

# COSE212: Programming Languages

## Lecture 6 — Design and Implementation of PLs (2) Procedures

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2016 Fall

# Review: The Let Language

Syntax:

$$\begin{array}{l} P \rightarrow E \\ E \rightarrow n \\ \quad | \\ \quad x \\ \quad | \\ \quad E + E \\ \quad | \\ \quad E - E \\ \quad | \\ \quad \text{zero? } E \\ \quad | \\ \quad \text{if } E \text{ then } E \text{ else } E \\ \quad | \\ \quad \text{let } x = E \text{ in } E \\ \quad | \\ \quad \text{read} \end{array}$$

# Review: The Let Language

Semantic domain:

$$\begin{aligned} \mathit{Val} &= \mathbb{Z} + \mathit{Bool} \\ \mathit{Env} &= \mathit{Var} \rightarrow \mathit{Val} \end{aligned}$$

Semantics rules:

$$\frac{}{\rho \vdash n \Rightarrow n} \quad \frac{}{\rho \vdash x \Rightarrow \rho(x)}$$

$$\frac{\rho \vdash E_1 \Rightarrow n_1 \quad \rho \vdash E_2 \Rightarrow n_2}{\rho \vdash E_1 + E_2 \Rightarrow n_1 + n_2} \quad \frac{\rho \vdash E_1 \Rightarrow n_1 \quad \rho \vdash E_2 \Rightarrow n_2}{\rho \vdash E_1 - E_2 \Rightarrow n_1 - n_2}$$

$$\frac{}{\rho \vdash \text{read} \Rightarrow n} \quad \frac{\rho \vdash E \Rightarrow 0}{\rho \vdash \text{zero? } E \Rightarrow \text{true}} \quad \frac{\rho \vdash E \Rightarrow n}{\rho \vdash \text{zero? } E \Rightarrow \text{false}} \quad n \neq 0$$

$$\frac{\rho \vdash E_1 \Rightarrow \text{true} \quad \rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow v} \quad \frac{\rho \vdash E_1 \Rightarrow \text{false} \quad \rho \vdash E_3 \Rightarrow v}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow v}$$

$$\frac{\rho \vdash E_1 \Rightarrow v_1 \quad [x \mapsto v_1]\rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{let } x = E_1 \text{ in } E_2 \Rightarrow v}$$

# Proc = Let + Procedures

$P \rightarrow E$

$E \rightarrow n$

|  $x$

|  $E + E$

|  $E - E$

| zero?  $E$

| if  $E$  then  $E$  else  $E$

| let  $x = E$  in  $E$

| read

| proc  $x E$

|  $E E$

## Example

- `let f = proc (x) (x-11)`  
`in (f (f 77))`

## Example

- `let f = proc (x) (x-11)`  
`in (f (f 77))`
- `((proc (f) (f (f 77))) (proc (x) (x-11)))`

# Free/Bound Variables of Procedures

- An occurrence of the variable  $x$  is *bound* when it occurs without definitions in the body of a procedure whose formal parameter is  $x$ .
- Otherwise, the variable is *free*.
- Examples:
  - ▶ `proc (y) (x+y)`
  - ▶ `proc (x) (let y = 1 in x + y + z)`
  - ▶ `proc (x) (proc (y) (x+y))`
  - ▶ `let x = 1 in proc (y) (x+y)`
  - ▶ `let x = 1 in proc (y) (x+y+z)`

## Static vs. Dynamic Scoping

What is the result of the program?

```
let x = 1
in let f = proc (y) (x+y)
    in let x = 2
        in let g = proc (y) (x+y)
            in (f 1) + (g 1)
```



## Static vs. Dynamic Scoping

What is the result of the program?

```
let x = 1
in let f = proc (y) (x+y)
    in let x = 2
        in let g = proc (y) (x+y)
            in (f 1) + (g 1)
```

Two ways to determine free variables of procedures:

- In *static scoping* (*lexical scoping*), the procedure body is evaluated in the environment where the procedure is defined (i.e. procedure-creation environment).
- In *dynamic scoping*, the procedure body is evaluated in the environment where the procedure is called (i.e. calling environment)

## Exercises

What is the result of the program?

- In static scoping:
  - In dynamic scoping:
- 1 

```
let a = 3
  in let p = proc (z) a
      in let f = proc (x) (p 0)
          in let a = 5
              in (f 2)
```
  - 2 

```
let a = 3
  in let p = proc (z) a
      in let f = proc (a) (p 0)
          in let a = 5
              in (f 2)
```

## Why Static Scoping?

Most modern languages use static scoping. Why?

- Reasoning about programs is much simpler in static scoping.
- In static scoping, renaming bound variables by their lexical definitions does not change the semantics, which is unsafe in dynamic scoping.

```
let x = 1
in let f = proc (y) (x+y)
    in let x = 2
        in let g = proc (y) (x+y)
            in (f 1) + (g 1)
```

- In static scoping, names are resolved at compile-time.
- In dynamic scoping, names are resolved only at runtime.

# Semantics of Procedures: Static Scoping

- Domain:

$$\begin{aligned} \mathit{Val} &= \mathbb{Z} + \mathit{Bool} + \mathit{Procedure} \\ \mathit{Procedure} &= \mathit{Var} \times \mathit{E} \times \mathit{Env} \\ \mathit{Env} &= \mathit{Var} \rightarrow \mathit{Val} \end{aligned}$$

The procedure value is called *closures*. The procedure is closed in its creation environment.

# Semantics of Procedures: Static Scoping

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The procedure value is called *closures*. The procedure is closed in its creation environment.

- Semantics rules:

$$\frac{}{\rho \vdash \text{proc } x \ E \Rightarrow (x, E, \rho)}$$
$$\frac{\rho \vdash E_1 \vdash (x, E, \rho') \quad \rho \vdash E_2 \Rightarrow v \quad [x \mapsto v]\rho' \vdash E \Rightarrow v'}{\rho \vdash E_1 \ E_2 \Rightarrow v'}$$

# Examples

$$\overline{\square \vdash (\text{proc } (x) (x)) \mathbf{1} \Rightarrow \mathbf{1}}$$

# Examples

---

$\square \vdash$  `let x = 1`  
`in let f = proc (y) (x+y)`  
`in let x = 2`  
`in (f 3)`  $\Rightarrow 4$

# Semantics of Procedures: Dynamic Scoping

- Domain:

$$\begin{aligned} \mathit{Val} &= \mathbb{Z} + \mathit{Bool} + \mathit{Procedure} \\ \mathit{Procedure} &= \mathit{Var} \times \mathit{E} \\ \mathit{Env} &= \mathit{Var} \rightarrow \mathit{Val} \end{aligned}$$

- Semantics rules:

$$\frac{}{\rho \vdash \text{proc } x \ E \Rightarrow (x, E)}$$
$$\frac{\rho \vdash E_1 \vdash (x, E) \quad \rho \vdash E_2 \Rightarrow v \quad [x \mapsto v]\rho \vdash E \Rightarrow v'}{\rho \vdash E_1 \ E_2 \Rightarrow v'}$$



# Examples

---

$\square \vdash$  `let x = 1`  
`in let f = proc (y) (x+y)`  
`in let x = 2`  
`in (f 3)`  $\Rightarrow$  **5**

## cf) Multiple Argument Procedures

- We can get the effect of multiple argument procedures by using procedures that return other procedures.
- ex) a function that takes two arguments and return their sum:

```
let f = proc (x) proc (y) (x+y)
in ((f 3) 4)
```

## Adding Recursive Procedures

The current language does not support recursive procedures, e.g.,

```
let f = proc (x) (f x)
in (f 1)
```

for which evaluation gets stuck:

$$\frac{[f \mapsto (x, f \ x, [])] \vdash f \Rightarrow (x, f \ x, []) \quad \frac{[x \mapsto 1] \vdash f \Rightarrow? \quad [x \mapsto 1] \vdash x \Rightarrow 1}{[x \mapsto 1] \vdash f \ x \Rightarrow?}}{[f \mapsto (x, f \ x, [])] \vdash (f \ 1) \Rightarrow?}$$

# Adding Recursive Procedures

$$\begin{array}{l} P \rightarrow E \\ E \rightarrow n \\ \quad | \quad x \\ \quad | \quad E + E \\ \quad | \quad E - E \\ \quad | \quad \text{zero? } E \\ \quad | \quad \text{if } E \text{ then } E \text{ else } E \\ \quad | \quad \text{let } x = E \text{ in } E \\ \quad | \quad \text{read} \\ \quad | \quad \text{letrec } f(x) = E \text{ in } E \\ \quad | \quad \text{proc } x E \\ \quad | \quad E E \end{array}$$

## Example

```
letrec double(x) =  
  if zero?(x) then 0 else ((double (x-1)) + 2)  
in (double 1)
```

# Semantics of Recursive Procedures

- Domain:

$$\begin{aligned} \mathit{Val} &= \mathbb{Z} + \mathit{Bool} + \mathit{Procedure} + \mathit{RecProcedure} \\ \mathit{Procedure} &= \mathit{Var} \times \mathit{E} \times \mathit{Env} \\ \mathit{RecProcedure} &= \mathit{Var} \times \mathit{Var} \times \mathit{E} \times \mathit{Env} \\ \mathit{Env} &= \mathit{Var} \rightarrow \mathit{Val} \end{aligned}$$

- Semantics rules:

$$\frac{[f \mapsto (f, x, E_1, \rho)]\rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{letrec } f(x) = E_1 \text{ in } E_2 \Rightarrow v}$$

$$\frac{\begin{array}{l} \rho \vdash E_1 \Rightarrow (f, x, E, \rho') \quad \rho \vdash E_2 \Rightarrow v \\ [x \mapsto v, f \mapsto (f, x, E, \rho')]\rho' \vdash E \Rightarrow v' \end{array}}{\rho \vdash E_1 E_2 \Rightarrow v'}$$

## cf) Recursion is Not Special in Dynamic Scoping

With dynamic scoping, recursive procedures require no special mechanism.  
Running the program

```
let f = proc (x) (f x)
in (f 1)
```

via dynamic scoping semantics

$$\frac{\rho \vdash E_1 \vdash (x, E) \quad \rho \vdash E_2 \Rightarrow v \quad [x \mapsto v]\rho \vdash E \Rightarrow v'}{\rho \vdash E_1 E_2 \Rightarrow v'}$$

proceeds well:

$$\frac{\begin{array}{c} \vdots \\ \hline [f \mapsto (x, f x), x \mapsto 1] \vdash f x \Rightarrow \\ \hline [f \mapsto (x, f x), x \mapsto 1] \vdash f x \Rightarrow \\ \hline [f \mapsto (x, f x)] \vdash f 1 \Rightarrow \end{array}}{\hline [] \vdash \text{let } f = \text{proc } (x) (f x) \text{ in } (f 1) \Rightarrow}$$

# Summary: The Proc Language

A programming language with expressions and procedures:

Syntax

$$\begin{array}{l} P \rightarrow E \\ E \rightarrow n \\ \quad | x \\ \quad | E + E \\ \quad | E - E \\ \quad | \text{zero? } E \\ \quad | \text{if } E \text{ then } E \text{ else } E \\ \quad | \text{let } x = E \text{ in } E \\ \quad | \text{read} \\ \quad | \text{letrec } f(x) = E \text{ in } E \\ \quad | \text{proc } x E \\ \quad | E E \end{array}$$



# Summary

## Semantics

$$\frac{}{\rho \vdash n \Rightarrow n} \quad \frac{}{\rho \vdash x \Rightarrow \rho(x)} \quad \frac{\rho \vdash E_1 \Rightarrow n_1 \quad \rho \vdash E_2 \Rightarrow n_2}{\rho \vdash E_1 + E_2 \Rightarrow n_1 + n_2}$$

$$\frac{\rho \vdash E \Rightarrow 0}{\rho \vdash \text{zero? } E \Rightarrow \text{true}} \quad \frac{\rho \vdash E \Rightarrow n \quad n \neq 0}{\rho \vdash \text{zero? } E \Rightarrow \text{false}} \quad \frac{}{\rho \vdash \text{read} \Rightarrow n}$$

$$\frac{\rho \vdash E_1 \Rightarrow \text{true} \quad \rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow v} \quad \frac{\rho \vdash E_1 \Rightarrow \text{false} \quad \rho \vdash E_3 \Rightarrow v}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow v}$$

$$\frac{\rho \vdash E_1 \Rightarrow v_1 \quad [x \mapsto v_1]\rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{let } x = E_1 \text{ in } E_2 \Rightarrow v} \quad \frac{[f \mapsto (f, x, E_1, \rho)]\rho \vdash E_2 \Rightarrow v}{\rho \vdash \text{letrec } f(x) = E_1 \text{ in } E_2 \Rightarrow v}$$

$$\frac{}{\rho \vdash \text{proc } x \ E \Rightarrow (x, E, \rho)}$$

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$$\frac{\rho \vdash E_1 \Rightarrow (f, x, E, \rho') \quad \rho \vdash E_2 \Rightarrow v \quad [x \mapsto v, f \mapsto (f, x, E, \rho')]\rho' \vdash E \Rightarrow v'}{\rho \vdash E_1 \ E_2 \Rightarrow v'}$$

## Mid-term

- No mid-term exam.
- We will have class next Wed (10/26). No class on Monday (10/24).