CVO103: Programming Languages

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

Hakjoo Oh
2018 Spring

Review: The Let Language

Syntax:

$$
\begin{array}{rcl}
P & \rightarrow & E \\
E & \rightarrow & n \\
 & | & x \\
 & | & E + E \\
 & | & E - E \\
 & | & \texttt{iszero } E \\
 & | & \texttt{if } E \texttt{ then } E \texttt{ else } E \\
 & | & \texttt{let } x = E \texttt{ in } E \\
 & | & \texttt{read}
\end{array}
$$

Review: The Let Language

Semantic domain:

$$\begin{array}{rcl} \boldsymbol{Val} & = & \mathbb{Z} + \boldsymbol{Bool} \\ \boldsymbol{Env} & = & \boldsymbol{Var} \to \boldsymbol{Val} \end{array}$$

Semantics rules:

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

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

$$\frac{}{\rho \vdash \texttt{read} \Rightarrow n} \qquad \frac{\rho \vdash E \Rightarrow 0}{\rho \vdash \texttt{iszero}\ E \Rightarrow \mathit{true}} \qquad \frac{\rho \vdash E \Rightarrow n}{\rho \vdash \texttt{iszero}\ E \Rightarrow \mathit{false}}\ n \neq 0$$

$$\frac{\rho \vdash E_1 \Rightarrow \mathit{true} \qquad \rho \vdash E_2 \Rightarrow v}{\rho \vdash \texttt{if}\ E_1\ \texttt{then}\ E_2\ \texttt{else}\ E_3 \Rightarrow v} \qquad \frac{\rho \vdash E_1 \Rightarrow \mathit{false} \qquad \rho \vdash E_3 \Rightarrow v}{\rho \vdash \texttt{if}\ E_1\ \texttt{then}\ E_2\ \texttt{else}\ E_3 \Rightarrow v}$$

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

Proc = Let + Procedures

$$
\begin{array}{lcl}
P & \rightarrow & E \\
E & \rightarrow & n \\
 & | & x \\
 & | & E + E \\
 & | & E - E \\
 & | & \texttt{iszero } E \\
 & | & \texttt{if } E \texttt{ then } E \texttt{ else } E \\
 & | & \texttt{let } x = E \texttt{ in } E \\
 & | & \texttt{read} \\
 & | & \texttt{proc } x\ E \\
 & | & E\ E
\end{array}
$$

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:

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

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

Semantics of Procedures: Static Scoping

- Domain:

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

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

- Semantics rules:

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

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

Examples

$$\frac{}{[] \vdash \texttt{(proc (x) (x))}\ 1 \Rightarrow \mathbf{1}}$$

Examples

$$[] \vdash \begin{array}{l}\texttt{let x = 1}\\ \texttt{in let f = proc (y) (x+y)}\\ \quad\texttt{in let x = 2}\\ \quad\quad\texttt{in (f 3)}\end{array} \Rightarrow \mathbf{4}$$

Semantics of Procedures: Dynamic Scoping

- Domain:

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

- Semantics rules:

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

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

Examples

$$[] \vdash \begin{array}{l}\texttt{let x = 1}\\ \texttt{in let f = proc (y) (x+y)}\\ \quad\texttt{in let x = 2}\\ \quad\quad\texttt{in (f 3)}\end{array} \Rightarrow \mathbf{5}$$

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:

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

Two solutions:

- go back to dynamic scoping :-(
- modify the language syntax and semantics for procedure :-)

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

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

proceeds well:

$$\dfrac{\dfrac{\dfrac{\vdots}{[f \mapsto (x, f\ x), x \mapsto 1] \vdash \texttt{f x} \Rightarrow}}{[f \mapsto (x, f\ x), x \mapsto 1] \vdash \texttt{f x} \Rightarrow}}{[f \mapsto (x, f\ x)] \vdash \texttt{f 1} \Rightarrow}$$

$$\overline{[] \vdash \texttt{let f = proc (x) (f x) in (f 1)} \Rightarrow}$$

Adding Recursive Procedures

$$
\begin{array}{lcl}
P & \rightarrow & E \\
E & \rightarrow & n \\
 & | & x \\
 & | & E + E \\
 & | & E - E \\
 & | & \texttt{iszero } E \\
 & | & \texttt{if } E \texttt{ then } E \texttt{ else } E \\
 & | & \texttt{let } x = E \texttt{ in } E \\
 & | & \texttt{read} \\
 & | & \texttt{letrec } f(x) = E \texttt{ in } E \\
 & | & \texttt{proc } x \ E \\
 & | & E \ E
\end{array}
$$

Example

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

Semantics of Recursive Procedures

- Domain:

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

- Semantics rules:

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

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

Example

$$\dfrac{[f \mapsto (f, x, f\ x, [])] \vdash f \Rightarrow (f, x, f\ x, []) \qquad \dfrac{\vdots}{[x \mapsto 1, f \mapsto (f, x, f\ x, [])] \vdash f\ x \Rightarrow}}{\dfrac{[f \mapsto (f, x, f\ x, [])] \vdash f\ 1 \Rightarrow}{[] \vdash \texttt{letrec}\ f(x) = f\ x\ \texttt{in}\ f\ 1 \Rightarrow}}$$

Summary: The Proc Language

A programming language with expressions and procedures:

Syntax

$$
\begin{array}{lcl}
\boldsymbol{P} & \rightarrow & \boldsymbol{E} \\
\boldsymbol{E} & \rightarrow & \boldsymbol{n} \\
 & | & \boldsymbol{x} \\
 & | & \boldsymbol{E} + \boldsymbol{E} \\
 & | & \boldsymbol{E} - \boldsymbol{E} \\
 & | & \texttt{iszero } \boldsymbol{E} \\
 & | & \texttt{if } \boldsymbol{E} \texttt{ then } \boldsymbol{E} \texttt{ else } \boldsymbol{E} \\
 & | & \texttt{let } \boldsymbol{x} = \boldsymbol{E} \texttt{ in } \boldsymbol{E} \\
 & | & \texttt{read} \\
 & | & \texttt{letrec } \boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{E} \texttt{ in } \boldsymbol{E} \\
 & | & \texttt{proc } \boldsymbol{x}\ \boldsymbol{E} \\
 & | & \boldsymbol{E}\ \boldsymbol{E}
\end{array}
$$

Summary

Semantics

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

$$\frac{\rho \vdash E \Rightarrow 0}{\rho \vdash \texttt{iszero}\ E \Rightarrow true} \qquad \frac{\rho \vdash E \Rightarrow n}{\rho \vdash \texttt{iszero}\ E \Rightarrow false}\ n \neq 0 \qquad \frac{}{\rho \vdash \texttt{read} \Rightarrow n}$$

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

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

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

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

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

cf) Mutually Recursive Procedures

$$
\begin{array}{lcl}
P & \rightarrow & E \\
E & \rightarrow & n \\
 & | & x \\
 & | & E + E \\
 & | & E - E \\
 & | & \texttt{iszero } E \\
 & | & \texttt{if } E \texttt{ then } E \texttt{ else } E \\
 & | & \texttt{let } x = E \texttt{ in } E \\
 & | & \texttt{read} \\
 & | & \texttt{letrec } f(x) = E \texttt{ in } E \\
 & | & \texttt{letrec } f(x_1) = E_1 \texttt{ and } g(x_2) = E_2 \texttt{ in } E \\
 & | & \texttt{proc } x \ E \\
 & | & E \ E
\end{array}
$$

Example

```
letrec
  even(x) = if iszero(x) then 1 else odd(x-1)
  odd(x)  = if iszero(x) then 0 else even(x-1)
in (odd 13)
```

Semantics of Recursive Procedures

- Domain:

$$\begin{aligned} \boldsymbol{Val} &= \cdots + \boldsymbol{MRecProcedure} \\ \boldsymbol{MRecProcedure} &= \boldsymbol{Var} \times \boldsymbol{Var} \times \boldsymbol{E} \times \boldsymbol{Var} \times \boldsymbol{Var} \times \boldsymbol{E} \times \boldsymbol{Env} \end{aligned}$$

- Semantics rules:

$$\frac{[f \mapsto (f, x, E_1, g, y, E_2, \rho), g \mapsto (g, y, E_2, f, x, E_1, \rho)]\rho \vdash E_3 \Rightarrow v}{\rho \vdash \texttt{letrec } f(x) = E_1 \text{ and } g(y) = E_2 \texttt{ in } E_3 \Rightarrow v}$$

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