State – Effects – Review

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Languages considered so far

- LET
- PROC
- LETREC
- EXPLICIT-REFS (EREF)

New concepts

- Storable values
  - What sorts of things can we store?
- Memory stores
  - Where do we store things?
- Memory references (pointers)
  - How do we access the stores?

The new design

- Denotable and Expressed values

$$
\begin{aligned}
ExpVal &= Int + Bool + Proc + Ref(ExpVal) \\
DenVal &= ExpVal
\end{aligned}
$$

- Three new operations
  - `newref`
  - `deref`
  - `setref`

Example: references help us share variables

```
let x = newref(0)
in letrec even(dummy)
           = if zero?(deref(x))
             then 1
             else begin
                   setref(x, -(deref(x),1));
                   (odd 888)
                  end
          odd(dummy)
           = if zero?(deref(x))
             then 0
             else begin
                   setref(x, -(deref(x),1));
                   (even 888)
                  end
   in begin setref(x,13); (odd 888) end
```

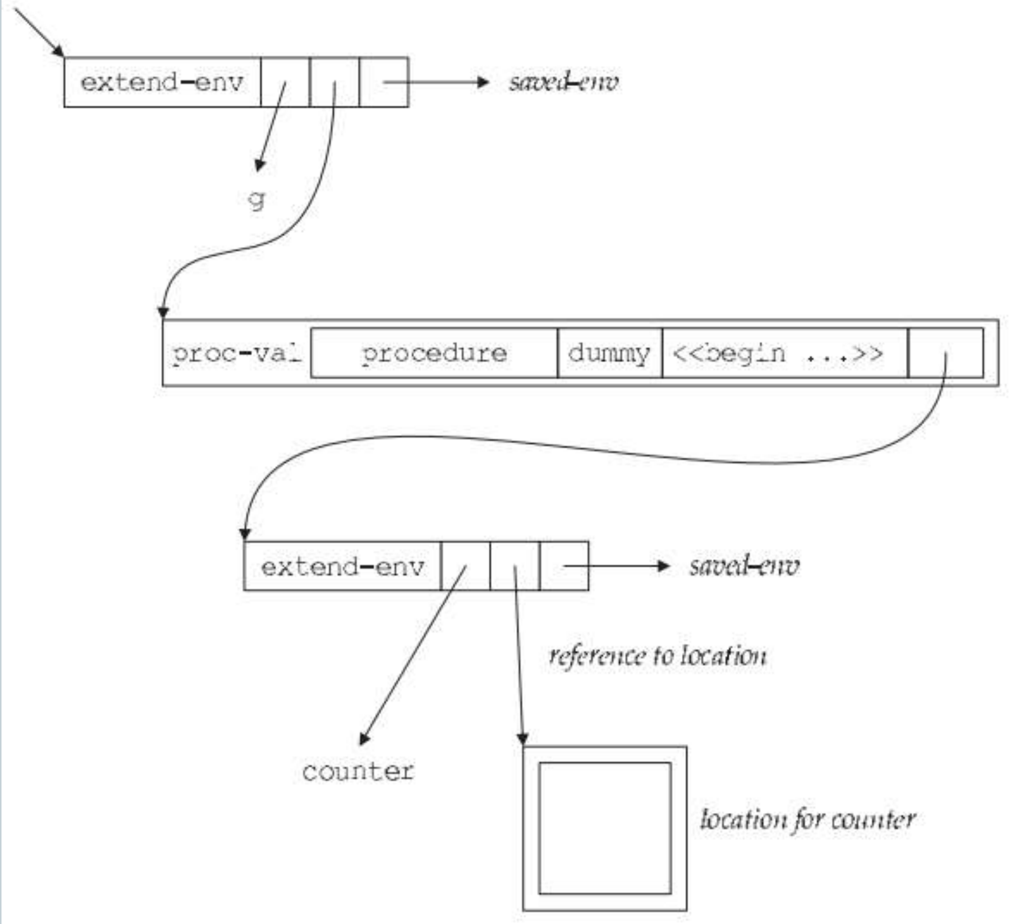
Example: references help us create hidden state

```
let g = let counter = newref(0)
        in proc (dummy)
            begin
             setref(counter, -(deref(counter), -1));
             deref(counter)
            end
in let a = (g 11)
   in let b = (g 11)
      in -(a,b)
```

The entire expression evaluates to -1

Behind the scenes…

```
let g = let counter = newref(0)
        in proc (dummy)
            begin
             setref(counter, -(deref(counter), -1));
             deref(counter)
            end
in let a = (g 11)
   in let b = (g 11)
      in -(a,b)
```



Example: reference to a reference

```
let x = newref(newref(0))
in begin
     setref(deref(x), 11);
     deref(deref(x))
   end
```

What does this evaluate to?

State – Effects – Implementation

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EREF implementation

- What happens to the store?
- How do we represent/implement stores?

- Behavior specification
- Implementation

Nugget

In order to add the memory feature to the language, we need a data structure

Store passing specifications

- The new **`value-of`** $(\texttt{value-of}\ exp_1\ \rho\ \sigma_0) = (val_1, \sigma_1)$

Nugget

We also need to rewrite the rules of evaluation to use the memory

Store passing specifications

- The new **`value-of`** $\texttt{(value-of } exp_1\ \rho\ \sigma_0\texttt{)} = \texttt{(}val_1\texttt{,}\sigma_1\texttt{)}$

- Example $\texttt{(value-of (const-exp } n\texttt{)}\ \rho\ \sigma\texttt{)} = \texttt{(}n\texttt{,}\sigma\texttt{)}$

- More examples

$$\frac{\begin{array}{c}\texttt{(value-of } exp_1\ \rho\ \sigma_0\texttt{)} = \texttt{(}val_1\texttt{,}\sigma_1\texttt{)} \\ \texttt{(value-of } exp_2\ \rho\ \sigma_1\texttt{)} = \texttt{(}val_2\texttt{,}\sigma_2\texttt{)}\end{array}}{\texttt{(value-of (diff-exp } exp_1\ exp_2\texttt{)}\ \rho\ \sigma_0\texttt{)} = \texttt{(}\lceil\lfloor val_1\rfloor \texttt{-} \lfloor val_2\rfloor\rceil\texttt{,}\sigma_2\texttt{)}}$$

$$\frac{\texttt{(value-of } exp_1\ \rho\ \sigma_0\texttt{)} = \texttt{(}val_1\texttt{,}\sigma_1\texttt{)}}{\begin{array}{l}\texttt{(value-of (if-exp } exp_1\ exp_2\ exp_3\texttt{)}\ \rho\ \sigma_0\texttt{)} \\ = \begin{cases}\texttt{(value-of } exp_2\ \rho\ \sigma_1\texttt{)} & \text{if } \texttt{(expval->bool } val_1\texttt{)} = \texttt{\#t} \\ \texttt{(value-of } exp_3\ \rho\ \sigma_1\texttt{)} & \text{if } \texttt{(expval->bool } val_1\texttt{)} = \texttt{\#f}\end{cases}\end{array}}$$

Nugget

We also need to write the rules of evaluation for the new expressions

Grammar specification

- The new grammar

$Expression$ ::= `newref (`$Expression$`)`
`newref-exp (exp1)`

$Expression$ ::= `deref (`$Expression$`)`
`deref-exp (exp1)`

$Expression$ ::= `setref (`$Expression$ `,` $Expression$`)`
`setref-exp (exp1 exp2)`

- Specification

$$\frac{(\texttt{value-of}\ exp\ \rho\ \sigma_0) = (val, \sigma_1) \qquad l \notin \mathrm{dom}(\sigma_1)}{(\texttt{value-of}\ (\texttt{newref-exp}\ exp)\ \rho\ \sigma_0) = ((\texttt{ref-val}\ l), [l{=}val]\sigma_1)}$$

$$\frac{(\texttt{value-of}\ exp\ \rho\ \sigma_0) = (l, \sigma_1)}{(\texttt{value-of}\ (\texttt{deref-exp}\ exp)\ \rho\ \sigma_0) = (\sigma_1(l), \sigma_1)}$$

$$\frac{\begin{array}{c}(\texttt{value-of}\ exp_1\ \rho\ \sigma_0) = (l, \sigma_1)\\ (\texttt{value-of}\ exp_2\ \rho\ \sigma_1) = (val, \sigma_2)\end{array}}{(\texttt{value-of}\ (\texttt{setref-exp}\ exp_1\ exp_2)\ \rho\ \sigma_0) = (\lceil 23 \rceil, [l{=}val]\sigma_2)}$$

Nugget

The implementation will require adding and initializing a **store** structure

Implementation

value-of-program : *Program* → *ExpVal*

```
(define value-of-program
  (lambda (pgm)
    (initialize-store!)
    (cases program pgm
      (a-program (exp1)
        (value-of exp1 (init-env))))))
```

Nugget

We need ways of accessing and manipulating the **store**

Implementation of Stores

empty-store : () → *Sto*
```
(define empty-store
  (lambda () '()))
```

get-store : () → *Sto*
```
(define get-store
  (lambda () the-store))
```

reference? : *SchemeVal* → *Bool*
```
(define reference?
  (lambda (v)
    (integer? v)))
```

deref : *Ref* → *ExpVal*
```
(define deref
  (lambda (ref)
    (list-ref the-store ref)))
```

usage: A Scheme variable containing the current state of the store. Initially set to a dummy value.
```
(define the-store 'uninitialized)
```

initialize-store! : () → *Unspecified*

usage: (initialize-store!) sets the-store to the empty store
```
(define initialize-store!
    ambda ()
    (set! the-store (empty-store))))
```

newref : *ExpVal* → *Ref*
```
(define newref
  (lambda (val)
    (let ((next-ref (length the-store)))
      (set! the-store (append the-store (list val)))
      next-ref)))
```

setref!

setref! : *Ref* × *ExpVal* → *Unspecified*
usage: sets the-store to a state like the original, but with position ref containing val.

```
(define setref!
  (lambda (ref val)
    (set! the-store
      (letrec
        ((setref-inner
            usage: returns a list like storel, except that
            position refl contains val.
            (lambda (storel refl)
              (cond
                ((null? storel)
                 (report-invalid-reference ref the-store))
                ((zero? refl)
                 (cons val (cdr storel)))
                (else
                  (cons
                    (car storel)
                    (setref-inner
                      (cdr storel) (- refl 1))))))))
        (setref-inner the-store ref)))))
```

Implementation

newref-exp, deref-exp, setref-exp

```
(newref-exp (exp1)
  (let ((v1 (value-of exp1 env)))
    (ref-val (newref v1))))

(deref-exp (exp1)
  (let ((v1 (value-of exp1 env)))
    (let ((ref1 (expval->ref v1)))
      (deref ref1))))

(setref-exp (exp1 exp2)
  (let ((ref (expval->ref (value-of exp1 env))))
    (let ((val2 (value-of exp2 env)))
      (begin
        (setref! ref val2)
        (num-val 23)))))
```