

# CS6848 - Principles of Programming Languages

## Principles of Programming Languages

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## Data Types and their Representations

- Want to define new data types.
  - a specification - tells us what data (and what operations on that data) we are trying to represent.
  - implementation - tells us how we do it.
- We want to arrange things so that you can change the implementation without changing the code that uses the data type (user = client; implementation = supplier/server).
- Both the specification and implementation have to deal with two things: the data and the operations on the data.
- Vital part of the implementation is the specification of how the data is represented. We will use the notation  $[v]$  for “the representation of data ‘v’”.



## Outline

- 1 Extending the Scheme language
  - Data types
- 2 Interpreters
  - Stack machine
  - Environments for an interpreter
  - Cells for Variables
  - Closures
  - Recursive environments
  - Interpreting MicroJava



## Numbers

- **Data specification:** Non negative numbers.

$$\begin{aligned} \text{zero} &= [0] \\ (\text{is-zero? } [n]) &= \begin{cases} \#t & n = 0 \\ \#f & n \neq 0 \end{cases} \end{aligned}$$

- **operations:**

$$\begin{aligned} (\text{succ } [n]) &= [n + 1] \\ (\text{pred } [n + 1]) &= [n] \end{aligned}$$

- **Extensions to do other operations:** Should work irrespective of the underlying representation.

```
(define plus
  (lambda (x y)
    (if (is-zero? x) y
        (succ (plus (pred x) y)))))
```

- Irrespective of the representation  $(\text{plus } [x][y]) = [x + y]$



## Scheme Representation of Numbers

$[n]$  = the Scheme integer  $n$

```
(define zero 0)
(define is-zero? zero?)
(define succ (lambda (n) (+ n 1)))
(define prec (lambda (n) (- n 1)))
```



## Data Representation (contd). Example 2: Finite functions

- **Data specification:** a function whose domain is a finite set of Scheme symbols, and whose range is unspecified.
- **Specification of operation:** *Aka - the interface*

```
empty-ff           = [ $\phi$ ]
(apply-ff [f] s)   = f(s)
(extend-ff s v [f]) = [g]
```

$$\text{where } g(s') = \begin{cases} v & s' = s \\ f(s') & \text{Otherwise} \end{cases}$$

- Interface gives the type of each procedure and a description of the intended behavior of each procedure.



## Unary Representation of Numbers

```
[0]      ()
[n+1]    = ( cons #t [n] )
```

- So the integer  $n$  is represented by a list of  $n$  #t's.
- Satisfy the specification:

```
(define zero = ' ( ) )

(define is-zero? null?)

(define succ
  (lambda (n) (cons #t n)))

(define pred cdr)
```



## Procedural Representation

$f = [\{(s_1, v_1), \dots, (s_n, v_n)\}]$  iff  $(f s_i) = v_i$ .  
Implement the operations by:

```
(define apply-ff
  (lambda (ff z) (ff z)))

(define empty-ff
  (lambda (z)
    (error 'env-lookup
           (format "couldn't find ~s" z))))

(define extend-ff
  (lambda (key val ff)
    (lambda (z)
      (if (eq? z key)
          val
          (apply-ff ff z)))))
```



## Procedural Representation

### Examples

```
> (define ff-1 (extend-ff 'a 1 empty-ff))
> (define ff-2 (extend-ff 'b 2 ff-1))
> (define ff-3 (extend-ff 'c 3 ff-2))
> (define ff-4 (extend-ff 'd 4 ff-3))
> (define ff-5 (extend-ff 'e 5 ff-4))
> ff-5
<Procedure>
> (apply-ff ff-5 'd)
4
> (apply-ff empty-ff 'c)
error in env-lookup: couldn't find c.
> (apply-ff ff-3 'd)
error in env-lookup: couldn't find d.
> (define ff-new (extend-ff 'd 6 ff-4))
> (apply-ff ff-new 'd)
> 6
```



## Association-list Representation

$$[\{(s_1, v_1), \dots, (s_n, v_n)\}] = ((s_1 . v_1) \dots (s_n . v_n))$$

```
(define empty-ff '())

(define extend-ff
  (lambda (key val ff)
    (cons (cons key val) ff)))

(define apply-ff
  (lambda (alist z)
    (if (null? alist)
        (error 'env-lookup
              (format "couldn't find ~s" z))
        (let ((key (caar alist))
              (val (cdar alist))
              (ff (cdr alist)))
          (if (eq? z key) val (apply-ff ff z))))))
```



## Association-list Representation

### Examples

```
> (define ff-1 (extend-ff 'a 1 empty-ff))
> (define ff-2 (extend-ff 'b 2 ff-1))
> (define ff-3 (extend-ff 'c 3 ff-2))
> (define ff-4 (extend-ff 'd 4 ff-3))
> ff-4
((d . 4) (c . 3) (b . 2) (a . 1))
> (apply-ff ff-4 'd)
4
```



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The complexity of Interpreters depend on the language under consideration.

- Simple/Complex
- Environments
- Cells
- Closures
- Recursive Environments



## Specification of Operations

**Specification for** `eval-action`. *Our VM*

- What `(eval-action a s)` does for each possible value of `a`.

```
(eval-action halt s) = (car s)
```

```
(eval-action incr; a (v w ...)) =
  (eval-action a (v+1 w ...))
```

```
(eval-action add; a (v w x ...)) =
  (eval-action a ((v+w) x ...))
```

```
(eval-action push v; a (w ...)) =
  (eval-action a (v w ...))
```

```
(eval-action pop; a (v w ...)) =
  (eval-action a (w ...))
```

- Is the specification complete? How to prove the same?



- **Goal:** interpreter for a stack machine.
- The machine will have two components: an action and a stack.
- The stack contains the data in the machine.
- We will represent the stack as a list of Scheme values, with the top of the stack at the front of the list.
- The action represents the instruction stream being executed by the machine.
- Action ::= `halt`

```

| incr; Action
| add; Action;
| push Integer ; Action
| pop; Action

```
- Our interpreter - `eval-action`: takes an action and a stack and returns the value produced by the machine at the completion of the action.
- Convention: the machine produces a value by leaving it on the top of the stack when it halts.



## Representation of Operations

To write Scheme code to implement the specification of `eval-action`, we need to specify a representation of the type of actions. (*Our bytecode*).

- A simple choice - use lists.
 

<code>[halt]</code>	=	<code>(halt)</code>
<code>[incr; a]</code>	=	<code>(incr . [a])</code>
<code>[add; a]</code>	=	<code>(add . [a])</code>
<code>[push v; a]</code>	=	<code>(push v . [a])</code>
<code>[pop; a]</code>	=	<code>(pop . [a])</code>
- An action is represented as a list of instructions.
- Typical action is `(push 3 push 4 add halt)`



## A Stack Machine Interpreter

```
(define eval-action
  (lambda (action stack)
    (let ((op-code (car action)))
      (case op-code
        ((halt)
         (car stack))
        ((incr)
         (eval-action (cdr action)
                      (cons (+ (car stack) 1) (cdr stack))))
        ((add)
         (eval-action (cdr action)
                      (cons (+ (car stack) (cadr stack)) (cddr stack))))
        ((push)
         (let ((v (cadr action)))
           (eval-action (cddr action) (cons v stack))))
        ((pop)
         (eval-action (cdr action) (cdr stack)))
        (else
         (error 'eval-action "unknown op-code:" op-code))))
```



## Interpreter in action

### Running the Interpreter

```
> (define start
  (lambda (action)
    (eval-action action ' ())))

> (start '(push 3 push 4 add halt))
7
```



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## Interpreters (contd.): Environment

- An environment is a finite function - that maps identifiers to values.
- Why do we need an environment?

### • Specification:

$$\begin{aligned} \text{empty-Env} &= [\phi] \\ (\text{apply-Env } [f] s) &= f(s) \\ (\text{extend-Env } s v [f]) &= [g] \end{aligned}$$
$$\text{where } g(s') = \begin{cases} v & s' = s \\ f(s') & \text{Otherwise} \end{cases}$$


## Environment implementation

```
(define empty-env
  (lambda () '()))

(define extend-env
  (lambda (id val env)
    (cons (cons id val) env)))

(define apply-env
  (lambda (env id)
    (if (or (null? env) (null? id))
        null
        (let ((key (caar env))
              (val (cdar env))
              (env-prime (cdr env)))
          (if (eq? id key) val (apply-env env-prime z))))))

(define extend-env-list
  (lambda (ids vals env) ... ))
```



## extend-env-list

```
(define extend-env-list
  (lambda (ids vals env)
    (if (null? ids)
        env
        (extend-env-list
         (cdr ids)
         (cdr vals)
         (extend-env (car ids) (car vals) env)))))
```

**Home reading:** Read Scheme alist representation and see how the above routines can be compacted.



## Interpreter with environment

```
(define eval-Expression
  (lambda (Expression)
    (record-case Expression
      ...
      (PlusExpression (Tkn1 Tkn2 Expression1 Expression2 Tkn3)
        (+ (eval-Expression Expression1)
           (eval-Expression Expression2))))
      (Identifier (Token) (apply-env env Token))
      ... ))

(define run
  (lambda ()
    (record-case root
      (Goal (Expression Token)
        (eval-Expression Expression (empty-env)))
      (else (error 'run ``Goal not found``))))))
```



## Extending an environment - let expression

```
(LetExpression (Token1 Token2 Token3
               List Token4 Expression Token5)
  (let* ((ids (get-ids List))
        (exps (get-exprs List))
        (vals (map (lambda (Expression)
                     (eval-Expression Expression env))
                   exps))
        (new-env (extend-env-list ids vals env)))
    (eval-Expression Expression new-env)))
```

```
> (map cdr '((1 2 3) (3 4 5)))
((2 3) (4 5))
```

**Useless assignment:** How to interpret Let\*?



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## Example: Interpreting a let expression

```
(let ((x 7))
  (+ (let ((y x)
           (x (+ 2 x)))
      (* x y)) x)
```



## Update to variables

- One undesirable feature of Scheme: assignment to variables.
- A variable has a name and address where it stores the value, which can be updated.

```
(define make-cell
  (lambda (value)
    (cons '*cell value)))
```

```
(define deref-cell cdr)
```

```
(define set-cell! set-cdr!)
```

- When we extend an environment, we will create a cell, store the initial value in the cell, and bind the identifier to the cell.

```
(define extend-env
  (lambda (id value env)
    (cons (id (make-cell value)) env)))
```



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```
(load "recscm.scm")
(load "records")
(load "tree")
```



To represent user-defined procedures, we will use closures.

```
(define-record closure (formals body env))
```



```
(define eval-Expression
  (lambda (Expression env)
    (record-case Expression
      ...
      (ProcedureExp (Token1 Token2 Token3
                    List Token4 Expression Token5)
        (make-closure List Expression env))
      (Application (Token1 Expression List Token2)
        (let*
          ((clos (eval-Expression Expression env))
            (ids (get-formals clos))
            (vals (map (lambda (Exp)
                        (eval-Expression Exp env))
                       List))
            (static-env (get-closure-env clos))
            (new-env
             (extend-env-list ids vals static-env)))
          (body (get-body clos))
          (eval-Expression body new-env)))
      ...)))
```



```
(define eval-Expression
  (lambda (Expression env)
    (record-case Expression
      ...
      (IfExpression (Token1 Token2 Expression1
                    Expression2 Expression3 Token3)
        (if (eval-Expression Expression1 env)
            (eval-Expression Expression2 env)
            (eval-Expression Expression3 env)
            ...)))
```





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- We need two kinds of environment records.
  - Normal environments contain cells.
  - A recursive environment contains a RecDeclarationList. If one looks up a recursively-defined procedure, then it gets closed in the environment frame that contains it:

```
(define-record normal-env (ids vals env))

(define-record rec-env (recdecl-list env))

(define eval-Expression
  (lambda (Expression env)
    (record-case Expression
      ...
      (RecExpression (Token1 Token2 Token3
                      List Token4 Expression Token5)
                     (eval-Expression
                      Expression
                      (make-rec-env List env)))
      (else (error ...))))))
```



# Recursive environments

```
(define apply-env
  (lambda (env id)
    (record-case env
      ...
      (rec-env (recdecl-list old-env)
               (let ((id-list (get-ids recdecl-list)))
                 (if (member? id id-list)
                     (let* ((RecProc (get-decl id recdecl-list))
                           (ProcExpr (get-proc-expr RecProc)))
                       (make-cell (make-closure ;; a cell
                                   (get-formals ProcExpr)
                                   (get-body ProcExpr) env)))
                     (apply-env old-env id))))))))
```



# Microjava

- Evaluating a method, env - stmt List; return expr
- Evaluating a stmt, env - a switch case.
- Evaluating an Expr, env - a switch case.
- Inheritance
- Finding classes.
- Finding Methods
- Finding variables.
- Allocating Objects

