Programming Abstractions

Week 2: Environments and Closures

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Using variables

Recall that when Racket evaluates a variable, the result is the value that the variable is bound to

- If we have `(define x 10)`, then evaluating `x` gives us the value `10`
- If we have `(define (foo x) (- x y))`, then evaluating `foo` gives us the procedure `(λ (x) (- x y))` along with a way to get the value of `y`

Racket needs a way to look up values that correspond to variables: an environment

Environments

Environments are mappings from identifiers to values

There's a top-level environment containing many default mappings

- `list ↦ #<procedure:list>`

  (↦ is read as "maps to", #<procedure:xxx> is how DrRacket displays procedures)
- `+ ↦ #<procedure:+>`

Each file in Racket (technically, a module) has an environment that extends the top-level environment that contains all of the defines in the file

Basic operations on environments

Lookup an identifier in an environment

Bind an identifier to a value in an environment

Extend an environment

- This creates a new environment with mappings from identifiers to values as well as a reference to the environment being extended
- The extended and original environment may both contain mappings for the same identifier

Modify the binding of an identifier in an environment (we will avoid doing this in this course)

Looking up an identifier in an environment

If an identifier has been bound in the current environment, its value is returned

Otherwise, if the current environment extends another environment, the identifier is (recursively) looked up in the other environment.

Otherwise, there's no binding for the identifier and an error is reported

Consider the environments where (A → B means A extends B).

Identifier	Value
`w`	-8
`x`	22
`y`	19
`z`	6

→

Identifier	Value
`name`	`"steve"`
`count`	`3`
`max`	`27`

→

Identifier	Value
`+`	`#<procedure:+>`
`count`	`#<procedure>`
`max`	`#<procedure>`
…	…

What is the value of looking up `count` in the left-most environment?

A. Error: `count` is undefined in that environment

B. `3`

C. A procedure

Adding a new mapping to an environment

`(define identifier s-exp)`

`define` will add `identifier` to the current environment and bind the value that results from evaluating `s-exp` to it

In any environment, an identifier may only be defined once

- except in the interpreter which lets you redefine identifiers

Adding a new mapping to an environment

`(define (identifier params) body)`

Recall that `(define (foo x y) body)` is the same as
`(define foo (λ (x y) body))`
in that it binds the value of the λ-expression, namely a closure, to `foo`

A closure keeps a reference to the current environment in which the λ-expression was evaluated

Extending an environment

Calling a closure

Calling a closure extends the environment of the closure with the values of the arguments bound to the procedure's parameters

```
(define (sum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (sum (rest lst)))]))

(define (average lst)
  (/ (sum lst) (length lst)))
```

Calling `(average '(1 2 3))` extends the environment of average (namely the module's environment which contains mappings for `sum` and `average`) with the mapping `lst ↦ '(1 2 3)` and runs `average` with that environment

Example bindings

Shadowing a binding

```
(define (sum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (sum (rest lst)))]))

(define (foo sum x y)
  (average (list sum x y)))

(define (average lst)
  (/ (sum lst) (length lst)))
```

Inside the body of `foo`, `sum` refers to the parameter
Inside the body of `average`, `sum` refers to the procedure

Example bindings

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Shadowing a binding

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(define (sum lst)
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  (average (list sum x y)))

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Example bindings

Shadowing a binding

```
(define (sum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (sum (rest lst)))]))

(define (foo sum x y)
  (average (list sum x y)))

(define (average lst)
  (/ (sum lst) (length lst)))
```

Inside the body of `foo`, `sum` refers to the parameter
Inside the body of `average`, `sum` refers to the procedure

Extending an environment

`(let ([id1 s-exp1] [id2 s-exp2]…) body)`

let enables us to create some new bindings that are visible only inside `body`

```
(let ([x 37]          ; binds 37 to x
      [y (foo 42)]) ; binds the result of (foo 42) to y
  (if (< x y)
      (bar x)
      (bar y)))
```

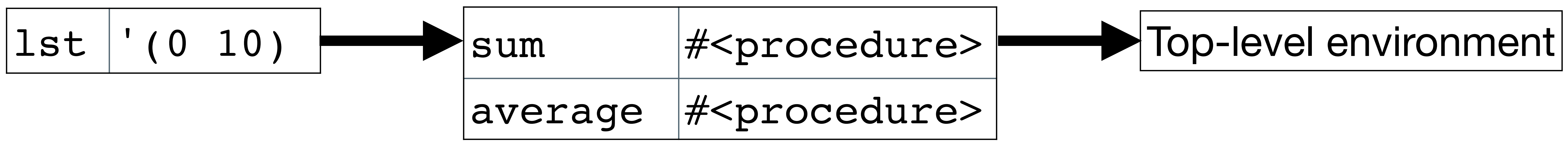
`x` and `y` are only bound inside the body of the let expression

That is, the *scope* of the identifiers bound by `let` is `body`

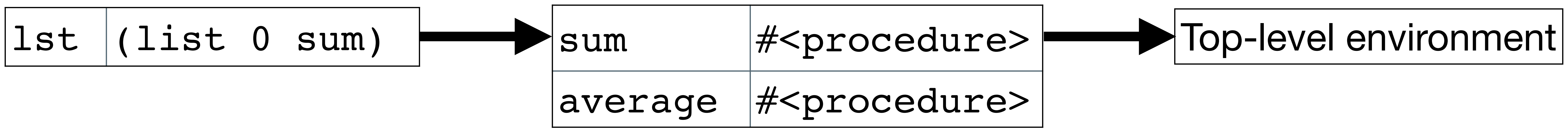
```
(define (sum lst)
  (if (empty? lst)
      0
      (+ (first lst) (sum (rest lst)))))
(define (average lst)
  (/ (sum lst) (length lst)))
(let ([sum 10])
  (average (list 0 sum)))
```

While computing `(average (list 0 sum))`, which of the following is `average`'s environment (arrow means points at an environment being extended)?

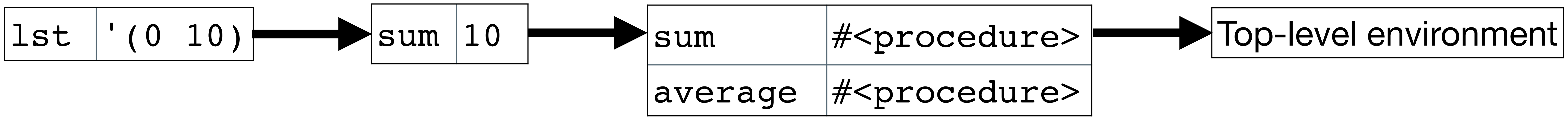
A.



B.



C.



Modifying a binding

(set! identifier s-exp)

`set!` (read "set bang") can modify an existing binding in an environment

```
(define (bar)
  (define x 10) ; We can use define inside procedures
  (writeln x) ; Output the value of x
  (set! x 25)
  (writeln x))
```

This outputs `10` on one line and then `25` on another

This type of side-effect makes reasoning about code much harder

Except for one time later in the semester, we're not going to be using `set!`

- (We won't actually *need* `set!`, it just makes things easier)

Variations on let

A common problem

When writing programs, it's not uncommon to define some local variables in terms of other local variables

Example: Return the elements of a list of numbers that are at least as large as the first element (the head) of the list, in reverse order

```
(define (at-least-as-large lst)
  (cond [(empty? lst) empty]
        [else
          (let ([head (first lst)]
                [bigger (filter (λ (x) (>= x head)) lst)])
            (reverse bigger))]))
```

This doesn't work; we can't use `head` in the definition of `bigger`

The issue

The issue is the scope of the binding for `head`: just the body of the `let`

One (bad) work around would be to use multiple `lets`

```
(define (at-least-as-large lst)
  (cond [(empty? lst) empty]
        [else
          (let ([head (first lst)])
            (let ([bigger (filter (λ (x) (>= x head)) lst)])
              (reverse bigger)))]))
```

Sequential let

`(let* ([id1 s-exp1] [id2 s-exp2]…) body)`

Later s-exps can use earlier ids, e.g.,

```
(let* ([x 5]
       [y (foo x)]
       [z (+ x y)])
  (bar z y))
```

Another problem: recursion

Often, we're going to want to define a recursive procedure but we can't do that with let or let*

```
(let ([fact (λ (n)
              (if (<= n 1)
                  n
                  (* n (fact (- n 1)))))])
  (fact 5))
```

We can't use `fact` in the definition of `fact`

Recursive let

`(letrec ([id1 s-exp1] [id2 s-exp2]…) body)`

All of the s-exps can refer to all of the ids

- This is used to make recursive procedures

```
(letrec ([fact (λ (n)
                 (if (<= n 1)
                     n
                     (* n (fact (- n 1)))))])
  (fact 5))
```

Recursive let drawback

The values of the identifiers we're binding can't be used in the bindings

Invalid (the value of `x` is used to define `y`)

- ```
  (letrec ([x 1]
           [y (+ x 1)])
    y)
  ```

Valid (the value of `x` isn't used to *define* `y`, only when `y` is called)

- ```
  (letrec ([x 1]
           [y (λ () (+ x 1))])
    (y))
  ```

We can use define inside procedures

```
(define (sum-of-squares lst)
  (define (sq x) (* x x))
  (cond [(empty? lst) 0]
        [else (+ (sq (first lst))
                 (sum-of-squares (rest lst)))]))
```

Avoiding defining sq each time

See also: premature optimization

```
(define sum-of-squares2
  (let ([sq (λ (x) (* x x))])
    (λ (lst)
      (cond [(empty? lst) 0]
            [else (+ (sq (first lst))
                     (sum-of-squares2 (rest lst)))]))))
```

The environment of `sum-of-squares2` contains `sq` whereas the environment for `sum-of-squares` is the module-level environment and `sq` is defined each time

Is this worth doing? Probably not. It's much harder to read

Accumulator-passing style

Loops and efficiency

Compare a C (or Java) function to compute the factorial

```
int fact(int n) {
  int product = 1;
  while (n > 0) {
    product *= n;
    n -= 1;
  }
  return product;
}
```

to our recursive Racket implementation

```
(define (fact n)
  (if (<= n 1)
      1
      (* n
         (fact (- n 1)))))
```

How do these differ?

In C, just one function call

In Racket, `(fact 10)` makes 10 calls to fact (the original one and then nine more)

Loops and efficiency

To be efficient, Racket internally converts all **tail-recursions** into loops

A function is tail-recursive if the last thing it does is to recurse and return the result of that recursion

Example:

```
(define (foo x y)
  (if (zero? x)
    y
    (foo (sub1 x) (+ x y))))
```

When the condition is satisfied, some-value is returned, otherwise foo is called again with some different parameters and that value is returned

Our factorial is *not* tail recursive

```
(define (fact n)
  (if (<= n 1)
      1
      (* n
         (fact (- n 1)))))
```

The last thing fact does is perform a multiplication; the recursion happens before the multiplication

Our factorial is *not* tail recursive

Given `(fact 4)`, we end up with

```
(fact 4) => (* 4 (fact 3))
         => (* 4 (* 3 (fact 2)))
         => (* 4 (* 3 (* 2 (fact 1))))
         => (* 4 (* 3 (* 2 1)))
         => (* 4 (* 3 2))
         => (* 4 6)
         => 24
```

We can see this in DrRacket

Solution: Use an accumulator

(Accumulator-passing style isn't the real name of this technique)

```
(define (fact2 n)
  (define (fact-a n acc)
    (if (<= n 1)
        acc ; return the accumulator
        (fact-a (sub1 n) (* n acc))))
  (fact-a n 1))
```

Three things to notice

- We defined a recursive helper function that takes an additional param
- We provide an initial value for the accumulator in `fact2`'s call to `fact-a`
- `fact-a` is tail-recursive

fact2 is tail-recursive

```
(fact2 4) => (fact-a 4 1)
          => (fact-a 3 4)
          => (fact-a 2 12)
          => (fact-a 1 24)
          => 24
```

We can use `letrec` instead of an inner define

```
(define (fact-3 n)
  (letrec ([fact-a (λ (n acc)
                     (if (<= n 1)
                         acc
                         (fact-a (sub1 n) (* n acc))))])
    (fact-a n 1)))

(define fact-4
  (letrec ([fact-a (λ (n acc)
                     (if (<= n 1)
                         acc
                         (fact-a (sub1 n) (* n acc))))])
    (λ (n) (fact-a n 1))))
```

So how does this become a loop?

Use variables for the parameters and update them each time through the loop

```
(define (fact-a n acc)
  (if (<= n 1)
      acc ; return the accumulator
      (fact-a (sub1 n) (* n acc))))
```

becomes (pseudocode)

```
def fact-a(n, acc):
  loop:
    if n <= 1:
      return acc
    n, acc = n - 1, n * acc
```

Is this procedure tail recursive?

```
(define (length lst)
  (cond [(empty? lst) 0]
        [else (+ 1 (length (rest lst)))]))
```

A. Yes

B. No

C. It depends on how long the list is

Is this procedure tail recursive?

```
; Return the nth element of lst
(define (list-ref lst n)
  (cond [(empty? lst) (error 'list-ref "List too short")]
        [(zero? n) (first lst)]
        [else (list-ref (rest lst) (sub1 n))]))
```

A. Yes

B. No

C. I have no idea!

Two strategies for tail recursive procedures

Accumulator-passing style with one or more accumulator parameters

- Usually, the procedure we really want doesn't have these parameters
- Use helper functions

Continuation-passing style

- This uses something called *continuations* which we'll talk about later in the semester

Let's write some tail-recursion procedures

`(sum lst)` — Add all the numbers in the lst

`(maximum lst)` — Find the maximum value in a nonempty list

`(reverse lst)` — Reverses the list lst

`(remove* x lst)` — Remove all instances of x from lst

`(remove x lst)` — Remove the first instance of x from lst