Principles of Programming Languages (S)

Matteo Pradella

September 17, 2019

Overview

Main coordinates

- **email** `matteo.pradella@polimi.it`
- **office**
  DEIB, Politecnico di Milano
  via Golgi 42, building 22, floor 3, room 322
- **phone** 3495
- **web-page** `http://home.deib.polimi.it/pradella/PL.html`
- **twitter** @bzoto, tag #corsopl

Motivation and preliminaries

- programming languages are tools for writing software
- i.e. tools for talking to the machine
- but not only to the machine: often code is created also to be read by human beings
- (debugging, pair programming, modifications/extensions)

Motivation and preliminaries (cont.)

- several levels of abstraction in a computer: hw, operating system, network, applications, daemons, virtual machines, frameworks, web, clouds, ...
- no "holy grail" language
- different languages are to be used for programming at different levels
- close to human: abstract, hard to "control"
- close to machine: too many details, hard to understand what is going on
- various (often conflicting) aspects: expressiveness and conciseness; ease of use; ease to control; efficiency of compiled code ...

Motivation and preliminaries (cont.)

- why is a language successful?
- sometimes right tool at the right time; often hype, good marketing, good tools, luck, who knows. . .
- e.g. often is better a so-so language with great compilers, than a very nice language with a partial implementation
- (thanks especially to the Internet and open source software:) <u>many</u> new languages, strong evolution in recent years
- but often the concepts are those introduced 30+ years ago!

Motivation and preliminaries (cont.)

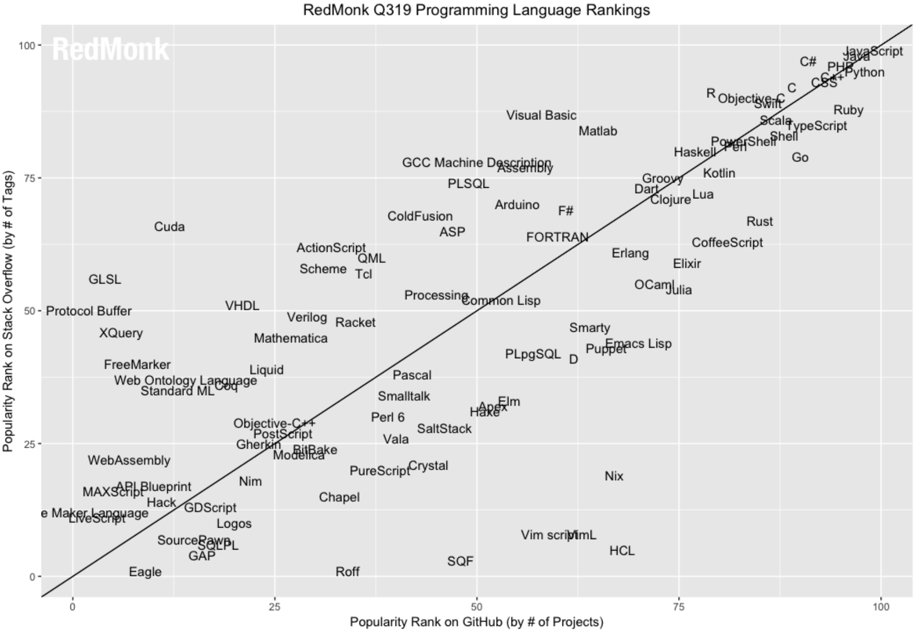
- Recent, competitive technologies are based on new languages, especially w.r.t. the Web
- e.g. Ruby on Rails, Node.js
- more and more new technologies and language-based frameworks emerge (or re-emerge, think about Objective-C and then Swift)
- Hence, we need to know and understand not particular languages, but their **main principles and concepts**

An incomplete timeline of PLs

- 1957 Fortran (Formula Translator)
- 1958 LISP (LISt Processor)
- 1959 COBOL (Common Business Oriented Language)
- 1960 ALGOL 60 (Algorithmic Language)
- 1964 BASIC (Beginner's All-purpose Symbolic Instruction Code)
- 1967 Simula (first object-oriented lang.)
- 1970 Pascal, Forth
- 1972 C, Prolog, Smalltalk
- 1975 Scheme (Lisp + Algol)
- 1978 ML (Meta-Language)
- 1980 Ada

An incomplete timeline of PLs (cont.)

- 1983 C++, Objective-C
- 1984 Common Lisp (Lisp + OO)
- 1986 Erlang
- 1987 Perl
- 1990 Haskell
- 1991 Python
- 1995 Java, JavaScript, Ruby, PHP
- 2001 C#
- 2002 F#
- 2003 Scala
- 2007 Clojure
- 2009 Go; '11 Dart, '12 Rust, '14 Swift ...


RedMonk Q319 Programming Language Rankings
RedMonk
Popularity Rank on Stack Overflow (by # of Tags)
Popularity Rank on GitHub (by # of Projects)
0
25
50
75
100
JavaScript
Java
Python
PHP
C#
C++
CSS
C
R
Objective-C
Swift
Ruby
Scala
TypeScript
Shell
PowerShell
Perl
Haskell
Go
Visual Basic
Matlab
GCC Machine Description
Assembly
PLSQL
Groovy
Dart
Kotlin
Clojure
Lua
Arduino
F#
ColdFusion
ASP
Rust
Cuda
FORTRAN
CoffeeScript
ActionScript
QML
Erlang
Scheme
Tcl
Elixir
GLSL
OCaml
Julia
Processing
Common Lisp
Protocol Buffer
VHDL
Verilog
Racket
Smarty
XQuery
Mathematica
Emacs Lisp
Puppet
PLpgSQL
D
FreeMarker
Liquid
Pascal
Web Ontology Language
Standard ML
Coq
Smalltalk
Elm
Apex
Haxe
Perl 6
Objective-C++
SaltStack
PostScript
Vala
Gherkin
BitBake
Modelica
WebAssembly
Crystal
PureScript
Nix
Nim
MAXScript
API Blueprint
Chapel
Hack
GDScript
e Maker Language
LiveScript
Logos
Vim script
VimL
HCL
SourcePawn
SQLPL
GAP
SQF
Eagle
Roff

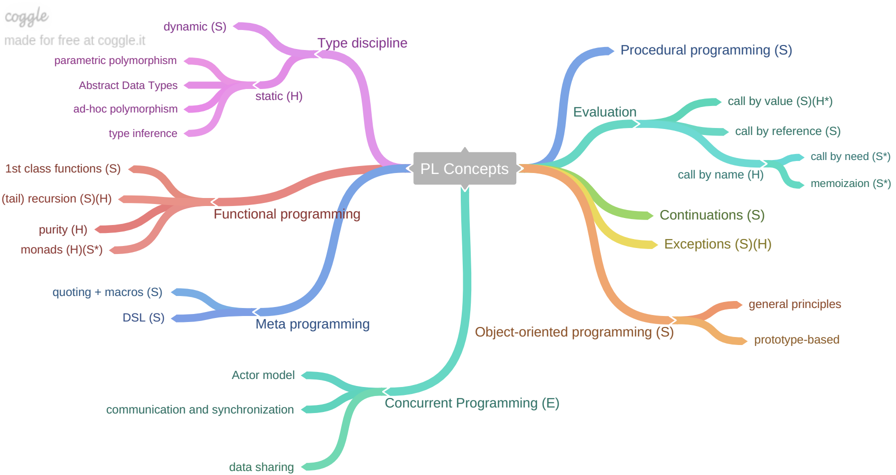
Pre-(and post-)requisites

- Good knowledge of procedural and object-oriented programming (I assume at least with C and Java, respectively)
- **Exam**: written exercises, small programs, translations from different paradigms.
  Emphasis on **concepts** and **elegance** of the chosen approach; no code obfuscation contest!

Map of used languages

- **Scheme**, for basics, memory management, introduction to functional programming and object orientation, meta-stuff
- **Haskell**, for static type systems and algebraic data types, functional "purity"
- **Erlang**, for concurrency-oriented programming
- Some of them are "academic" languages (but with reference with more mainstream ones): they are simpler, more orthogonal and with less "cruft"
- We need to understand the **concepts** and to be able to adapt and learn to new languages with little effort.
  (It is useless to focus on one particular, temporarily successful language.)

Map of concepts



Scheme: Why?

- Scheme is a language of the ancient and glorious Lisp Family
- *[Scheme is intended to] allow researchers to use the language to explore the design, implementation, and semantics of programming languages. (From the R6RS standard)*
- It is unique because it has extremely simple and flexible syntax and semantics, very few basic ideas
- Good to understand and experiment new concepts/constructs
- We will build new constructs and an OO language with it

A fast and incomplete introduction to Scheme

- Main (and free) material:
- We will use the **Racket** dialect of Scheme, which has a very good implementation and environment: `http://racket-lang.org/`
- The last **standard** is "The Revised^7 Report on the Algorithmic Language Scheme" (aka R7RS).
- A good book: `http://www.scheme.com/tspl4/` (R6RS)
- #lang directive at the beginning of the file to choose the Scheme dialect that we are using (in our case **#lang racket**)

The obligatory quotes on Lisp

- Anyone could learn Lisp in one day, except that if they already knew Fortran, it would take three days.
  – *Marvin Minsky*
- If you give someone Fortran, he has Fortran. If you give someone Lisp, he has any language he pleases.
  – *Guy Steele*
- A Lisp programmer knows the value of everything, but the cost of nothing.
  – *Alan Perlis*

Syntax (I hope you really like parentheses)

- The typical procedure call $f(x, y)$; (C/Java) is written like this: (f x y)
- No special syntax for expressions, no infix operators, no precedence rules. E.g.

```
x == y + 3*x + z;
```

is written

```
(= x (+ y (* 3 x) z))
```

- Such expressions are called **s-expressions**

Basic types

- Booleans: `#t`, `#f`
- Numbers: 132897132989731289713, 1.23e+33, 23/169, 12+4i
- Characters: `#\a`, `#\Z`
- Symbols: a-symbol, another-symbol?, indeed!
- Vectors: `#(1 2 3 4)`
- Strings: "this is a string"
- Pairs and Lists: `(1 2 #\a)`, `(a . b)`, `()` (we'll see later)

Expressions

- Scheme is mainly a **functional** language, so every program is an **expression**, and computation is based on evaluating expressions (no statements).
- Evaluation of an expression produces a **value** (if it terminates)
- Evaluation of an expression (e_1 e_2 e_3 ...) is based on the evaluation of e_1, which identifies an operation f (e.g. is the name of a procedure). The other sub-expressions (i.e. e_i, $i > 1$) are evaluated, and their values are passed to f.
- The evaluation order of e_i, $i \geq 1$ is **unspecified**, e.g. e_4 could be evaluated before e_2.

Procedures and the λ-calculus ancestry

- **lambdas** are unnamed procedures:

```
(lambda (x y) ; this is a comment
   (+ (* x x) (* y y)))
```

- example usage
  ((lambda (x y) (+ (* x x) (* y y))) 2 3) $\Longrightarrow$ 13
  i.e. $(\lambda(x, y) := x^2 + y^2)(2, 3)$
- Lambdas are called **blocks** in Smalltalk, Ruby, Objective-C, and are present in many languages (e.g. in C++11, Java 8).
- Procedures are **values** in Scheme, hence are **first class objects**.
- λ-calculus introduced by Alonzo Church in the '30s, theory of **computable** functions based on recursion (i.e. **recursive** functions)

Variables and binding

- **let** is used for binding variables:

```
(let ((x 2)    ; in Scheme
      (y 3))
      ...)
```

```
{ int x = 2, y = 3; // in C
  ... }
```

- Scoping rules are **static** (or lexical): traditional/old Lisps are dynamic (e.g. Emacs Lisp).
  Scheme was the first Lisp taking static scoping from Algol.

Static vs Dynamic scoping

- Consider this code:

```
(let ((a 1))
  (let ((f (lambda ()
             (display a))))
    (let ((a 2))
      (f))))
```

Static vs Dynamic scoping

- Consider this code:

```
(let ((a 1))
  (let ((f (lambda ()
             (display a))))
    (let ((a 2))
      (f))))
```

- With static scoping rules, it prints 1; with dynamic scoping rules, 2.
- A few interpreted languages are still based on dynamic scoping. Some languages can optionally support it (e.g. Common Lisp, Perl). In Perl "my" variables are static, while "local" are dynamic.

let, again

- let binds variables "in parallel", e.g.:

```
(let ((x 1)
      (y 2))
      (let ((x y)   ; swap x and y
            (y x))
      ...x))
```

- Evaluates to 2. There is a "sequential" variant called let*.
  With it, x is bound before y.
- if mutual recursion is needed, there are also **letrec** and letrec*

Homoiconicity

- Scheme, like Lisp and a few other languages (e.g. Prolog), is **homoiconic**, i.e. there is no distinction between code and data (like machine code in the von Neumann architecture)
- This can be cumbersome, e.g. the prefixed full-parenthesizes syntax is not for everyone, but it can be very effective for **meta-programming**:
- As code-is-data, it is very easy to define procedures that build and compose other procedures.
- We will consider this aspect later, with many examples.

Syntactic forms

- Not everything is a procedure or a value. E.g. **if** in general does not evaluate all its arguments
  `(if <condition> <then-part> <else-part>)`
  - variants: `(when <condition> <then-part>)`, `(unless <condition> <else-part>)`
- **if** is a **syntactic form**. In Scheme it is possible to define new syntax through **macros** (we will see them later).
- e.g. try to evaluate + and `if` at the REPL (read-eval-print-loop)

Quoting

- There is a syntax form that is used to **prevent** evaluation: `(quote <expr>)`
- `<expr>` is left unevaluated.
- Shorthand notation: `'<expr>`
- e.g.
  (quote (1 2 3)) is a list – without the quote, ⇒ error
  (quote (+ 2 3)) is another list – without the quote, ⇒ 5

Quoting (cont.)

- `quasiquote` (`) and `unquote` (,) are used for partial evaluation
- e.g. with shorthand notation:

```
'(1 2 3)            ; = (quote (1 2 3)) => (1 2 3)
`(1 ,(+ 1 1) 3)     ; = (quasiquote
                    ;       (1 (unquote (+ 1 1)) 3))
                    ; => (1 2 3)
```

Eval

- procedure **eval** is typical of Lisps, and it is present in many Lisp-inspired/derived languages, e.g. Python, Ruby, JavaScript...
- in such languages, it has one argument, which is a string containing code to be evaluated
- in Scheme, it is just code (e.g. the list `(+ 1 2)`)
- it is the "inverse" of quote: `(eval '(+ 1 2 3))` is 6

Sequence of operations: **begin**

- If we are writing a block of procedural code, we can use the **begin** construct

```
(begin
   (op_1 ...)
   (op_2 ...)
   ...
   (op_n ...))
```

- every `op_i` is evaluated in order, and the value of the begin block is the value obtained by the last expression

Definitions

- Variables created by `let` are local. To create top-level bindings there is **define**:
  ```
  (define <name> <what>)
  ```
- e.g.
  ```
  (define x 12)
  (define y #(1 2 3))
  ```
- Note that defining a procedure is no different:
  ```
  (define cube (lambda (x) (* x x x)))
  ```
  `(cube 3)` $\Rightarrow$ 27
- `define` can be also used instead of `let` in procedures

Defining procedures

- There is a shorthand notation for defining procedures, that mimics their usage:
  `(define (cube x) (* x x x))`
- **set!** is for assignment:

```
(begin
  (define x 23)
  (set! x 42)
  x)
```

- evaluates to 42.
- NB: in general, procedures with side effects have a trailing bang (!) character.

Lists

- Lisp traditionally stands for LISt Processor and Scheme takes lists management directly from Lisp
- Lists are memorized as concatenated **pairs**, a pair (written `(x . y)`, also called a **cons** node) consists of two parts:
  - **car** (i.e. x) aka *Content of the Address Register*
  - **cdr** (i.e. y) aka *Content of the Data Register*
- a list `(1 2 3)` is stored like this `(1 . (2 . (3 . ())))`
- () is the **empty list** also called **nil** in Lisp
- the two procedures `car` and `cdr` are used as accessors
- to check if a list contains a value, use `member`: e.g. `(member 2 '(1 2 3))` is '(2 3)

Lists and procedures

- Procedures bodies and parameter lists are all plain lists
- this can be used to implement procedures with a variable number of arguments
- e.g.

```
(define (x . y) y)

(x 1 2 3) ;; => '(1 2 3)
```

- **apply** can be used to apply a procedure to a list of elements

```
(apply + '(1 2 3 4))  ;; => 10
```

- to build a pair we can use **cons**: e.g. `(cons 1 2)` is `(1 . 2)`; `(cons 1 '(2))` is `(1 2)`

A classical example on lists

- find the minimum of a list

```
(define (minimum L)
  (let ((x  (car L))
        (xs (cdr L)))
    (if (null? xs)   ; is xs = ()?
      x              ; then return x
      (minimum       ; else: recursive call
        (cons
          (if (< x (car xs))
            x
            (car xs))
          (cdr xs))))))

(minimum '(11 -3 2 3 8 -15 0)) ; => -15
```

A classical example on lists (cont.)

- a variant with variable number of arguments:

```
(define (minimum x . rest)
  (if (null? rest)      ; is rest = ()?
      x                 ; then return x
      (apply minimum    ; else: recursive call
       (cons
         (if (< x (car rest))
             x
             (car rest))
         (cdr rest)))))

(minimum 11 -3 2 3 8 -15 0) ; => -15
```

General loops: the named **let**

- Let us start with a "non-idiomatic" example:

```
(let ((x 0))
  (let label () ; why an empty list?
    (when (< x 10)
          (display x)
          (newline)
          (set! x (+ 1 x))
          (label))))  ; go-to label
```

- in C or Java:

```
for (x = 0; x < 10; x++) {
  printf("%d/n", x);
}
```

General loops: the named **let** (cont.)

- the strange empty list is used for variables that are used in the loop
- indeed, this is the correct, idiomatic way of doing the same thing:

```
(let label ((x 0))
  (when (< x 10)
      (display x)
      (newline)
      (label (+ x 1)))) ; x++
```

- of course we can use as many variables as we like
- like with **begin**, the value is the one obtained by the last expression

Proper tail recursion

- Every Scheme implementation is required to be properly tail recursive
- A procedure is called tail recursive if its recursive call is "at the tail", i.e. is the last operation performed
- e.g. not tail recursive:

```
(define (factorial n)
 (if (= n 0)
     1
     (* n (factorial (- n 1)))))
```

- e.g. tail recursive:

```
(define (fact x)
  (define (fact-tail x accum) ; local proc
    (if (= x 0) accum
        (fact-tail (- x 1) (* x accum))))
  (fact-tail x 1))
```

Proper tail recursion (cont.)

- Tail recursive procedures can be optimized to avoid stack consumption
- indeed, the previous tail call is translated in the following low-level code:

```
(define (fact-low-level n)
  (define x n)
  (define accum 1)
  (let loop ()  ;; see this as the "loop" label
    (if (= x 0)
      accum
      (begin
        (set! accum (* x accum))
        (set! x (- x 1))
        (loop))))) ;; jump to "loop"
```

Proper tail recursion (cont.)

- of course, a more idiomatic way of writing it is the following:

```
(define (fact-low-level-idiomatic n)
  (let loop ((x n)
             (accum 1))
    (if (= x 0)
        accum
        (loop (- x 1)(* x accum)))))
```

- but note that this looks like a tail call...
- (In reality, the named let is translated into a local recursive function. If tail recursive, when compiled it becomes a simple jump.)

Loops on lists: **for-each**

- Nothing much to say, besides the syntax:
- e.g.

```
(for-each (lambda (x)
              (display x)(newline))
          '(this is it))
```

for-each for vectors

- es:

```
(vector-for-each (lambda (x)
                   (display x)(newline))
                 #(this is it))
```

- here is the definition:

```
(define (vector-for-each body vect)
  (let ((max (- (vector-length vect) 1)))
    (let loop ((i 0))
         (body (vector-ref vect i)) ; vect[i] in C
         (when (< i max)
            (loop (+ i 1))))))
```

Equivalence predicates

- A predicate is a procedure that returns a Boolean. Its name usually ends with ? (e.g. we already saw **null?**)
- = is used only for numbers
- there are **eq?**, **eqv?**, and **equal?**
- very roughly:
  - **eq?** tests if two objects are the same (good for symbols)
    - `(eq? 'casa 'casa)`, but not `(eq? "casa" (string-append "ca" "sa"))`, `(eq? 2 2)` is unspecified
  - **eqv?** like **eq?**, but checks also numbers
  - **equal?** predicate is `#t` iff the (possibly infinite) unfoldings of its arguments into regular trees are equal as ordered trees.
    - `(equal? (make-vector 5 'a)(make-vector 5 'a))` is true

case and cond

- case:

```
(case (car '(c d))
      ((a e i o u) 'vowel)
      ((w y)       'semivowel)
      (else        'consonant)) ; => consonant
```

- cond:

```
(cond ((> 3 3) 'greater)
      ((< 3 3) 'less)
      (else    'equal))   ; => equal
```

- Note: they are all **symbols**; neither strings, nor characters
- the predicate used in **case** is **eqv?**

Storage model and mutability

- Variables and object implicitly refer to locations or sequence of locations in memory (usually the **heap**)
- Scheme is **garbage collected**: every object has unlimited extent – memory used by objects that are no longer reachable is reclaimed by the GC
- Constants reside in read-only memory (i.e. regions of the heap explicitly marked to prevent modifications), therefore literal constants (e.g. the vector `#(1 2 3)`) are **immutable**
- If you need e.g. a mutable vector, use the constructor `(vector 1 2 3)`
- Mutation, when possible, is achieved through "bang procedures", e.g. `(vector-set! v 0 "moose")`

Example on literal constants and mutability

- with standard constructors, e.g. vectors are mutable

```
(define (f)
  (let ((x (vector 1 2 3)))
    x))

(define v (f))
(vector-set! v 0 10)
(display v)(newline) ; => #(10 2 3)
```

Example on literal constants and mutability (cont.)

- literal constants should be immutable:

```
(define (g)
  (let ((x #(1 2 3)))
    x))

(display (g))(newline) ; => #(1 2 3)
(vector-set! (g) 0 10) ; => error!
```

- in Racket, lists are immutable (so no `set-car!`, `set-cdr!`) - this is different from most Scheme implementations (but it is getting more common)
- There is also a *mutable pair* datatype, with `mcons`, `set-mcar!`, `set-mcdr!`

Evaluation strategy

- Evaluation strategy: **call by object sharing** (like in Java): objects are allocated on the heap and references to them are passed **by value**.

```
(define (test-setting-local d)
  (set! d "Local")  ; setting the local d
  (display d)(newline))

(define ob "Global")
(test-setting-local ob) ;; => Local
(display ob)            ;; => Global
```

Evaluation strategy (cont.)

- It is also often called **call by value**, because objects are evaluated before the call, and such values are **copied** into the activation record
- The copied value is not the object itself, which remains in the heap, but a **reference** to the object
- This means that, if the object is mutable, the procedure may exhibit **side effects** on it

```
(define (set-my-mutable d)
  (vector-set! d 1 "done")
  (display d))

(define ob1 (vector 1 2 3)) ;; i.e. #(1 2 3)
(set-my-mutable ob1)  ;; => #(1 done 3)
(display ob1)         ;; => #(1 done 3)
```

Introducing new types: structs

- It is possible to define new types, through **struct**
- The main idea is like **struct** in C, with some differences
- e.g.

```
(struct being (
  name              ; name is immutable
  (age #:mutable) ; flag for mutability
  ))
```

- a number of related procedures are automatically created, e.g. the constructor `being` and a predicate to check if an object is of this type: `being?` in this case

Structs (2)

- also accessors (and setters for mutable fields) are created
- e.g., we can define the following procedure:

```
(define (being-show x)
  (display (being-name x))
  (display " (")
  (display (being-age x))
  (display ")"))

(define (say-hello x)
  (if (being? x) ;; check if it is a being
      (begin
        (being-show x)
        (display ": my regards.")
        (newline))
      (error "not a being" x)))
```

Structs (3)

- example usage:

```
(define james (being "James" 58))
(say-hello james)
        ;; => James (58): my regards.
(set-being-age! james 60) ; a setter
(say-hello james)
        ;; => James (60): my regards.
```

- clearly it is not possible to change its name

Structs and inheritance

- structs can inherit

```
(struct may-being being    ; being is the father
  ((alive? #:mutable))     ; to be or not to be
  )
```

- this being can be killed:

```
(define (kill! x)
  (if (may-being? x)
      (set-may-being-alive?! x #f)
      (error "not a may-being" x)))
```

Structs and inheritance (cont.)

- dead being are usually untalkative:

```
(define (try-to-say-hello x)
  (if (and
        (may-being? x)
        (not (may-being-alive? x)))
      (begin
        (display "I hear only silence.")
        (newline))
      (say-hello x)))
```

Structs and inheritance (cont.)

- now we create:

```
(define john (may-being "John" 77 #t))
(say-hello john)
        ; => John (77): my regards.
```

- note that John is also a being
- and destroy:

```
(kill! john)
(try-to-say-hello john)
        ; => I hear only silence.
```

Structs vs Object-Oriented programming

- The main difference is in *methods* vs *procedures*:
- procedures are *external*, so with inheritance we cannot redefine/override them
- still, a **may-being** behaves like a **being**
- but we had to define a new procedure (i.e. **try-to-say-hello**), to cover the role of **say-hello** for a **may-being**
- **structs** are called **records** in the standard.

Closures

- a **closure** is a function together with a referencing environment for the non-local variables of that function
- i.e. a function object that "closes" over its visible variables
- e.g.

```
(define (make-adder n)
   (lambda (x)
      (+ x n)))
```

- it returns an object that maintains its local value of `n`

```
(define add5 (make-adder 5))
(define sub5 (make-adder -5))
(= (add5 5) (sub5 15))  ; => #t
```

Closures (cont.)

- Here is a simple application, a closure can be used as an *iterator*:

```
(define (iter-vector vec)
  (let ((cur 0)
        (top (vector-length vec)))
    (lambda ()
      (if (= cur top)
        '<<end>>
        (let ((v (vector-ref vec cur)))
          (set! cur (+ cur 1))
          v)))))

(define i (iter-vector #(1 2)))
(i)    ; => 1
(i)    ; => 2
(i)    ; => '<<end>>
```

An interlude on some classical higher order functions

- remember the famous map/reduce framework introduced by Google
- the following operations are supported also by many other languages, e.g. Python and Ruby
- **map**: $map(f, (e_1, e_2, \ldots, e_n)) = (f(e_1), f(e_2), \ldots, f(e_n))$
- **filter**: $filter(p, (e_1, e_2, \ldots, e_n)) = (e_i \mid 1 \leq i \leq n, p(e_i))$
- folds: **foldr** and **foldl** (aka **reduce** in Python, **inject** in Ruby, **std::accumulate** in C++)
- let $\circ$ be a binary operation

$$fold_{left}(\circ, \iota, (e_1, e_2, \ldots, e_n)) = (e_n \circ (e_{n-1} \circ \ldots (e_1 \circ \iota)))$$

$$fold_{right}(\circ, \iota, (e_1, e_2, \ldots, e_n)) = (e_1 \circ (e_2 \circ \ldots (e_n \circ \iota)))$$

Examples

```
(map (lambda (x) (+ 1 x)) '(0 1 2))
  ; => (1 2 3)
(filter (lambda (x) (> x 0)) '(10 -11 0))
  ; => (10)
(foldl string-append ""
           '("una" " " "bella" " " "giornata"))
  ; => "giornata bella una"
(foldl cons '() '(1 2 3))
  ; => (3 2 1)
(foldr cons '() '(1 2 3))
  ; => (1 2 3)
(foldl * 1 '(1 2 3 4 5 6)) ; i.e. factorial
  ; => 720
```

Example implementation of folds

- **foldl** is tail recursive, while **foldr** isn't

```
(define (fold-left f i L)
  (if (null? L)
      i
      (fold-left f
                 (f (car L) i)
                 (cdr L))))

(define (fold-right f i L)
  (if (null? L)
      i
      (f (car L)
         (fold-right f i (cdr L)))))
```

A tail-recursive foldr

- Actually, there is a way of making **foldr** tail rec.

```
(define (fold-right-tail f i L)
  (define (fold-right-tail-h f i L out)
    (if (null? L)
        (out i)
        (fold-right-tail-h f i
                           (cdr L)
                           (lambda (x)
                             (out (f (car L) x))))))
  (fold-right-tail-h f i L (lambda (x) x)))
```

- The idea is to save the code to be performed *after* the recursive call in a closure
- Do we gain anything, as far as memory occupation is concerned?

while loops?

- If you are fond of **while** loops, rest assured that it is possible to introduce them in Scheme
- E.g. the previous factorial could be written like this:

```
(define (fact-with-while n)
  (let ((x n)
        (accum 1))
    (while (> x 0)
     (set! accum (* x accum))
     (set! x (- x 1)))
    accum))
```

- clearly, we cannot define it as a procedure (why?)
- but how is it possible to extend the syntax?

Meta-programming through macros: i.e. how to program your compiler

- Scheme has a very powerful, Turing-complete macro system (unlike that of C)
- like in C, macros are expanded at *compile-time*
- macros are defined through `define-syntax` and `syntax-rules`
- `syntax-rules` are pairs `(pattern expansion)`:
  - **pattern** is matched by the compiler,
  - then expanded into **expansion**

while as a macro

- Let us start with an example: the while loop

```
(define-syntax while
  (syntax-rules () ; no other needed keywords
    ((_ condition body ...) ; pattern P
     (let loop ()           ; expansion of P
       (when condition
           (begin
             body ...
             (loop)))))))
```

- _ in the pattern stands for `while`, `...` is a keyword used to match sequences of items

let* as a recursive macro

- Note that `(let ((x 1)) ...)` can be expressed with a lambda form:
- `((lambda (x) ...) 1)`
- So we could define for instance **let*** as a recursive macro:

```
(define-syntax my-let*
  (syntax-rules ()
    ;; base (= only one variable)
    ((_ ((var val)) istr ...)
     ((lambda (var) istr ...)
      val))
    ;; more than one
    ((_ ((var val) . rest) istr ...)
     ((lambda (var)
        (my-let* rest istr ...))
      val))))
```

and **let** as a macro

- It is also very simple to define **let**:

```
(define-syntax my-let
  (syntax-rules ()
    ((_ ((var expr) ...) body ...)
     ((lambda (var ...) body ...) expr ...))))
```

- in it there is an interesting usage of operator `...`
- the first `...` in the pattern is used to match a sequence of pairs `(var expr)`, but in the expansion the first `...` gets only the `var` elements, while the last `...` gets only the `expr` elements

Hygiene

- Scheme macros are *hygienic*
- this means that symbols used in their definitions are actually replaced with special symbols not used anywhere else in the program
- therefore it is impossible to have name clashes when the macro is expanded
- Note that other macro systems, e.g. that of Common Lisp, are not hygienic, so this aspect must be manually managed
- on the other hand, sometime we *want* name clashes, so these particular cases can be tricky (we will see an example later)

Continuations

- A continuation is an abstract representation of the control state of a program
- in practice, it is a data structure used to represent the state of a running program
- the **current continuation** is the continuation that, from the perspective of running code, would be derived from the current point in a program execution
- if the language supports first class functions, it is always possible to refactor code in *continuation passing style*, where control is passed **explicitly** in the form of a continuation
- (hint: we saw an example with the tail-recursive fold-right)

Native continuations

- Scheme, unlike many mainstream languages, natively supports continuations:
- **call-with-current-continuation** (or **call/cc**) accepts a procedure with one argument, to which it passes the current continuation, implemented as a *closure*
- there are other languages that support first-class continuations: e.g. Ruby (but not JRuby), C in POSIX with `setcontext`, some implementations of JavaScript
- a similar (but severely limited) mechanism is also present in Python, with **generators** (see `yield`)
- critics also call them *glorified gotos*: they are powerful but abusing them makes the program control hard to understand

Native continuations (cont.)

- The argument of call/cc is also called an **escape procedure**;
- the escape procedure can then be called with an argument that becomes the result of **call/cc**.
- This means that the escape procedure abandons its own continuation, and reinstates the continuation of **call/cc** (see next example)
- In practice: we save/restore the call stack (we will talk about the implementation later)

A first example

```
(+ 3
   (call/cc
    (lambda (exit)
      (for-each (lambda (x)
                  (when (negative? x)
                    (exit x)))
                '(54 0 37 -3 245 19))
      10)))
```

- here we obtain 0
- Important: an escape procedure has *unlimited extent*: if stored, it can be called after the continuation has been invoked, also multiple times

call/cc: a simple example

```
(define saved-cont #f) ; place to save k

(define (test-cont)
   (let ((x 0))
     (call/cc
      (lambda (k) ; k contains the continuation
        (set! saved-cont k))) ; here is saved

     ;; this *is* the continuation
     (set! x (+ x 1))
     (display x)
     (newline)))
```

call/cc: a simple example (cont.)

- let us try it at the REPL:

```
(test-cont) ;; => 1
(saved-cont) ;; => 2
(define other-cont saved-cont)
(test-cont)  ;; => 1 (here we reset saved-cont)
(other-cont) ;; => 3 (other is still going...)
(saved-cont) ;; => 2
```

- What if I put these instructions in a function and call it?

Implementation of call/cc

- there are various way of implementing call/cc
- we consider here two approaches (there are many variants):
  - the garbage-collection strategy
  - the stack strategy
- if you are interested:
  W. Clinger, A. Hartheimer, E. Ost, *Implementation Strategies for First-Class Continuations*, Higher-Order and Symbolic Computation, 12, 7-45 (1999)

Garbage-collection strategy

- in it, we do not use the stack **at all**: call frames are allocated on the heap
- frames that are not used anymore are reclaimed by the GC
- call/cc simply saves the **frame pointer** of the current frame
- when we call the continuation, we are just setting the current frame pointer to the one saved before
- (note: the stackless implementation of Python works like this)

Stack strategy

- in it, we use the stack as usual
- when call/cc is issued, we create a **continuation object** in the heap by copying the current stack
- when we call the continuation, we reinstate the saved stack, discarding the current one
- it is a **zero-overhead** strategy: if we do not use call/cc, we do not pay its cost
- nonetheless, here call/cc can be quite expensive if used

Another example: a for with break

- The idea is to introduce a For loop with a break-like statement, like:

```
(For i from 1 to 10
     do
     (displayln i)
     (when (= i 5)
       (break)))
```

- Problem with hygenic macros: we need to be able to access to the parameter containing the escape continuation. This is not so easy with syntax-rules.

A simple solution

```
(define-syntax For
  (syntax-rules (from to break: do)
    ((_ var from min to max break: br-sym do body ...)
     (let* ((min1 min)
            (max1 max)
            (inc (if (< min1 max1) + -)))
       (call/cc (lambda (br-sym)
                  (let loop ((var min1))
                    body ...
                    (unless (= var max1)
                      (loop (inc var 1))))))))))
```

- this can be used e.g. like this:

```
(For i from 1 to 10 break: get-out
     do (displayln i)
        (when (= i 5)
           (get-out)))
```

Exceptions

- Exception handling is quite common in programming languages (see e.g. Java, where they are pervasive)
- Recent Scheme standards have exception handling; Racket has its own variant
- We do not want to cover here the details (there is the reference manual for that, and you already know them well), but just show how to implement a `throw` / `catch` exception mechanism using continuations

Exceptions: Handlers

- first we need a stack for installed handlers:

```
(define *handlers* (list))

(define (push-handler proc)
     (set! *handlers* (cons proc *handlers*)))

(define (pop-handler)
     (let ((h (car *handlers*)))
          (set! *handlers* (cdr *handlers*))
          h))
```

Exceptions: Throw

- `throw`: if there is a handler, we pop and call it; otherwise we raise an error

```
(define (throw x)
     (if (pair? *handlers*)
          ((pop-handler) x)
          (apply error x)))
```

Exceptions: Try-Catch

```
(define-syntax try
  (syntax-rules (catch)
     ((_ exp1 ...
         (catch what hand ...))
      (call/cc (lambda (exit)
                 ; install the handler
                 (push-handler (lambda (x)
                                 (if (equal? x what)
                                   (exit
                                     (begin
                                       hand ...))
                                   (throw x))))
                 (let ((res ;; evaluate the body
                         (begin exp1 ...)))
                   ; ok: discard the handler
                   (pop-handler)
                   res)))))))
```

An example with throw/catch

```
(define (foo x)
  (display x) (newline)
  (throw "hello"))

(try
  (display "Before foo ")
  (newline)
  (foo "hi!")
  (display "After foo") ; unreached code
  (catch "hello"
    ; this is the handler block
    (display "I caught a throw.") (newline)
    #f))
```

Catch, macro-expanded

```
(call/cc
    (lambda (exit)
       (push-handler
          (lambda (x)
             (if (equal? x "hello")
                 (exit (begin
                         (display "I caught a throw.")
                         (newline)
                         #f))
                 (throw x))))
       (let ((res (begin
                      (display "Before foo ")
                      (newline)
                      (foo "hi!")
                      (display "After foo"))))
         (pop-handler)
         res)))
```

What is Object Oriented programming?

- First of all, I assume you already know the main concepts from Java
- OO means different things to different people
- According to Alan Kay, who introduced the term:
  - *OOP to me means only messaging, local retention and protection and hiding of state-process, and extreme late-binding of all things. It can be done in Smalltalk and in Lisp. There are possibly other systems in which this is possible, but I'm not aware of them.*
  - *Actually I made up the term "object-oriented", and I can tell you I did not have C++ in mind.*
- On the other hand, Stroustrup based C++'s OO model on Simula, not Smalltalk. Interesting comparison with Objective-C.

OO programming today

- In recent years, there has been a re-thinking about the basics of OO
- we can see that in some recent languages, see e.g. Scala, Go, Rust, and Swift
- many provide only some of the classical characteristics of OO, e.g. they are class-less, sometimes don't offer explicit inheritance, or are based on different basic ideas, e.g. interfaces
- there has also been a gradual shift toward *functional programming* facilities and principles (see also Java 8 and C++11)

Closures vs OO

- It is possible to use closures to do some basic OO programming
- the main idea is to define a procedure which assumes the role of a *class*
- this procedure, when called, returns a *closure* that works like an *object*
- it works by implementing information hiding through the "enclosed" values of the closure
- access to the state is through *messages* to a function that works like a *dispatcher*

Closures as objects (1)

```scheme
(define (make-simple-object)
  (let ((my-var 0))   ; attribute

    ;; methods:
    (define (my-add x)
      (set! my-var (+ my-var x))
      my-var)
    (define (get-my-var)
      my-var)
    (define (my-display)
      (newline)
      (display "my Var is: ")
      (display my-var)
      (newline))
```

Closures as objects (2)

Finally, we need a hand-made *dispatcher*

```
(lambda (message . args)
  (apply (case message
           ((my-add)     my-add)
           ((my-display) my-display)
           ((get-my-var) get-my-var)
           (else (error "Unknown Method!")))
         args)))
```

Closures as objects (3)

- `make-simple-object` returns a closure which contains the dispatcher
- Example usage:

```
(define a (make-simple-object))
(define b (make-simple-object))
(a 'my-add 3)   ; => 3
(a 'my-add 4)   ; => 7
(a 'get-my-var) ; => 7
(b 'get-my-var) ; => 0
(a 'my-display) ; => My Var is: 7
```

Inheritance by delegation (1)

```
(define (make-son)
  (let ((parent (make-simple-object)) ; inheritance
        (name   "an object"))

    (define (hello)
      "hi!")
    (define (my-display)
        (display "My name is ")
        (display name)
        (display " and")
        (parent 'my-display))
```

Inheritance by delegation (2)

```
(lambda (message . args)
  (case message
    ((hello)      (apply hello args))
    ;; overriding
    ((my-display) (apply my-display args))
    ;; parent needed
    (else (apply parent (cons message args)))))))
```

Inheritance by delegation (3)

- Example usage:

```
(define c (make-son))
(c 'my-add 2)
(c 'my-display)   ; => My name is an object and
                  ;    my Var is: 2
(display (c 'hello)) ; => hi!
```

A prototype-based object system

- **Self** (1987), a variant of Smalltalk, is the programming language that introduced **prototype-based** object orientation
- There are no classes: new objects are obtained by **cloning** and modifying existing objects
- Its OO model inspired the one of JavaScript
- We will see here how to implement it on top of Scheme, using **hash tables** as the main data structure

Proto-oo

- An object is implemented with a hash table

```
(define new-object make-hash)

(define clone hash-copy)
```

- keys are attribute/method names

Proto-oo: syntactic sugar

- just for convenience (btw, do we need macros here?)

```
(define-syntax !!     ;; setter
  (syntax-rules ()
    ((_ object msg new-val)
     (hash-set! object 'msg new-val))))

(define-syntax ??     ;; reader
  (syntax-rules ()
    ((_ object msg)
     (hash-ref object 'msg))))

(define-syntax ->     ;; send message
  (syntax-rules ()
    ((_ object msg arg ...)
     ((hash-ref object 'msg) object arg ...))))
```

An example

- First, we define an object and its methods

```
(define Pino (new-object))
(!! Pino name "Pino") ;; slot added
(!! Pino hello
    (lambda (self x) ;; method added
      (display (?? self name))
      (display ": hi, ")
      (display (?? x name))
      (display "!")
      (newline)))
```

An example (cont.)

- a couple of other methods:

```
(!! Pino set-name
    (lambda (self x)
      (!! self name x)))
(!! Pino set-name-&-age
    (lambda (self n a)
      (!! self name n)
      (!! self age a)))
```

- and a clone:

```
(define Pina (clone Pino))
(!! Pina name "Pina")
```

Using the example

```
(-> Pino hello Pina)        ; Pino: hi, Pina!
(-> Pino set-name "Ugo")
(-> Pina set-name-&-age
        "Lucia" 25)
(-> Pino hello Pina)        ; Ugo: hi, Lucia!
```

Proto-oo: inheritance

- Inheritance is not typical of prototype object systems
- Still, it is used in JavaScript to provide a "more standard" way of reusing code
- Again, inheritance by delegation:

```
(define (son-of parent)
  (let ((o (new-object)))
    (!! o <<parent>> parent)
    o))
```

Proto-oo: dispatching

- basic dispatching:

```
(define (dispatch object msg)
  (if (eq? object 'unknown)
      (error "Unknown message" msg)
      (let ((slot (hash-ref
                       object msg 'unknown)))
        (if (eq? slot 'unknown)
            (dispatch (hash-ref object
                                '<<parent>>
                                'unknown) msg)
            slot))))
```

Proto-oo: dispatching (cont.)

- we now have to modify ?? and -> for dispatching

```
(define-syntax ?? ;; reader
  (syntax-rules ()
     ((_ object msg)
      (dispatch object 'msg))))

(define-syntax -> ;; send message
  (syntax-rules ()
     ((_ object msg arg ...)
      ((dispatch object 'msg) object arg ...))))
```

And the example:

```
(define Glenn (son-of Pino))
(!! Glenn name "Glenn")
(!! Glenn age 50)
(!! Glenn get-older
    (lambda (self)
      (!! self age (+ 1 (?? self age)))))

(-> Glenn hello Pina)  ; Glenn: hi, Lucia!
(-> Glenn ciao)        ; error: Unknown message
(-> Glenn get-older)   ; Glenn is now 51
```

Legal stuff