a way that is also explained in the next section, §16.3.4 “Lazy Visits via Available Modules”.

Meanwhile, `dynamic-require` only instantiates a module; it does not visit the module. That simplification is why some of the preceding examples use `dynamic-require` instead of `require`. The extra visits of a top-level `require` would make the earlier examples less clear.

16.3.4 Lazy Visits via Available Modules

A top-level `require` of a module does not actually visit the module. Instead, it makes the module *available*. An available module will be visited when a future expression needs to be expanded in the same context. The next expression may or may not involve some imported macro that needs its compile-time helpers evaluated by visiting, but the module system proactively visits the module, just in case.

In the following example, a random number is picked as a result of visiting a module’s own body while that module is being expanded. A `require` of the module instantiates it, printing “running”, and also makes the module available. Evaluating any other expression implies expanding the expression, and that expansion triggers a visit of the available module—which picks another random number:

```
> (module another-compile-time-number racket/base
    (require (for-syntax racket/base))
    (begin-for-syntax
      (printf "picked ~a\n" (random)))
    (printf "running\n"))
picked 0.3634379786893492
> (require 'another-compile-time-number)
running
> 'next
picked 0.5057086679589476
'next
> 'another
'another
```

[2]

The final evaluation of `'another` also visits any available modules, but no modules were made newly available by simply evaluating `'next`.

When a module `requires` another module using `for-meta` *n* for some *n* greater than 1, the `required` module is made available at phase *n*. A module that is available at phase *n* is visited when some expression at phase *n*-1 is expanded.

To help illustrate, the following examples use `(variable-reference->module-base-phase (#%variable-reference))`, which returns a number for the phase at which the enclosing module is instantiated:

```
> (module show-phase racket/base
    (printf "running at ~a\n"
            (variable-reference->module-base-phase (#%variable-
reference))))
> (require 'show-phase)
running at 0
> (module use-at-phase-1 racket/base
    (require (for-syntax 'show-phase)))
running at 1
> (module unused-at-phase-2 racket/base
    (require (for-meta 2 'show-phase)))
```

For the last module above, `show-phase` is made available at phase 2, but no expressions within the module are ever expanded at phase 1, so there's no phase-2 printout. The following module includes a phase-1 expression after the phase-2 `require`, so there's a printout:

[2] Beware that the expander flattens the content of a top-level `begin` into the top level as soon as the `begin` is discovered. So, `(begin (require 'another-compile-time-number) 'next)` would still have printed "picked" before "next".

```
> (module use-at-phase-2 racket/base
    (require (for-meta 2 'show-phase)
             (for-syntax racket/base))
    (define-syntax x 'ok))
running at 2
```

If we `require` the module `use-at-phase-1` at the top level, then `show-phase` is made available at phase 1. Evaluating another expression causes `use-at-phase-1` to be visited, which in turn instantiates `show-phase`:

```
> (require 'use-at-phase-1)
> 'next
running at 1
'next
```

A `require` of `use-at-phase-2` is similar, except that `show-phase` is made available at phase 2, so it is not instantiated until some expression is expanded at phase 1:

```
> (require 'use-at-phase-2)
> 'next
'next
> (require (for-syntax racket/base))
> (begin-for-syntax 'compile-time-next)
running at 2
```

17 Creating Languages

The macro facilities defined in the preceding chapter let a programmer define syntactic extensions to a language, but a macro is limited in two ways:

- a macro cannot restrict the syntax available in its context or change the meaning of surrounding forms; and
- a macro can extend the syntax of a language only within the parameters of the language's lexical conventions, such as using parentheses to group the macro name with its subforms and using the core syntax of identifiers, keywords, and literals.

The distinction between the reader and expander layer is introduced in §2.4.3 "Lists and Racket Syntax".

That is, a macro can only extend a language, and it can do so only at the expander layer. Racket offers additional facilities for defining a starting point of the expander layer, for extending the reader layer, for defining the starting point of the reader layer, and for packaging a reader and expander starting point into a conveniently named language.

17.1 Module Languages

When using the longhand `module` form for writing modules, the module path that is specified after the new module's name provides the initial imports for the module. Since the initial-import module determines even the most basic bindings that are available in a module's body, such as `require`, the initial import can be called a *module language*.

The most common module languages are `racket` or `racket/base`, but you can define your own module language by defining a suitable module. For example, using `provide` subforms like `all-from-out`, `except-out`, and `rename-out`, you can add, remove, or rename bindings from `racket` to produce a module language that is a variant of `racket`:

§6.2.1 "The `module` Form" introduces the longhand `module` form.

```
> (module raquet racket
    (provide (except-out (all-from-out racket) lambda)
             (rename-out [lambda function])))
> (module score 'raquet
    (map (function (points) (case points
                              [(0) "love"] [(1) "fifteen"]
                              [(2) "thirty"] [(3) "forty"]))
         (list 0 2)))
> (require 'score)
'("love" "thirty")
```

17.1.1 Implicit Form Bindings

If you try to remove too much from `racket` in defining your own module language, then the resulting module will no longer work right as a module language:

```
> (module just-lambda racket
    (provide lambda))
> (module identity 'just-lambda
    (lambda (x) x))
eval:2:0: module: no #%module-begin binding in the module's
language
  in: (module identity (quote just-lambda) (lambda (x) x))
```

The `#%module-begin` form is an implicit form that wraps the body of a module. It must be provided by a module that is to be used as module language:

```
> (module just-lambda racket
    (provide lambda #%module-begin))
> (module identity 'just-lambda
    (lambda (x) x))
> (require 'identity)
#<procedure>
```

The other implicit forms provided by `racket/base` are `#%app` for function calls, `#%datum` for literals, and `#%top` for identifiers that have no binding:

```
> (module just-lambda racket
    (provide lambda #%module-begin
             ; ten needs these, too:
             #%app #%datum))
> (module ten 'just-lambda
    ((lambda (x) x) 10))
> (require 'ten)
10
```

Implicit forms such as `#%app` can be used explicitly in a module, but they exist mainly to allow a module language to restrict or change the meaning of implicit uses. For example, a `lambda-calculus` module language might restrict functions to a single argument, restrict function calls to supply a single argument, restrict the module body to a single expression, disallow literals, and treat unbound identifiers as uninterpreted symbols:

```
> (module lambda-calculus racket
    (provide (rename-out [1-arg-lambda lambda]
                         [1-arg-app #%app]
```

```
                          [1-form-module-begin #%module-begin]
                          [no-literals #%datum]
                          [unbound-as-quoted #%top]))
    (define-syntax-rule (1-arg-lambda (x) expr)
      (lambda (x) expr))
    (define-syntax-rule (1-arg-app e1 e2)
      (#%app e1 e2))
    (define-syntax-rule (1-form-module-begin e)
      (#%module-begin e))
    (define-syntax (no-literals stx)
      (raise-syntax-error #f "no" stx))
    (define-syntax-rule (unbound-as-quoted . id)
      'id))
> (module ok 'lambda-calculus
    ((lambda (x) (x z))
     (lambda (y) y)))
> (require 'ok)
'z
> (module not-ok 'lambda-calculus
    (lambda (x y) x))
eval:4:0: lambda: use does not match pattern: (lambda (x)
expr)
  in: (lambda (x y) x)
> (module not-ok 'lambda-calculus
    (lambda (x) x)
    (lambda (y) (y y)))
eval:5:0: #%module-begin: use does not match pattern:
(#%module-begin e)
  in: (#%module-begin (lambda (x) x) (lambda (y) (y y)))
> (module not-ok 'lambda-calculus
    (lambda (x) (x x x)))
eval:6:0: #%app: use does not match pattern: (#%app e1 e2)
  in: (#%app x x x)
> (module not-ok 'lambda-calculus
    10)
eval:7:0: #%datum: no
  in: (#%datum . 10)
```

Module languages rarely redefine `#%app`, `#%datum`, and `#%top`, but redefining `#%module-begin` is more frequently useful. For example, when using modules to construct descriptions of HTML pages where a description is exported from the module as `page`, an alternate `#%module-begin` can help eliminate `provide` and quasiquoting boilerplate, as in `"html.rkt"`:

`"html.rkt"`

```
#lang racket
```

```
(require racket/date)

(provide (except-out (all-from-out racket)
                     #%module-begin)
         (rename-out [module-begin #%module-begin])
         now)

(define-syntax-rule (module-begin expr ...)
  (#%module-begin
   (define page `(html expr ...))
   (provide page)))

(define (now)
  (parameterize ([date-display-format 'iso-8601])
    (date->string (seconds->date (current-seconds)))))
```

Using the `"html.rkt"` module language, a simple web page can be described without having to explicitly define or export `page` and starting in `quasiquoted` mode instead of expression mode:

```
> (module lady-with-the-spinning-head "html.rkt"
    (title "Queen of Diamonds")
    (p "Updated: " ,(now)))
> (require 'lady-with-the-spinning-head)
> page
'(html (title "Queen of Diamonds") (p "Updated: " "2026-10-31"))
```

17.1.2 Using `#lang s-exp`

Implementing a language at the level of `#lang` is more complex than declaring a single module, because `#lang` lets programmers control several different facets of a language. The `s-exp` language, however, acts as a kind of meta-language for using a module language with the `#lang` shorthand:

```
#lang s-exp module-name
form ...
```

is the same as

```
(module name module-name
  form ...)
```

where *name* is derived from the source file containing the `#lang` program. The name `s-exp` is short for "S-expression," which is a traditional name for Racket's reader-level lexical

conventions: parentheses, identifiers, numbers, double-quoted strings with certain backslash escapes, and so on.

Using `#lang s-exp`, the `lady-with-the-spinning-head` example from before can be written more compactly as:

```
#lang s-exp "html.rkt"

(title "Queen of Diamonds")
(p "Updated: " ,(now))
```

Later in this guide, §17.3 "Defining new `#lang` Languages" explains how to define your own `#lang` language, but first we explain how you can write reader-level extensions to Racket.

17.2 Reader Extensions

§1.3.18 "Reading via an Extension" in *The Racket Reference* provides more on reader extensions.

The reader layer of the Racket language can be extended through the `#reader` form. A reader extension is implemented as a module that is named after `#reader`. The module exports functions that parse raw characters into a form to be consumed by the expander layer.

The syntax of `#reader` is

`#reader` ⟨*module-path*⟩ ⟨*reader-specific*⟩

where ⟨*module-path*⟩ names a module that provides `read` and `read-syntax` functions. The ⟨*reader-specific*⟩ part is a sequence of characters that is parsed as determined by the `read` and `read-syntax` functions from ⟨*module-path*⟩.

For example, suppose that file `"five.rkt"` contains

`"five.rkt"`

```
#lang racket/base

(provide read read-syntax)

(define (read in) (list (read-string 5 in)))
(define (read-syntax src in) (list (read-string 5 in)))
```

Then, the program

```
#lang racket/base

'(1 #reader"five.rkt"234567 8)
```

is equivalent to

```
#lang racket/base

'(1 ("23456") 7 8)
```

because the `read` and `read-syntax` functions of `"five.rkt"` both read five characters from the input stream and put them into a string and then a list. The reader functions from `"five.rkt"` are not obliged to follow Racket lexical conventions and treat the continuous sequence `234567` as a single number. Since only the `23456` part is consumed by `read` or `read-syntax`, the `7` remains to be parsed in the usual Racket way. Similarly, the reader functions from `"five.rkt"` are not obliged to ignore whitespace, and

```
#lang racket/base

'(1 #reader"five.rkt" 234567 8)
```

is equivalent to

```
#lang racket/base

'(1 (" 2345") 67 8)
```

since the first character immediately after `"five.rkt"` is a space.

A `#reader` form can be used in the REPL, too:

```
> '#reader"five.rkt"abcde
'("abcde")
```

17.2.1 Source Locations

The difference between `read` and `read-syntax` is that `read` is meant to be used for data while `read-syntax` is meant to be used to parse programs. More precisely, the `read` function will be used when the enclosing stream is being parsed by the Racket `read`, and `read-syntax` is used when the enclosing stream is being parsed by the Racket `read-syntax` function. Nothing requires `read` and `read-syntax` to parse input in the same way, but making them different would confuse programmers and tools.

The `read-syntax` function can return the same kind of value as `read`, but it should normally return a syntax object that connects the parsed expression with source locations. Unlike the `"five.rkt"` example, the `read-syntax` function is typically implemented directly to produce syntax objects, and then `read` can use `read-syntax` and strip away syntax object wrappers to produce a raw result.

The following "arith.rkt" module implements a reader to parse simple infix arithmetic expressions into Racket forms. For example, `1*2+3` parses into the Racket form `(+ (* 1 2) 3)`. The supported operators are `+`, `-`, `*`, and `/`, while operands can be unsigned integers or single-letter variables. The implementation uses `port-next-location` to obtain the current source location, and it uses `datum->syntax` to turn raw values into syntax objects.

"arith.rkt"

```
#lang racket
(require syntax/readerr)

(provide read read-syntax)

(define (read in)
  (syntax->datum (read-syntax #f in)))

(define (read-syntax src in)
  (skip-whitespace in)
  (read-arith src in))

(define (skip-whitespace in)
  (regexp-match #px"^\\s*" in))

(define (read-arith src in)
  (define-values (line col pos) (port-next-location in))
  (define expr-match
    (regexp-match
     ; Match an operand followed by any number of
     ; operator-operand sequences, and prohibit an
     ; additional operator from following immediately:
     #px"^([a-z]|[0-9]+)(?:[-+*/]([a-z]|[0-9]+))*(?![-+*/])"
     in))

  (define (to-syntax v delta span-str)
    (datum->syntax #f v (make-srcloc delta span-str)))
  (define (make-srcloc delta span-str)
    (and line
         (vector src line (+ col delta) (+ pos delta)
                 (string-length span-str))))

  (define (parse-expr s delta)
    (match (or (regexp-match #rx"^(.*)([+-])(.*?)$" s)
               (regexp-match #rx"^(.*)([*/])(.*?)$" s))
      [(list _ a-str op-str b-str)
       (define a-len (string-length a-str))
       (define a (parse-expr a-str delta))
       (define b (parse-expr b-str (+ delta 1 a-len)))
```

```
      (define op (to-syntax (string->symbol op-str)
                            (+ delta a-len) op-str))
      (to-syntax (list op a b) delta s)]
     [_ (to-syntax (or (string->number s)
                       (string->symbol s))
                   delta s)]))

(unless expr-match
  (raise-read-error "bad arithmetic syntax"
                    src line col pos
                    (and pos (- (file-position in) pos))))
(parse-expr (bytes->string/utf-8 (car expr-match)) 0))
```

If the `"arith.rkt"` reader is used in an expression position, then its parse result will be treated as a Racket expression. If it is used in a quoted form, however, then it just produces a number or a list:

```
> #reader"arith.rkt" 1*2+3
5
> '#reader"arith.rkt" 1*2+3
'(+ (* 1 2) 3)
```

The `"arith.rkt"` reader could also be used in positions that make no sense. Since the `read-syntax` implementation tracks source locations, syntax errors can at least refer to parts of the input in terms of their original locations (at the beginning of the error message):

```
> (let #reader"arith.rkt" 1*2+3 8)
repl:1:27: let: bad syntax (not an identifier and expression
for a binding)
  at: +
  in: (let (+ (* 1 2) 3) 8)
```

17.2.2 Readtables

A reader extension's ability to parse input characters in an arbitrary way can be powerful, but many cases of lexical extension call for a less general but more composable approach. In much the same way that the expander level of Racket syntax can be extended through macros, the reader level of Racket syntax can be composably extended through a *readtable*.

The Racket reader is a recursive-descent parser, and the readtable maps characters to parsing handlers. For example, the default readtable maps `(` to a handler that recursively parses subforms until it finds a `)`. The `current-readtable` parameter determines the readtable that is used by `read` or `read-syntax`. Rather than parsing raw characters directly, a reader extension can install an extended readtable and then chain to `read` or `read-syntax`.

See §4.13 "Dynamic Binding: `parameterize`" for an introduction to parameters.

The `make-readtable` function constructs a new readtable as an extension of an existing one. It accepts a sequence of specifications in terms of a character, a type of mapping for the character, and (for certain types of mappings) a parsing procedure. For example, to extend the readtable so that `$` can be used to start and end infix expressions, implement a `read-dollar` function and use:

```
(make-readtable (current-readtable)
                #\$ 'terminating-macro read-dollar)
```

The protocol for `read-dollar` requires the function to accept different numbers of arguments depending on whether it is being used in `read` or `read-syntax` mode. In `read` mode, the parser function is given two arguments: the character that triggered the parser function and the input port that is being read. In `read-syntax` mode, the function must accept four additional arguments that provide the source location of the character.

The following `"dollar.rkt"` module defines a `read-dollar` function in terms of the `read` and `read-syntax` functions provided by `"arith.rkt"`, and it puts `read-dollar` together with new `read` and `read-syntax` functions that install the readtable and chain to Racket's `read` or `read-syntax`:

`"dollar.rkt"`

```
#lang racket
(require syntax/readerr
         (prefix-in arith: "arith.rkt"))

(provide (rename-out [$-read read]
                     [$-read-syntax read-syntax]))

(define ($-read in)
  (parameterize ([current-readtable (make-$-readtable)])
    (read in)))

(define ($-read-syntax src in)
  (parameterize ([current-readtable (make-$-readtable)])
    (read-syntax src in)))

(define (make-$-readtable)
  (make-readtable (current-readtable)
                  #\$ 'terminating-macro read-dollar))

(define read-dollar
  (case-lambda
   [(ch in)
    (check-$-after (arith:read in) in (object-name in))]
   [(ch in src line col pos)
    (check-$-after (arith:read-syntax src in) in src)]))
```

```
(define (check-$-after val in src)
  (regexp-match #px"^\\s*" in) ; skip whitespace
  (let ([ch (peek-char in)])
    (unless (equal? ch #\$) (bad-ending ch src in))
    (read-char in))
  val)

(define (bad-ending ch src in)
  (let-values ([(line col pos) (port-next-location in)])
    ((if (eof-object? ch)
         raise-read-error
         raise-read-eof-error)
     "expected a closing `$'"
     src line col pos
     (if (eof-object? ch) 0 1))))
```

With this reader extension, a single `#reader` can be used at the beginning of an expression to enable multiple uses of `$` that switch to infix arithmetic:

```
> #reader"dollar.rkt" (let ([a $1*2+3$] [b $5/6$]) $a+b$)
35/6
```

17.3 Defining new `#lang` Languages

When loading a module as a source program that starts

```
#lang language
```

the *language* determines the way that the rest of the module is parsed at the reader level. The reader-level parse must produce a `module` form as a syntax object. As always, the second sub-form after `module` specifies the module language that controls the meaning of the module's body forms. Thus, a *language* specified after `#lang` controls both the reader-level and expander-level parsing of a module.

17.3.1 Designating a `#lang` Language

The syntax of a *language* intentionally overlaps with the syntax of a module path as used in `require` or as a module language, so that names like `racket`, `racket/base`, `slideshow`, or `scribble/manual` can be used both as `#lang` languages and as module paths.

At the same time, the syntax of *language* is far more restricted than a module path, because only `a`-`z`, `A`-`Z`, `0`-`9`, `/` (not at the start or end), `_`, `-`, and `+` are allowed in a *language* name.

These restrictions keep the syntax of #lang as simple as possible. Keeping the syntax of #lang simple, in turn, is important because the syntax is inherently inflexible and non-extensible; the #lang protocol allows a *language* to refine and define syntax in a practically unconstrained way, but the #lang protocol itself must remain fixed so that various different tools can "boot" into the extended world.

Fortunately, the #lang protocol provides a natural way to refer to languages in ways other than the rigid *language* syntax: by defining a *language* that implements its own nested protocol. We have already seen one example (in §17.1.2 "Using #lang s-exp"): the s-exp *language* allows a programmer to specify a module language using the general module path syntax. Meanwhile, s-exp takes care of the reader-level responsibilities of a #lang language.

Unlike racket, s-exp cannot be used as a module path with require. Although the syntax of *language* for #lang overlaps with the syntax of module paths, a *language* is not used directly as a module path. Instead, a *language* obtains a module path by trying two locations: first, it looks for a reader submodule of the main module for *language*. If this is not a valid module path, then *language* is suffixed with /lang/reader. (If neither is a valid module path, an error is raised.) The resulting module supplies read and read-syntax functions using a protocol that is similar to the one for #reader.

§17.2 "Reader Extensions" introduces #reader.

A consequence of the way that a #lang *language* is turned into a module path is that the language must be installed in a collection, similar to the way that "racket" or "slideshow" are collections that are distributed with Racket. Again, however, there's an escape from this restriction: the reader language lets you specify a reader-level implementation of a language using a general module path.

17.3.2 Using #lang reader

The reader language for #lang is similar to s-exp, in that it acts as a kind of meta-language. Whereas s-exp lets a programmer specify a module language at the expander layer of parsing, reader lets a programmer specify a language at the reader level.

A #lang reader must be followed by a module path, and the specified module must provide two functions: read and read-syntax. The protocol is the same as for a #reader implementation, but for #lang, the read and read-syntax functions must produce a module form that is based on the rest of the input file for the module.

The following "literal.rkt" module implements a language that treats its entire body as literal text and exports the text as a data string:

"literal.rkt"

```
#lang racket
(require syntax/strip-context)
```

```
(provide (rename-out [literal-read read]
                     [literal-read-syntax read-syntax]))

(define (literal-read in)
  (syntax->datum
   (literal-read-syntax #f in)))

(define (literal-read-syntax src in)
  (with-syntax ([str (port->string in)])
    (strip-context
     #'(module anything racket
         (provide data)
         (define data 'str)))))
```

The `"literal.rkt"` language uses `strip-context` on the generated `module` expression, because a `read-syntax` function should return a syntax object with no lexical context. Also, the `"literal.rkt"` language creates a module named `anything`, which is an arbitrary choice; the language is intended to be used in a file, and the longhand module name is ignored when it appears in a `required` file.

The `"literal.rkt"` language can be used in a module `"tuvalu.rkt"`:

`"tuvalu.rkt"`

```
#lang reader "literal.rkt"
Technology!
System!
Perfect!
```

Importing `"tuvalu.rkt"` binds `data` to a string version of the module content:

```
> (require "tuvalu.rkt")
> data
"\nTechnology!\nSystem!\nPerfect!\n"
```

17.3.3 Using `#lang s-exp syntax/module-reader`

Parsing a module body is usually not as trivial as in `"literal.rkt"`. A more typical module parser must iterate to parse multiple forms for a module body. A language is also more likely to extend Racket syntax—perhaps through a readtable—instead of replacing Racket syntax completely.

The `syntax/module-reader` module language abstracts over common parts of a language implementation to simplify the creation of new languages. In its most basic form, a language implemented with `syntax/module-reader` simply specifies the module language to be

used for the language, in which case the reader layer of the language is the same as Racket. For example, with

"raquet-mlang.rkt"

```
#lang racket
(provide (except-out (all-from-out racket) lambda)
         (rename-out [lambda function]))
```

and

"raquet.rkt"

```
#lang s-exp syntax/module-reader
"raquet-mlang.rkt"
```

then

```
#lang reader "raquet.rkt"
(define identity (function (x) x))
(provide identity)
```

implements and exports the `identity` function, since `"raquet-mlang.rkt"` exports `lambda` as `function`.

The `syntax/module-reader` language accepts many optional specifications to adjust other features of the language. For example, an alternate `read` and `read-syntax` for parsing the language can be specified with `#:read` and `#:read-syntax`, respectively. The following `"dollar-racket.rkt"` language uses `"dollar.rkt"` (see §17.2.2 “Readtables”) to build a language that is like `racket` but with a `$` escape to simple infix arithmetic:

"dollar-racket.rkt"

```
#lang s-exp syntax/module-reader
racket
#:read $-read
#:read-syntax $-read-syntax

(require (prefix-in $- "dollar.rkt"))
```

The `require` form appears at the end of the module, because all of the keyword-tagged optional specifications for `syntax/module-reader` must appear before any helper imports or definitions.

The following module uses `"dollar-racket.rkt"` to implement a `cost` function using a `$` escape:

"store.rkt"

```
#lang reader "dollar-racket.rkt"

(provide cost)

; Cost of `n' $1 rackets with 7% sales
; tax and shipping-and-handling fee `h':
(define (cost n h)
  $n*107/100+h$)
```

17.3.4 Installing a Language

So far, we have used the `reader` meta-language to access languages like `"literal.rkt"` and `"dollar-racket.rkt"`. If you want to use something like `#lang literal` directly, then you must move `"literal.rkt"` into a Racket collection named `"literal"` (see also §6.1.4 “Adding Collections”). Specifically, move `"literal.rkt"` to a `reader` submodule of `"literal/main.rkt"` for any directory name `"literal"`, like so:

`"literal/main.rkt"`

```
#lang racket

(module reader racket
  (require syntax/strip-context)

  (provide (rename-out [literal-read read]
                       [literal-read-syntax read-syntax]))

  (define (literal-read in)
    (syntax->datum
     (literal-read-syntax #f in)))

  (define (literal-read-syntax src in)
    (with-syntax ([str (port->string in)])
      (strip-context
       #'(module anything racket
           (provide data)
           (define data 'str))))))
```

Then, install the `"literal"` directory as a package:

```
cd /path/to/literal ; raco pkg install
```

After moving the file and installing the package, you can use `literal` directly after `#lang`:

```
#lang literal
Technology!
```

```
System!
Perfect!
```

See *raco: Racket Command-Line Tools* for more information on using `raco`.

You can also make your language available for others to install by using the Racket package manager (see *Package Management in Racket*). After you create a `"literal"` package and register it with the Racket package catalog (see §2.3 “Package Catalogs”), others can install it using `raco pkg`:

```
raco pkg install literal
```

Once installed, others can invoke the language the same way: by using `#lang literal` at the top of a source file.

If you use a public source repository (e.g., GitHub), you can link your package to the source. As you improve the package, others can update their version using `raco pkg`:

```
raco pkg update literal
```

See *Package Management in Racket* for more information about the Racket package manager.

17.3.5 Source-Handling Configuration

The Racket distribution includes a Scribble language for writing prose documents, where Scribble extends the normal Racket to better support text. Here is an example Scribble document:

```
#lang scribble/base

@(define (get-name) "Self-Describing Document")

@title[(get-name)]

The title of this document is ``@(get-name).''
```

If you put that program in DrRacket’s definitions area and click Run, then nothing much appears to happen. The `scribble/base` language just binds and exports `doc` as a description of a document, similar to the way that `"literal.rkt"` exports a string as `data`.

Simply opening a module with the language `scribble/base` in DrRacket, however, causes a Scribble HTML button to appear. Furthermore, DrRacket knows how to colorize Scribble syntax by coloring green those parts of the document that correspond to literal text. The language name `scribble/base` is not hard-wired into DrRacket. Instead, the implementation of the `scribble/base` language provides button and syntax-coloring information in response to a query from DrRacket.

If you have installed the `literal` language as described in §17.3.4 “Installing a Language”, then you can adjust `"literal/main.rkt"` so that DrRacket treats the content of a module

in the `literal` language as plain text instead of (erroneously) as Racket syntax:

`"literal/main.rkt"`

```
#lang racket

(module reader racket
  (require syntax/strip-context)

  (provide (rename-out [literal-read read]
                       [literal-read-syntax read-syntax])
           get-info)

  (define (literal-read in)
    (syntax->datum
     (literal-read-syntax #f in)))

  (define (literal-read-syntax src in)
    (with-syntax ([str (port->string in)])
      (strip-context
       #'(module anything racket
           (provide data)
           (define data 'str)))))

  (define (get-info in mod line col pos)
    (lambda (key default)
      (case key
        [(color-lexer)
         (dynamic-require 'syntax-color/default-lexer
                          'default-lexer)]
        [else default]))))
```

This revised `literal` implementation provides a `get-info` function. The `get-info` function is called by `read-language` (which DrRacket calls) with the source input stream and location information, in case query results should depend on the content of the module after the language name (which is not the case for `literal`). The result of `get-info` is a function of two arguments. The first argument is always a symbol, indicating the kind of information that a tool requests from the language; the second argument is the default result to be returned if the language does not recognize the query or has no information for it.

After DrRacket obtains the result of `get-info` for a language, it calls the function with a `'color-lexer` query; the result should be a function that implements syntax-coloring parsing on an input stream. For `literal`, the `syntax-color/default-lexer` module provides a `default-lexer` syntax-coloring parser that is suitable for plain text, so `literal` loads and returns that parser in response to a `'color-lexer` query.

The set of symbols that a programming tool uses for queries is entirely between the tool and

the languages that choose to cooperate with it. For example, in addition to `'color-lexer`, DrRacket uses a `'drracket:toolbar-buttons` query to determine which buttons should be available in the toolbar to operate on modules using the language.

The `syntax/module-reader` language lets you specify `get-info` handling through a `#:info` optional specification. The protocol for an `#:info` function is slightly different from the raw `get-info` protocol; the revised protocol allows `syntax/module-reader` the possibility of handling future language-information queries automatically.

17.3.6 Module-Handling Configuration

Suppose that the file `"death-list-5.rkt"` contains

`"death-list-5.rkt"`

```
#lang racket
(list "O-Ren Ishii"
      "Vernita Green"
      "Budd"
      "Elle Driver"
      "Bill")
```

If you `require` `"death-list-5.rkt"` directly, then it prints the list in the usual Racket result format:

```
> (require "death-list-5.rkt")
'("O-Ren Ishii" "Vernita Green" "Budd" "Elle Driver" "Bill")
```

However, if `"death-list-5.rkt"` is required by a `"kiddo.rkt"` that is implemented with `scheme` instead of `racket`:

`"kiddo.rkt"`

```
#lang scheme
(require "death-list-5.rkt")
```

then, if you run `"kiddo.rkt"` file in DrRacket or if you run it directly with `racket`, `"kiddo.rkt"` causes `"death-list-5.rkt"` to print its list in traditional Scheme format, without the leading quote:

```
("O-Ren Ishii" "Vernita Green" "Budd" "Elle Driver" "Bill")
```

The `"kiddo.rkt"` example illustrates how the format for printing a result value can depend on the main module of a program instead of the language that is used to implement it.

More broadly, certain features of a language are only invoked when a module written in that language is run directly with `racket` (as opposed to being imported into another module). One example is result-printing style (as shown above). Another example is REPL behavior. These features are part of what's called the *run-time configuration* of a language.

Unlike the syntax-coloring property of a language (as described in §17.3.5 "Source-Handling Configuration"), the run-time configuration is a property of a *module* per se as opposed to a property of the *source text* representing the module. For that reason, the run-time configuration for a module needs to be available even if the module is compiled to bytecode form and the source is unavailable. Therefore, run-time configuration cannot be handled by the `get-info` function we're exporting from the language's parser module.

Instead, it will be handled by a new `configure-runtime` submodule that we'll add inside the parsed `module` form. When a module is run directly with `racket`, `racket` looks for a `configure-runtime` submodule. If it exists, `racket` runs it. But if the module is imported into another module, the `'configure-runtime` submodule is ignored. (And if the `configure-runtime` submodule doesn't exist, `racket` just evaluates the module as usual.) That means that the `configure-runtime` submodule can be used for any special setup tasks that need to happen when the module is run directly.

Going back to the `literal` language (see §17.3.5 "Source-Handling Configuration"), we can adjust the language so that directly running a `literal` module causes it to print out its string, while using a `literal` module in a larger program simply provides `data` without printing. To make this work, we will need an extra module. (For clarity here, we will implement this module as a separate file. But it could equally well be a submodule of an existing file.)

```
.... (the main installation or the user's space)
|- "literal"
   |- "main.rkt"          (with reader submodule)
   |- "show.rkt"          (new)
```

- The `"literal/show.rkt"` module will provide a `show` function to be applied to the string content of a `literal` module, and also provide a `show-enabled` parameter that controls whether `show` actually prints the result.
- The new `configure-runtime` submodule in `"literal/main.rkt"` will set the `show-enabled` parameter to `#t`. The net effect is that `show` will print the strings that it's given, but only when a module using the `literal` language is run directly (because only then will the `configure-runtime` submodule be invoked).

These changes are implemented in the following revised `"literal/main.rkt"`:

`"literal/main.rkt"`

```
#lang racket
```

```
(module reader racket
  (require syntax/strip-context)

  (provide (rename-out [literal-read read]
                       [literal-read-syntax read-syntax])
           get-info)

  (define (literal-read in)
    (syntax->datum
     (literal-read-syntax #f in)))

  (define (literal-read-syntax src in)
    (with-syntax ([str (port->string in)])
      (strip-context
       #'(module anything racket
           (module configure-runtime racket
             (require literal/show)
             (show-enabled #t))
           (require literal/show)
           (provide data)
           (define data 'str)
           (show data)))))

  (define (get-info in mod line col pos)
    (lambda (key default)
      (case key
        [(color-lexer)
         (dynamic-require 'syntax-color/default-lexer
                          'default-lexer)]
        [else default]))))
```

Then the `"literal/show.rkt"` module must provide the `show-enabled` parameter and `show` function:

`"literal/show.rkt"`

```
#lang racket

(provide show show-enabled)

(define show-enabled (make-parameter #f))

(define (show v)
  (when (show-enabled)
    (display v)))
```

With all of the pieces for `literal` in place, try running the following variant of

"tuvalu.rkt" directly and through a require from another module:

"tuvalu.rkt"

```
#lang literal
Technology!
System!
Perfect!
```

When run directly, we'll see the result printed like so, because our configure-runtime submodule will have set the show-enabled parameter to #t:

```
Technology!
System!
Perfect!
```

But when imported into another module, printing will be suppressed, because the configure-runtime submodule will not be invoked, and therefore the show-enabled parameter will remain at its default value of #f.

18 Concurrency and Synchronization

Racket provides *concurrency* in the form of *threads*, and it provides a general `sync` function that can be used to synchronize both threads and other implicit forms of concurrency, such as ports.

Threads run concurrently in the sense that one thread can preempt another without its cooperation, but by default, threads do not run in parallel in the sense of using multiple hardware processors. That default kind of thread is a *coroutine thread*. See §20 "Parallelism" for information on parallelism in Racket.

18.1 Threads

To execute a procedure concurrently, use `thread`. The following example creates two new threads from the main thread:

```
(displayln "This is the original thread")
(thread (lambda () (displayln "This is a new thread.")))
(thread (lambda () (displayln "This is another new thread.")))
```

The next example creates a new thread that would otherwise loop forever, but the main thread uses `sleep` to pause itself for 2.5 seconds, then uses `kill-thread` to terminate the worker thread:

```
(define worker (thread (lambda ()
                         (let loop ()
                           (displayln "Working...")
                           (sleep 0.2)
                           (loop)))))
(sleep 2.5)
(kill-thread worker)
```

In DrRacket, the main thread keeps going until the Stop button is clicked, so in DrRacket the `thread-wait` is not necessary.

If the main thread finishes or is killed, the application exits, even if other threads are still running. A thread can use `thread-wait` to wait for another thread to finish. Here, the main thread uses `thread-wait` to make sure the worker thread finishes before the main thread exits:

```
(define worker (thread
                (lambda ()
                  (for ([i 100])
                    (printf "Working hard... ~a~n" i)))))
(thread-wait worker)
(displayln "Worker finished")
```

To receive a result back from a thread, use `#:keep 'results` when creating the thread, and then `thread-wait` can return the values that the thread's procedure returned:

```
(define worker (thread (lambda () (+ 1 2))
                       #:keep 'results))
(thread-wait worker)
```

18.2 Thread Mailboxes

Each thread has a mailbox for receiving messages. The `thread-send` function asynchronously sends a message to another thread's mailbox, while `thread-receive` returns the oldest message from the current thread's mailbox, blocking to wait for a message if necessary. In the following example, the main thread sends data to the worker thread to be processed, then sends a `'done` message when there is no more data and waits for the worker thread to finish.

```
(define worker-thread (thread
                       (lambda ()
                         (let loop ()
                           (match (thread-receive)
                             [(? number? num)
                              (printf "Processing ~a~n" num)
                              (loop)]
                             ['done
                              (printf "Done~n")])))))
(for ([i 20])
  (thread-send worker-thread i))
(thread-send worker-thread 'done)
(thread-wait worker-thread)
```

In the next example, the main thread delegates work to multiple arithmetic threads, then waits to receive the results. The arithmetic threads process work items then send the results to the main thread.

```
(define (make-arithmetic-thread operation)
  (thread (lambda ()
            (let loop ()
              (match (thread-receive)
                [(list oper1 oper2 result-thread)
                 (thread-send result-thread
                              (format "~a ~a ~a = ~a"
                                      oper1
                                      (object-name operation)
                                      oper2
```

```
                                        (operation oper1 oper2)))
                (loop)])))))

(define addition-thread (make-arithmetic-thread +))
(define subtraction-thread (make-arithmetic-thread -))

(define worklist '((+ 1 1) (+ 2 2) (- 3 2) (- 4 1)))
(for ([item worklist])
  (match item
    [(list '+ o1 o2)
     (thread-send addition-thread
                  (list o1 o2 (current-thread)))]
    [(list '- o1 o2)
     (thread-send subtraction-thread
                  (list o1 o2 (current-thread)))]))

(for ([i (length worklist)])
  (displayln (thread-receive)))
```

18.3 Semaphores

Semaphores facilitate synchronized access to an arbitrary shared resource. Use semaphores when multiple threads must perform non-atomic operations on a single resource.

In the following example, multiple threads print to standard output concurrently. Without synchronization, a line printed by one thread might appear in the middle of a line printed by another thread. By using a semaphore initialized with a count of `1`, only one thread will print at a time. The `semaphore-wait` function blocks until the semaphore's internal counter is non-zero, then decrements the counter and returns. The `semaphore-post` function increments the counter so that another thread can unblock and then print.

```
(define output-semaphore (make-semaphore 1))
(define (make-thread name)
  (thread (lambda ()
            (for [(i 10)]
              (semaphore-wait output-semaphore)
              (printf "thread ~a: ~a~n" name i)
              (semaphore-post output-semaphore)))))
(define threads
  (map make-thread '(A B C)))
(for-each thread-wait threads)
```

The pattern of waiting on a semaphore, working, and posting to the semaphore can also be expressed using `call-with-semaphore`,which has the advantage of posting to the

semaphore if control escapes (e.g., due to an exception):

```
(define output-semaphore (make-semaphore 1))
(define (make-thread name)
  (thread (lambda ()
            (for [(i 10)]
              (call-with-semaphore
               output-semaphore
               (lambda ()
                (printf "thread ~a: ~a~n" name i)))))))
(define threads
  (map make-thread '(A B C)))
(for-each thread-wait threads)
```

Semaphores are a low-level technique. Often, a better solution is to restrict resource access to a single thread. For example, synchronizing access to standard output might be better accomplished by having a dedicated thread for printing output.

18.4 Channels

Channels synchronize two threads while a value is passed from one thread to the other. Unlike a thread mailbox, multiple threads can get items from a single channel, so channels should be used when multiple threads need to consume items from a single work queue.

In the following example, the main thread adds items to a channel using `channel-put`, while multiple worker threads consume those items using `channel-get`. Each call to either procedure blocks until another thread calls the other procedure with the same channel. The workers process the items and then pass their results to the result thread via the `result-channel`.

```
(define result-channel (make-channel))
(define result-thread
        (thread (lambda ()
                  (let loop ()
                    (display (channel-get result-channel))
                    (loop)))))

(define work-channel (make-channel))
(define (make-worker thread-id)
  (thread
   (lambda ()
     (let loop ()
       (define item (channel-get work-channel))
       (case item
```

```
          [(DONE)
           (channel-put result-channel
                        (format "Thread ~a done\n" thread-id))]
          [else
           (channel-put result-channel
                        (format "Thread ~a processed ~a\n"
                                thread-id
                                item))
           (loop)])))))
(define work-threads (map make-worker '(1 2)))
(for ([item '(A B C D E F G H DONE DONE)])
  (channel-put work-channel item))
(for-each thread-wait work-threads)
(channel-put result-channel "") ; waits until result-thread has
printed all other output
```

18.5 Buffered Asynchronous Channels

Buffered asynchronous channels are similar to the channels described above, but the "put" operation of asynchronous channels does not block—unless the given channel was created with a buffer limit and the limit has been reached. The asynchronous-put operation is therefore somewhat similar to `thread-send`, but unlike thread mailboxes, asynchronous channels allow multiple threads to consume items from a single channel.

In the following example, the main thread adds items to the work channel, which holds a maximum of three items at a time. The worker threads process items from this channel and then send results to the print thread.

```
(require racket/async-channel)

(define print-thread
  (thread (lambda ()
            (let loop ()
              (displayln (thread-receive))
              (loop)))))
(define (safer-printf . items)
  (thread-send print-thread
               (apply format items)))

(define work-channel (make-async-channel 3))
(define (make-worker-thread thread-id)
  (thread
   (lambda ()
     (let loop ()
       (define item (async-channel-get work-channel))
```

```
       (safer-printf "Thread ~a processing item: ~a" thread-
id item)
       (loop)))))

(for-each make-worker-thread '(1 2 3))
(for ([item '(a b c d e f g h i j k l m)])
  (async-channel-put work-channel item))
```

Note the above example lacks any synchronization to verify that all items were processed. If the main thread were to exit without such synchronization, it is possible that the worker threads will not finish processing some items or the print thread will not print all items.

18.6 Synchronizable Events and `sync`

There are other ways to synchronize threads. The `sync` function allows threads to coordinate via synchronizable events. Many values double as events, allowing a uniform way to synchronize threads using different types. Examples of events include channels, ports, threads, and alarms. This section builds up a number of examples that show how the combination of events, threads, and `sync` (along with recursive functions) allow you to implement arbitrarily sophisticated communication protocols to coordinate concurrent parts of a program.

In the next example, a channel and an alarm are used as synchronizable events. The workers `sync` on both so that they can process channel items until the alarm is activated. The channel items are processed, and then results are sent back to the main thread.

```
(define main-thread (current-thread))
(define alarm (alarm-evt (+ 3000 (current-inexact-milliseconds))))
(define channel (make-channel))
(define (make-worker-thread thread-id)
  (thread
   (lambda ()
     (define evt (sync channel alarm))
     (cond
       [(equal? evt alarm)
        (thread-send main-thread 'alarm)]
       [else
        (thread-send main-thread
                     (format "Thread ~a received ~a"
                             thread-id
                             evt))]))))
(make-worker-thread 1)
(make-worker-thread 2)
(make-worker-thread 3)
(channel-put channel 'A)
```

```
(channel-put channel 'B)
(let loop ()
  (match (thread-receive)
    ['alarm
     (displayln "Done")]
    [result
     (displayln result)
     (loop)]))
```

The next example shows a function for use in a simple TCP echo server. The function uses `sync/timeout` to synchronize on input from the given port or a message in the thread's mailbox. The first argument to `sync/timeout` specifies the maximum number of seconds it should wait on the given events. The `read-line-evt` function returns an event that is ready when a line of input is available in the given input port. The result of `thread-receive-evt` is ready when `thread-receive` would not block. In a real application, the messages received in the thread mailbox could be used for control messages, etc.

```
(define (serve in-port out-port)
  (let loop []
    (define evt (sync/timeout 2
                              (read-line-evt in-port 'any)
                              (thread-receive-evt)))
    (cond
      [(not evt)
       (displayln "Timed out, exiting")
       (tcp-abandon-port in-port)
       (tcp-abandon-port out-port)]
      [(string? evt)
       (fprintf out-port "~a~n" evt)
       (flush-output out-port)
       (loop)]
      [else
       (printf "Received a message in mailbox: ~a~n"
               (thread-receive))
       (loop)])))
```

The `serve` function is used in the following example, which starts a server thread and a client thread that communicate over TCP. The client prints three lines to the server, which echoes them back. The client's `copy-port` call blocks until EOF is received. The server times out after two seconds, closing the ports, which allows `copy-port` to finish and the client to exit. The main thread uses `thread-wait` to wait for the client thread to exit (since, without `thread-wait`, the main thread might exit before the other threads are finished).

```
(define port-num 4321)
(define (start-server)
```

```
  (define listener (tcp-listen port-num))
  (thread
    (lambda ()
      (define-values [in-port out-port] (tcp-accept listener))
      (serve in-port out-port))))

(start-server)

(define client-thread
  (thread
   (lambda ()
     (define-values [in-port out-port] (tcp-
connect "localhost" port-num))
     (display "first\nsecond\nthird\n" out-port)
     (flush-output out-port)
     ; copy-port will block until EOF is read from in-port
     (copy-port in-port (current-output-port)))))

(thread-wait client-thread)
```

Sometimes, you want to attach result behavior directly to the event passed to `sync`. In the following example, the worker thread synchronizes on three channels, but each channel must be handled differently. Using `handle-evt` associates a callback with the given event. When `sync` selects the given event, it calls the callback to generate the synchronization result, rather than using the event's normal synchronization result. Since the event is handled in the callback, there is no need to dispatch on the return value of `sync`.

```
(define add-channel (make-channel))
(define multiply-channel (make-channel))
(define append-channel (make-channel))

(define (work)
  (let loop ()
    (sync (handle-evt add-channel
                      (lambda (list-of-numbers)
                        (printf "Sum of ~a is ~a~n"
                                list-of-numbers
                                (apply + list-of-numbers))))
          (handle-evt multiply-channel
                      (lambda (list-of-numbers)
                        (printf "Product of ~a is ~a~n"
                                list-of-numbers
                                (apply * list-of-numbers))))
          (handle-evt append-channel
                      (lambda (list-of-strings)
                        (printf "Concatenation of ~s is ~s~n"
```

```
                                  list-of-strings
                                  (apply string-append list-of-
strings)))))
    (loop)))

(define worker (thread work))
(channel-put add-channel '(1 2))
(channel-put multiply-channel '(3 4))
(channel-put multiply-channel '(5 6))
(channel-put add-channel '(7 8))
(channel-put append-channel '("a" "b"))
```

The result of `handle-evt` invokes its callback in tail position with respect to `sync`, so it is safe to use recursion as in the following example.

```
(define control-channel (make-channel))
(define add-channel (make-channel))
(define subtract-channel (make-channel))
(define (work state)
  (printf "Current state: ~a~n" state)
  (sync (handle-evt add-channel
                    (lambda (number)
                      (printf "Adding: ~a~n" number)
                      (work (+ state number))))
        (handle-evt subtract-channel
                    (lambda (number)
                      (printf "Subtracting: ~a~n" number)
                      (work (- state number))))
        (handle-evt control-channel
                    (lambda (kill-message)
                      (printf "Done~n")))))

(define worker (thread (lambda () (work 0))))
(channel-put add-channel 2)
(channel-put subtract-channel 3)
(channel-put add-channel 4)
(channel-put add-channel 5)
(channel-put subtract-channel 1)
(channel-put control-channel 'done)
(thread-wait worker)
```

The `wrap-evt` function is like `handle-evt`, except that its handler is not called in tail position with respect to `sync`. At the same time, `wrap-evt` disables break exceptions during its handler's invocation.

18.7 Building Your Own Synchronization Patterns

Events also allow you to encode many different communication patterns between multiple concurrent parts of a program. One common such pattern is producer-consumer. Here is a way to implement a variation on it using the above ideas. Generally speaking, these communication patterns are implemented via a server loop that uses `sync` to wait for any number of different possibilities to occur and then reacts to them, updating some local state.

```
(define/contract (produce x)
  (-> any/c void?)
  (channel-put producer-chan x))

(define/contract (consume)
  (-> any/c)
  (channel-get consumer-chan))

; private state and server loop

(define producer-chan (make-channel))
(define consumer-chan (make-channel))
(void
 (thread
  (λ ()
    ; the items variable holds the items that
    ; have been produced but not yet consumed
    (let loop ([items '()])
      (sync

       ; wait for production
       (handle-evt
        producer-chan
        (λ (i)
          ; if that event was chosen,
          ; we add an item to our list
          ; and go back around the loop
          (loop (cons i items))))

       ; wait for consumption, but only
       ; if we have something to produce
       (handle-evt
        (if (null? items)
            never-evt
            (channel-put-evt consumer-chan (car items)))
        (λ (_)
          ; if that event was chosen,
          ; we know that the first item item
```

```
          ; has been consumed; drop it and
          ; and go back around the loop
          (loop (cdr items)))))))))

; an example (non-deterministic) interaction
> (void
   (thread (λ () (sleep (/ (random 10) 100)) (produce 1)))
   (thread (λ () (sleep (/ (random 10) 100)) (produce 2))))
> (list (consume) (consume))
'(1 2)
```

It is possible to build up more complex synchronization patterns. Here is a silly example where we extend the producer consumer with an operation to wait until at least a certain number of items have been produced.

```
(define/contract (produce x)
  (-> any/c void?)
  (channel-put producer-chan x))

(define/contract (consume)
  (-> any/c)
  (channel-get consumer-chan))

(define/contract (wait-at-least n)
  (-> natural? void?)
  (define c (make-channel))
  ; we send a new channel over to the
  ; main loop so that we can wait here
  (channel-put wait-at-least-chan (cons n c))
  (channel-get c))

(define producer-chan (make-channel))
(define consumer-chan (make-channel))
(define wait-at-least-chan (make-channel))
(void
 (thread
  (λ ()
    (let loop ([items '()]
               [total-items-seen 0]
               [waiters '()])
      ; instead of waiting on just production/
      ; consumption now we wait to learn about
      ; threads that want to wait for a certain
      ; number of elements to be reached
      (apply
       sync
```

```
        (handle-evt
         producer-chan
         (λ (i) (loop (cons i items)
                      (+ total-items-seen 1)
                      waiters)))
        (handle-evt
         (if (null? items)
             never-evt
             (channel-put-evt consumer-chan (car items)))
         (λ (_) (loop (cdr items) total-items-seen waiters)))

        ; wait for threads that are interested
        ; the number of items produced
        (handle-evt
         wait-at-least-chan
         (λ (waiter) (loop items total-items-
seen (cons waiter waiters))))

        ; for each thread that wants to wait,
        (for/list ([waiter (in-list waiters)])
          ; we check to see if there has been enough
          ; production
          (cond
            [(<= (car waiter) total-items-seen)
             ; if so, we send a message back on the channel
             ; and continue the loop without that item
             (handle-evt
              (channel-put-evt
               (cdr waiter)
               (void))
              (λ (_) (loop items total-items-
seen (remove waiter waiters))))]
            [else
             ; otherwise, we just ignore that one
             never-evt])))))))

; an example (non-deterministic) interaction
> (define thds
    (for/list ([i (in-range 10)])
      (thread (λ ()
                (produce i)
                (wait-at-least 10)
                (display (format "~a -> ~a\n" i (consume)))))))
> (for ([thd (in-list thds)])
    (thread-wait thd))
3 -> 3
```

```
9 -> 2
0 -> 1
8 -> 0
6 -> 9
7 -> 8
2 -> 7
1 -> 6
5 -> 5
4 -> 4
```

19 Performance

Alan Perlis famously quipped “Lisp programmers know the value of everything and the cost of nothing.” A Racket programmer knows, for example, that a `lambda` anywhere in a program produces a value that is closed over its lexical environment—but how much does allocating that value cost? While most programmers have a reasonable grasp of the cost of various operations and data structures at the machine level, the gap between the Racket language model and the underlying computing machinery can be quite large.

In this chapter, we narrow the gap by explaining details of the Racket compiler and runtime system and how they affect the runtime and memory performance of Racket code.

19.1 Performance in DrRacket

By default, DrRacket instruments programs for debugging, and debugging instrumentation (provided by the *Errortrace: Debugging and Profiling* library) can significantly degrade performance for some programs. Even when debugging is disabled through the Choose Language... dialog's Show Details panel, the Preserve stacktrace checkbox is clicked by default, which also affects performance. Disabling debugging and stacktrace preservation provides performance results that are more consistent with running in plain `racket`.

Even so, DrRacket and programs developed within DrRacket use the same Racket virtual machine, so garbage collection times (see §19.12 “Memory Management”) may be longer in DrRacket than when a program is run by itself, and DrRacket threads may impede execution of program threads. **For the most reliable timing results for a program, run in plain `racket` instead of in the DrRacket development environment.** Non-interactive mode should be used instead of the REPL to benefit from the module system. See §19.4 “Modules and Performance” for details.

19.2 Racket Virtual Machine Implementations

Racket is available in two implementations, *CS* and *BC*:

- CS is the current default implementation. It is a newer implementation that builds on Chez Scheme as its core virtual machine. This implementation performs better than the BC implementation for most programs.

  For this implementation, `(system-type 'vm)` reports `'chez-scheme` and `(system-type 'gc)` reports `'cs`.

- BC is an older implementation, and was the default until version 8.0. The implementation features a compiler and runtime written in C, with a precise garbage collector and a just-in-time compiler (JIT) on most platforms.

For this implementation, `(system-type 'vm)` reports `'racket`.

The BC implementation itself has two variants, *3m* and *CGC*:

- 3m is the normal BC variant with a precise garbage collector.
  For this variant, `(system-type 'gc)` reports `'3m`.
- CGC is the oldest variant. It's the same basic implementation as 3m (i.e., the same virtual machine), but compiled to rely on a "conservative" garbage collector, which affects the way that Racket interacts with C code. See §8.2 "CGC versus 3m" in *Inside: Racket C API* for more information.
  For this variant, `(system-type 'gc)` reports `'cgc`.

In general, Racket programs should run the same in all variants. Furthermore, the performance characteristics of Racket program should be similar in the CS and BC implementations. The cases where a program may depend on the implementation will typically involve interactions with foreign libraries; in particular, the Racket C API described in *Inside: Racket C API* is different for the CS implementation versus the BC implementation.

19.3 Bytecode, Machine Code, and Just-in-Time (JIT) Compilers

Every definition or expression to be evaluated by Racket is compiled to an internal bytecode format, although "bytecode" may actually be native machine code. In interactive mode, this compilation occurs automatically and on-the-fly. Tools like `raco make` and `raco setup` marshal compiled bytecode to a file, so that you do not have to compile from source every time that you run a program. See §24.1.1 "Compilation and Configuration: `raco`" for more information on generating bytecode files.

The bytecode compiler applies all standard optimizations, such as constant propagation, constant folding, inlining, and dead-code elimination. For example, in an environment where `+` has its usual binding, the expression `(let ([x 1] [y (lambda () 4)]) (+ 1 (y)))` is compiled the same as the constant `5`.

For the CS implementation of Racket, the main bytecode format is non-portable machine code. For the BC implementation of Racket, bytecode is portable in the sense that it is machine-independent. Setting `current-compile-target-machine` to `#f` selects a separate machine-independent and variant-independent format on all Racket implementations, but running code in that format requires an additional internal conversion step to the implementation's main bytecode format.

Machine-independent bytecode for the BC implementation is further compiled to native code via a *just-in-time* or *JIT* compiler. The JIT compiler substantially speeds programs that execute tight loops, arithmetic on small integers, and arithmetic on inexact real numbers. Currently, JIT compilation is supported for x86, x86_64 (a.k.a. AMD64), 32-bit ARM, and 32-bit PowerPC processors. The JIT compiler can be disabled via the `eval-jit-enabled`

parameter or the `--no-jit/-j` command-line flag for `racket`. Setting `eval-jit-enabled` to `#f` has no effect on the CS implementation of Racket.

The JIT compiler works incrementally as functions are applied, but the JIT compiler makes only limited use of run-time information when compiling procedures, since the code for a given module body or `lambda` abstraction is compiled only once. The JIT's granularity of compilation is a single procedure body, not counting the bodies of any lexically nested procedures. The overhead for JIT compilation is normally so small that it is difficult to detect.

For information about viewing intermediate Racket code representations, especially for the CS implementation, see §18.7.2 "Inspecting Compiler Passes".

19.4 Modules and Performance

The module system aids optimization by helping to ensure that identifiers have the usual bindings. That is, the `+` provided by `racket/base` can be recognized by the compiler and inlined. In contrast, in a traditional interactive Scheme system, the top-level `+` binding might be redefined, so the compiler cannot assume a fixed `+` binding (unless special flags or declarations are used to compensate for the lack of a module system).

Even in the top-level environment, importing with `require` enables some inlining optimizations. Although a `+` definition at the top level might shadow an imported `+`, the shadowing definition applies only to expressions evaluated later.

Within a module, inlining and constant-propagation optimizations take additional advantage of the fact that definitions within a module cannot be mutated when no `set!` is visible at compile time. Such optimizations are unavailable in the top-level environment. Although this optimization within modules is important for performance, it hinders some forms of interactive development and exploration. The `compile-enforce-module-constants` parameter disables the compiler's assumptions about module definitions when interactive exploration is more important. See §6.6 "Assignment and Redefinition" for more information.

The compiler may inline functions or propagate constants across module boundaries. To avoid generating too much code in the case of function inlining, the compiler is conservative when choosing candidates for cross-module inlining; see §19.5 "Function-Call Optimizations" for information on providing inlining hints to the compiler.

The later section §19.7 "`letrec` Performance" provides some additional caveats concerning inlining of module bindings.

19.5 Function-Call Optimizations

When the compiler detects a function call to an immediately visible function, it generates more efficient code than for a generic call, especially for tail calls. For example, given the program

```
(letrec ([odd (lambda (x)
                (if (zero? x)
                    #f
                    (even (sub1 x))))]
         [even (lambda (x)
                 (if (zero? x)
                     #t
                     (odd (sub1 x))))])
  (odd 40000000))
```

the compiler can detect the `odd`–`even` loop and produce code that runs much faster via loop unrolling and related optimizations.

Within a module form, `defined` variables are lexically scoped like `letrec` bindings, and definitions within a module therefore permit call optimizations, so

```
(define (odd x) ....)
(define (even x) ....)
```

within a module would perform the same as the `letrec` version.

For direct calls to functions with keyword arguments, the compiler can typically check keyword arguments statically and generate a direct call to a non-keyword variant of the function, which reduces the run-time overhead of keyword checking. This optimization applies only for keyword-accepting procedures that are bound with `define`.

For immediate calls to functions that are small enough, the compiler may inline the function call by replacing the call with the body of the function. In addition to the size of the target function's body, the compiler's heuristics take into account the amount of inlining already performed at the call site and whether the called function itself calls functions other than simple primitive operations. When a module is compiled, some functions defined at the module level are determined to be candidates for inlining into other modules; normally, only trivial functions are considered candidates for cross-module inlining, but a programmer can wrap a function definition with `begin-encourage-inline` to encourage inlining of the function.

Primitive operations like `pair?`, `car`, and `cdr` are inlined at the machine-code level by the bytecode or JIT compiler. See also the later section §19.8 "Fixnum and Flonum Optimizations" for information about inlined arithmetic operations.

19.6 Mutation and Performance

Using `set!` to mutate a variable can lead to bad performance. For example, the microbenchmark

```
#lang racket/base

(define (subtract-one x)
  (set! x (sub1 x))
  x)

(time
  (let loop ([n 4000000])
    (if (zero? n)
        'done
        (loop (subtract-one n)))))
```

runs much more slowly than the equivalent

```
#lang racket/base

(define (subtract-one x)
  (sub1 x))

(time
  (let loop ([n 4000000])
    (if (zero? n)
        'done
        (loop (subtract-one n)))))
```

In the first variant, a new location is allocated for `x` on every iteration, leading to poor performance. A more clever compiler could unravel the use of `set!` in the first example, but since mutation is discouraged (see §4.9.1 “Guidelines for Using Assignment”), the compiler’s effort is spent elsewhere.

More significantly, mutation can obscure bindings where inlining and constant-propagation might otherwise apply. For example, in

```
(let ([minus1 #f])
  (set! minus1 sub1)
  (let loop ([n 4000000])
    (if (zero? n)
        'done
        (loop (minus1 n)))))
```

the `set!` obscures the fact that `minus1` is just another name for the built-in `sub1`.

19.7 `letrec` Performance

When `letrec` is used to bind only procedures and literals, then the compiler can treat the bindings in an optimal manner, compiling uses of the bindings efficiently. When other kinds of bindings are mixed with procedures, the compiler may be less able to determine the control flow.

For example,

```
(letrec ([loop (lambda (x)
                 (if (zero? x)
                     'done
                     (loop (next x))))]
         [junk (display loop)]
         [next (lambda (x) (sub1 x))])
  (loop 40000000))
```

likely compiles to less efficient code than

```
(letrec ([loop (lambda (x)
                 (if (zero? x)
                     'done
                     (loop (next x))))]
         [next (lambda (x) (sub1 x))])
  (loop 40000000))
```

In the first case, the compiler likely does not know that `display` does not call `loop`. If it did, then `loop` might refer to `next` before the binding is available.

This caveat about `letrec` also applies to definitions of functions and constants as internal definitions or in modules. A definition sequence in a module body is analogous to a sequence of `letrec` bindings, and non-constant expressions in a module body can interfere with the optimization of references to later bindings.

19.8 Fixnum and Flonum Optimizations

A *fixnum* is a small exact integer. In this case, "small" depends on the platform. For a 32-bit machine, numbers that can be expressed in 29-30 bits plus a sign bit are represented as fixnums. On a 64-bit machine, 60-62 bits plus a sign bit are available.

A *flonum* is used to represent any inexact real number. They correspond to 64-bit IEEE floating-point numbers on all platforms.

Inlined fixnum and flonum arithmetic operations are among the most important advantages of the compiler. For example, when `+` is applied to two arguments, the generated machine

code tests whether the two arguments are fixnums, and if so, it uses the machine's instruction to add the numbers (and check for overflow). If the two numbers are not fixnums, then it checks whether both are flonums; in that case, the machine's floating-point operations are used directly. For functions that take any number of arguments, such as `+`, inlining works for two or more arguments (except for `-`, whose one-argument case is also inlined) when the arguments are either all fixnums or all flonums.

Flonums are typically *boxed*, which means that memory is allocated to hold every result of a flonum computation. Fortunately, the generational garbage collector (described later in §19.12 "Memory Management") makes allocation for short-lived results reasonably cheap. Fixnums, in contrast are never boxed, so they are typically cheap to use.

See §20.2 "Parallelism with Futures" for an example use of flonum-specific operations.

The `racket/flonum` library provides flonum-specific operations, and combinations of flonum operations allow the compiler to generate code that avoids boxing and unboxing intermediate results. Besides results within immediate combinations, flonum-specific results that are bound with `let` and consumed by a later flonum-specific operation are unboxed within temporary storage. Finally, the compiler can detect some flonum-valued loop accumulators and avoid boxing of the accumulator.

Unboxing applies most reliably to uses of a flonum-specific operation with two arguments.

For some loop patterns, the compiler may need hints to enable unboxing. For example:

```
(define (flvector-sum vec init)
  (let loop ([i 0] [sum init])
    (if (fx= i (flvector-length vec))
        sum
        (loop (fx+ i 1) (fl+ sum (flvector-ref vec i))))))
```

Unboxing of local bindings and accumulators is not supported by the BC implementation's JIT for PowerPC.

The compiler may not be able to unbox `sum` in this example for two reasons: it cannot determine locally that its initial value from `init` will be a flonum, and it cannot tell locally that the `eq?` identity of the result `sum` is irrelevant. Changing the reference `init` to `(fl+ init)` and changing the result `sum` to `(fl+ sum)` gives the compiler hints and license to unbox `sum`.

The bytecode decompiler (see §7 "`raco decompile`: Decompiling Bytecode") for the BC implementation annotates combinations where the JIT can avoid boxes with `#%flonum`, `#%as-flonum`, and `#%from-flonum`. For the CS variant, the "bytecode" decompiler shows machine code, but install the `"disassemble"` package to potentially see the machine code as machine-specific assembly code. See also §18.7.2 "Inspecting Compiler Passes".

The `racket/unsafe/ops` library provides unchecked fixnum- and flonum-specific operations. Unchecked flonum-specific operations allow unboxing, and sometimes they allow the compiler to reorder expressions to improve performance. See also §19.9 "Unchecked, Unsafe Operations", especially the warnings about unsafety.

19.9 Unchecked, Unsafe Operations

The racket/unsafe/ops library provides functions that are like other functions in racket/base, but they assume (instead of checking) that provided arguments are of the right type. For example, unsafe-vector-ref accesses an element from a vector without checking that its first argument is actually a vector and without checking that the given index is in bounds. For tight loops that use these functions, avoiding checks can sometimes speed the computation, though the benefits vary for different unchecked functions and different contexts.

Beware that, as "unsafe" in the library and function names suggest, misusing the exports of racket/unsafe/ops can lead to crashes or memory corruption.

19.10 Foreign Pointers

The ffi/unsafe library provides functions for unsafely reading and writing arbitrary pointer values. The compiler recognizes uses of ptr-ref and ptr-set! where the second argument is a direct reference to one of the following built-in C types: _int8, _int16, _int32, _int64, _double, _float, and _pointer. Then, if the first argument to ptr-ref or ptr-set! is a C pointer (not a byte string), then the pointer read or write is performed inline in the generated code.

The bytecode compiler will optimize references to integer abbreviations like _int to C types like _int32—where the representation sizes are constant across platforms—so the compiler can specialize access with those C types. C types such as _long or _intptr are not constant across platforms, so their uses are not as consistently specialized.

Pointer reads and writes using _float or _double are not currently subject to unboxing optimizations.

19.11 Regular Expression Performance

When a string or byte string is provided to a function like regexp-match, then the string is internally compiled into a regexp value. Instead of supplying a string or byte string multiple times as a pattern for matching, compile the pattern once to a regexp value using regexp, byte-regexp, pregexp, or byte-pregexp. In place of a constant string or byte string, write a constant regexp using an #rx or #px prefix.

```
(define (slow-matcher str)
  (regexp-match? "[0-9]+" str))

(define (fast-matcher str)
  (regexp-match? #rx"[0-9]+" str))
```

```
(define (make-slow-matcher pattern-str)
  (lambda (str)
    (regexp-match? pattern-str str)))

(define (make-fast-matcher pattern-str)
  (define pattern-rx (regexp pattern-str))
  (lambda (str)
    (regexp-match? pattern-rx str)))
```

19.12 Memory Management

The CS (default) and BC Racket virtual machines each use a modern, *generational garbage collector* that makes allocation relatively cheap for short-lived objects. The CGC variant of BC uses a *conservative garbage collector* which facilitates interaction with C code at the expense of both precision and speed for Racket memory management.

Although memory allocation is reasonably cheap, avoiding allocation altogether is often faster. One particular place where allocation can be avoided sometimes is in *closures*, which are the run-time representation of functions that contain free variables. For example,

```
(let loop ([n 40000000] [prev-thunk (lambda () #f)])
  (if (zero? n)
      (prev-thunk)
      (loop (sub1 n)
            (lambda () n))))
```

allocates a closure on every iteration, since `(lambda () n)` effectively saves `n`.

The compiler can eliminate many closures automatically. For example, in

```
(let loop ([n 40000000] [prev-val #f])
  (let ([prev-thunk (lambda () n)])
    (if (zero? n)
        prev-val
        (loop (sub1 n) (prev-thunk)))))
```

no closure is ever allocated for `prev-thunk`, because its only application is visible, and so it is inlined. Similarly, in

```
(let n-loop ([n 400000])
  (if (zero? n)
      'done
      (let m-loop ([m 100])
```

```
(if (zero? m)
    (n-loop (sub1 n))
    (m-loop (sub1 m))))))
```

then the expansion of the `let` form to implement `m-loop` involves a closure over `n`, but the compiler automatically converts the closure to pass itself `n` as an argument instead.

19.13 Reachability and Garbage Collection

In general, Racket re-uses the storage for a value when the garbage collector can prove that the object is unreachable from any other (reachable) value. Reachability is a low-level, abstraction-breaking concept, and thus it requires detailed knowledge of the runtime system to predict exactly when values are reachable from each other. But generally one value is reachable from a second one when there is some operation to recover the original value from the second one.

To help programmers understand when an object is no longer reachable and its storage can be reused, Racket provides `make-weak-box` and `weak-box-value`, the creator and accessor for a one-record struct that the garbage collector treats specially. An object inside a weak box does not count as reachable, and so `weak-box-value` might return the object inside the box, but it might also return `#f` to indicate that the object was otherwise unreachable and garbage collected. Note that unless a garbage collection actually occurs, the value will remain inside the weak box, even if it is unreachable.

For example, consider this program:

```
#lang racket
(struct fish (weight color) #:transparent)
(define f (fish 7 'blue))
(define b (make-weak-box f))
(printf "b has ~s\n" (weak-box-value b))
(collect-garbage)
(printf "b has ~s\n" (weak-box-value b))
```

It will print `b has #(struct:fish 7 blue)` twice because the definition of `f` still holds onto the fish. If the program were this, however:

```
#lang racket
(struct fish (weight color) #:transparent)
(define f (fish 7 'blue))
(define b (make-weak-box f))
(printf "b has ~s\n" (weak-box-value b))
(set! f #f)
(collect-garbage)
(printf "b has ~s\n" (weak-box-value b))
```

the second printout will be `b has #f` because no reference to the fish exists (other than the one in the box).

As a first approximation, all values in Racket must be allocated and will demonstrate behavior similar to the fish above. There are a number of exceptions, however:

- Small integers (recognizable with `fixnum?`) are always available without explicit allocation. From the perspective of the garbage collector and weak boxes, their storage is never reclaimed. (Due to clever representation techniques, however, their storage does not count towards the space that Racket uses. That is, they are effectively free.)
- Procedures where the compiler can see all of their call sites may never be allocated at all (as discussed above). Similar optimizations may also eliminate the allocation for other kinds of values.
- Interned symbols are allocated only once (per place). A table inside Racket tracks this allocation so a symbol may not become garbage because that table holds onto it.
- Reachability is only approximate with the CGC collector (i.e., a value may appear reachable to that collector when there is, in fact, no way to reach it anymore).

19.14 Weak Boxes and Testing

One important use of weak boxes is in testing that some abstraction properly releases storage for data it no longer needs, but there is a gotcha that can easily cause such test cases to pass improperly.

Imagine you're designing a data structure that needs to hold onto some value temporarily but then should clear a field or somehow break a link to avoid referencing that value so it can be collected. Weak boxes are a good way to test that your data structure properly clears the value. That is, you might write a test case that builds a value, extracts some other value from it (that you hope becomes unreachable), puts the extracted value into a weak-box, and then checks to see if the value disappears from the box.

This code is one attempt to follow that pattern, but it has a subtle bug:

```
#lang racket
(let* ([fishes (list (fish 8 'red)
                     (fish 7 'blue))]
       [wb (make-weak-box (list-ref fishes 0))])
  (collect-garbage)
  (printf "still there? ~s\n" (weak-box-value wb)))
```

Specifically, it will show that the weak box is empty, but not because *`fishes`* no longer holds onto the value, but because *`fishes`* itself is not reachable anymore!

Change the program to this one:

```
#lang racket
(let* ([fishes (list (fish 8 'red)
                     (fish 7 'blue))]
       [wb (make-weak-box (list-ref fishes 0))])
  (collect-garbage)
  (printf "still there? ~s\n" (weak-box-value wb))
  (printf "fishes is ~s\n" fishes))
```

and now we see the expected result. The difference is that last occurrence of the variable *fishes*. That constitutes a reference to the list, ensuring that the list is not itself garbage collected, and thus the red fish is not either.

19.15 Reducing Garbage Collection Pauses

By default, Racket's generational garbage collector creates brief pauses for frequent *minor collections*, which inspect only the most recently allocated objects, and long pauses for infrequent *major collections*, which re-inspect all memory.

For some applications, such as animations and games, long pauses due to a major collection can interfere unacceptably with a program's operation. To reduce major-collection pauses, the 3m garbage collector supports *incremental garbage-collection* mode, and the CS garbage collector supports a useful approximation:

- In 3m's incremental mode, minor collections create longer (but still relatively short) pauses by performing extra work toward the next major collection. If all goes well, most of a major collection's work has been performed by minor collections the time that a major collection is needed, so the major collection's pause is as short as a minor collection's pause. Incremental mode tends to run more slowly overall, but it can provide much more consistent real-time behavior.

- In CS's incremental mode, objects are never promoted out of the category of "recently allocated," although there are degrees of "recently" so that most minor collections can still skip recent-but-not-too-recent objects. In the common case that most of the memory use for animation or game is allocated on startup (including its code and the code of the Racket runtime system), a major collection may never become necessary.

If the `PLT_INCREMENTAL_GC` environment variable is set to a value that starts with `0`, `n`, or `N` when Racket starts, incremental mode is permanently disabled. For 3m, if the `PLT_INCREMENTAL_GC` environment variable is set to a value that starts with `1`, `y`, or `Y` when Racket starts, incremental mode is permanently enabled. Since incremental mode is only useful for certain parts of some programs, however, and since the need for incremental

mode is a property of a program rather than its environment, the preferred way to enable incremental mode is with `(collect-garbage 'incremental)`.

Calling `(collect-garbage 'incremental)` does not perform an immediate garbage collection, but instead requests that each minor collection perform incremental work up to the next major collection (unless incremental model is permanently disabled). The request expires with the next major collection. Make a call to `(collect-garbage 'incremental)` in any repeating task within an application that needs to be responsive in real time. Force a full collection with `(collect-garbage)` just before an initial `(collect-garbage 'incremental)` to initiate incremental mode from an optimal state.

To check whether incremental mode is in use and how it affects pause times, enable `debug`-level logging output for the `GC` topic. For example,

```
racket -W "debug@GC error" main.rkt
```

runs `"main.rkt"` with garbage-collection logging to stderr (while preserving `error`-level logging for all topics). Minor collections are reported by `min` lines, increment-mode minor collections on 3m are reported with `mIn` lines, and major collections are reported with `MAJ` lines.

20 Parallelism

Racket provides three forms of *parallelism*: parallel threads, futures, and places. On a platform that provides multiple processors, parallelism can improve the run-time performance of a program.

See also §19 "Performance" for information on sequential performance in Racket. Racket also provides threads for concurrency, but coroutine threads for concurrency do not provide parallelism; see §18 "Concurrency and Synchronization" for more information.

20.1 Parallel Threads

A thread that is created with a *parallel thread pool* can use a different hardware processor than other threads, providing parallelism in addition to concurrency. When hardware is available, using these *parallel threads* can reduce the latency of a computation.

The BC-off with parallel threads is Racket computation that is used to run threads as a coroutine thread, instead of forcing them to overhead creating and managing parallel tasks.

Create a parallel thread using the `#:pool` argument to `thread`, where `'own` means that the thread gets its own, single-thread pool.

```
(define (fib n)
  (cond
   [(= n 0) 1]
   [(= n 1) 1]
   [else (+ (fib (- n 1)) (fib (- n 2)))]))
(define n1 (thread (lambda () (fib 35))
                   #:pool 'own
                   #:keep 'results))
(define n2 (thread (lambda () (fib 35))
                   #:pool 'own
                   #:keep 'results))
(time (= (thread-wait n1)
         (thread-wait n2)))
```

Whether parallel threads improve performance depends on the nature of the computation. The kinds of computations that can run efficiently in parallel are mostly the same ones that can run in a future, and §20.2 "Parallelism with Futures" provides more information and describes how the futures visualizer can help explain a program's performance. The difference with a parallel thread is that when a future would block, a parallel thread instead synchronizes enough with other threads to continue—in the hope of quickly reaching a point that is clear of blocking actions. Also, a parallel thread can freely use parameters and exception handlers, which are limited in futures until a `touch` provides a full dynamic context to the future. Finally, parallel threads implement the same interface for synchronization as coroutine threads, including `thread-wait`, `thread-send`, and `kill-thread`.

Racket's predefined constructs, such as input and output ports or mutable hash tables, are thread-safe and use locks internally as needed. Threads can perform some input and output operations in parallel, especially on regular files that never block. Meanwhile, blocking input and output operations not only interfere with parallelism, they can be significantly more expensive for parallel threads than for coroutine threads, because extra synchronization is required. Operations that interact with thread scheduling, such `sleep`, `sync`, `thread`, `thread-wait`, `kill-thread`, and `custodian-shutdown-all`, all require synchronization that can be more expensive when triggered from a parallel thread.

The `semaphore-post` and `semaphore-wait` operations can be inexpensive in a parallel thread as long as no thread ends up blocking on the semaphore. When a thread is blocked on a semaphore, then operations on the semaphore interact with thread scheduling and are therefore slower in parallel threads. In some cases, using a future semaphore (which is more limited than a normal semaphore) can provide better performance for parallel threads.

20.2 Parallelism with Futures

The `racket/future` library provides support for performance improvement through parallelism with *futures* and the `future` and `touch` functions. Achieving parallelism through those constructs depends on avoiding blocking operations: anything that inspects the full continuation or requires atomic execution relative to Racket threads. The caveats in §19.1 "Performance in DrRacket" also apply to futures; notably, debugging instrumentation currently defeats futures.

Other functions, such as `thread`, support the creation of reliably concurrent tasks.

As a starting example, the `any-double?` function below takes a list of numbers and determines whether any number in the list has a double that is also in the list:

```
(define (any-double? l)
  (for/or ([i (in-list l)])
    (for/or ([i2 (in-list l)])
      (= i2 (* 2 i)))))
```

This function runs in quadratic time, so it can take a long time (on the order of a second) on large lists like `l1` and `l2`:

```
(define l1 (for/list ([i (in-range 5000)])
             (+ (* 2 i) 1)))
(define l2 (for/list ([i (in-range 5000)])
             (- (* 2 i) 1)))
(or (any-double? l1)
    (any-double? l2))
```

The best way to speed up `any-double?` is to use a different algorithm. However, on a machine that offers at least two processing units, the example above can run in about half the time using `future` and `touch`:

```
(let ([f (future (lambda () (any-double? l2)))])
  (or (any-double? l1)
      (touch f)))
```

The future `f` runs `(any-double? l2)` in parallel to `(any-double? l1)`, and the result for `(any-double? l2)` becomes available about the same time that it is demanded by `(touch f)`.

Futures run in parallel as long as they can do so safely and independent of any continuation context that a `touch` might provide. Continuation context can include an exception handler, parameter value, continuation prompts, or other values accessible via continuation marks. Safety concerns shared mutable objects, such as input ports, output ports, and `equal?`-based hash tables, where concurrent access is managed either internally or explicitly via locks. The remainder of this section works through an example to illustrate safety and continuation obstacles, and it also shows how the *futures visualizer* (provided by `future-visualizer`) can help shed light on those obstacles.

Consider the following core of a Mandelbrot-set computation:

```
(define (mandelbrot iterations x y n)
  (printf "starting\n")
  (let ([ci (- (/ (* 2.0 y) n) 1.0)]
        [cr (- (/ (* 2.0 x) n) 1.5)])
    (let loop ([i 0] [zr 0.0] [zi 0.0])
      (if (> i iterations)
          i
          (let ([zrq (* zr zr)]
                [ziq (* zi zi)])
            (cond
              [(> (+ zrq ziq) 4) i]
              [else (loop (add1 i)
                          (+ (- zrq ziq) cr)
                          (+ (* 2 zr zi) ci))])))))))
```

The expressions `(mandelbrot 10000000 62 500 1000)` and `(mandelbrot 10000000 62 501 1000)` each take a while to produce an answer. Computing them both, of course, takes twice as long:

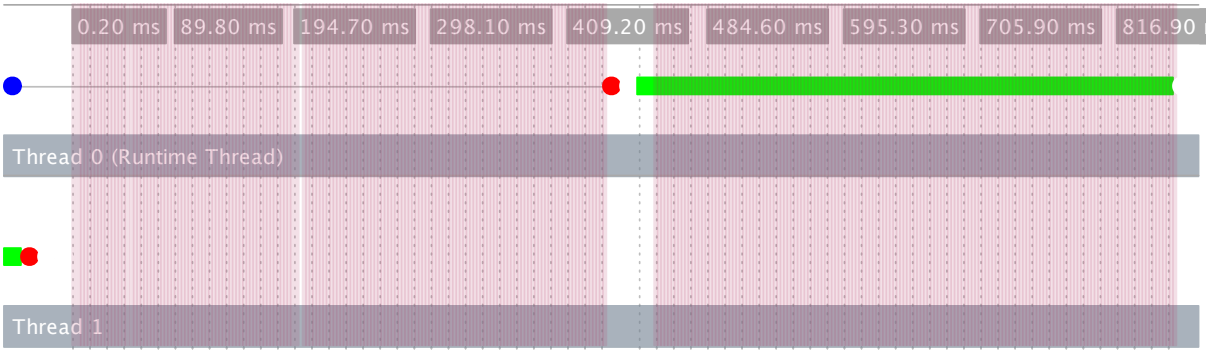
```
(list (mandelbrot 10000000 62 500 1000)
      (mandelbrot 10000000 62 501 1000))
```

Unfortunately, attempting to run the two computations in parallel by using one `future` does not improve performance:

```
(let ([f (future (lambda () (mandelbrot 10000000 62 501 1000)))])
```

```
(list (mandelbrot 10000000 62 500 1000)
      (touch f)))
```

To see why, use the futures visualizer from `future-visualizer` to visualize the execution of the above program. The visualizer opens a window showing a graphical view of a trace of the computation. The upper-left portion of the window contains an execution timeline:

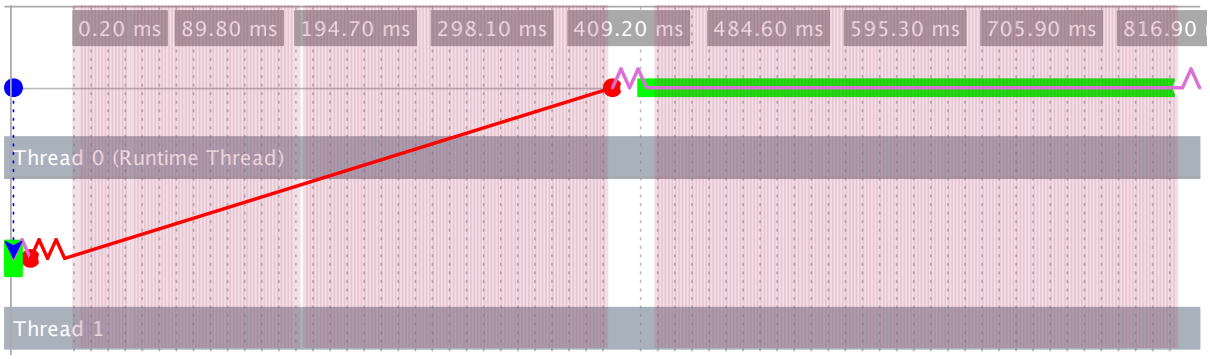


Each horizontal row represents a parallel task, and the colored dots represent important events in the execution of the program; they are color-coded to distinguish one event type from another. The upper-left blue dot in the timeline represents the future's creation. The future executes for a brief period (represented by a green bar in the second line) on thread 1. It then pauses, because the Racket thread will need to perform a future-unsafe operation (as represented by a red dot). That pause is long, because the Racket thread is performing its own copy of the calculation before it `touch`es the future. Meanwhile, the pink vertical lines represent garbage-collection events, which imply a synchronization across parallel tasks.

A future-unsafe operation or an operation that needs continuation context is a *blocking* operation. A blocking operation halts evaluation of a future and will not allow it to continue until the future is touched. A `touch` of the future in a thread causes its work to be evaluated sequentially by the thread, which provides a continuation context and can synchronize with Racket threads.

When you move your mouse over an event, the visualizer shows you detailed information about the event and draws arrows connecting all of the events in the corresponding future. This image shows those connections for our future.

In the BC implementation of Racket, a *synchronized* operation also halts the future. A background thread may perform the operation at any time and, once completed, the future may continue running in parallel. The CS implementation can perform synchronized operations without stopping a future or relying on a background thread.



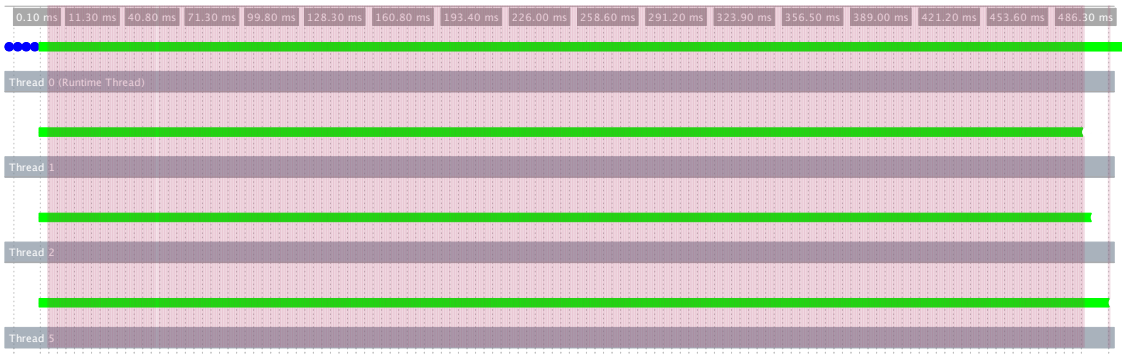
A dotted blue line connects the first event in the future to the future that created it, a red line connects a future blocking event to its resumptions, and the purple lines connect adjacent events within the future.

The reason that we see no parallelism is that the `printf` operation before the loop in `mandelbrot` needs to look up the `current-output-port` parameter's value, which depends on the evaluation context of the `touch`. Even if that is fixed by using `fprintf` and variable that refers directly to the port, writing to a port is also a blocking operation, because it must take a lock on the port. Removing the `printf` avoids both problems.

More generally, we can create `N` futures to perform the same computation, and they will run in parallel:

```
(define fs
  (for/list ([i (in-range N)])
    (future (lambda () (mandelbrot 10000000 62 500 1000)))))
(for/list ([f (in-list fs)])
  (touch f))
```

With `N` as `4` on a machine with at least 4 processing units:

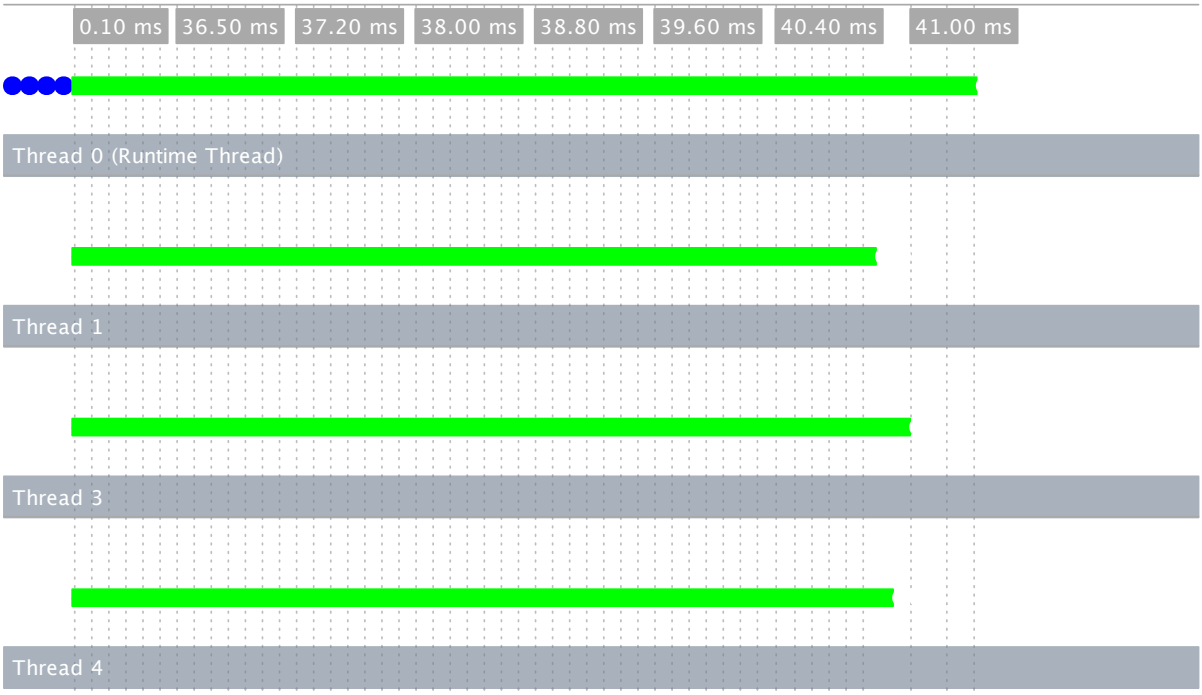


Most every arithmetic operation in this example produces an inexact number whose storage must be allocated, and that triggers frequent garbage collections as reflected by dense pink lines, effectively giving the whole graph a pink background. Garbage collection is not necessarily a problem, but since a garbage collection requires synchronization across parallel tasks, it can sometimes limit performance.

By using flonum-specific operations (see §19.8 “Fixnum and Flonum Optimizations”), we can re-write `mandelbrot` to use much less allocation:

```
(define (mandelbrot iterations x y n)
  (let ([ci (fl- (fl/ (* 2.0 (->fl y)) (->fl n)) 1.0)]
        [cr (fl- (fl/ (* 2.0 (->fl x)) (->fl n)) 1.5)])
    (let loop ([i 0] [zr 0.0] [zi 0.0])
      (if (> i iterations)
          i
          (let ([zrq (fl* zr zr)]
                [ziq (fl* zi zi)])
            (cond
              [(fl> (fl+ zrq ziq) 4.0) i]
              [else (loop (add1 i)
                          (fl+ (fl- zrq ziq) cr)
                          (fl+ (fl* 2.0 (fl* zr zi)) ci))])))))))
```

This conversion can speed `mandelbrot` by a factor of 10 or so, even in sequential mode, but avoiding allocation also allows `mandelbrot` to run more consistently in parallel. Executing this program yields the following pink-free result the visualizer (not to scale relative to previous graphs):



As a general guideline, an operation is blocking if it needs to consult the continuation (such as obtaining a parameter value) or if it interacts with Racket's thread system, such as taking a lock within the implementation of an output port or an `equal?`-based hash table. In the CS implementation of Racket, most primitives are non-blocking, while the BC implementation includes many more blocking or synchronized operations.

20.3 Parallelism with Places

The `racket/place` library provides support for performance improvement through parallelism with the `place` form. The `place` form creates a *place*, which is effectively a new Racket instance that can run in parallel to other places, including the initial place. The full power of the Racket language is available at each place, but places can communicate only through message passing—using the `place-channel-put` and `place-channel-get` functions on a limited set of values—which helps ensure the safety and independence of parallel computations.

As a starting example, the racket program below uses a place to determine whether any number in the list has a double that is also in the list:

```
#lang racket

(provide main)
```

```
(define (any-double? l)
  (for/or ([i (in-list l)])
    (for/or ([i2 (in-list l)])
      (= i2 (* 2 i)))))

(define (main)
  (define p
    (place ch
      (define l (place-channel-get ch))
      (define l-double? (any-double? l))
      (place-channel-put ch l-double?)))

  (place-channel-put p (list 1 2 4 8))

  (place-channel-get p))
```

The identifier `ch` after `place` is bound to a *place channel*. The remaining body expressions within the `place` form are evaluated in a new place, and the body expressions use `ch` to communicate with the place that spawned the new place.

In the body of the `place` form above, the new place receives a list of numbers over `ch` and binds the list to `l`. It then calls `any-double?` on the list and binds the result to `l-double?`. The final body expression sends the `l-double?` result back to the original place over `ch`.

In DrRacket, after saving and running the above program, evaluate `(main)` in the interactions window to create the new place. Alternatively, save the program as `"double.rkt"` and run from a command line with

When using places inside DrRacket, the module containing place code must be saved to a file before it will execute.

```
racket -tm double.rkt
```

where the `-t` flag tells `racket` to load the `double.rkt` module, the `-m` flag calls the exported `main` function, and `-tm` combines the two flags.

The `place` form has two subtle features. First, it lifts the `place` body to an anonymous, module-level function. This lifting means that any binding referenced by the `place` body must be available in the module's top level. Second, the `place` form `dynamic-require`s the enclosing module in a newly created place. As part of the `dynamic-require`, the current module body is evaluated in the new place. The consequence of this second feature is that `place` should not appear immediately in a module or in a function that is called in a module's top level; otherwise, invoking the module will invoke the same module in a new place, and so on, triggering a cascade of place creations that will soon exhaust memory.

```
#lang racket

(provide main)
```

```
; Don't do this!
(define p (place ch (place-channel-get ch)))

(define (indirect-place-invocation)
  (define p2 (place ch (place-channel-get ch))))

; Don't do this, either!
(indirect-place-invocation)
```

20.4 Distributed Places

The racket/place/distributed library provides support for distributed programming.

The example below demonstrates how to launch a remote racket node instance, launch remote places on the new remote node instance, and start an event loop that monitors the remote node instance.

The example code can also be found in "racket/distributed/examples/named/master.rkt".

The spawn-remote-racket-node primitive connects to "localhost" and starts a racloud node there that listens on port 6344 for further instructions. The handle to the new racloud node is assigned to the remote-node variable. Localhost is used so that the example can be run using only a single machine. However localhost can be replaced by any host with ssh publickey access and racket. The supervise-place-at creates a new place on the remote-node. The new place will be identified in the future by its name symbol 'tuple-server. A place descriptor is expected to be returned by invoking dynamic-place with the tuple-path module path and the 'make-tuple-server symbol.

The code for the tuple-server place exists in the file "tuple.rkt". The "tuple.rkt" file contains the use of define-named-remote-server form, which defines a RPC server suitable for invocation by supervise-place-at.

The define-named-remote-server form takes an identifier and a list of custom expressions as its arguments. From the identifier a place-thunk function is created by prepending the make- prefix. In this case make-tuple-server. The make-tuple-server identifier is the place-function-name given to the supervise-named-dynamic-place-at form above. The define-state custom form translates into a simple define form, which is closed over by the define-rpc form.

The define-rpc form is expanded into two parts. The first part is the client stubs that call the rpc functions. The client function name is formed by concatenating the define-named-remote-server identifier, tuple-server, with the RPC function name set to form tuple-server-set. The RPC client functions take a destination argument which is a remote-connection% descriptor and then the RPC function arguments. The RPC client function sends the RPC function name, set, and the RPC arguments to the destination

```
#lang racket/base
(require racket/place/distributed
         racket/class
         racket/place
         racket/runtime-path
         "bank.rkt"
         "tuple.rkt")
(define-runtime-path bank-path "bank.rkt")
(define-runtime-path tuple-path "tuple.rkt")

(provide main)

(define (main)
  (define remote-node (spawn-remote-racket-node
                       "localhost"
                       #:listen-port 6344))
  (define tuple-place (supervise-place-at
                       remote-node
                       #:named 'tuple-server
                       tuple-path
                       'make-tuple-server))
  (define bank-place  (supervise-place-at
                       remote-node bank-path
                       'make-bank))

  (message-router
    remote-node
    (after-seconds 4
      (displayln (bank-new-account bank-place 'user0))
      (displayln (bank-add bank-place 'user0 10))
      (displayln (bank-removeM bank-place 'user0 5)))

    (after-seconds 2
      (define c (connect-to-named-place remote-node
                                        'tuple-server))
      (define d (connect-to-named-place remote-node
                                        'tuple-server))
      (tuple-server-hello c)
      (tuple-server-hello d)
      (displayln (tuple-server-set c "user0" 100))
      (displayln (tuple-server-set d "user2" 200))
      (displayln (tuple-server-get c "user0"))
      (displayln (tuple-server-get d "user2"))
      (displayln (tuple-server-get d "user0"))
      (displayln (tuple-server-get c "user2"))
      )
    (after-seconds 8
      (node-send-exit remote-node))
    (after-seconds 10
      (exit 0))))
```


Figure 1: examples/named/master.rkt

```
#lang racket/base
(require racket/match
         racket/place/define-remote-server)

(define-named-remote-server tuple-server
  (define-state h (make-hash))
  (define-rpc (set k v)
    (hash-set! h k v)
    v)
  (define-rpc (get k)
    (hash-ref h k #f))
  (define-cast (hello)
    (printf "Hello from define-cast\n")
    (flush-output)))
```

Figure 2: examples/named/tuple.rkt

by calling an internal function `named-place-channel-put`. The RPC client then calls `named-place-channel-get` to wait for the RPC response.

The second expansion part of `define-rpc` is the server implementation of the RPC call. The server is implemented by a match expression inside the `make-tuple-server` function. The match clause for `tuple-server-set` matches on messages beginning with the `'set` symbol. The server executes the RPC call with the communicated arguments and sends the result back to the RPC client.

The `define-cast` form is similar to the `define-rpc` form except there is no reply message from the server to client

```
(module tuple racket/base
  (require racket/place
           racket/match)
  (define/provide
   (tuple-server-set dest k v)
   (named-place-channel-put dest (list 'set k v))
   (named-place-channel-get dest))
  (define/provide
   (tuple-server-get dest k)
   (named-place-channel-put dest (list 'get k))
   (named-place-channel-get dest))
  (define/provide
   (tuple-server-hello dest)
   (named-place-channel-put dest (list 'hello)))
  (define/provide
   (make-tuple-server ch)
    (let ()
      (define h (make-hash))
      (let loop ()
        (define msg (place-channel-get ch))
        (define (log-to-parent-real
                 msg
                 #:severity (severity 'info))
          (place-channel-put
            ch
            (log-message severity msg)))
        (syntax-parameterize
         ((log-to-parent (make-rename-transformer
                          #'log-to-parent-real)))
         (match
          msg
          ((list (list 'set k v) src)
           (define result (let () (hash-set! h k v) v))
           (place-channel-put src result)
           (loop))
          ((list (list 'get k) src)
           (define result (let () (hash-ref h k #f)))
           (place-channel-put src result)
           (loop))
          ((list (list 'hello) src)
           (define result
             (let ()
               (printf "Hello from define-cast\n")
               (flush-output)))
           (loop))))
        loop))))
```

Figure 3: Expansion of define-named-remote-server

21 Running and Creating Executables

While developing programs, many Racket programmers use the DrRacket programming environment. To run a program without the development environment, use `racket` (for console-based programs) or `gracket` (for GUI programs). This chapter mainly explains how to run `racket` and `gracket`.

21.1 Running `racket` and `gracket`

The `gracket` executable is the same as `racket`, but with small adjustments to behave as a GUI application rather than a console application. For example, `gracket` by default runs in interactive mode with a GUI window instead of a console prompt. GUI applications can be run with plain `racket`, however.

Depending on command-line arguments, `racket` or `gracket` runs in interactive mode, module mode, or load mode.

21.1.1 Interactive Mode

When `racket` is run with no command-line arguments (other than configuration options, like `-j`), then it starts a REPL with a `>` prompt:

```
Welcome to Racket v9.4.0.3 [cs].
>
```

For enhancing your REPL experience, see `xrepl`; for information on GNU Readline support, see `readline`.

To initialize the REPL's environment, `racket` first requires the `racket/init` module, which provides all of `racket`, and also installs `pretty-print` for display results. Finally, `racket` loads the file reported by `(find-system-path 'init-file)`, if it exists, before starting the REPL.

If any command-line arguments are provided (other than configuration options), add `-i` or `--repl` to re-enable the REPL. For example,

```
racket -e '(display "hi\n")' -i
```

displays "hi" on start-up, but still presents a REPL.

If module-requiring flags appear before `-i`/`--repl`, they cancel the automatic requiring of `racket/init`. This behavior can be used to initialize the REPL's environment with a different language. For example,

```
racket -l racket/base -i
```

starts a REPL using a much smaller initial language (that loads much faster). Beware that most modules do not provide the basic syntax of Racket, including function-call syntax and `require`. For example,

```
racket -l racket/date -i
```

produces a REPL that fails for every expression, because `racket/date` provides only a few functions, and not the `#%top-interaction` and `#%app` bindings that are needed to evaluate top-level function calls in the REPL.

If a module-requiring flag appears after `-i`/`--repl` instead of before it, then the module is required after `racket/init` to augment the initial environment. For example,

```
racket -i -l racket/date
```

starts a useful REPL with `racket/date` available in addition to the exports of `racket`.

21.1.2 Module Mode

If a file argument is supplied to `racket` before any command-line switch (other than configuration options), then the file is required as a module, and (unless `-i`/`--repl` is specified), no REPL is started. For example,

```
racket hello.rkt
```

requires the `"hello.rkt"` module and then exits. Any argument after the file name, flag or otherwise, is preserved as a command-line argument for use by the required module via `current-command-line-arguments`.

If command-line flags are used, then the `-u` or `--require-script` flag can be used to explicitly require a file as a module. The `-t` or `--require` flag is similar, except that additional command-line flags are processed by `racket`, instead of preserved for the required module. For example,

```
racket -t hello.rkt -t goodbye.rkt
```

requires the `"hello.rkt"` module, then requires the `"goodbye.rkt"` module, and then exits.

The `-l` or `--lib` flag is similar to `-t`/`--require`, but it requires a module using a `lib` module path instead of a file path. For example,

```
racket -l raco
```

is the same as running the `raco` executable with no arguments, since the `raco` module is the executable's main module.

Note that if you wanted to pass command-line flags to raco above, you would need to protect the flags with a --, so that racket doesn't try to parse them itself:

```
racket -l raco -- --help
```

21.1.3 Load Mode

The -f or --load flag supports loading top-level expressions in a file directly, as opposed to expressions within a module file. This evaluation is like starting a REPL and typing the expressions directly, except that the results are not printed. For example,

```
racket -f hi.rkts
```

loads "hi.rkts" and exits. Note that load mode is generally a bad idea, for the reasons explained in §1.4 "A Note to Readers with Lisp/Scheme Experience"; using module mode is typically better.

The -e or --eval flag accepts an expression to evaluate directly. Unlike file loading, the result of the expression is printed, as in a REPL. For example,

```
racket -e '(current-seconds)'
```

prints the number of seconds since January 1, 1970.

For file loading and expression evaluation, the top-level environment is created in the same way for interactive mode: racket/init is required unless another module is specified first. For example,

```
racket -l racket/base -e '(current-seconds)'
```

likely runs faster, because it initializes the environment for evaluation using the smaller racket/base language, instead of racket/init.

21.2 Scripts

Racket files can be turned into executable scripts on Unix and Mac OS. On Windows, a compatibility layer like Cygwin support the same kind of scripts, or scripts can be implemented as batch files.

21.2.1 Unix Scripts

In a Unix environment (including Linux and Mac OS), a Racket file can be turned into an executable script using the shell's #! convention. The first two characters of the file must be

`#!`; the next character must be either a space or `/`, and the remainder of the first line must be a command to execute the script. For some platforms, the total length of the first line is restricted to 32 characters, and sometimes the space is required.

Use `#lang racket/base` instead of `#lang racket` to produce scripts with a faster startup time.

The simplest script format uses an absolute path to a `racket` executable followed by a module declaration. For example, if `racket` is installed in `"/usr/local/bin"`, then a file containing the following text acts as a "hello world" script:

```
#! /usr/local/bin/racket
#lang racket/base
"Hello, world!"
```

In particular, if the above is put into a file `"hello"` and the file is made executable (e.g., with `chmod a+x hello`), then typing `./hello` at the shell prompt produces the output `"Hello, world!"`.

The above script works because the operating system automatically puts the path to the script as the argument to the program started by the `#!` line, and because `racket` treats a single non-flag argument as a file containing a module to run.

Instead of specifying a complete path to the `racket` executable, a popular alternative is to require that `racket` is in the user's command path, and then "trampoline" using `/usr/bin/env`:

```
#! /usr/bin/env racket
#lang racket/base
"Hello, world!"
```

In either case, command-line arguments to a script are available via `current-command-line-arguments`:

```
#! /usr/bin/env racket
#lang racket/base
(printf "Given arguments: ~s\n"
        (current-command-line-arguments))
```

If the name of the script is needed, it is available via `(find-system-path 'run-file)`, instead of via `(current-command-line-arguments)`.

Usually, the best way to handle command-line arguments is to parse them using the `command-line` form provided by `racket`. The `command-line` form extracts command-line arguments from `(current-command-line-arguments)` by default:

```
#! /usr/bin/env racket
#lang racket

(define verbose? (make-parameter #f))
```

```
(define greeting
  (command-line
   #:once-each
   [("-v") "Verbose mode" (verbose? #t)]
   #:args
   (str) str))

(printf "~a~a\n"
        greeting
        (if (verbose?) " to you, too!" ""))
```

Try running the above script with the `--help` flag to see what command-line arguments are allowed by the script.

An even more general trampoline uses `/bin/sh` plus some lines that are comments in one language and expressions in the other. This trampoline is more complicated, but it provides more control over command-line arguments to `racket`:

```
#! /bin/sh
#|
exec racket -e '(printf "Running...\n")' -u "$0" ${1+"$@"}
|#
#lang racket/base
(printf "The above line of output had been produced via\n")
(printf "a use of the `-e' flag.\n")
(printf "Given arguments: ~s\n"
        (current-command-line-arguments))
```

Note that `#!` starts a line comment in Racket, and `#|`...`|#` forms a block comment. Meanwhile, `#` also starts a shell-script comment, while `exec racket` aborts the shell script to start `racket`. That way, the script file turns out to be valid input to both `/bin/sh` and `racket`.

21.2.2 Windows Batch Files

A similar trick can be used to write Racket code in Windows `.bat` batch files:

```
; @echo off
; Racket.exe "%~f0" %*
; exit /b
#lang racket/base
"Hello, world!"
```

Newer versions of Windows include the PowerShell scripting language. Using Racket through a PowerShell script is a little different than using it in a batch file. PowerShell

scripts use a `.ps1` extension:

```
; Racket.exe (Resolve-Path $PSCommandPath) $args
; Exit
#lang racket/base
"Hello, world!"
```

21.3 Creating Stand-Alone Executables

For information on creating and distributing executables, see §2 “`raco exe`: Creating Stand-Alone Executables” and §3 “`raco distribute`: Sharing Stand-Alone Executables” in *raco: Racket Command-Line Tools*.

22 More Libraries

This guide covers only the Racket language and libraries that are documented in *The Racket Reference*. The Racket distribution includes many additional libraries.

22.1 Graphics and GUIs

Racket provides many libraries for graphics and graphical user interfaces (GUIs):

- The `racket/draw` library provides basic drawing tools, including drawing contexts such as bitmaps and PostScript files.

  See the Racket Drawing Toolkit documentation for more information.

- The `racket/gui` library provides GUI widgets such as windows, buttons, checkboxes, and text fields. The library also includes a sophisticated and extensible text editor.

  See the Racket Graphical Interface Toolkit documentation for more information.

- The `pict` library provides a more functional abstraction layer over `racket/draw`. This layer is especially useful for creating slide presentations with Slideshow, but it is also useful for creating images for Scribble documents or other drawing tasks. Pictures created with the `pict` library can be rendered to any drawing context.

  See the Slideshow: Figure and Presentation Tools documentation for more information.

- The `2htdp/image` library is similar to `pict`. It is more streamlined for pedagogical use, but also slightly more specific to screen and bitmap drawing.

  See `2htdp/image` for more information.

- The `sgl` library provides OpenGL for 3-D graphics. The context for rendering OpenGL can be a window or bitmap created with `racket/gui`.

  See the SGL documentation for more information.

22.2 The Web Server

the Web Applications in Racket documentation describes the Racket web server, which supports servlets implemented in Racket.

22.3 Using Foreign Libraries

The Racket Foreign Interface describes tools for using Racket to access libraries that are normally used by C programs.

22.4 And More

Racket Documentation lists documentation for other libraries, including libraries that are installed as packages. Run `raco docs` to find documentation for libraries that are installed on your system and specific to your user account.

Racket Package Catalog at `https://pkgs.racket-lang.org` offers even more downloadable packages contributed by Racketeers. The online Racket documentation includes documentation for packages in that catalog, updated daily. For more information about packages, see *Package Management in Racket*.

PLaneT serves packages that were developed using an older package system. Racket packages should use the newer system, instead.

23 Dialects of Racket and Scheme

We use "Racket" to refer to a specific dialect of the Lisp language, and one that is based on the Scheme branch of the Lisp family. Despite Racket's similarity to Scheme, the `#lang` prefix on modules is a particular feature of Racket, and programs that start with `#lang` are unlikely to run in other implementations of Scheme. At the same time, programs that do not start with `#lang` do not work with the default mode of most Racket tools.

"Racket" is not, however, the only dialect of Lisp that is supported by Racket tools. On the contrary, Racket tools are designed to support multiple dialects of Lisp and even multiple languages, which allows the Racket tool suite to serve multiple communities. Racket also gives programmers and researchers the tools they need to explore and create new languages.

23.1 More Rackets

"Racket" is more of an idea about programming languages than a language in the usual sense. Macros can extend a base language (as described in §16 "Macros"), and alternate parsers can construct an entirely new language from the ground up (as described in §17 "Creating Languages").

The `#lang` line that starts a Racket module declares the base language of the module. By "Racket," we usually mean `#lang` followed by the base language `racket` or `racket/base` (of which `racket` is an extension). The Racket distribution provides additional languages, including the following:

- `typed/racket` — like `racket`, but statically typed; see the Typed Racket Guide documentation.
- `lazy` — like `racket/base`, but avoids evaluating an expression until its value is needed; see the Lazy Racket documentation.
- `frtime` — changes evaluation in an even more radical way to support reactive programming; see the FrTime documentation.
- `scribble/base` — a language, which looks more like Latex than Racket, for writing documentation; see *Scribble: The Racket Documentation Tool*

Each of these languages is used by starting module with the language name after `#lang`. For example, this source of this document starts with `#lang scribble/base`.

Furthermore, Racket users can define their own languages, as discussed in §17 "Creating Languages". Typically, a language name maps to its implementation through a module path by adding `/lang/reader`; for example, the language name `scribble/base` is expanded to `scribble/base/lang/reader`, which is the module that implements the

surface-syntax parser. Some language names act as language loaders; for example, `#lang planet planet-path` downloads, installs, and uses a language via PLaneT.

23.2 Standards

Standard dialects of Scheme include the ones defined by R^{5}RS and R^{6}RS.

23.2.1 R^{5}RS

"R^{5}RS" stands for The Revised^5 Report on the Algorithmic Language Scheme, and it is currently the most widely implemented Scheme standard.

Racket tools in their default modes do not conform to R^{5}RS, mainly because Racket tools generally expect modules, and R^{5}RS does not define a module system. Typical single-file R^{5}RS programs can be converted to Racket programs by prefixing them with `#lang r5rs`, but other Scheme systems do not recognize `#lang r5rs`. The `plt-r5rs` executable (see `plt-r5rs`) more directly conforms to the R^{5}RS standard.

Aside from the module system, the syntactic forms and functions of R^{5}RS and Racket differ. Only simple R^{5}RS become Racket programs when prefixed with `#lang racket`, and relatively few Racket programs become R^{5}RS programs when a `#lang` line is removed. Also, when mixing "R^{5}RS modules" with Racket modules, beware that R^{5}RS pairs correspond to Racket mutable pairs (as constructed with `mcons`).

See the R5RS: Legacy Scheme documentation for more information about running R^{5}RS programs with Racket.

23.2.2 R^{6}RS

"R^{6}RS" stands for The Revised^6 Report on the Algorithmic Language Scheme, which extends R^{5}RS with a module system that is similar to the Racket module system.

When an R^{6}RS library or top-level program is prefixed with `#!r6rs` (which is valid R^{6}RS syntax), then it can also be used as a Racket program. This works because `#!` in Racket is treated as a shorthand for `#lang` followed by a space, so `#!r6rs` selects the `r6rs` module language. As with R^{5}RS, however, beware that the syntactic forms and functions of R^{6}RS differ from Racket, and R^{6}RS pairs are mutable pairs.

See the R6RS: Scheme documentation for more information about running R^{6}RS programs with Racket.

23.3 Teaching

The *How to Design Programs* textbook relies on pedagogic variants of Racket that smooth the introduction of programming concepts for new programmers. See the How to Design Programs language documentation.

24 Command-Line Tools and Your Editor of Choice

Although DrRacket is the easiest way for most people to start with Racket, many Racketeers prefer command-line tools and other text editors. The Racket distribution includes several command-line tools, and popular editors include or support packages to make them work well with Racket.

24.1 Command-Line Tools

Racket provides, as part of its standard distribution, a number of command-line tools that can make racketeering more pleasant.

24.1.1 Compilation and Configuration: `raco`

The `raco` (short for "**Ra**cket **co**mmand") program provides a command-line interface to many additional tools for compiling Racket programs and maintaining a Racket installation.

- `raco make` compiles Racket source to bytecode.

  For example, if you have a program `"take-over-world.rkt"` and you'd like to compile it to bytecode, along with all of its dependencies, so that it loads more quickly, then run

  ```
  raco make take-over-the-world.rkt
  ```

  The bytecode file is written as `"take-over-the-world_rkt.zo"` in a `"compiled"` subdirectory; `".zo"` is the file suffix for a bytecode file.

- `raco setup` manages a Racket installation, including manually installed packages.

  For example, if you create your own library collection called `"take-over"`, and you'd like to build all bytecode and documentation for the collection, then run

  ```
  raco setup take-over
  ```

- `raco pkg` manages packages that can be installed through the Racket package manager.

  For example, to see the list of installed packages run:

  ```
  raco pkg show
  ```

  To install a new package named `<package-name>` run:

  ```
  raco pkg install <package-name>
  ```

  See *Package Management in Racket* for more details about package management.

For more information on `raco`, see *`raco`: Racket Command-Line Tools*.

24.1.2 Interactive evaluation

The Racket REPL provides everything you expect from a modern interactive environment. For example, it provides an `,enter` command to have a REPL that runs in the context of a given module, and an `,edit` command to invoke your editor (as specified by the `EDITOR` environment variable) on the file you entered. A `,drracket` command makes it easy to use your favorite editor to write code, and still have DrRacket at hand to try things out.

For more information, see *XREPL: eXtended REPL*.

24.1.3 Shell completion

Shell auto-completion for `bash` and `zsh` is available in `"share/pkgs/shell-completion/racket-completion.bash"` and `"share/pkgs/shell-completion/racket-completion.zsh"`, respectively. To enable it, just run the appropriate file from your `.bashrc` or your `.zshrc`.

The `"shell-completion"` collection is only available in the Racket Full distribution. The completion scripts are also available online.

24.2 Emacs

Emacs has long been a favorite among Lispers and Schemers, and is popular among Racketeers as well.

24.2.1 Major Modes

- Racket mode provides thorough syntax highlighting and DrRacket-style REPL and buffer execution support for Emacs.

  Racket mode can be installed via MELPA or manually from the Github repository.

- Quack is an extension of Emacs's `scheme-mode` that provides enhanced support for Racket, including highlighting and indentation of Racket-specific forms, and documentation integration.

  Quack is included in the Debian and Ubuntu repositories as part of the `emacs-goodies-el` package. A Gentoo port is also available (under the name `app-emacs/quack`).

- Geiser provides a programming environment where the editor is tightly integrated with the Racket REPL. Programmers accustomed to environments such as Slime or Squeak should feel at home using Geiser. Geiser requires GNU Emacs 23.2 or better.

Quack and Geiser can be used together, and complement each other nicely. More information is available in the Geiser manual.

Debian and Ubuntu packages for Geiser are available under the name `geiser`. A Gentoo port is also available (under the name `app-emacs/geiser`).

- Emacs ships with a major mode for Scheme, `scheme-mode`, that while not as featureful as the above options, works reasonably well for editing Racket code. However, this mode does not provide support for Racket-specific forms.

- No Racket program is complete without documentation. Scribble support for Emacs is available with Neil Van Dyke's Scribble Mode.

  In addition, `texinfo-mode` (included with GNU Emacs) and plain text modes work well when editing Scribble documents. The Racket major modes above are not really suited to this task, given how different Scribble's syntax is from Racket's.

24.2.2 Minor Modes

- Paredit is a minor mode for pseudo-structurally editing programs in Lisp-like languages. In addition to providing high-level S-expression editing commands, it prevents you from accidentally unbalancing parentheses.

  Debian and Ubuntu packages for Paredit are available under the name `paredit-el`.

- Smartparens is a minor mode for editing s-expressions, keeping parentheses balanced, etc. Similar to Paredit.

- Symex is an intuitive modal (Vim-like) way of editing code with minimum keystrokes, built on top of a DSL providing advanced structural editing features, and runtime integration with Racket Mode.

- Alex Shinn's scheme-complete provides intelligent, context-sensitive code completion. It also integrates with Emacs's `eldoc` mode to provide live documentation in the minibuffer.

  While this mode was designed for R^5RS, it can still be useful for Racket development. The tool is unaware of large portions of the Racket standard library, and there may be some discrepancies in the live documentation in cases where Scheme and Racket have diverged.

- The RainbowDelimiters mode colors parentheses and other delimiters according to their nesting depth. Coloring by nesting depth makes it easier to know, at a glance, which parentheses match.

- ParenFace lets you choose in which face (font, color, etc.) parentheses should be displayed. Choosing an alternate face makes it possible to make "tone down" parentheses.

- Mindstream lets you enter an interactive programming session (similar to DrRacket's Definitions and Interactions workflow) at any time, starting from templates you provide. Sessions are implicitly versioned, freeing you to experiment without fear of losing work, growing organically from throwaway scratch buffers to full projects.

24.2.3 Packages specific to Evil Mode

- on-parens is a wrapper for smartparens motions to work better with evil-mode's normal state.
- evil-surround provides commands to add, remove, and change parentheses and other delimiters.
- evil-textobj-anyblock adds a text-object that matches the closest of any parenthesis or other delimiter pair.

24.3 Vim

Many distributions of Vim ship with support for Scheme, which will mostly work for Racket. Vim also ships with some special support for Racket.

The `racket` filetype comes with

- syntax highlighting
- custom indentation for Racket forms
- and other support including comments and `raco fmt`

There is also support for several raco commands in the form of builtin `compiler` plugins; see `:help compiler` for more information.

For information about older Vim versions, see §24.3.8 "Older Versions of Vim".

24.3.1 Enhanced Racket Support

Vim will detect your Racket files as Scheme out of the box. To get the additional features of the Racket filetype, consider installing the `vim-racket` plugin from benknoble/vim-racket. It enables auto-detection of Racket files on top of enhanced indentation and syntax highlighting. Vim's default support comes from a subset of this plugin; installing it yourself provides additional features.

The vim-racket plugin detects the filetype option based on the #lang line. For example:

- A file starting with #lang racket or #lang racket/base has filetype equal to racket.
- A file starting with #lang scribble/base or #lang scribble/manual has filetype equal to scribble.

The vim-racket plugin comes with configuration for Racket and some other standard Racket languages.

Many Racket languages still need syntax and indent support. If you create Vim support for other Racket languages, please consider contributing them to benknoble/vim-racket so other Vim users will benefit.

24.3.2 Indentation

If you use §24.3.1 "Enhanced Racket Support" and Vim version 9 or greater, improved indentation for the racket filetype is configured out of the box.

Otherwise, you can manually enable indentation for Racket by setting both the lisp and autoindent options in Vim. You will want to customize the buffer-local lispwords option to control how special forms are indented. See :help 'lispwords'. However, using lispwords for indentation can be limited and may not be as complete as what you can get in Emacs. You can also use Dorai Sitaram's scmindent for better indentation of Racket code. The instructions on how to use the indenter are available on the website.

24.3.3 Highlighting

Syntax highlighting for Scheme and Racket is shipped with Vim on many platforms. You will want to use the racket filetype for the best syntax experience; see §24.3.1 "Enhanced Racket Support" for enhanced syntax highlighting for Racket languages.

The Rainbow Parenthesis script for Vim can be useful for more visible parenthesis matching.

24.3.4 Structured Editing

The Slimv plugin has a paredit mode that works like paredit in Emacs. However, the plugin is not aware of Racket. You can either set Vim to treat Racket as Scheme files or you can modify the paredit script to load on ".rkt" files.

For a more Vim-like set of key-mappings, pair either of

- guns/vim-sexp
- benknoble/vim-sexp

with tpope/vim-sexp-mappings-for-regular-people. The experience is on par with paredit, but more comfortable for the fingers.

The `benknoble/vim-sexp` fork is slightly more modern vimscript.

24.3.5 REPLs

There are many general-purpose Vim + REPL plugins out there. Here are a few that support Racket out of the box:

- rhysd/reply.vim
- kovisoft/slimv, if you are using the `scheme` filetype
- benknoble/vim-simpl

24.3.6 Scribble

Vim support for writing scribble documents is provided by benknoble/scribble.vim.

24.3.7 Miscellaneous

If you are installing many Vim plugins (not necessary specific to Racket), we recommend using a plugin that will make loading other plugins easier. There are many plugin managers.

Pathogen is one plugin that does this; using it, you can install new plugins by extracting them to subdirectories in the `"bundle"` folder of your personal Vim files (`"~/.vim"` on Unix, `"$HOME/vimfiles"` on MS-Windows).

With newer Vim versions, you can use the package system (`:help packages`).

One relatively up-to-date reference on the various managers is What are the differences between the vim plugin managers?. The same site, Vi & Vim is a great place to get help from Vimmers.

24.3.8 Older Versions of Vim

As of Version 9.0.0336, Vim ships with runtime files from §24.3.1 “Enhanced Racket Support”, but these exclude filetype detection for the `racket` filetype. If you are using this version or versions newer than this you probably want to tweak the suggestions in this document to use the `racket` filetype instead of `scheme`. You should also consider installing the plugin yourself to get the latest changes, since Ben is slow to sync changes upstream to Vim and since the plugin contains improved filetype detection.

As of version 7.3.518, Vim detects files with the extension `.rkt` as having the `scheme` filetype. Version 8.2.3368 added support for `.rktd` and `.rktl`.

In older versions, you can enable filetype detection of Racket files as Scheme with the following:

```
  if has("autocmd")
    autocmd filetypedetect BufReadPost *.rkt,*.rktl,*.rktd set file-
type=scheme
  endif
```

If your Vim supports the ftdetect system, in which case it’s likely new enough to support Racket already, you can nevertheless put the following in `"~/.vim/ftdetect/racket.vim"` (`"$HOME/vimfiles/ftdetect/racket.vim"` on MS-Windows; see `:help runtimepath`).

```
  " :help ftdetect
  " If you want to change the filetype only if one has not been set
  autocmd BufRead,BufNewFile *.rkt,*.rktl,*.rktd setfiletype scheme
  " If you always want to set this filetype
  autocmd BufRead,BufNewFile *.rkt,*.rktl,*.rktd set filetype=scheme
```

24.4 Sublime Text

The Racket package provides support for syntax highlighting and building for Sublime Text.

24.5 Visual Studio Code

The Magic Racket extension provides Racket support including REPL integration and syntax highlighting in Visual Studio Code.

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Index

"main.rkt"
#!
.bat
.ps1
.zo
3m
A Customer-Manager Component
A Dictionary
A Note to Readers with Lisp/Scheme Experience
A Parameteric (Simple) Stack
A Queue
Abbreviating quote with '
aborts
Abstract Contracts using #:exists and #:∃
accessor
Adding Collections
Adding Contracts to Signatures
Adding Contracts to Units
Additional Examples
Alternation
An Aside on Indenting Code
An Extended Example
And More
Anonymous Functions with lambda
any and any/c
Argument and Result Dependencies
Arity-Sensitive Functions: case-lambda
assertions
Assignment and Redefinition
Assignment: set!
attached
available
backreference
Backreferences
Backtracking
backtracking
Basic Assertions
BC
benchmarking
blocking
Booleans
box
Boxes
bracketed character class
Breaking an Iteration
Buffered Asynchronous Channels
Building New Contracts
Building Your Own Synchronization Patterns
Built-In Datatypes
byte
byte string
Bytecode, Machine Code, and Just-in-Time (JIT) Compilers
Bytes and Byte Strings
Bytes, Characters, and Encodings
call-by-reference
CGC
Chaining Tests: cond
Channels
character
character class
Characters
Characters and Character Classes
Checking Properties of Data Structures
Checking State Changes
Class Contracts
Classes and Objects
cloister
Cloisters
closures
Clustering
Clusters
Code inspectors
Code Inspectors for Trusted and Untrusted Code
collection
Combining Tests: and and or
Command-Line Tools
Command-Line Tools and Your Editor of Choice

comments
Compilation and Configuration: raco
Compile and Run-Time Phases
Compile-Time Instantiation
complex
components
composable continuations
concurrency
Concurrency and Synchronization
Conditionals
Conditionals with if, and, or, and cond
conservative garbage collector
constructor
constructor guard
continuation
Continuations
Contract boundaries and define/contract
contract combinator
Contract Messages with "???"
Contract Struct Properties
Contract Violations
Contracts
Contracts and Boundaries
Contracts and eq?
Contracts for case-lambda
Contracts for Units
Contracts on Functions in General
Contracts on Higher-order Functions
Contracts on Structures
Contracts: A Thorough Example
Controlling the Scope of External Names
Copying and Update
coroutine thread
Creating and Installing Namespaces
Creating Executables
Creating Languages
Creating Stand-Alone Executables
CS
current continuation
current namespace
Curried Function Shorthand
Datatypes and Serialization
Declaration versus Instantiation
Declaring a Rest Argument
Declaring Keyword Arguments
Declaring Optional Arguments
Default Ports
default prompt tag
define-syntax and syntax-rules
define-syntax-rule
Defining new #lang Languages
Defining Recursive Contracts
Definitions
Definitions and Interactions
definitions area
Definitions: define
delimited continuations
Designating a #lang Language
destructing bind
Dialects of Racket and Scheme
Dissecting a contract error message
Distributed Places
domain
Dynamic Binding: parameterize
Effects After: begin0
Effects Before: begin
Effects If...: when and unless
Emacs
Enhanced Racket Support
eval
Evaluation Order and Arity
exception
Exceptions
Exceptions and Control
Exists Contracts and Predicates
expander
expands
Experimenting with Contracts and Modules
Experimenting with Nested Contract Boundaries
Exports: provide
Expressions and Definitions
Extended Example: Call-by-Reference Functions

External Class Contracts
Final, Augment, and Inner
First-Class Units
Fixed but Statically Unknown Arities
fixnum
Fixnum and Flonum Optimizations
flat named contracts
flonum
`for` and `for*`
`for/and` and `for/or`
`for/first` and `for/last`
`for/fold` and `for*/fold`
`for/list` and `for*/list`
`for/vector` and `for*/vector`
Foreign Pointers
Function Calls (Procedure Applications)
Function Calls (Procedure Applications)
Function Calls, Again
Function Shorthand
Function-Call Optimizations
functional update
Functions (Procedures): `lambda`
futures
futures visualizer
General Macro Transformers
General Phase Levels
generational garbage collector
Gotchas
Graphics and GUIs
greedy
Guarantees for a Specific Value
Guarantees for All Values
Guidelines for Using Assignment
hash table
Hash Tables
Highlighting
I/O Patterns
identifier macro
Identifier Macros
identifier syntax object
Identifiers
Identifiers and Binding
implicit begin
Implicit Form Bindings
Imports: `require`
incremental garbage-collection
Indentation
index pairs
Inherit and Super in Traits
Initialization Arguments
Input and Output
Installing a Language
instantiated
instantiates
instantiation
integer
Interacting with Racket
Interactive evaluation
Interactive Mode
Interfaces
Internal and External Names
Internal Class Contracts
Internal Definitions
invoked
Invoking Units
Iteration Performance
Iterations and Comprehensions
JIT
just-in-time
keyword
Keyword Arguments
Keyword Arguments
Keywords
Lazy Visits via Available Modules
`letrec` Performance
Lexical Scope
Library Collections
link
Linking Units
list
List Iteration from Scratch
Lists and Racket Syntax
Lists, Iteration, and Recursion
Load Mode

Local Binding
Local Binding with `define`, `let`, and `let*`
Local Scopes
Lookahead
Lookbehind
Looking Ahead and Behind
macro
macro pattern variables
macro transformer
Macro Transformer Procedures
macro-generating macro
Macro-Generating Macros
Macros
Main and Test Submodules
`main` submodule
major collections
Major Modes
Manipulating Namespaces
Matching Regexp Patterns
Matching Sequences
Memory Management
meta-compile phase level
metacharacters
metasequences
Methods
minor collections
Minor Modes
Miscellaneous
mixin
Mixing Patterns and Expressions: `syntax-case`
Mixing `set!` and `contract-out`
Mixins
Mixins and Interfaces
Module Basics
Module Instantiations and Visits
module language
Module Languages
Module Mode
module path
Module Paths
Module References Within a Collection
Module Syntax
Module-Handling Configuration
Modules
Modules and Macros
Modules and Performance
More Libraries
More Rackets
More Structure Type Options
multi-line mode
Multiple Result Values
Multiple Values and `define-values`
Multiple Values: `let-values`, `let*-values`, `letrec-values`
Multiple Values: `set!-values`
Multiple-Valued Sequences
mutable pair
Mutation and Performance
mutator
Named `let`
namespace
Namespaces
Namespaces and Modules
non-capturing
Non-capturing Clusters
non-greedy
Notation
number
Numbers
Older Versions of Vim
opaque
Opaque versus Transparent Structure Types
Optional Arguments
Optional Keyword Arguments
Organizing Modules
package
Packages and Collections
Packages specific to Evil Mode
pair
Pairs and Lists
Pairs, Lists, and Racket Syntax
Parallel Binding: `let`
parallel thread pool

Parallel Threads
parallel threads
Parallelism
parallelism
Parallelism with Futures
Parallelism with Places
parameter
Parameterized Mixins
Pattern Matching
pattern variables
pattern-based macro
Pattern-Based Macros
Performance
Performance in DrRacket
phase
phase level
phase level -1
phase level 2
Phases and Bindings
Phases and Modules
place
place channel
port
POSIX character class
POSIX character classes
Predefined List Loops
predicate
prefab
Prefab Structure Types
Programmer-Defined Datatypes
prompt
prompt tag
Prompts and Aborts
property
protected
Protected Exports
protected method
Quantifiers
quantifiers
Quasiquoting: `quasiquote` and `‘`
Quoting Pairs and Symbols with `quote`
Quoting: `quote` and `’`
R^{5}RS
R^{6}RS
Racket Essentials
Racket Virtual Machine Implementations
range
rational
Reachability and Garbage Collection
reader
Reader Extensions
Reading and Writing Racket Data
readtable
Readtables
real
Recursion versus Iteration
Recursive Binding: `letrec`
Reducing Garbage Collection Pauses
Reflection and Dynamic Evaluation
regexp
Regular Expression Performance
Regular Expressions
REPL
REPLs
rest argument
Rest Arguments
Rolling Your Own Contracts
run-time configuration
Running and Creating Executables
Running `racket` and `gracket`
S-expression
Scribble
Scripting Evaluation and Using `load`
Scripts
Semaphores
Sequence Constructors
Sequencing
Sequential Binding: `let*`
serialization
`set!` Transformers
shadows
Sharing Data and Code Across Namespaces
Shell completion
signatures

Signatures and Units
Simple Branching: `if`
Simple Contracts on Functions
Simple Definitions and Expressions
Simple Dispatch: `case`
Simple Structure Types: `struct`
Simple Values
Some Frequently Used Character Classes
Source Locations
Source-Handling Configuration
speed
Standards
string
Strings (Unicode)
Structure Comparisons
Structure Subtypes
structure type descriptor
Structure Type Generativity
Structured Editing
Styles of `->`
subcluster
Sublime Text
submatch
submodule
Submodules
subpattern
symbol
Symbols
Synchronizable Events and `sync`
synchronized
Syntax Objects
syntax objects
tail position
Tail Recursion
tainted
Tainted Syntax
Teaching
template
template phase level
text string
The `#lang` Shorthand
The `apply` Function
The `mixin` Form
The `module` Form
The Racket Guide
The `trait` Form
The Web Server
Thread Mailboxes
Threads
threads
Traits
Traits as Sets of Mixins
transformer
transformer binding
transparent
Unchecked, Unsafe Operations
`unit` versus `module`
Units
Units (Components)
Unix Scripts
Using `#lang reader`
Using `#lang s-exp`
Using `#lang s-exp syntax/module-reader`
Using `define/contract` and `->`
Using Foreign Libraries
variadic
Varieties of Ports
vector
Vectors
Vim
visit
Visiting Modules
Visual Studio Code
Void and Undefined
Weak Boxes and Testing
Welcome to Racket
Whole-`module` Signatures and Units
Windows Batch Files
With all the Bells and Whistles
`with-syntax` and `generate-temporaries`
Writing Regexp Patterns