Robot Programming with Lisp

3. Functional Programming: Functions, Lexical Scope and Closures

Gayane Kazhoyan

Institute for Artificial Intelligence
Universität Bremen

27th October, 2015

Outline

Background

Theory

Organizational

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;
- avoid mutable data, i.e. once created, data structure values don't change (*immutable data*);

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;
- avoid mutable data, i.e. once created, data structure values don't change (*immutable data*);
- heavy usage of *recursions*, as opposed to iterative approaches;

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;
- avoid mutable data, i.e. once created, data structure values don't change (*immutable data*);
- heavy usage of *recursions*, as opposed to iterative approaches;
- functions as *first class citizens*, as a result, higher-order functions (simplest analogy: callbacks);

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;
- avoid mutable data, i.e. once created, data structure values don't change (*immutable data*);
- heavy usage of *recursions*, as opposed to iterative approaches;
- functions as *first class citizens*, as a result, higher-order functions (simplest analogy: callbacks);
- *lazy evaluations*, i.e. only execute a function call when its result is actually used;

Functional Programming

Pure functional programming concepts include:

- no program *state* (e.g. no global variables);
- *referential transparency*, i.e. a function called twice with same arguments always generates the same output;
- functions don't have *side effects*;
- avoid mutable data, i.e. once created, data structure values don't change (*immutable data*);
- heavy usage of *recursions*, as opposed to iterative approaches;
- functions as *first class citizens*, as a result, higher-order functions (simplest analogy: callbacks);
- *lazy evaluations*, i.e. only execute a function call when its result is actually used;
- usage of lists as a main data structure; ....

Popular Languages

- **Scheme**: 1975, latest release in 2013, introduced many core functional programming concepts that are widely accepted today

Popular Languages

- **Scheme**: 1975, latest release in 2013, introduced many core functional programming concepts that are widely accepted today
- **Common Lisp**: 1984, latest release (SBCL) in 2015, successor of Scheme, possibly the most influential, general-purpose, widely-used Lisp dialect

Popular Languages

- **Scheme**: 1975, latest release in 2013, introduced many core functional programming concepts that are widely accepted today
- **Common Lisp**: 1984, latest release (SBCL) in 2015, successor of Scheme, possibly the most influential, general-purpose, widely-used Lisp dialect
- **Erlang**: 1986, latest release in 2015, focused on concurrency and distributed systems, supports hot patching, used within AWS

Popular Languages

- **Scheme**: 1975, latest release in 2013, introduced many core functional programming concepts that are widely accepted today
- **Common Lisp**: 1984, latest release (SBCL) in 2015, successor of Scheme, possibly the most influential, general-purpose, widely-used Lisp dialect
- **Erlang**: 1986, latest release in 2015, focused on concurrency and distributed systems, supports hot patching, used within AWS
- **Haskell**: 1990, latest release in 2010, purely functional, in contrast to all others in this list

Popular Languages

- **Scheme**: 1975, latest release in 2013, introduced many core functional programming concepts that are widely accepted today
- **Common Lisp**: 1984, latest release (SBCL) in 2015, successor of Scheme, possibly the most influential, general-purpose, widely-used Lisp dialect
- **Erlang**: 1986, latest release in 2015, focused on concurrency and distributed systems, supports hot patching, used within AWS
- **Haskell**: 1990, latest release in 2010, purely functional, in contrast to all others in this list
- **Racket**: 1994, latest release in 2015, focused on writing domain-specific programming languages

Popular Languages [2]

- **OCaml**: 1996, latest release in 2015, very high performance, static-typed, one of the first inherently object-oriented functional programming languages

Popular Languages [2]

- **OCaml**: 1996, latest release in 2015, very high performance, static-typed, one of the first inherently object-oriented functional programming languages
- **Scala**: 2003, latest release in 2015, compiled to JVM code, static-typed, object-oriented, Java-like syntax {}

Popular Languages [2]

- **OCaml**: 1996, latest release in 2015, very high performance, static-typed, one of the first inherently object-oriented functional programming languages
- **Scala**: 2003, latest release in 2015, compiled to JVM code, static-typed, object-oriented, Java-like syntax {}
- **Clojure**: 2007, latest release in 2015, compiled to JVM code and JavaScript, therefore mostly used in Web, seems to be fashionable in the programming subculture at the moment

Popular Languages [2]

- **OCaml**: 1996, latest release in 2015, very high performance, static-typed, one of the first inherently object-oriented functional programming languages
- **Scala**: 2003, latest release in 2015, compiled to JVM code, static-typed, object-oriented, Java-like syntax {}
- **Clojure**: 2007, latest release in 2015, compiled to JVM code and JavaScript, therefore mostly used in Web, seems to be fashionable in the programming subculture at the moment
- **Julia**: 2012, latest release in 2015, focused on high-performance numerical and scientific computing, means for distributed computation, strong FFI support, Python-like syntax

Popular Languages [2]

- **OCaml**: 1996, latest release in 2015, very high performance, static-typed, one of the first inherently object-oriented functional programming languages
- **Scala**: 2003, latest release in 2015, compiled to JVM code, static-typed, object-oriented, Java-like syntax {}
- **Clojure**: 2007, latest release in 2015, compiled to JVM code and JavaScript, therefore mostly used in Web, seems to be fashionable in the programming subculture at the moment
- **Julia**: 2012, latest release in 2015, focused on high-performance numerical and scientific computing, means for distributed computation, strong FFI support, Python-like syntax

Conclusion: functional programming becomes more and more popular.

Outline

Background

Theory

Organizational

Defining a Function

Signature

```
CL-USER>
(defun my-cool-function-name (arg-1 arg-2 arg-3 arg-4)
  "This function combines its 4 input arguments into a list
and returns it."
  (list arg-1 arg-2 arg-3 arg-4))
```

Optional Arguments

```
CL-USER> (defun optional-arguments (arg-1 arg-2 &optional arg-3 arg-4)
           (list arg-1 arg-2 arg-3 arg-4))
CL-USER> (optional-arguments 1 2 3 4)
(1 2 3 4)
CL-USER> (optional-arguments 1 2 3)
(1 2 3 NIL)
CL-USER> (optional-arguments 304)
invalid number of arguments: 1
```

Defining a Function [2]

Key Arguments

```
CL-USER>
(defun specific-optional (arg-1 arg-2 &key arg-3 arg-4)
  "This function demonstrates how to pass a value to
a specific optional argument."
  (list arg-1 arg-2 arg-3 arg-4))
SPECIFIC-OPTIONAL

CL-USER> (specific-optional 1 2 3 4)
unknown &KEY argument: 3

CL-USER> (specific-optional 1 2 :arg-4 4)
(1 2 NIL 4)
```

Defining a Function [3]

Unlimited Number of Arguments

```
CL-USER> (defun unlimited-args (arg-1 &rest args)
           (format t "Type of args is ~a.~%" (type-of args))
           (cons (list arg-1) args))
UNLIMITED-ARGS

CL-USER> (unlimited-args 1 2 3 4)
Type of args is CONS.
(1 2 3 4)

CL-USER> (unlimited-args 1)
Type of args is NULL.
(1)
```

Multiple Values

list vs. values

```
CL-USER> (defvar *some-list* (list 1 2 3))
*SOME-LIST*
CL-USER> *some-list*
(1 2 3)
CL-USER> (defvar *values?* (values 1 2 3))
*VALUES?*
CL-USER> *values?*
1
CL-USER> (values 1 2 3)
1
2
3
CL-USER> *
1
CL-USER> //
(1 2 3)
```

Multiple Values [2]

Returning Multiple Values!

```
CL-USER> (defvar *db* '((Anna 1987) (Bob 1899) (Charlie 1980)))
         (defun name-and-birth-year (id)
           (values (first (nth (- id 1) *db*))
                   (second (nth (- id 1) *db*))))
NAME-AND-BIRTH-YEAR

CL-USER> (name-and-birth-year 2)
BOB
1899

CL-USER> (multiple-value-bind (name year) (name-and-birth-year 2)
           (format t "~a was born in ~a.~%" name year))
BOB was born in 1899.
NIL
```

Function Designators

Similar to C pointers or Java references

Designator of a Function

```
CL-USER> (describe '+)
COMMON-LISP:+
  [symbol]
+ names a special variable:
+ names a compiled function:
CL-USER> #'+
CL-USER> (symbol-function '+)
#<FUNCTION +>
CL-USER> (describe #'+)
#<FUNCTION +>
  [compiled function]
Lambda-list: (&REST NUMBERS)
Declared type: (FUNCTION (&REST NUMBER) (VALUES NUMBER &OPTIONAL))
Derived type: (FUNCTION (&REST T) (VALUES NUMBER &OPTIONAL))
Documentation: ...
Source file: SYS:SRC;CODE;NUMBERS.LISP
```

Higher-order Functions

Function as Argument

```
CL-USER> (funcall #'+ 1 2 3)
CL-USER> (apply #'+ '(1 2 3))
6
CL-USER> (defun transform-1 (num) (/ 1.0 num))
TRANSFORM-1
CL-USER> (defun transform-2 (num) (sqrt num))
TRANSFORM-2
CL-USER> (defun print-transformed (a-number a-function)
           (format t "~a transformed with ~a becomes ~a.~%"
                   a-number a-function (funcall a-function a-number)))
PRINT-TRANSFORMED
CL-USER> (print-transformed 4 #'transform-1)
4 transformed with #<FUNCTION TRANSFORM-1> becomes 0.25.
CL-USER> (print-transformed 4 #'transform-2)
4 transformed with #<FUNCTION TRANSFORM-2> becomes 2.0.
CL-USER> (sort '(2 6 3 7 1 5) #'>)
(7 6 5 3 2 1)
```

Higher-order Functions [2]

Function as Return Value

```
CL-USER> (defun give-me-some-function ()
           (case (random 5)
             (0 #'+)
             (1 #'-)
             (2 #'*)
             (3 #'/)
             (4 #'values)))
GIVE-ME-SOME-FUNCTION

CL-USER> (give-me-some-function)
#<FUNCTION ->

CL-USER> (funcall (give-me-some-function) 10 5)
5

CL-USER> (funcall (give-me-some-function) 10 5)
2
```

Anonymous Functions

lambda

```
CL-USER> (sort '((1 2 3 4) (3 4) (6 3 6)) #'>)
The value (3 4) is not of type NUMBER.
CL-USER> (sort '((1 2 3 4) (3 4) (6 3 6))
               (lambda (x y)
                 (> (length x) (length y))))
((1 2 3 4) (6 3 6) (3 4))
CL-USER> (sort '((1 2 3 4) (3 4) (6 3 6)) #'> :key #'car)
((6 3 6) (3 4) (1 2 3 4))

CL-USER> (defun random-generator-a-to-b (a b)
           (lambda () (+ (random (- b a)) a)))
RANDOM-GENERATOR-A-TO-B
CL-USER> (random-generator-a-to-b 5 10)
#<CLOSURE (LAMBDA () :IN RANDOM-GENERATOR-A-TO-B) {100D31F90B}>
CL-USER> (funcall (random-generator-a-to-b 5 10))
9
```

The let Environment

let

```
CL-USER> (let ((a 1)
               (b 2))
           (values a b))
1
2
CL-USER> (values a b)
The variable A is unbound.

CL-USER> (defvar some-var 'global)
         (let ((some-var 'outer))
           (let ((some-var 'inter))
             (format t "some-var inner: ~a~%" some-var))
           (format t "some-var outer: ~a~%" some-var))
         (format t "global-var: ~a~%" some-var)
?
```

The let Environment

let

```
CL-USER> (let ((a 1)
               (b 2))
           (values a b))
1
2
CL-USER> (values a b)
The variable A is unbound.

CL-USER> (defvar some-var 'global)
         (let ((some-var 'outer))
           (let ((some-var 'inter))
             (format t "some-var inner: ~a~%" some-var))
           (format t "some-var outer: ~a~%" some-var))
         (format t "global-var: ~a~%" some-var)
some-var inner: INTER
some-var outer: OUTER
global-var: GLOBAL
```

The let Environment [2]

let*

```
CL-USER> (let ((a 4)
               (a^2 (expt a 2)))
           (values a a^2))
The variable A is unbound.

CL-USER> (let* ((a 4)
                (a^2 (expt a 2)))
           (values a a^2))
4
16
```

Lexical Scope

In Lisp, non-global **variable values are**, when possible, **determined at compile time**. They are **bound lexically**, i.e. they are bound to the code they're defined in, not to the run-time state of the program.

Riddle

```
CL-USER> (let* ((lexical-var 304)
                (some-lambda (lambda () (+ lexical-var 100))))
           (setf lexical-var 4)
           (funcall some-lambda))
?
```

Lexical Scope

In Lisp, non-global **variable values are**, when possible, **determined at compile time**. They are **bound lexically**, i.e. they are bound to the code they're defined in, not to the run-time state of the program.

Riddle

```
CL-USER> (let* ((lexical-var 304)
                (some-lambda (lambda () (+ lexical-var 100))))
           (setf lexical-var 4)
           (funcall some-lambda))
104
```

This is one single `let` block, therefore `lexical-var` is the same everywhere in the block.

Lexical Scope [2]

Lexical scope with `lambda` and `defun`

```
CL-USER> (defun return-x (x)
           (let ((x 304))
             x))
         (return-x 3)
?
```

Lexical Scope [2]

Lexical scope with lambda and defun

```
CL-USER> (defun return-x (x)
           (let ((x 304))
             x))
         (return-x 3)
304
```

lambda-s and defun-s create lexical local variables per default.

Lexical Scope [3]

More Examples

```
CL-USER> (let* ((lexical-var 304)
                (some-lambda (lambda () (+ lexical-var 100))))
           (setf lexical-var 4)
           (funcall some-lambda))
104
CL-USER> lexical-var
?
```

Lexical Scope [3]

More Examples

```
CL-USER> (let* ((lexical-var 304)
                (some-lambda (lambda () (+ lexical-var 100))))
           (setf lexical-var 4)
           (funcall some-lambda))
104
CL-USER> lexical-var
; Evaluation aborted on #<UNBOUND-VARIABLE LEXICAL-VAR {100AA9C403}>.

CL-USER> (let ((another-var 304)
               (another-lambda (lambda () (+ another-var 100))))
           (setf another-var 4)
           (funcall another-lambda))
?
```

Lexical Scope [3]

More Examples

```
CL-USER> (let* ((lexical-var 304)
                (some-lambda (lambda () (+ lexical-var 100))))
           (setf lexical-var 4)
           (funcall some-lambda))
104
CL-USER> lexical-var
; Evaluation aborted on #<UNBOUND-VARIABLE LEXICAL-VAR {100AA9C403}>.

CL-USER> (let ((another-var 304)
               (another-lambda (lambda () (+ another-var 100))))
           (setf another-var 4)
           (funcall another-lambda))
; caught WARNING:
;   undefined variable: ANOTHER-VAR
; Evaluation aborted on #<UNBOUND-VARIABLE ANOTHER-VAR {100AD51473}>.
```

Lexical Scope [3]

More Examples

```
CL-USER> (let ((other-lambda (lambda () (+ other-var 100))))
           (setf other-var 4)
           (funcall other-lambda))
?
```

Lexical Scope [3]

More Examples

```
CL-USER> (let ((other-lambda (lambda () (+ other-var 100))))
           (setf other-var 4)
           (funcall other-lambda))
; caught WARNING:
;   undefined variable: OTHER-VAR
104
CL-USER> other-var
4
CL-USER> (describe 'other-var)
COMMON-LISP-USER::OTHER-VAR
  [symbol]
OTHER-VAR names an undefined variable:
  Value: 4
```

Lexical Scope [3]

More Examples

```
CL-USER> (let ((some-var 304))
           (defun some-fun () (+ some-var 100))
           (setf some-var 4)
           (funcall #'some-fun))
?
```

Lexical Scope [3]

More Examples

```
CL-USER> (let ((some-var 304))
           (defun some-fun () (+ some-var 100))
           (setf some-var 4)
           (funcall #'some-fun))
104

;; Alt-. on DEFUN brings you to "defboot.lisp"
(defmacro-mundanely defun (&environment env name args &body body)
  (multiple-value-bind (forms decls doc) (parse-body body)
    (let* ((lambda-guts `(,args ...))
           (lambda `(lambda ,@lambda-guts)) ...
```

Lexical Scope [3]

Riddle #2

```
CL-USER> (defvar y 'global)
CL-USER> (defun return-global-y ()
           y)
         (return-global-y)
GLOBAL
CL-USER> (defun return-local-y (y)
           y)
         (return-local-y 'argument)
ARGUMENT
CL-USER> (defun return-?-y (y)
           (return-global-y))
         (return-?-y 'argument-again)
?
```

Lexical Scope [3]

Riddle #2

```
CL-USER> (defvar y 'global)
CL-USER> (defun return-global-y ()
           y)
         (return-global-y)
GLOBAL
CL-USER> (defun return-local-y (y)
           y)
         (return-local-y 'argument)
ARGUMENT
CL-USER> (defun return-?-y (y)
           (return-global-y))
         (return-?-y 'argument-again)
ARGUMENT-AGAIN
```

`defvar` and `defparameter` create dynamically-bound variables.

Closures

Counter

```
CL-USER> (defun increment-counter ()
           (let ((counter 0))
             (incf counter)))
         (increment-counter)
         (increment-counter)
1
CL-USER> (defun increment-counter-closure ()
           (let ((counter 0))
             (lambda () (incf counter))))
INCREMENT-COUNTER-CLOSURE
CL-USER> (let ((function-object (increment-counter-closure)))
           (format t "counting: ~a ~a~%"
                   (funcall function-object) (funcall function-object)))
counting: 1 2
```

Closure is a function that, in addition to its specific functionality, also encloses its lexical environment (environment as in, e.g., terminal environment variables).

Closures [2]

Counter Again

```
CL-USER> (defun increment-counter-lambda ()
           (let ((counter 0))
             (lambda (counter) (incf counter))))
INCREMENT-COUNTER-LAMBDA
CL-USER> (let ((function-object (increment-counter-lambda)))
           (format t "counter: ~a~%" (funcall function-object 0))
           (format t "once more: ~a~%" (funcall function-object 0)))
counter: 1
once more: 1
CL-USER> (let ((function-object (increment-counter-closure)))
           (format t "counter: ~a~%" (funcall function-object))
           (setf counter 0)
           (format t "counter: ~a~%" (funcall function-object)))
counter: 1
counter: 2
```

Encapsulation!

Currying

Back to Generators

```
CL-USER> (let ((x^10-lambda (lambda (x) (expt x 10))))
           (dolist (elem '(2 3))
             (format t "~a^10 = ~a~%" elem (funcall x^10-lambda elem))))
2^10 = 1024
3^10 = 59049
;; The following only works with roslisp_repl. Otherwise do first:
;; (pushnew #p"/.../alexandria" asdf:*central-registry* :test #'equal)
CL-USER> (asdf:load-system :alexandria)
CL-USER> (dolist (elem '(2 3))
           (format t "~a^10 = ~a~%"
                   elem (funcall (alexandria:curry #'expt 10) elem)))
2^10 = 100
3^10 = 1000
CL-USER> (dolist (elem '(2 3))
           (format t "~a^10 = ~a~%"
                   elem (funcall (alexandria:rcurry #'expt 10) elem)))
2^10 = 1024
3^10 = 59049
```

Guidelines

- Don't use global variables! Only for constants.
- If your function generates side-effects, name it correspondingly (either `foo!` which is preferred, or `foof` as in `setf`, or `nfoo` as in `nconc`)

- Use `Ctrl-Alt-\` on a selected region to fix indentation
- Try to keep the brackets all together:

This looks weird in Lisp

```
(if condition
    do-this
    do-that
    )
```

Links

- Alexandria documentation:
  http://common-lisp.net/project/alexandria/draft/alexandria.html

Outline

Background

Theory

Organizational

Info Summary

- Assignment code:
  `REPO/assignment_3/src/two-robots-world.lisp`
- Assignment due: 03.11, Tuesday, 08:00 AM German time
- Next class: 03.11, 14:15, room below current one, 1. EG (TAB 1.63)

Q & A

Thanks for your attention!