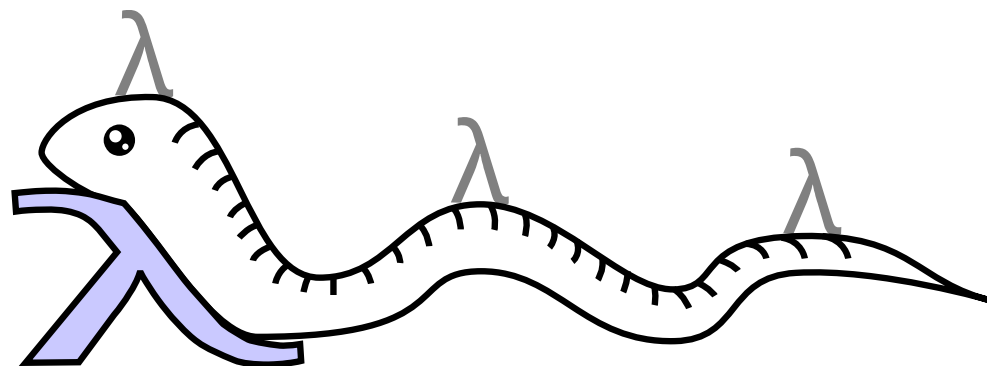


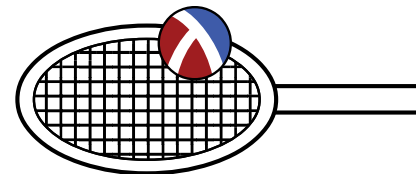
Python 3 for scientific computing ☆

Lecture 11, 25.4.2018
Functional programming (FP), part 2

Juha Jeronen
juha.jeronen@tut.fi



☆ *With a flavoring of Racket.*



Spring 2018, TUT, Tampere
RAK-19006 Various Topics of Civil Engineering



TAMPERE
UNIVERSITY OF
TECHNOLOGY

Meta


- The grand finale!
- Last week, we introduced Lisp and Racket, *so that we can now observe certain ideas in their natural habitat*:
 - Syntactic macros
 - Continuations
 - Pattern matching ☆
 - Currying ☆
 - High-level implementation of some programming language constructs
- **Why?** Even if you never actually program in Racket:
 - **Exposure** – encounter concepts from outside the Python community.
 - Python is much more advanced than C or Fortran, but there are ideas that could make your code shorter that Python doesn't currently employ. Part of the **general knowledge** of a software developer is to know them.
 - **Curiosity** – look under the hood of programming languages.
 - Understand the fundamentals; *see how code reduces to λ -calculus*. ☆ (Similar topics in mathematics: the construction of **naturals** and **reals**.)
 - **Techniques** – **get ideas to borrow into Python**.
 - We'll look at libraries that implement some of this stuff in Python.

☆ To be fair, Haskell is *the* natural habitat of these two, but we had to pick just one language. In Racket, consider them as **introduced species**.

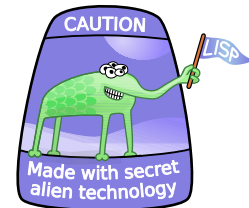
☆ Exaggerating slightly. But not much.

Meta

Selective recap

- **Primitives**, means of **combination**, means of **abstraction**
—SICP, 1.1 The Elements of Programming
- Pure vs. impure FP  Here's an intro to pure FP for the adventurous.
- First-class functions
- Higher-order functions
- Closures
- Partial application, currying
- **map, filter, fold, unfold**
- Basic syntax of Lisps, its distinctive features
- *Lambdas as code blocks* – code “more fluid than solid”
 - (A highly **viscous** fluid, obviously; but perhaps not **this viscous**.)

Macros

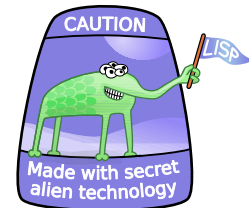


- *Scheme code is not meant to be written by humans, [but] ... automatically by macros.*
–Michele Simionato
- **What:** **Syntactic macros** transform the AST, by running arbitrary code on it, at compile time.
 - Contrast **C preprocessor macros**, which perform only text substitution.
 - Contrast **C++ generics**: *Lisp itself as metalanguage* (no separate templating mini-language).
 - [StackOverflow](#). [Understanding macros](#). [Perl perspective](#). [Macros and washing machines](#).
 - [Paul Graham \(1993\): Programming bottom-up; Metaprogramming; Extensible programming](#).
 - *Lisp isn't a language, it's a building material.* –Alan Kay (of [Smalltalk](#) fame; on Lisp, [\[1\]](#) [\[2\]](#))
- **Why:** *Design patterns: a symptom of being unable to extract an abstraction* ([Paul Graham](#)).
 - E.g. **with** [\[1\]](#) or **assert** [\[2\]](#) in Python, which encode particular design patterns.
 - Syntactic macros allow *the programmer* to create such constructs:
 - **with** in Clojure.
 - Delayed evaluation in Racket.
 - Just like in mathematics [\[1\]](#) [\[2\]](#): code is for humans, so **notation matters**.
 - Macros are another important feature that make **Lisp more like a fluid than a solid**.
 - Democratization of language design? On the other hand, [herd of cats](#) ([according to some](#), [with machine guns](#)), no **BDFL**. No process to pick, polish and promote the best abstractions; [thus](#), “lowest common denominator” often used. *The Lisp Curse* [\[1\]](#) [\[2\]](#).
- History, in 30 seconds:
 - Early Lisp macros had the problems of *identifier capture* and *free symbol capture* [\[1\]](#) [\[2\]](#).
 - Scheme introduced *hygienic macros* [\[1\]](#) [\[2\]](#) specifically to solve those issues.
 - Racket adds a tower of [phase levels](#); see [short explanation](#) and the paper by [Flatt \(2002\)](#).
- Syntactic macros are *almost* unique to the Lisp family. Exceptions: [Julia](#), [R](#).



Macros

When and how?



- **The nuclear option:** only create a macro if the job is not suitable for a run-of-the-mill function!
 - *Extract design patterns that cannot be extracted as functions.*
 - Although Racket is **eager**, macro arguments avoid immediate evaluation; highly useful [1][2].
 - **Macros replacing design patterns** is what “**programs writing programs**” means in Lisp; it's not about “source code generation” à la Cython (which takes Cython and writes C).
 - It's also robust, **unlike source filters in many languages**.
 - Add syntactic forms the original designer of the language might not approve. [1]
 - Create a **DSL** (*domain-specific language*) to fit the language to your domain; shorter code.
 - **DRY** out repetition in a set of similar macros, by **macro-writing macros**.
 - Programmatically create lookup tables at compile time. [1]
- **Limitations:**
 - **Second-class**; e.g. cannot **compose** on a macro, since it is expanded at compile time!
 - Local: a macro call cannot rewrite any forms *surrounding* it (due to Lisp's prefix notation)
 - Macros cannot change the lexical conventions (use of parentheses, prefix notation, ...)
 - If you want to do that, you could modify or extend the **reader** [1] [2].
- In Racket, there are many macro definition tools; **the flagship is syntax-parse**.
 - **syntax-parser** and **define-syntax-parser** are just **convenience forms** on top of **syntax-parse**.
 - **syntax-rules** and **syntax-case** come from Scheme; simpler, but not quite as full-featured.
 - Start from **Fear of Macros** to learn the concepts, starting with the **syntax transformer**.
Then look at [1] [2] [3], **examples on GitHub**, and any examples you can dig up online (e.g. [1]).
 - Reference for **syntax patterns** and **syntax classes**; and **directives** such as **#:fail-unless**.
- Non-deterministic evaluation, automatic currying, Python-inspired syntactic forms, simple infix, User-programmable infix operators, Algebraic Data Types (ADTs) in Typed Racket.



Macros

A simple `for` loop

- Recall the functional looping strategy (lecture 3, slide 24). In Racket, we could write a looped hello world like this:

The loop body.

```
define looped-hello(n)
  define last {n - 1}
  let loop ([i 0])
    displayln
    format
      "hello from loop, iteration ~a"
      i
  cond
    {i < last}
    loop {i + 1}

(looped-hello 5)
```

- In the Scheme family, *tail call optimization* is **required** by the language spec, so this won't overflow the call stack.
- But we would have to repeat the marked lines whenever we wanted to make a loop.

- To turn this into a template, to make it reusable without having to remember a design pattern, we can define a macro:

```
require syntax/parse/define

define-syntax-parser for-range
  [_ (counter start end) body ...]
  syntax
    let ([last {end - 1}])
    let loop ([counter start])
      body
    ...
    cond
      {counter < last}
      loop {counter + 1}
```

```
for-range (i 0 5)
  displayln
  format
    "hello from loop, iteration ~a"
    i
```

[Downloadable source file.](#)



Macros

A simple for loop

- Recall the functional looping strategy (lecture 3, slide 24). In Racket, we could write a looped hello world like this:

```
define looped-hello(n)
  define last {n - 1}
  let loop ([i 0])
    displayln
    format
      "hello from loop, iteration ~a"
    i
  cond
    {i < last}
    loop {i + 1}

(looped-hello 5)
```

The loop body.

named let; "loop" is just a name.

— means ignore.
The first element is always the name of the macro itself, e.g. here "for-range".

- To turn this into a template, to make it reusable without having to remember a design pattern, we can define a macro:

```
require syntax/parse/define

define-syntax-parser for-range
  [ (counter start end) body ... ]
  syntax
    let ([last {end - 1}])
    let loop ([counter start])
    body
    ...
    cond
      {counter < last}
      loop {counter + 1}
```

Yes, "..."; syntax-parse uses pattern matching.

- In the Scheme family, *tail call optimization* is **required** by the language spec, so this won't overflow the call stack.
- But we would have to repeat the marked lines whenever we wanted to make a loop.

```
for-range (i 0 5)
  displayln
  format
    "hello from loop, iteration ~a"
  i
```

[Downloadable source file.](#)



Macros

Named **let**

Here we mean just
“there may be more of these”,
although that's not too far
from a syntax-parse pattern.

- We used **named let**, which is a looping and recursion construct:

```
define looped-hello(n)
  define last {n - 1}
  → let loop ([i 0])
    displayln
    format
    "hello from loop, iteration ~a"
    i
    cond
    {i < last}
    loop {i + 1}

(looped-hello 5)
```

☆ To maintain backwards compatibility with traditional s-exprs, sweet-exp switches off indentation processing inside `()`, `[]` and `{}`, so there one must use traditional parenthesization.

For constructs like the bindings block of **let**, this is unfortunate. Another option is to use `\` (a.k.a. **GROUP**), also from [SRFI-110](#), but it is a matter of opinion which looks more readable.

- Roughly, its usage is:

```
let loop-name ([var init] ...)
  body
  ...
  cond
  (loop-again?)
  loop-name next-value ...
```

Perform whatever
check you want.

which expands to

```
letrec ([loop-name
  (λ (var ...) body ...
    (cond
      [(loop-again?)
        (loop-name next-value ...)]))])
  loop-name init ...
```

☆ *Should be
balanced
...maybe?*

- **The named let is also a macro!**
- This is what we meant when we said the Racket language is mostly defined in terms of itself; see [Flatt et al. \(2012\)](#).



Macros

let

- Exercise 1–2, 4. d), solutions p. 9. A **let**:

```
let ([var value] ...)
  body
  ...
```

is equivalent to a **λ**, called immediately:

```
((λ (var ...) body ...) value ...)
```

but having the **[var init]** specifications appear in one place – instead of separated by the function body, which may be long – makes the code much more readable.

- Racket also provides a similar convenience form to help write macros – **with-syntax** [1] [2] binds *syntax patterns* in a **let**-like fashion.

(This latter point is mainly of interest if you want to explore macro writing; useful to keep in mind that “there was a **let** for this” for when you eventually need it.)

- Difference between **let**, **let***, **letrec**:

- let**: parallel binding
 - Just syntactically; not concurrent.
- let***: sequential binding
- letrec**: (mutually) recursive binding

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

–TRG 4.6.3: Recursive Binding: **letrec**

- This is why named **let** uses **letrec**; the loop must have access to its own name to be able to call itself for the next iteration.
- letrec** can be used to locally define (mutually) recursive functions.
 - If you Common Lisp, this use of **letrec** corresponds to **labels**.



Macros

Promises: **delay**, **force**

- **Promise**: delayed evaluation.

require syntax/parse/define

define-syntax-parser delay

```
(_ expr ...)
  syntax
  λ () (expr ...)
```

define force(promise)
 promise()

- Usage:

```
define my-promise
  delay
  displayln 'hello
```

```
;; ...possibly much later...
force my-promise
```

- **delay** makes a **thunk**, i.e. a 0-argument function, representing a *promise* to compute something later.
 - Because a function runs only when called, this delays evaluation of the given code; hence the name **delay**.
- In an **eager** language (e.g. Python and most Lisps including Racket), **delay** needs to be a macro.
 - If **delay** was a function, the given code would be immediately evaluated (because it is then a function argument) before **delay** had a chance to make a thunk out of it.
 - Why define **delay** at all? **For humans**. We want to convey the intended meaning, not the details of implementation – and **delay**, **force** do that much better than a raw **λ** and a call into it.
 - *Package the design pattern as an abstraction.*
- The counterpart of **delay**, called **force** – meaning “compute it now” – can be a function, so there is no point in making it a macro.

⚠ Barebones implementation! Racket provides much better **promises**, with automatic memoization of results.



Macros and, or

- Essentially, sugar on top of nested **ifs**:

require syntax/parse/define

define-syntax-parser or

```
(_ a b more ...+) ; ...+: one or more
  #'(or (or a b) more ...)
(_ a b)
  #'(if a a b) ; if test true-expr false-expr
(_ a)
  #'(a)
( )
  #'(#f)
```

define-syntax-parser and

```
(_ a b more ...+)
  #'(and (and a b) more ...)
(_ a b)
  #'(if a b #f)
(_ a)
  #'(a)
( )
  #'(#t)
```

- In Racket, **if** is a special case of **cond**.
 - Usually, **it is more idiomatic** to use **cond**.
 - Different Lisps, different preferences.
- These evaluate left-to-right, and return truthy or **#f**.
- Racket automatically applies the rule for a reducible case recursively, until the process “bottoms out” into the base cases.
- They need to be macros to avoid evaluating **b**, if **a** already fully determines the result.
- Testing:

```
(and #t #t #f)
(or #f 'hello 42)
```

⚠ Racket **already provides** **and** and **or**.
The ones given here are meant only to illustrate how **and** and **or** desugar into a sequence of nested **ifs**.



Macros and, or

- To avoid an extra evaluation:

require syntax/parse/define

define-syntax-parser or

```
(_ a b more ...+)
  #'(or (or a b) more ...)
(_ a b)
  #'(let ([value a])
      (if value value b))
(_ a)
  #'(a)
(_)
  #'(#f)
```

← The only change:
evaluate “a” once,
and bind a name
to the result.

- This is more efficient, because the body of the two-argument base case of **or** may need *a* twice, and *a* may be a compound expression.
- Keep in mind that this is a macro, so in effect, we are splicing source code.

(Or, more precisely, editing the AST. Being based on *syntactic* macros, this is **much less error-prone** than if we tried to do something similar in the C preprocessor – in those very few cases where that is at all possible.)
- The body of **and** mentions each argument only once, so it is efficient as-is.



Macros

Infix math

- One final example. Lisps have no infix math by default, and [sweet-exp sidesteps the issue](#) by providing a hook for a custom macro called *nfx*.
- Opinions vary on what features are desirable:
 - With operator precedence, or simple left-to-right?
 - Support only basic arithmetic, or try to support anything that could be considered an operator?
- There are many ways to do this, including [this quick hack](#) (left-to-right) and the very advanced [User-programmable infix operators in Racket](#).
- A simple one with precedence, from the [Learning Racket blog series by Artyom](#) (with minor edits):

require syntax/parse/define

define-syntax-parser nfx #:datum-literals (+ - * / ^)

(_ left ... + right ...) #'(+ (nfx left ...) (nfx right ...))

(_ left ... - right ...) #'(- (nfx left ...) (nfx right ...))

(_ left ... * right ...) #'(* (nfx left ...) (nfx right ...))

(_ left ... / right ...) #'(/ (nfx left ...) (nfx right ...))

(_ left ^ right ...) #'(expt left (nfx right ...)) ← Exponentiation is right-associative.

(_ x) #'x

nfx 1 + 3 - (+ 1 2 3) * 4 / 5 + 3 * 7 ^ 2 ^ 2 * 5 - 3 / 5 / 8 - 9 / 7 ;; 36012 47/56

{1 + 3 - (+ 1 2 3) * 4 / 5 + 3 * 7 ^ 2 ^ 2 * 5 - 3 / 5 / 8 - 9 / 7} ;; sweet-exp hook: mixed ops, {} → nfx



Macros

Breaking hygiene

Maybe advanced...ish?

See [1] and [2].

- A standard silly example: *the anaphoric if*.
(*anaphora*: referring to a preceding expression.)

We need a literal “it” to be available in the user code that calls the macro; but hygienic macros are specifically designed to prevent name leakage. So we need a special technique to expose “it”, while still reaping the benefits of hygienic macros:

require syntax/parse/define

define-syntax it(stx)

raise-syntax-error 'it "only meaningful inside an aif"

define-syntax-parser aif

(**_** test if-true if-false)

→ **with-syntax** ([it (datum->syntax #'test 'it)])
syntax

→ **let** ([it test])
if test
if-true
if-false

aif (* 3 7) (* 2 it) 'nope

- **define-syntax** gives “it” a transformer binding – i.e. makes a syntax transformer – that by default (outside any “aif”) just raises a syntax error.
 - *This is how to make reserved words that may only appear inside certain macros.*
 - This catches invalid uses early.
- **with-syntax** binds a syntax pattern in a **let**-like fashion, allowing us – *inside the RHS of our macro definition* – to refer to the bound value by the *syntax pattern* “it”.
- For the value, we say that in the code, its textual form is “it” (the symbol 'it), and give it a *non-default lexical context* with **datum->syntax**.
- Copying the lexical context from the **syntax object** captured by the pattern *test*, we “leak” (*break hygiene on*) this “it”, intentionally exposing it to user code *at the macro call site*.
- Finally, the **let** actually binds this “it” to a value.
 - Here we're inside a syntax template, so we can use **it** like any captured pattern.



Macros

Maybe advanced...ish?

Literal reserved words in Racket

- How to make literal reserved words, like Python's **in** in expressions like **for** x **in** range(...):

```
require syntax/parse/define
```

```
define-syntax bar(stx)
```

```
  raise-syntax-error 'bar "only meaningful inside a went-to-bar"
```

```
define-syntax-parser went-to-bar #:literals (bar)
```

```
  (_ a bar b)
```

```
    syntax
```

```
      displayln
```

```
      format
```

```
        "~a went to a ~a"
```

```
        a
```

```
        b
```

```
(went-to-bar 'tom bar 'pub)
```

```
(went-to-bar 'jerry bar 'tavern)
```

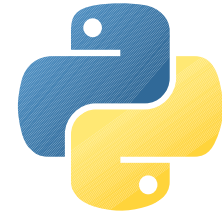
```
;; syntax error: expected the identifier 'bar'
```

```
(went-to-bar 'jerry tavern 'tavern)
```

The macro was originally called **foo**, hence a literal **bar**; but the Racket Style Guide recommends using semantically meaningful names in code examples.

- We tell **define-syntax-parser** that if the word “**bar**” appears in the syntax pattern being matched, it is to be taken literally.
- Without the **#:literals**, the syntax parser would match the “**bar**” to *anything*, and let us refer to it as **bar** – great for default behavior, but not what we want here.
- This **requires a binding**. Almost always you want that, but when not, use **#:datum-literals** instead of **#:literals**.

Macros in Python



- [Macropy](#) for Python 3.4+, with [examples](#) and [how to write your own macros](#).
 - For documentation on the Python AST, see the [standard library docs](#) and [Green Tree Snakes](#).
 - ⚠ Not as easy to write your own macros as in Lisps; Python's syntax is not homoiconic, and is much more complex than Lisp's.
 - ⚠ Writing macros is a subset of programming language design – “easy” is relative.
- Example – memoizing thunk (like Racket's [delay](#), [force](#)):

```
from macropy.quick_lambda import macros, lazy
```

← Import the magic name **macros**, and then any macros you want to use.

```
# count how many times expensive_func runs
```

```
count = [0]
def expensive_func():
    count[0] += 1
```

```
thunk = lazy[expensive_func()]
```

```
print(count[0] # 0)
```

```
thunk()
print(count[0]) # 1
thunk()
print(count[0]) # 1
```

General usage:

```
from my_macro_module import macros, ...
```

```
val = my_expr_macro[...]
```

```
with my_block_macro:
```

```
...
```

```
@my_decorator_macro
```

```
class X():
```

```
...
```

⚠ MacroPy macros run **at import time** (using [PEP302](#) import hooks), so cannot be used in a file that is run directly. See the [minimal viable setup](#) in MacroPy documentation.

let over λ

A Lisp idiom

- A puzzle – what does this code do?

```
define f
```

```
  let ([x 0])  
    λ ()  
      set! x {x + 1}  
      x
```

← Here “the **let** hangs over the λ ”;
hence the name.

Language-specific design pattern;
typically so small that there is
no point in extracting it as a macro.

In Racket, see also [splicing-let](#).

- Defines a function **f**, as we saw further above, discussing **define** and λ .
 - *Correct, but not the main point here.*
- The trick is in the **let** sandwiched between the **define** and the λ – it creates a local name **x**... outside the function body.
 - Lexically scoped, as usual: this **x** is not visible outside the **let** block.
 - The **let** is set up first, before the λ is bound to the name **f**. The body of **f()** starts just below the λ . Thus, the **let** runs only once (**not** at each call of **f**).
 - Hence, in this example, **f** counts how many times it has been called.
- **let over λ : local data that persists across calls to the function!**
 - For now the interaction with it is very limited, but that's easily fixed...

let over λ

Introducing the dispatcher

- Read-and-write local data, using a **dispatcher**:

```
define f
  let ([x 0])
    define set!-x(value) (set! x value)
    define get-x() x
    define call()
      set!-x {x + 1}
      x
  λ (msg)
    cond
      (eq? msg 'set!-x)
        set!-x
      (eq? msg 'get-x)
        get-x
      else ; default
        call
```

Dispatcher: take a message,
return the corresponding function.
This gets bound to the name **f**.

Just a symbol; no relation
to the function with the
same name.

```
define f-set!-x (f 'set!-x)
define f-get-x (f 'get-x)
define f-call (f 'call)
```

- Testing it:

```
f-call() ; 1
f-call() ; 2
f-call() ; 3
f-get-x() ; 3
f-set!-x(42)
f-get-x() ; 42
f-call() ; 43
f-call() ; 44
f-call() ; 45
```

Could also use **case** instead of **cond** to implement the dispatcher; refer to the [Racket docs on case](#).

This dispatch technique is also known as *message passing* (no relation to MPI).

- Methods?* Starting to look a bit like OOP?

λ over *let* over λ

Constructor; instance variables

- How about some OOP?

```
define Myobj() ← Constructor, now a function.  
  let ([x 0]) ← Its args would go here.  
    define set!-x(value) (set! x value)  
    define get-x() x  
    define call()  
      set!-x {x + 1}  
      x  
    λ (msg) ← The constructor returns  
      cond ← the dispatcher, which is  
        (eq? msg 'set!-x) a functional representation  
          set!-x of the object instance.  
        (eq? msg 'get-x)  
          get-x  
        else ; default  
          call  
          (Keep in mind that when  
            returning a function, what  
            actually gets returned is a  
            lexical closure.)
```

- Now we can construct `Myobj` instances,
(usage omitted; works the same as for `f` above):

```
define myobj1 (Myobj)  
define myobj1-set!-x (myobj1 'set!-x)  
define myobj1-get-x (myobj1 'get-x)  
define myobj1-call (myobj1 'call)
```

Now the **let** re-runs each time the constructor is called; hence, each created object instance gets its own copy of `x`.

⚠ Observe that this is built out of the “fundamental bricks” of Lisp; there is no reference to any existing object system.

⚠ In the real world, when writing an OO program in Racket, see **struct** and **class**; Racket already provides OOP!

λ over **let** over λ in **let** over λ ?

Class variables; OOP in FP

- Refining our OOP a bit:

In Python terms,
a type object
constructor.

```
define Myobj-typeinit(s0)
  let ([s s0]) ; class ("static") variables
  define set!-s(value) (set! s value)
  define get-s() s
  define init(a0) ; instance constructor
    let ([a a0]) ; instance variables
    define set!-a(value) (set! a value)
    define get-a() a
    define call()
      set!-a {a + 1}
      a
    λ (msg) ; instance dispatcher
    cond
      (eq? msg 'set!-s) set!-s
      (eq? msg 'get-s) get-s
      (eq? msg 'set!-a) set!-a
      (eq? msg 'get-a) get-a
      else call
    λ (msg) ; class dispatcher
    cond
      (eq? msg 'set!-s) set!-s
      (eq? msg 'get-s) get-s
      else init
```

Lexical
scoping.

- Testing it:

```
define Myobj Myobj-typeinit(42)
define myobj1 (Myobj 'init)(17)
define myobj2 (Myobj 'init)(23)

(myobj1 'get-a()) ; 17
(myobj2 'get-a()) ; 23
(myobj2 'call()) ; 24
(myobj1 'get-s()) ; 42
(myobj2 'get-s()) ; 42
(Myobj 'get-s()) ; 42
(myobj1 'set!-s)(9001)
(myobj2 'get-s()) ; 9001; class variable.
```

- Full example on GitHub.

⚠ Note how class variables live
in a surrounding lexical scope,
as seen from the viewpoint of
an object instance.

We'll stop this here, but for more, see
[Doug Hoyte \(2008\): Let over Lambda: 50 Years of Lisp](#),
a koan about objects and closures, and
OOP in FP with inheritance (delegation is inheritance!).

Continuations

Not to be confused with [the mathematical concept](#).

- Partial motivation:
 - Macros alone would be useless; a means of abstraction needs primitives.
 - We have seen, roughly, how to build – out of the basic bricks of Lisp – simple versions of things such as loops, promises, logical operators, and objects.
 - How about things that require more general [control flow](#), e.g. **return** or generators?
 - Enter the...
- **Continuation:**
 - The remaining steps in a computation. –[Matthew Might: Continuations by example](#)
 - The control state of the program. –[TRG 10.3: Continuations](#); [Wikipedia](#)
- See also [Matthew Butterick: Beautiful Racket: Continuations](#).
- Or see this story [about a sandwich](#); or this one about [continuations and coffee](#).
- In plain English, a continuation is a bookmark to a point in the program's execution, making it possible to jump back to that point later.
- When jumping back to such a “bookmark”, only the control flow resets. Any mutations to the state of the program's data will remain – this is what makes it useful.
- Modern variant: [delimited continuations](#).
- Possible applications: **return**, **while**, backtracking search, generators, threads, coroutines, exceptions.

call/cc

- **call/cc** (a.k.a. *call-with-current-continuation*) is a primitive that takes as its argument a function, and gives to that function the current continuation as a first-class object. It is a low-level “brick” for creating control flow constructs.
- Why would anyone want to **call** anything **with** the cc? *What does that even mean?*
 - It's a lispy API that leans on the composability of the syntax and “lambdas as code blocks”:

```
call/cc  
  λ (cc)  
    ... ; in this block cc is the current continuation
```

From the viewpoint of understanding this code, the λ is really just a code block that will run immediately. The fact that it also happens to be a function is immaterial.

- No need for parameters other than cc – any free variables in the λ block are closed over by lexical scoping!
- Python **lambdas** do not lend themselves to this programming style (perhaps on purpose).
- The call-with-something is an idiom to insert a handler to run before a particular code block is entered. The handler passes the “something” as an argument into that code block.
 - Lexical scoping then ensures that the name originally bound to the “something” is only accessible inside that code block.
 - But it can be **set!**d into something visible from outside, or returned when the block ends.

call/cc

- The continuation bookmarks the point where the *call/cc* ends.
- When the continuation – which can be called as if it was a function – is called, program execution will jump to the bookmarked point.
- Hence, calling (*cc*) while still inside the block will exit the block. It behaves like a **break**.
 - If this is all you need to do, there is also a more limited *call/ec* (*call-with-escape-continuation*), which gives better performance.
 - The difference is that the *ec* must be called (if it is to be called at all) *within the dynamic extent* of the *call/ec*'d block, whereas a *cc* may be called *any time later*.
 - An *ec* is slightly more general than a **break**. With a properly placed *call/ec*, you can break out of multiple nested loops *with one call*.
 - Actually, **continue**, **break** and **return** are *ecs*, recorded at different points.
- When called later, a continuation allows jumping back to an already visited point in the code.
- The first time, on normal exit, *call/cc* returns whatever the λ block returns.
- When the continuation is invoked, any arguments given to the continuation, as in (*cc arg1 arg2 ... argn*), become the return value(s) of the *call/cc*.
- There is also a **let/cc**, which can sometimes be more readable:

let/cc *cc*

... ; in this block *cc* is the current continuation

This bookmarks the point where the **let** block ends.

Implementing **return**

- Lisps don't have a **return** statement, but we can add one with **call/cc** ([full example](#)):
(Useful for returning early, i.e. before falling through the end.)

require syntax/parse/define

define-syntax-parser **define/return** ← We have chosen the name **define/return** for this syntax to express the idea “define a function that uses **return**”.

(this-stx (f args ...) body ...)

with-syntax ([return datum->syntax(#'this-stx 'return)])

syntax

define (f args ...)
let/ec return
body
...

← This code is spliced to the macro call site.
We have inserted a **let/ec**; otherwise it's just a regular **define**.

define-syntax-parser **λ/return**

(this-stx args body ...)

with-syntax ([return datum->syntax(#'this-stx 'return)])

syntax

λ args
let/ec return
body
...

← The same for a **λ** that uses **return**.

Usage:

```
define/return f()  
  displayln "hi"  
  return 42  
  displayln "not reached"
```

- A **while** loop [can be defined similarly](#), making appropriate bookmarks for **continue** and **break**.
- [Matthew Might: You don't understand exceptions, but you should](#)
 - To understand exceptions is to implement exceptions.*
 - return**, **while**, exception handling with **call/cc**. These interact! (Advanced but enlightening.)

Implementing **return**

- Lisps don't have a **return** statement, but we can add one with **call/cc** ([full example](#)):
(Useful for returning early, i.e. before falling through the end.)

require syntax/parse/define

define-syntax-parser define/return

(this-stx (f args ...) body ...)

with-syntax ([return datum->syntax(#'this-stx 'return)])

syntax

define (f args ...)

let/ec return

body

...

The magic: bind the name “return”
to the *escape continuation*;
i.e. bookmark the point
where this block ends.

Break hygiene, i.e. leak the
name “return” to user code
at the macro call site.

User
code
goes
here.

define-syntax-parser λ/return

(this-stx args body ...)

with-syntax ([return datum->syntax(#'this-stx 'return)])

syntax

λ args

let/ec return

body

...

This invokes the continuation.
The result of the **let/ec** block,
and hence also of the function,
becomes whatever we give
here as arguments to **return**.

Usage:

define/return f()

displayln "hi"

return 42

displayln "not reached"

- A **while** loop [can be defined similarly](#), making appropriate bookmarks for **continue** and **break**.
- [Matthew Might: You don't understand exceptions, but you should](#)
 - To understand exceptions is to implement exceptions.*
 - return**, **while**, exception handling with **call/cc**. These interact! (Advanced but enlightening.)

Implementing generators

- Maybe more interesting from a Python viewpoint: *how does a generator work?* ([Full example.](#))

require syntax/parse/define

define-syntax-parser make-generator

```
(  
  raise-syntax-error 'make-generator "missing body"  
(this-stx body ...)  
  with-syntax ([yield (datum->syntax #'this-stx 'yield)])  
    syntax
```

let
over
λ!

```
  let ([k 'none])  
    λ/return ()  
    let ([yield (λ args  
                  (let/cc cc  
                    (set! k cc)  
                    (apply return args))))])  
  
    cond  
      (not (eq? k 'none)) ; resume?  
      k()  
      body  
    ...
```

Kontinuations are konventionally kalled *k*.

Again, this is what
gets spliced to the
macro call site.

Usage:

```
define g  
  make-generator  
  let loop ([x 42])  
    yield x  
    loop {x + 1}  
g() ; 42  
g() ; 43  
g() ; 44
```

- See also [Matthew Might: Continuations by example](#)
 - Backtracking search, generators, threads, coroutines.

Implementing generators

- Maybe more interesting from a Python viewpoint: *how does a generator work?* ([Full example.](#))

require syntax/parse/define

define-syntax-parser make-generator

```
(_)
  raise-syntax-error 'make-generator "missing body"
  (this-stx body ...)
  with-syntax ([yield (datum->syntax #'this-stx 'yield)])
    syntax
```

⚠ Like Python, Racket already provides **generators**.

The usual fandango to make **yield** visible.

Current → **let** ([k 'none])
bookmark. **λ/return** () ← Since **yield** kinda-is-a **return**,
we base this on our **return** implementation.

```
  let ([yield (λ args
    (let/cc cc
      (set! k cc)
      (apply return args))))])
```

Magic, vol. 1: bookmark the place just after the current **yield**.

Magic, vol. 2: when we are called, check whether we have an active bookmark, and resume if so.

```
  cond
    (not (eq? k 'none)) ; resume?
    k()
    body
  ...
```

Usage:

```
define g
  make-generator
  let loop ([x 42])
    yield x
    loop {x + 1}
g() ; 42
g() ; 43
g() ; 44
```

- See also [Matthew Might: Continuations by example](#)
 - Backtracking search, generators, threads, coroutines.

What else could we do with call/cc?

- How about some [declarative programming](#) – *nondeterministic evaluation*? [\[1\]](#) [\[2\]](#) [\[3\]](#) ([Full example.](#))

```
require "choice.rkt"
```

```
choice 1 2 3 ; 1  
next() ; 2  
next() ; 3  
next() ; #f
```

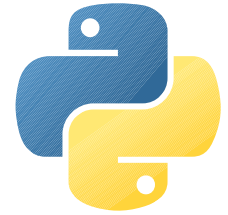
```
all {choice(3 10 6) + choice(100 200)} ; '(103 203 110 210 106 206)
```

```
all-query(even? {choice(4 5) + choice(11 14)}) ; '(18 16)
```

```
let ([a (choice 1 2 3 4 5 6 7)]  
     [b (choice 1 2 3 4 5 6 7)]  
     [c (choice 1 2 3 4 5 6 7)])  
  assert (= (* c c) (+ (* a a) (* b b)))  
  displayln (list a b c) ; (3 4 5)  
  assert (< b a)  
  displayln (list a b c) ; (4 3 5)
```

- Based on [David Liu \(2014\): Continuations and Backtracking in Racket.](#)
- The [Pythagorean triples](#) example is from [Matthew Might: Continuations by example.](#)
- SICP [approaches this problem](#) from the interpreter side, showing how to build the choice operator *amb* into the language core, while demonstrating [continuation-passing style](#).
- If you seriously need this sort of thing in Racket, consider [Racklog: Prolog-Style Logic Programming.](#)

Continuations in Python



- `continuation` (any version of Python) implements *continuation-passing style* with simple syntax:
- Example: `tail-recursive` factorial with the *continuation* library:

```
from continuation import with_CC, with_continuation
```

```
@with_continuation
```

```
def k_factorial(k):
```

```
    def inner(n, acc):
```

Explicit
return —→
as
usual
in
Python.

```
        return acc if n < 2 else (k << k_factorial)(n - 1, n * acc)  
    return inner
```

```
factorial = lambda n: (with_CC >> k_factorial)(n, 1)
```

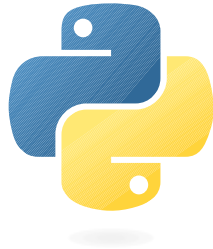
```
print(factorial(7))
```

This library doesn't add `call/cc`. It's likely that could be done with Python's powerful introspection features (by manipulating the call stack directly), but the author has chosen another, perhaps somewhat more robust approach.

- `with_CC >> func` sets up a continuation object. Execution starts from *func*, which must be decorated by `@with_continuation`.
 - *func* will receive one argument, the continuation object.
 - Feed other arguments using the above pattern.
- `k << func` sends the function *func* to *k* to use as the continuation – i.e. as what happens next; **the remaining steps in the computation**. Call that (like above) to jump to the continuation.
- This *trampolines* [\[1\]](#) [\[2\]](#) [\[3\]](#) automatically, so it won't overflow the call stack.
- For *tail call optimization* (TCO), there is another library from the same author...

FP loop with TCO

More on the *tco* library on the next slide.



```
from tco import C, with_continuations
```

```
def looped_hello(n):  
    @with_continuations() # TCO  
    def loop(i, self=None):  
        print("hello from loop, i = {}".format(i))  
        return self(i - 1) if i > 1 else None  
    return loop(n) # start the loop
```

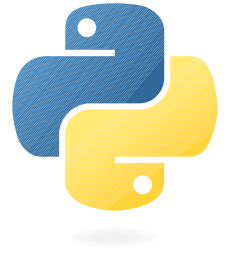
```
looped_hello(5)
```



```
define looped-hello(n)  
  let loop ([i n]) ; named let; starts implicitly  
  displayln  
  format  
    "hello from loop, i = ~a"  
    i  
  cond  
    {i > 1}  
    loop {i - 1}
```

```
(looped-hello 5)
```

More continuations in Python



- **Tail call optimization** is provided by `tco` (any version of Python).
- Example: tail-recursive factorial with the `tco` library:

```
from tco import C, with_continuations # "C" is the low-level API; see documentation.
```

```
def factorial(n):  
    @with_continuations()  
    def inner(n, acc, self=None):  
        return self(n - 1, n * acc) if n > 1 else acc  
    return inner(n, 1) # start the loop
```

```
print(factorial(7))
```

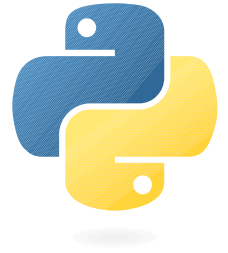
To apply TCO, the call must be in *tail position*.

Tail position: the last thing the function does before **returning** (in a particular code path).

⚠ Not necessarily last in the source code of that function; **returning** earlier is also allowed.

- The function *inner* is a functional loop. **With `tco`, FP loops work properly in Python!**
 - *n* counts down how many steps are remaining, *acc* is the accumulator.
 - **This example uses no mutation!** Each iteration of the functional loop gets a fresh *n* and *acc*.
- The continuation *self* is used for tail-call-optimized recursive calls.
 - Its default value can be anything; it is not used. (But **None** is an obvious placeholder.)
 - The `@with_continuations` decorator sets up the continuation when the function is called.
- Different from the usual use of *self* in Python!
 - It's not the first argument; instead, it's passed by name. Indeed, it's not Python's *self*. It's just a parameter that happens to be called "*self*", having somewhat similar semantics.

More continuations in Python



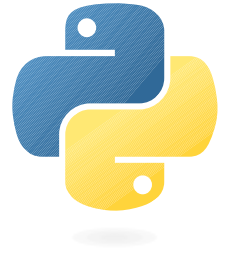
- In effect, the `tco` library, in a manner of speaking, also adds **call/ec** to Python.
- How to use: beside *self*, more continuations can be given, e.g. to be called in success and failure cases; or to be called **to escape from multiple levels of nested loops**.
- Example: tail-recursive factorial, using an escape continuation to finish.
 - There is only one level of looping in this example, but this illustrates how to use an *ec*.

```
from tco import C, with_continuations
```

```
def factorial(n):  
    @with_continuations() # let's make a continuation...  
    def identity(x, self=None):  
        return x  
    @with_continuations(ec=identity) # bind any extra continuations here...  
    def inner(n, acc, self=None, ec=None): # ...and just declare them here.  
        return self(n - 1, n * acc) if n > 1 else ec(acc)  
    return inner(n, 1)
```

- We set up a function, *identity()*, that we can use as an *ec* in continuation-passing style.
 - The mind-bending part: the **return** in *identity()* returns from the **original** top-level call!
 - This is basically because our function *identity()* is a continuation.
- See:
 - [GitHub page of the tco library](#)
 - [Thomas Baruchel: Explaining functional aspects in Python](#), an explanation from the author.

Breaking out of a code block



- OTOH, `continue`, `break` and `return` already are second-class escape continuations.
- Taking a page from Lisps: how to set up a custom “escape bookmark” in pure Python?
 - We can do this with a not-really-a-function, to run immediately – like a Lisp λ as a code block.
 - Abuse `def`, `return`, and decorators!

```
def immediate(thunk): # decorator to replace a thunk definition by its result.  
    return thunk()
```

We could also name this decorator `call_ec`, which it *almost* is. (Almost, because `return` is not a first-class value.)

```
def main():  
    @immediate # the grammar insists on a newline (“@immediate def” would sound nicer).  
    def result():  
        return "hello" # return to escape (possibly early) from the block and return a value.  
    # now result is the string “hello”.
```

- Compare the usual use of `decorators` (note *caveats!*):

```
def deco(f):  
    def decorated(*args, **kws):  
        print("deco says hi!")  
        return f(*args, **kws)  
    return decorated
```

The factory returns a decorator Python then implicitly calls to actually decorate the user function.

```
@deco  
def myfunc():  
    print("hello from myfunc")
```

Same as
`def myfunc(): ...`
`myfunc = deco(myfunc)`

Closed over the free var `f`.

△ Need arguments? Factory-wrap it:

```
def make_deco(a, b):  
    def deco(f):  
        def decorated(*args, **kws):  
            print("deco says {}, {}".format(a, b))  
            return f(*args, **kws)  
        return decorated  
    return deco
```

```
@make_deco(17, 23)  
def myfunc():  
    print("hello from myfunc")
```

Pattern matching

Not to be confused with [string matching](#) or [pattern recognition](#).

- **What:** A conditional based on shape and value of input data; seen in FP languages.
 - Destructuring bind, with a vengeance – switch on structure of input, while naming its parts.
 - Function overloading *by argument value*, not only by argument type.
- Contrast *string matching*: pattern matching operates on structured data, such as expressions.
- Contrast *pattern recognition*: a pattern match must be exact.
- Commonly used in Haskell; combos well with ADTs ([algebraic data types](#)).
- Something of an introduced species in untyped languages. Racket has an [extensible match](#).
 - Also [syntax-parse](#) uses pattern matching, but the syntax is slightly different.
- **Why:** *Code is for humans* – pattern matching improves readability. A simple destructuring:

Traditional lispy solution.

```
define foldl(f x lst)
  cond
    empty?(lst) x
    else (foldl f (f (car lst) x) (cdr lst))
```

```
define foldr(f x lst)
  cond
    empty?(lst) x
    else (f (car lst) (foldr f x (cdr lst)))
```

(Could name the parts, but needs more code.)

With pattern matching.

Docs: →

```
define foldl(f x lst)
  match lst
    '() x
    (cons a l) (foldl f (f a x) l)
```

```
define foldr(f x lst)
  match lst
    '() x
    (cons a l) (f a (foldr f x l))
```

Name the parts
right away.

“If *lst* is a *cons* of *a* and *l*, then...”

Pattern matching

- Function overloading *by value* (full example):

Traditional lispy solution.

```
define factorial(n)
  let loop ([m n]
            [acc 1])
    cond
      {m = 1} acc
      else (loop {m - 1} {m * acc})
```

(factorial 4)

With pattern matching.

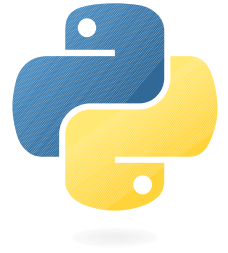
```
define factorial(n)
  let loop ([m n]
            [acc 1])
    match m
      1 acc
      v (loop {v - 1} {v * acc})
```

Match anything;
bind identifier.



(factorial 4)

- In both solutions, we have used [the same linear process](#) as in the Python continuation example:
 - Functional loop.
 - m keeps track of remaining steps, acc is the accumulator.
- We are essentially overloading *loop* to do different things based on the **value** of m .
 - On the other hand, we're essentially using PM as a **cond** with fancy syntax.
- To demonstrate the full power of this approach, we would need a typed language and something like [algebraic data types](#).
 - [Can be done in typed/racket](#).
- If none of the given patterns match the given input, it is an error.
 - In static typing, the type system may catch missing cases, issuing a compile-time warning [\[1\]](#) [\[2\]](#).
 - In dynamic typing, runtime error.



Pattern matching in Python

- **Wait, doesn't Python already do that?** Almost, but not quite:
 - Python supports a limited form of destructuring bind with the tuple unpacking operator, *
 - Can pull from nested tuples, like in the *zip-as-an-unfold* example in lecture 10, slide 14.
 - Tuples, lists **and namedtuples** only. No generators (**maybe reasonable**), no custom objects.
 - *But Python doesn't have a concise way to match different input data structure shapes.*
 - Important for choosing the correct destructuring for variably shaped input.

- **Libraries:**

- **MacroPy** has PM; **example**:

Case classes [\[1\]](#) [\[2\]](#) [\[3\]](#).

Roughly speaking,
here used to
approximate an **ADT**.

Look familiar?

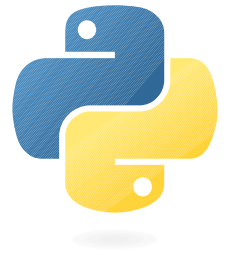
```
from macropy.case_classes import macros, case
from macropy.experimental.pattern import macros, switch
```

```
@case
class Nil():
    pass
```

```
@case
class Cons(x, xs):
    pass
```

```
def reduce(op, my_list):
    with switch(my_list):
        if Cons(x, Nil()):
            return x
        elif Cons(x, xs):
            return op(x, reduce(op, xs))
```

```
print(reduce(lambda a, b: a + b, Cons(1, Cons(2, Cons(4, Nil()))))) # 7
print(reduce(lambda a, b: a * b, Cons(1, Cons(3, Cons(5, Nil()))))) # 15
print(reduce(Nil(), lambda a, b: a * b)) # None
```



Pattern matching in Python

- For PM only, there's also [PyPatt: Python Pattern Matching](#).
 - But untested with Python 3; might not currently work.
 - See [its PyPI page](#) for links to alternatives and further reading.
- Example from the README (converted to Python 3 syntax):

```
import pypatt
```

```
@pypatt.transform
```

```
def test_demo():
```

```
    values = [[1, 2, 3], ('a', 'b', 'c'), 'hello world',
```

```
               False, [4, 5, 6], (1, ['a', True, (0,)], 3)]
```

```
    for value in values:
```

```
        with match(value):
```

```
            with 'hello world':
```

```
                print('Match strings!')
```

```
            with False:
```

```
                print('Match booleans!')
```

```
            with [1, 2, 3]:
```

```
                print('Match lists!')
```

```
            with ('a', 'b', 'c'):
```

```
                print('Match tuples!')
```

```
            with [4, 5, quote(temp)]:
```

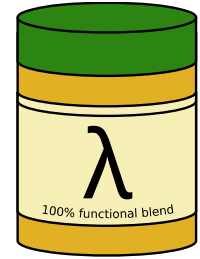
```
                print('Bind variables! temp =', temp)
```

```
            with (1, ['a', True, quote(result)], 3):
```

```
                print('Nest expressions! result =', result)
```

```
    print('Wow, pretty great!')
```

Automatic currying



- Recall *currying* (lecture 10, slide 17). *What if the language did that automatically?*

#lang sweet-exp spicy

```
define reverse  
  foldl cons empty
```

```
define append(a b)  
  foldr cons b a
```

```
define sum  
  foldl + 0
```

```
define product  
  foldl * 1
```

```
define map(f)  
  foldr (compose cons f) empty
```

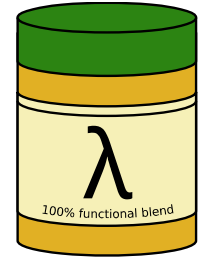
```
define sum-matrix  
  compose sum (map sum)
```

```
module+ main  
  define a '(1 2)  
  define b '(3 4)  
  define c '(5 6 7)  
  define M '((1 2)  
            (3 4))  
  
  define f(x) {x * x}  
  append a b  
  reverse c  
  sum a  
  product b  
  product (append a b)  
  map f c  
  sum-matrix M
```

Full example on GitHub.
Same example *without auto-currying*.

- Examples taken from [Hughes \(1984\): Why Functional Programming Matters](#) and racketified.

Automatic currying



- Recall *currying* (lecture 10, slide 17). *What if the language did that automatically?*

#lang sweet-exp spicy

Point-free style (PFS): omit declaring the arguments when possible.

```
define reverse  
  foldl cons empty
```

Usage is (foldl f x lst)
so this becomes
a function of one
argument.

```
define append(a b)  
  foldr cons b a
```

```
define sum  
  foldl + 0
```

Note the *arity* mismatch;
f is expected to take 1,
return 1, whereas *cons*
takes 2, returns 1.

```
define product  
  foldl * 1
```

The extra arg to *f* is
“passed through” on the right.

```
define map(f)  
  foldr (compose cons f) empty
```

```
define sum-matrix  
  compose sum (map sum)
```

```
module+ main  
  define a '(1 2)  
  define b '(3 4)  
  define c '(5 6 7)  
  define M '((1 2)  
             (3 4))
```

Racket's
conditional main
construct.

```
  define f(x) {x * x}  
  append a b  
  reverse c  
  sum a  
  product b  
  product (append a b)  
  map f c  
  sum-matrix M
```

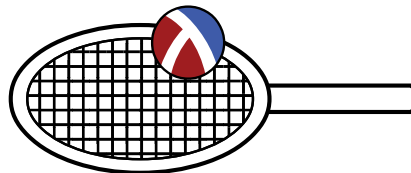
Full example on GitHub.
Same example *without auto-currying*.

- Examples taken from [Hughes \(1984\): Why Functional Programming Matters](#) and racketified.

Meta

The finish line

- Racket code examples in this lecture (plus a bunch more) are available on GitHub, in a subfolder of [examples](#), named [beyond Python](#).
- We didn't talk (much) about:
 - Infinite streams [\[1\]](#) [\[2\]](#) (custom SICP style; in production, [use Racket's](#)).
 - [Simple infix syntax processor](#) (manually implemented, left-to-right).
 - [Sieve of Eratosthenes in Racket](#) (several implementations).
 - [Quicksort: functional; imperative; Python for comparison](#).
 - [typed/racket: a simple gcd, parametric types, refined types](#).
 - Extra examples of pattern matching [\[1\]](#) [\[2\]](#).
- [spicy](#) (automatic currying for Racket) is provided as a separate project.
- Accompanied by this set of slides, the examples explain the basics, including some beginner and intermediate macrology.
- Intended as a starting point for self-study for the adventurous.



In conclusion

The future of programming – the next 30 years?

- *Prediction is very difficult, especially about the future.*
 - Niels Bohr? [[disputed](#)]
- Functional programming is rising. But which language will win? (Year of first release in parens.)
 - [Haskell](#) (1990): highly advanced statically typed language, pure FP.
 - Lisp? May be [cursed](#); “[worse is better](#)”.
 - [Racket](#) (1994): production-quality; excels at extensibility; highly modular ecosystem.
 - [Clojure](#) (2007): currently well positioned; runs on the Java VM and integrates with Java.
 - A [black swan](#)?
- OOP may be on the way out, very slowly. Widely adopted, but mostly incompatible with pure FP. OOP knowledge still needed to maintain legacy code.
- Languages will continue to rise and fall; no one language captures all of programming.
- Fortran will likely continue surviving as a special-purpose language for low-level numerics.
- C will likely remain the language of choice for implementing operating systems.
- Many Lisps will likely continue surviving, for teaching and for thinking about languages.
- Python? 1.0 in 1991; [too early to tell](#). Has found its niche as an easy, powerful, general-purpose high-level language, but a new unexpected contender replacing it cannot be ruled out.
- Parallelization paradigms will continue to evolve. Massively parallel supercomputing will likely remain relevant in scientific computing.
- Quantum computing may revolutionize some fields of application, but the programming model is so fundamentally different ([applied quantum mechanics](#)!) that algorithms must be completely reinvented to be able to use QC – a much harder task than the transition to the parallel model.

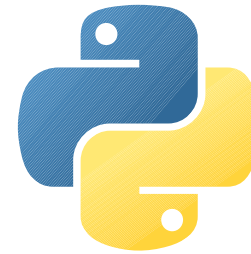
In conclusion

Meanwhile – which language?

- If you want...

- Ease of use, power plant included ⇒

Someone has even written [this](#)...



<https://www.python.org/>

- A pure functional language with a highly advanced static type system ⇒



<https://www.haskell.org/>

Secret alien technology,
vol. 2.

- The pinnacle of the first 60 years of Lisp; to discover [EP](#) and [LOP](#) ⇒



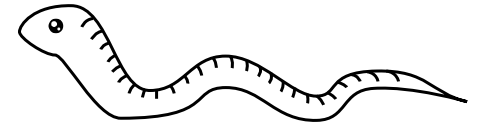
Programming language
construction kit.

([More useful than it sounds?](#))

<https://racket-lang.org>

In conclusion

Final words



```
import logging
from datetime import datetime
```

```
logger = logging.getLogger(__name__)
```

```
try:
    while True:
        with Funding(datetime.now()) as f:
            do_science(f)
except RuntimeError as e:
    logger.error(e)
    from sys import exit
    exit(-1)
```

For example:

- What went well?
- What could be done better?
- What you would like to hear in a second course?

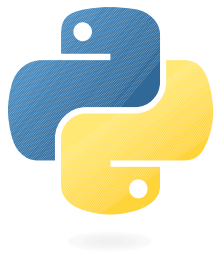
• Feedback? Questions? ► juha.jeronen@tut.fi

• **For course credit**, submit your final assignment by **31.5.2018 23:59:59.9**

Appendix: Racket resources



- **General:**
 - [Quick: An Introduction to Racket with Pictures](#)
 - [More: Systems Programming with Racket](#)
 - [The Racket Guide](#)
 - [How to Program Racket: a Style Guide](#) (the equivalent of Python's PEP8, for Racket)
 - [learning-racket](#) (a useful series of beginner to intermediate level blog posts)
 - [Learn Racket in Y Minutes](#)
 - [The Racket Reference](#) – see especially the [Language Model](#).
 - [Matthew Butterick: Beautiful Racket](#) (how to build programming languages in Racket)
 - [Rosetta Code](#) (code snippets for the same tasks in many languages, including Racket)
 - [The Computer Language Benchmarks Game](#) (includes entries written in Racket)
- **Indentation sensitive syntax:**
 - [⚠ For pythonistas, makes a lot of sense, but the Racket community prefers parentheses.](#)
 - [SRFI-110: Sweet-expressions \(t-expressions\)](#) (syntax reference)
 - [Sweet: an alternative to s-expressions](#) (Racket implementation)
- **Extending the syntax – macros:**
 - [Fear of Macros](#) (excellent introduction to macros, recommended)
 - [Macros in the Racket Guide](#)
 - [Syntax: Meta-Programming Helpers](#)
 - [Syntax Parse Examples](#)
 - [Macros in the API reference](#)
- **General, on the Scheme family:**
 - [The Adventures of a Pythonista in Schemeland](#)
 - [Abelson and Sussman: SICP, 2nd ed.](#) – also discusses SW design, interpreters, compilers.



Racket data structures

for Python users



Python

list
set
frozenset
dict
[no immutable dict type]
namedtuple, class
class

Racket

[gvector](#) require data/gvector
[mutable-set](#) require racket/set
[set](#) require racket/set
[make-hash](#)
[hash](#)
[struct](#) (granular control on mutability)
class [[guide](#)] [[reference](#)]
 require racket/class

Additionally:

[pair](#)
[mpair](#): mutable pair
[list](#): immutable singly linked list
[mlist](#): mutable; see [related functions](#)
 require compatibility/mlist
[vector](#): fixed-size vector
[box](#): minimal mutable storage

For dynamically scoped variables in Racket (like [dynscope.py](#) for Python), see [parameterize](#).

See [Datatypes](#) in the Racket reference.