

CS450

Structure of Higher Level Languages

Lecture 6: Functions as data-structures, currying

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Functions as data-structures

Exercises

Exercise 1

What is the output of this program?

```
(define x 10)
(define (f x)
  (+ x 20))
(f 30)
```

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```
(define x 10)
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  (+ x 20))
(f 30)
```

Output: 50

Because, parameter `x` shadows the outermost definition.

Exercise 2

What is the output of this program?

```
(define x 10)
(define f (lambda (x) (+ x 20)))
(f 30)
```

Exercise 2

What is the output of this program?

```
(define x 10)
(define f (lambda (x) (+ x 20)))
(f 30)
```

Output: 50

The code above is **equivalent** to the code below:

```
(define (f x) (+ x 20))
```

Exercise 3

What is the output of this program?

```
(define (factory k)
  (lambda () k))

(factory 10)
```

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```
(define (factory k)
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(factory 10)
```

Output: #<procedure>

Although if Racket displayed code, we would get: (lambda () 10)

```
((factory 10))
; Outputs: 10
```


Exercise 3

Step-by-step evaluation

```
(factory 10) =  
( (lambda (k) (lambda () k)) 10) =  
; ~~~~~\_____ the value *bound* to factory  
(lambda () 10)
```

Why is factory replaced by a lambda?

User input

```
(define (factory k)  
  (lambda () k))
```

Internal representation

```
(define factory  
  (lambda (k)  
    (lambda () k)))
```

Exercise 3

Looking at function application more closely

```
(  
  (lambda (k)      ; <- parameter k  
    (lambda () k)) ; <- body of function  
  10               ; <- argument  
)  
; Remove outer lambda and replace each parameter by argument  
; (lambda () k)      <- body of function  
; \_--- replace parameter k by argument 10  
(lambda () 10)      ; <- return value
```

The abstract syntactic tree (AST)

Exercises

Exercise

Q1: What is the output of this program?

```
(define (f x y)
  (lambda (b)
    (cond [b x] [else y])))
```

```
(define g (f 1 2))
```

```
g
```

Exercise

Q1: What is the output of this program?

```
(define (f x y)
  (lambda (b)
    (cond [b x] [else y])))
```

```
(define g (f 1 2))
g
```

Output: (lambda (b) (cond [b 1] [else 2]))

Q2: How do I call `g` to obtain `1`?

Exercise

Q1: What is the output of this program?

```
(define (f x y)
  (lambda (b)
    (cond [b x] [else y])))

(define g (f 1 2))

g
```

Output: (lambda (b) (cond [b 1] [else 2]))

Q2: How do I call `g` to obtain `1`?

Solution: (g #t)

Implementing a pair with functions alone

If we can capture one parameter, then we can also capture two parameter. **Let us implement a pair-data structure with only functions!** source: SICP 2.1.3

```
(define (pair l r)
  (lambda (op) ; <- we use a parameter to choose which stored data to return
    (match op
      ; if the operation is 'left then return l
      ['left l]
      ; if the operation is 'right then return r
      ['right r])))

; We now define our accessors
(define (pair-left p) (p 'left)) ; Returns the first element of the pair
(define (pair-right p) (p 'right)) ; Returns the second element of the pair

(define p (pair 10 20)) ; Same as: (define (p op) (match op ['left 10] ['right 20]))
(pair-left p) ; Returns 10 because (pair-left p) -> (p 'left) -> 10
(pair-right p) ; Returns 20 because (pair-right p) -> (p 'right) -> 20
```



Recursion exercise

String concatenation

```
(define (string-concat l) 'todo)

(check-equal?
 (string-concat (list "Hello" " ", " "world" "!"))
 "Hello, world!")
```

String concatenation (solution)

```
(define (string-concat l)
  (match l
    [(list) ""]
    [(list h l ...) (string-append h (string-concat l))]
  ))

(check-equal?
  (string-concat (list "hello" ", " "world" "!"))
  "Hello, world!")
```

Functions as values

What is functional programming

Functional programming has different meanings to different people

- Avoid mutation
- **Using functions as values**
- A programming style that encourages recursion and recursive data structures
- A programming model that uses *lazy* evaluation (discussed later)

First-class functions

- **Functions are values:** can be passed as arguments, stored in data structures, bound to variables, ...
- **Functions for extension points:** A powerful way to factor out a common functionality

Functions as parameters

Functions as parameters

Monotonic increasing function (for one input)

Function `monotonic?` takes a function `f` as a parameter and a value `x`, and then checks if `f` increases monotonically for a given `x`.

Example

```
#lang racket
(define (double n) (* 2 n))
(define (monotonic? f x)
  (>= (f x) x))
;; Tests
(require rackunit)
(check-true (monotonic? double 3))
(check-false (monotonic? (lambda (x) (- x 1)) 3))
```

How do we evaluate?

```
(monotonic? double 3)
```

Functions as parameters

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;; Tests
(require rackunit)
(check-true (monotonic? double 3))
(check-false (monotonic? (lambda (x) (- x 1)) 3))
```

How do we evaluate?

```
(monotonic? double 3)
= (>= (double 3) 3)
= (>= ((lambda (n) (* 2 n) 3) 3) 3)
= (>= (* 2 3) 3)
= (>= 6 3)
= #t
```


Functions as parameters

Recursively apply a function n-times

Function `apply-n` takes a function `f` as parameter, a number of times `n`, and some argument `x`, and then recursively calls `(f (f (... (f x))))` an `n`-number of times.

```
#lang racket
(define (apply-n f n x)
  (cond [(<= n 0) x]
        [else (apply-n f (- n 1) (f x))]))
;; Tests
(require rackunit)
(define double (lambda (x) (* 2 x)))
(check-equal? (* 2 (* 2 (* 2 1))) (apply-n double 3 1))
(check-equal? (+ 3 (+ 3 (+ 3 1))) (apply-n (lambda (x) (+ 3 x)) 3 1))
```

Example `apply-n`

Let us unfold the following...

```
(apply-n double 3 1) ; (<= 3 0) = #f
```

Example `apply-n`

Let us unfold the following...

```
(apply-n double 3 1) ; (<= 3 0) = #f
= (apply-n double (- 3 1) (double 1))
= (apply-n double 2 2) ; (<= 2 0) = #f
= (apply-n double (- 2 1) (double 2))
= (apply-n double 1 4) ; (<= 1 0) = #f
= (apply-n double (- 1 1) (double 4))
= (apply-n double 0 8) ; (<= 0 0) = #t
= 8
```

Functions as data-structures

Functions as data-structures

The following is a function that returns a constant value (returns 3 always):

```
(define three:2 (lambda () 3))
```

```
(three:2) ; <- We need to call the function to obtain its contents  
          ; Note that we are passing 0 parameters.
```

Note the difference...

The following is a variable binding (not a function!):

```
(define three:1 3)
```

Variable `three:1` **evaluates** to the number `3`.

A factory of constant-return functions

We can generalize the procedure by creating a function that returns a new function declaration that returns a given parameter `n`.

```
(define (factory n)
  (lambda () n)) ; <-- calling 'factory' creates a new function dynamically
                ; each new function captures the given 'n',
                ; which changes according to how it was called
```

```
(define three:4 (factory 3)) ; <- same as: (define three:4 (lambda () 3))
(three:4) ; Returns: 3
```

```
(define four:1 (factory 4)) ; <- same as: (define four:1 (lambda () 4))
(four:1) ; Returns 4
```

Functions in data structures

Functions stored in data structures

"Freeze" one parameter of a function

In this example, a frozen data-structure stores a binary-function and the first argument. Function `apply1` takes a frozen data structure and the second argument, and applies the stored function to the two arguments.

```
(struct frozen (func arg1) #:transparent)

(define (apply1 fr arg)
  (define func (frozen-func fr)) ; Bind a function to a local variable
  (define arg1 (frozen-arg1 fr))
  (func arg1 arg)) ; Call a function bound to a local variable

(define frozen-double (frozen * 2)) ; Store function '*' in a data structure
(define (double x) (apply1 frozen-double x))
(check-equal? (* 2 3) (double 3))
```


Unfolding (double 3)

```
(double 3)
= (apply1 frozen-double 3)
= (apply1 (frozen * 2) 3)
= (define fr (frozen * 2))
  ((frozen-func fr) (frozen-arg1 fr) 3)
= (* 2 3)
= 6
```

Functions stored in data structures

Apply a list of functions to a value

```
#lang racket
(define (double n) (* 2 n))
; A list with two functions:
; * doubles a number
; * increments a number
(define p (list double (lambda (x) (+ x 1))))
; Applies each function to a value
(define (pipeline funcs value)
  (match funcs
    [(list) value]
    [(list f funcs) (pipeline funcs (f value))]))
; Run the pipeline
(check-equal? (+ 1 (double 3)) (pipeline p 3))
```

Creating functions dynamically

Returning functions

Functions in Racket automatically capture the value of any variable referred in its body.

Example

```
#lang racket
(define (frozen-* arg1)
  (define (get-arg2 arg2)
    (* arg1 arg2))
  ; Returns a new function
  ; every time you call frozen-*
  get-arg2)
(require rackunit)
(define double (frozen-* 2))
(check-equal? (* 2 3) (double 3))
```

Evaluating (frozen-* 2)

```
(frozen-* 2)
= (define (get-arg2 arg2) (* 2 arg2)) get-arg2
= (lambda (arg2) (* 2 arg))
```

Evaluating (double 3)

```
(double 3)
= ((frozen-* 2) 3)
= ((lambda (arg2) (* 2 arg2)) 3)
= (* 2 3)
= 6
```

Currying functions

Revisiting "freeze" function

Freezing binary-function

```
(struct frozen (func arg1) #:transparent)

(define (apply1 fr arg)
  (define func (frozen-func fr))
  (define arg1 (frozen-arg1 fr))
  (func arg1 arg))

(define frozen-double (frozen * 2))
(define (double x) (apply1 frozen-double x))
(check-equal? (* 2 3) (double 3))
```

Attempt #1

```
(define (freeze f arg1)
  (define (get-arg2 arg2)
    (f arg1 arg2))
  get-arg2)

(define double (freeze * 2))
(check-equal? (* 2 3) (double 3))
```

Our `freeze` function is more general than `freeze-*` and simpler than `frozen-double`. We abstain from using a data-structure and use Racket's variable capture capabilities.

Generalizing "frozen" binary functions

Attempt #2

```
(define (freeze f)
  (define (expect-1 arg1)
    (define (expect-2 arg2)
      (f arg1 arg2))
      expect-2)
    expect-1)

(define frozen-* (freeze *))
(define double (frozen-* 2))
(check-equal? (* 2 3) (double 3))
```

Evaluation

```
(define frozen-* (freeze *))
= (define frozen-*
  (define (expect-1 arg1)
    (define (expect-2 arg2)
      (* arg1 arg2))
      expect-2)
    expect-1)

(define double (frozen-* 2))
= (define double
  (define (expect-2 arg2) (* 2 arg2))
  expect-2)

(double 3)
= (* 2 3)
```



Currying functions

Currying is the general technique of "freezing" functions with multiple parameters. It provides a way of delaying (and caching) the passage of multiple arguments by means of new functions.

A curried function $\text{curry}_{f,n,a}(x)$ is a unary function annotated with an uncurried function f arguments a and a number of expected arguments n that can be recursively defined as:

$$\begin{aligned}\text{curry}_{f,n+1,[a_1,\dots,a_n]}(x) &= \text{curry}_{f,n,[a_1,\dots,a_n,x]} \\ \text{curry}_{f,0,[a_1,\dots,a_n]}(x) &= f(a_1, \dots, a_n, x)\end{aligned}$$

```
#lang racket
(define frozen-* (curry *))
(define double (frozen-* 2))
(require rackunit)
(check-equal? (* 2 3) (double 3))
```


Haskell Curry

Did you know?

- In some programming languages functions are curried by default. Examples include Haskell and ML.
- The term currying is named after Haskell Curry, a notable logician who developed combinatory logic and the Curry-Howard correspondence (practical applications include proof assistants).

Haskell was born in Millis, MA (1 hour drive from UMB).



Source: public domain

Uncurried functions

■ All arguments must be provided at call-time, otherwise error.

Python example

```
def add(l, r):  
    return l + y
```

```
add(10)
```

```
# Traceback (most recent call last):
```

```
#   File "<stdin>", line 1, in <module>
```

```
# TypeError: add() missing 1 required positional argument: 'r'
```

Curried functions

If we provide one argument to a 2-parameters function, the result is a 1-parameter function that expects the second argument.

Haskell example

```
-- Define addition
add x y = x + y
-- Define adding 10 to some number
add10 = add 10
-- 10 + 30
add10 30
-- 40
```

Currying in Racket

Function `curry` **converts** an uncurried function into a curried function.

```
#lang racket
(define curried-add (curry +))
(define add10 (curried-add 10))
(require rackunit)
(check-equal? (+ 10 30) (add10 30))
```

Currying functions

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Exercise

What is the output of this program?

Program

```
(define curried-add
  (lambda (arg1)
    (lambda (arg2)
      (+ arg1 arg2))))

(define a (curried-add 10))
(define b (curried-add 20))
a
b
(a 30)
(b 40)
```

Exercise

What is the output of this program?

Program

```
(define curried-add
  (lambda (arg1)
    (lambda (arg2)
      (+ arg1 arg2))))

(define a (curried-add 10))
(define b (curried-add 20))
a
b
(a 30)
(b 40)
```

Output

```
(lambda (arg2) (+ 10 arg2))
(lambda (arg2) (+ 20 arg2))
40
60
```