
Functional Programming— Illustrated in Scheme

References:

- Dybvig, (available online and in the library)
Mitchell Chapter 3, 4.2.

Lisp slides © D. Horton 2000.

Scheme slides © S. Stevenson, D. Inkpen 2001.

Adapted for Scheme © E. Joanis 2000, 2002.

Modified and updated © S. McIlraith 2004.

Additional slides use material taken from © G. Baumgartner 2001.

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Jumping right in

A Scheme procedure

```
(define increment
  (lambda (n)
    (+ n 1)
  )
)
```

or

```
(define (increment n)
  (+ n 1)
)
```

A call to the procedure

```
(increment 21)
```

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The Spirit of Lisp-like Languages

We shall first define a class of **symbolic expressions** in terms of ordered pairs and lists. Then we shall define five elementary **functions and predicates**, and build from them by **composition, conditional expressions** and **recursive definitions** an extensive class of functions of which we shall give a number of examples. We shall then show how these **functions can themselves be expressed as symbolic expressions**, and we shall give a **universal function** *apply* that allows us to compute from the expressions for a given function its value for given arguments. Finally, we shall define some **functions with functions as arguments** and give some useful examples.

McCarthy, J, [1960]. Recursive functions of symbolic expressions and their computation by machine, Part I. *Comm. ACM* 3:4; quoted in Sethi.

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Pure Functional Languages

Fundamental concept: **application** of (mathematical) **functions to values**

1. **Referential transparency:** The value of a function application is independent of the context *t* in which it occurs
 - value of $f(a,b,c)$ depends only on the values of f , a , b and c
 - It does not depend on the global state of computation \Rightarrow all vars in function must be parameters

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Pure Functional Languages (cont.)

2. The concept of assignment is **not** part of functional programming
 - no explicit assignment statements
 - variables bound to values only through the association of actual parameters to formal parameters in function calls
 - function calls have no side effects
 - thus no need to consider global state
3. Control flow is governed by function calls and conditional expressions
 - ⇒ no iteration
 - ⇒ recursion is widely used

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A Functional Program

A program includes:

1. A set of function definitions
2. An expression to be evaluated

E.g. in Scheme:

```
1 ]=> (define (abs-val x)
      (if (>= x 0)
          x
          (- x)))
```

```
;Value: abs-val
```

```
1 ]=> (abs-val (- 3 5))
```

```
;Value: 2
```

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Pure Functional Languages (cont.)

4. All storage management is implicit
 - needs garbage collection
5. Functions are *First Class Values*
 - Can be returned as the value of an expression
 - Can be passed as an argument
 - Can be put in a data structure as a value
- Unnamed functions exist as values

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Jumping Back In

The MIT Scheme Interface

```
werewolf 1% scheme
Scheme Microcode Version ...
```

```
1 ]=> (+ 8 3 5 16 9)
;Value: 41
```

```
1 ]=> (define increment (lambda (n) (+ n 1)))
;Value: increment
```

```
1 ]=> (increment 21)
;Value: 22
```

```
1 ]=> (load "incr")
;Loading "incr.scm" -- done
;Value: increment-list
```

```
1 ]=> (increment-list (1 32 7))
;The object 1 is not applicable.
;To continue, call RESTART with an option number:
;(RESTART 2) => Specify a procedure to use in its place.
;(RESTART 1) => Return to read-eval-print level 1.
```

```
2 error> (restart 1)
;Abort!
```

```
1 ]=> (increment-list '(1 32 7))
;Value 1: (2 33 8)
```

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```

1 ]=> (trace increment-list)
;Unspecified return value

1 ]=> (increment-list '(1 32 7))

[Entering #[compound-procedure 2 increment-list]
  Args: (1 32 7)]
[Entering #[compound-procedure 2 increment-list]
  Args: (32 7)]
[Entering #[compound-procedure 2 increment-list]
  Args: (7)]
[Entering #[compound-procedure 2 increment-list]
  Args: ()]
[()
  <== #[compound-procedure 2 increment-list]
  Args: ()]
[(8)
  <== #[compound-procedure 2 increment-list]
  Args: (7)]
[(33 8)
  <== #[compound-procedure 2 increment-list]
  Args: (32 7)]
[(2 33 8)
  <== #[compound-procedure 2 increment-list]
  Args: (1 32 7)]
;Value 3: (2 33 8)

1 ]=> (exit)

Kill Scheme (y or n)? Yes
Happy Happy Joy Joy.
werewolf 2%

```

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λ-Calculus (cont.)

λ-calculus is a formal system for defining recursive functions and their properties.

- Expressions are called λ-expressions.
- Every λ-expression denotes a function.
- A λ-expression consists of 3 kinds of terms:
 - Variables:** x, y, z etc
 V denotes arbitrary variables
 - Abstractions:** $\lambda V.E$
 where V is some variable and E is another λ-term.
 - Applications:** $(E1 E2)$ where $E1$ and $E2$ are λ-terms. Applications are sometimes called combinations.

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Formal Roots: λ-Calculus

- Defined by Alonzo Church, a logician, in 1930s as a computational theory of recursive functions
- λ-calculus is equivalent in computational power to Turing machines
- Recall: what's a Turing machine?
 Turing machines are abstract machines that emphasize computation as a series of state transitions driven by symbols on an input tape (which leads naturally to an imperative style of programming based on assignment)
- How is λ-calculus different?
 - λ-calculus emphasizes typed expressions and functions (which naturally leads to a functional style of programming).
 - No state transitions.

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λ-Calculus (cont.)

Formal Syntax in BNF

```

<λ-term> ::= <variable>
           | λ<variable> . <λ-term>
           | (<λ-term> <λ-term>)

```

```

<variable> ::= x | y | z | ...

```

Or more compactly

```

E ::= V | λV.E | (E1 E2)
V ::= x | y | z | ...

```

Where V is an arbitrary variable and E is an arbitrary λ-expression. We call λV the **head** of the λ-expressions and E the **body**.

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λ-Calculus: Functional Forms

A higher-order function (functional form):

- Takes functions as parameters
- Yields a function as a result

E.g.: Given

$$f(x) = x + 2, \quad g(x) = 3 * x$$

then,

$$h(x) = f(g(x)) \text{ and}$$

$$h(x) = (3 * x) + 2$$

$h(x)$ is called a **higher-order function**.

Types of Functional Forms:

Construction form: E.g.,

$$g(x) = x * x, \quad h(x) = 2 * x, \quad i(x) = x / 2$$
$$[g, h, i] (4) = (16, 8, 2)$$

Apply-to-all form: E.g.,

$$h(x) = x * x$$

$$y(h, (2, 3, 4)) = (4, 9, 16)$$

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Scheme: A Functional Programming Language

1958: Lisp

1975: Scheme (revised over the years)

1980: Common Lisp ("CL")

1980s: Lisp Machines (e.g., Symbolics, TI Explorer, etc.)

Lisp, Scheme and CL contrasted on following pages.

Some features of Scheme:

- denotational semantics based on the λ-calculus.

I.e., the meaning of programming constructs in the language is defined in terms of mathematical functions.

- lexical scoping

I.e., all free variables in a λ-expression are assigned values at the time that the λ is defined (i.e., evaluated and returned).

- arbitrary ctrl structures w/ *continuations*.
- functions as first-class values
- automatic garbage collection.

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λ-Calculus Is it really Turing Complete?

Can we represent the class of Turing computable functions?

Yes, we can represent:

- Boolean and conditional functions
- Numerical and arithmetic functions
- Data structures: ordered pairs, lists, etc.
- Recursion

But, doing so in λ-calculus is tedious;

- Need syntactic sugar to simplify task,
- λ-calculus more suitable as an abstract model of a programming language rather than a practical programming language.

Both Turing machines and λ-calculus are idealized, mathematical models of computation.

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LISP

- Functional language developed by John McCarthy in 1958.
- Semantics based on λ-Calculus
- All functions operate on lists or atomic symbols: (called "S-expressions")
- Only five basic functions: list functions `cons`, `car`, `cdr`, `equal`, `atom` and one conditional construct: `cond`
- Uses dynamic scoping
- Useful for list-processing applications
- Programs and data have the same syntactic form: S-expressions
- Used in Artificial Intelligence

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SCHEME

- Developed in 1975 by G. Sussman and G. Steele
- A version of LISP
- Consistent syntax, small language
- Closer to initial semantics of LISP
- Provides basic list processing tools
- Allows functions to be first class objects
- Provides support for *lazy evaluation*
- lexical scoping of variables

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COMMON LISP (CL)

- Implementations of LISP did not completely adhere to semantics
- Semantics redefined to match implementations
- COMMON LISP has become the standard
- Committee-designed language (1980s) to unify LISP variants
- Many defined functions
- Simple syntax, large language

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Expressions

Common structure for both procedures and data. In Scheme, functions are called *procedures*.

When an expression is evaluated it creates a value or list of values that can be embedded into other expressions. Therefore programs can be written to manipulate other programs.

```
<expression> --> <variable>
| <literal>
| <procedure call>
| <lambda expression>
| <conditional>
| <assignment>
| <derived expression>
```

E.g.,

```
#t (true)
() (false)
(a b c)
(a (b c) d)
((a b c) (d e (f)))
(1 (b) 2)
(+ '1 2)
```

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Procedure Application

The main form of a Scheme expression is the procedure application. (Terminology: in Scheme, the official name for what you would think of as a function is *procedure*.)

```
(procedure arg1 arg2 ... argn)
```

Evaluation

- Each argument is evaluated.
- The procedure is applied to the results.

Exception: **syntactic forms**.

Syntactic forms violate the rule—they are built in to the language to handle cases the rule above can't handle. Examples: `define`, `if`, `cond`, `lambda`---more on this later.

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Examples

- `(- 1) => -1`
- `(* 5 7) => 35`
- `(+ 1 2 (* 2 3)) => 9`
- `(+ (- 6 3) (/ 10 2) 2 (* 2 3)) => 16`
- `(cos 0) => -1`

Exercise: run Scheme and try the arithmetic operators with 0, 1, 2 and 3 arguments, and figure out how the results make sense.

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Built-In Procedures

- `eq?`: identity on atoms
- `null?`: is list empty?
- `car`: selects first element of list
- `cdr`: selects rest of list
- `(cons element list)`: constructs lists by adding element to front of list
- `quote` or `'`: produces constants

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Variables

To bind a name to a value:

```
(define var value)
```

```
(define a 2)
```

```
=> a
```

```
a
```

```
=> 2
```

```
(+ a 2)
```

```
=> 4
```

```
(define b 3)
```

```
=> b
```

```
(define c (+ a (* 4 b)))
```

```
=> c ; LISP: Lots of Silly Parentheses
```

```
c
```

```
=> 14
```

Could `define` be a procedure?

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Built-In Procedures

- `'()` is the empty list
- `(car '(a b c)) =`
- `(car '((a) b (c d))) =`
- `(cdr '(a b c)) =`
- `(cdr '((a) b (c d))) =`

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- `car` and `cdr` can break up any list:
 - `(car (cdr (cdr '((a) b (c d)))))) =`
 - `(caddr '((a) b (c d)))`
- `cons` can construct any list:
 - `(cons 'a '()) =`
 - `(cons 'd '(e)) =`
 - `(cons '(a b) '(c d)) =`
 - `(cons '(a b c) '((a) b)) =`

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More about lists

Proper lists:

`()`, `(a (b (c) d) e)`

`(cons 'a '(b)) → (a b)`

Dotted pairs (improper lists):

`(cons 'a 'b) → (a . b)`

`(car '(a . b)) → a`

`(cdr '(a . b)) → b`

`(cons a '(b . c)) → (a b . c)`

`(a b c) → (a . (b . (c . ())))`

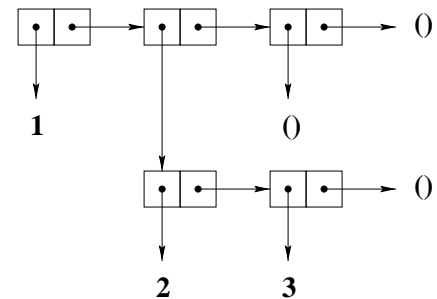
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Lists

A simple but powerful general-purpose datatype.
(How many datatypes have we seen so far?)

(1 #t 1)
()
(1 (2 3) ())

Building block: the cons cell.



Note: Sometimes you'll see `NIL`. This is `LISP` notation! In Scheme, we use `()`.

Things you should know about cons, pairs and lists

The *pair* or *cons cell* is the most fundamental of Scheme's structured object types.

A **list** is a sequence of **pairs**; each pair's `cdr` is the next pair in the sequence.

The `cdr` of the last pair in a **proper list** is the empty list. Otherwise the sequence of pairs forms an **improper list**. I.e., an empty list is a proper list, and any pair whose `cdr` is a proper list is a proper list.

An improper list is printed in **dotted-pair notation** with a period (dot) preceding the final element of the list. A pair whose `cdr` is not a list is often called a **dotted pair**.

cons vs. list: The procedure `cons` actually builds *pairs*, and there is no reason that the `cdr` of a pair must be a list, as illustrated on the previous page.

The procedure `list` is similar to `cons`, except that it takes an arbitrary number of arguments and always builds a proper list.

E.g., `(list 'a 'b 'c) → (a b c)`

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Other (Predicate) Procedures

Predicate procedures return `#t` or `()` (i.e., false).

- `+` `-` `*` `/` numeric operators, e.g.,
`(+ 5 3) = 8`, `(- 5 3) = 2`
`(* 5 3) = 15`, `(/ 5 3) = 1.6666666`
- `=` `<` `>` `<=` `>=` number comparison ops
- Run-time type checking procedures:
 - All return Boolean values: `#t` and `()`
 - `(number? 5)` is `#t`
 - `(zero? 0)` is `#t`
 - `(symbol? 'sam)` is `#t`
 - `(list? '(a b))` is `#t`
 - `(null? '())` is `#t`

Other Predicate Procedures

- `(number? 'sam)` evaluates to `()`
- `(null? '(a))` evaluates to `()`
- `(zero? (- 3 3))` evaluates to `#t`
- `(zero? '(- 3 3))` ⇒ type error
- `(list? (+ 3 4))` evaluates to `()`
- `(list? '(+ 3 4))` evaluates to `#t`