CS450

Structure of Higher Level Languages

Lecture 6: Nested definitions; caching

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Today we will learn...

- Manipulating the ASTs
- Functions as data-structures: exercises
- Storing functions in data-structures
- Currying
- Exists
- Map

The abstract syntactic tree (AST)

Representing code as data structures

The AST of values

value = *number* | *void* | *func-dec*
func-dec = `(lambda (` *variable** `)` *term+* `)`

Implementation

```
(define (r:value? v)
  (or (r:number? v)
      (r:void? v)
      (r:lambda? v)))
(struct r:void () #:transparent)
(struct r:number (value) #:transparent)
(struct r:lambda (params body) #:transparent)
```

How do we represent?

1. `10`
2. `(void)`
3. `(lambda () 10)`

AST

The AST of values

value = *number* | *void* | *func-dec*
func-dec = (lambda (*variable**) *term+*)

Implementation

```
(define (r:value? v)
  (or (r:number? v)
      (r:void? v)
      (r:lambda? v)))
(struct r:void () #:transparent)
(struct r:number (value) #:transparent)
(struct r:lambda (params body) #:transparent)
```

How do we represent?

1. `10`
2. `(void)`
3. `(lambda () 10)`

AST

```
(r:number 10)      ; ← 1
(r:void)           ; ← 2
(r:lambda (list)   ; ← 3
  (list (r:number 10)))
```

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The AST of expressions

expression = *value* | *variable* | *apply*
apply = `(` *expression*+ `)`

Implementation

```
(define (r:expression? e)
  (or (r:value? e)
      (r:variable? e)
      (r:apply? e)))
(struct r:variable (name) #:transparent)
(struct r:apply (func args) #:transparent)
```

How do we represent?

1. `x`
2. `(f 10)`

AST

The AST of expressions

```
expression = value | variable | apply
apply = ( expression+ )
```

Implementation

```
(define (r:expression? e)
  (or (r:value? e)
      (r:variable? e)
      (r:apply? e)))
(struct r:variable (name) #:transparent)
(struct r:apply (func args) #:transparent)
```

How do we represent?

1. `x`
2. `(f 10)`

AST

```
; 1:
(r:variable 'x)
; 2:
(r:apply
  (r:variable 'f)
  (list (r:number 10)))
```

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The AST of terms

```
term = define | expression
define = ( define identifier expression ) | ( define ( variable+ ) term+)
```

```racket
(define (r:term? t)
  (or (r:define? t)
      (r:expression? t)))
(struct r:define (var body) #:transparent)
```

Which Racket code is this?

```racket
(r:define (r:variable 'f)
  (r:lambda (list (r:variable 'y))
    (list
      (r:apply (r:variable '+)
               (list (r:variable 'y) (r:number 10)))))))
```

The AST of terms

term = *define* | *expression*
define = `( define` *identifier* *expression* `)` | `( define` `(` *variable+* `)` *term+*`)`

```
(define (r:term? t)
  (or (r:define? t)
      (r:expression? t)))
(struct r:define (var body) #:transparent)
```

Which Racket code is this?

```
(r:define (r:variable 'f)
  (r:lambda (list (r:variable 'y))
    (list
      (r:apply (r:variable '+)
               (list (r:variable 'y) (r:number 10)))))))
```

Answer 1

```
(define (f y) (+ y 10))
```

Answer 2

```
(define f
  (lambda (y) (+ y 10)))
```

Functions as data-structures

Exercises

Exercise 1

What is the output of this program?

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

Exercise 1

What is the output of this program?

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

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Exercise 3

What is the output of this program?

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

(factory 10)
```

Exercise 3

What is the output of this program?

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

(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)))
```

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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
```

Exercise 4

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 4

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 4

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!**

```
(define (cons x y)
  (lambda (b)  ; ← we use a parameter to choose which stored data to return
    (cond [b x] [else y]))) ; ← passing #t returns x
                            ;     passing #f returns y
; We now define our own 'car' and 'cdr'
(define (car f) (f #t))   ; Returns the first element of the pair
(define (cdr f) (f #f))   ; Returns the second element of the pair

(define p (cons 10 20))   ; Same as: (define (p b) (cond [b 10] [else 20])))
(car p)                   ; Returns 10 because (car p) → (p #f) → 10
(cdr p)                   ; Returns 20 because (cdr p) → (p #t) → 20
```

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)
  (cond [(empty? funcs) value]
        [else (pipeline (rest funcs) ((first funcs) 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)
```

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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 $\mathbf{curry}_{f,n,a}(x)$ 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:

$$\mathbf{curry}_{f,n+1,[a_1,...,a_n]}(x) = \mathbf{curry}_{f,n,[a_1,...,a_n,x]}$$
$$\mathbf{curry}_{f,0,[a_1,...,a_n]}(x) = f(a_1,\ldots,a_n,x)$$

```
#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

```python
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

```haskell
-- 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))
```

HW2

- In HW2 you will need to implement the reverse, function `uncurry`.
- You are now ready to solve exercises 1, 4, and 5.

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 $\mathbf{curry}_{f,n,a}(x)$ 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:

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

Exercise 6

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 6

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
```

Functional patterns:

Does it exist?

Element in the list?

- Let us implement a function `member` that tests whether or not a list contains a value.

Specification

```
; Unit test that tests
(require rackunit)
(check-true (member 1 (list 3 6 1)))
(check-true (member #t (list 3 #t (list))))
(check-false (member 1 (list 3 #t (list 1))))
(check-false (member #f (list)))
```

Element in the list?

- Let us implement a function `member` that tests whether or not a list contains a value.

Specification

```
; Unit test that tests
(require rackunit)
(check-true (member 1 (list 3 6 1)))
(check-true (member #t (list 3 #t (list))))
(check-false (member 1 (list 3 #t (list 1))))
(check-false (member #f (list)))
```

Solution

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

- Is the solution tail-recursive?

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Element in the list?

- Let us implement a function `member` that tests whether or not a list contains a value.

Specification

```
; Unit test that tests
(require rackunit)
(check-true (member 1 (list 3 6 1)))
(check-true (member #t (list 3 #t (list))))
(check-false (member 1 (list 3 #t (list 1))))
(check-false (member #f (list)))
```

Solution

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

- Is the solution tail-recursive? **Yes!**

Element in the list?

Overview of our solution

> Recursive code mirrors the structure your data!

Think of how many constructors your data has, those will be your recursive cases.

- Case `empty`: the `empty` list constructor, same as `(list)`
- Case `cons`: add one element to the list with the `(cons x l)` constructor
- Recursive call must handle "smaller" data
  - with lists: `(rest l)`
  - with numbers: `(+ n 1)` if you approach an upper bound
  - with numbers: `(- n 1)` if you approach a lower bound

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A general recursion pattern for handling lists

1. Case `empty` (handle-base)
2. Case `cons` (handle-step)
3. Recursive call handles "smaller"

```
(define (rec v)
  (cond
    [(base-case? v) (handle-base v)]
    [else (handle-step v (rec (decrement v)))]))
```

A general recursion pattern for handling lists

1. Case `empty` (handle-base)
2. Case `cons` (handle-step)
3. Recursive call handles "smaller"

```
(define (rec v)
  (cond
    [(base-case? v) (handle-base v)]
    [else (handle-step v (rec (decrement v)))]))
```

Example for `member`

```
(define (member x l)
  (cond
    [(empty? l) #f]  ; <---------------- handle-base: #f
    [else            ; <---------------- handle-step
     (cond [(equal? (first l) x) #t] ;
           [else (member x (rest l))])])) ; <--- (decrement v) = (rest l)
```

In this version, we make the base and handle-steps explicit. Previous solution coalesces nested conds into one.

Common mistake 1

Forgetting the base case

- **Symptom:** `first contract violation`

Example

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

Base case missing

```
(define (member x l)
  (cond
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
; first: contract violation
;   expected: (and/c list? (not/c empty?))
;   given: '()
; [,bt for context]
```

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Common mistake 2

Forgetting to make the list smaller

- **Symptom:** program hangs (runs forever) for some inputs

Correct

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

Incorrect

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x l)]))
```

Generalizing `member`

Exists prefix in list?

Spec

```
(require rackunit)
(check-true (string-prefix? "Racket" "R")) ; available in standard library
(check-true (match-prefix? "R" (list "foo" "Racket")))
(check-false (match-prefix? "R" (list "foo" "bar")))
```

Exists prefix in list?

Spec

```racket
(require rackunit)
(check-true (string-prefix? "Racket" "R")) ; available in standard library
(check-true (match-prefix? "R" (list "foo" "Racket")))
(check-false (match-prefix? "R" (list "foo" "bar")))
```

Solution

```racket
(define (match-prefix? prefix l)
  (cond
    [(empty? l) #f]
    [(string-prefix? (first l) prefix) #t]
    [else (match-prefix? prefix (rest l))]))
```

Can we generalize the search algorithm?

```
; Example 1
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

```
; Example 2
(define (match-prefix? x l)
  (cond
    [(empty? l) #f]
    [(string-prefix? (first l) x) #t]
    [else (match-prefix? x (rest l))]))
```

Can we generalize the search algorithm?

```
; Example 1
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))]))
```

```
; Example 2
(define (match-prefix? x l)
  (cond
    [(empty? l) #f]
    [(string-prefix? (first l) x) #t]
    [else (match-prefix? x (rest l))]))
```

Solution

```
(define (exists predicate l)
  (cond
    [(empty? l) #f]
    [(predicate (first l)) #t]
    [else (exists predicate (rest l))]))
```

```
; Example 1
(define (member x l)
  (exists
    (lambda (y) (equal? x y)) l))
; Example 2
(define (match-prefix? x l)
  (exists
    (lambda (y) (string-prefix? y x))) l))
```