6.037 Lecture 6

Implementation of

Object Oriented Programming Systems

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Some slides originally by Prof. Eric Grimson

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Overview

- Data abstraction, a few ways
- Object-Oriented Programming
  - What it is, and how to implement it:
    - via Procedures with State (Closures)
    - via simpler data structures

The role of abstractions

- Procedural abstractions
- Data abstractions

Goal: treat complex things as primitives, and hide details

- Questions:
  - How easy is it to break system into modules?
  - How easy is it to extend the system?
    - Adding new data types?
    - Adding new methods?

One View of Data

- Data structures
  - Some complex structure constructed from cons cells
    - **`point, line, 2dshape, 3dshape`**
  - Explicit tags to keep track of data types
    - **`(define (make-point x y) (list 'point x y))`**
  - Implement a data abstraction as a set of procedures that operate on the data

- "Generic" operations by dispatching on type:

```
(define (scale x factor)
   (cond ((point? x)   (point-scale x factor))
         ((line? x)    (line-scale x factor))
         ((2dshape? x) (2dshape-scale x factor))
         ((3dshape? x) (3dshape-scale x factor))
         (else (error "unknown type"))))
```

Generic Operations

	Point	**Line**	**2-dShape**	**3-dShape**
scale	point-scale	line-scale	2dshape-scale	3dshape-scale
translate	point-trans	line-trans	2dshape-trans	3dshape-trans

Generic Operations

- Adding new methods
  - Just create generic operations

	Point	**Line**	**2-dShape**	**3-dShape**
scale	point-scale	line-scale	2dshape-scale	3dshape-scale
translate	point-trans	line-trans	2dshape-trans	3dshape-trans

Generic Operations

- Adding new methods
  - Just create generic operations

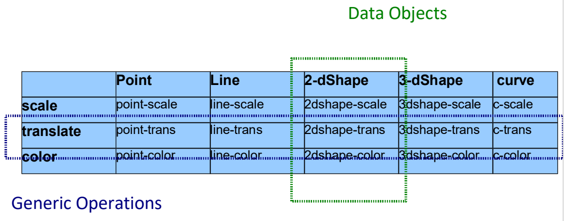
	Point	Line	2-dShape	3-dShape
scale	point-scale	line-scale	2dshape-scale	3dshape-scale
translate	point-trans	line-trans	2dshape-trans	3dshape-trans
color	point-color	line-color	2dshape-color	3dshape-color

Generic Operations

- Adding new methods
  - Just create generic operations
- Adding new data types
  - Must change every generic operation
  - Must keep names distinct

	Point	Line	2-dShape	3-dShape	curve
scale	point-scale	line-scale	2dshape-scale	3dshape-scale	c-scale
translate	point-trans	line-trans	2dshape-trans	3dshape-trans	c-trans
color	point-color	line-color	2dshape-color	3dshape-color	c-color

Two Views of Data



	Point	Line	2-dShape	3-dShape	curve
scale	point-scale	line-scale	2dshape-scale	3dshape-scale	c-scale
translate	point-trans	line-trans	2dshape-trans	3dshape-trans	c-trans
color	point-color	line-color	2dshape-color	3dshape-color	c-color

Object-Oriented Programming Terminology

- **Class**:
  - Template for state and behavior
    - Internal state (fields), operations (methods), relationships to other classes
- **Instance**:
  - A particular object or entity of a given class
  - The result of “instantiating” a class
  - Has its own identity separate from other instances

Programming Styles – Procedural vs. Object-Oriented

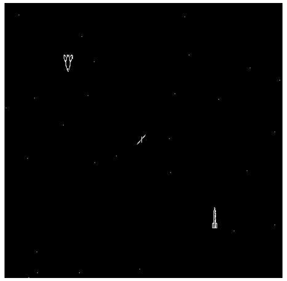
- Procedural programming:
  - Organize system around procedures that operate on data

```
(do-something <data> <arg> ...)
(do-another-thing <data>)
```

- Object-oriented programming:
  - Organize system around objects and methods to manipulate data

```
(invoke <object> 'do-something <arg>)
(invoke <object> 'do-another-thing)
```

  - An object encapsulates data and operations

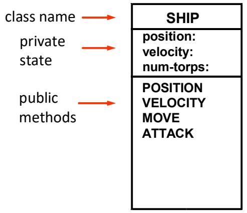


SPACEWAR: the *original* video game
First realized on the MIT PDP-1 in 1962
PDP-1 – 100KHz, 4K Ram, $100,000

Using classes and instances

- Suppose we wanted to build *Spacewar!*
- Start by thinking about what kinds of objects should exist (state and interfaces)
  - – Planets
  - – Ships
- Think about useful instances of these
  - – Centauri Prime
  - – Enterprise

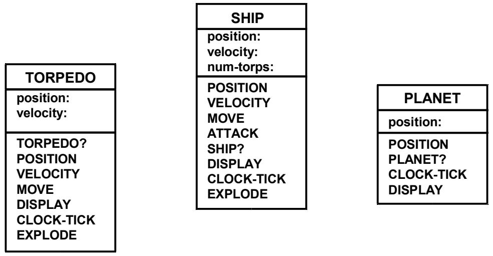
Space-Ship Class



class name
private state
public methods

SHIP
position:
velocity:
num-torps:
POSITION
VELOCITY
MOVE
ATTACK

Class Diagram

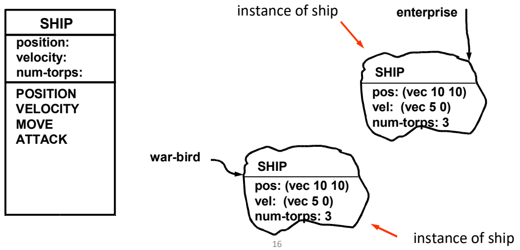


TORPEDO
position:
velocity:
TORPEDO?
POSITION
VELOCITY
MOVE
DISPLAY
CLOCK-TICK
EXPLODE

SHIP
position:
velocity:
num-torps:
POSITION
VELOCITY
MOVE
ATTACK
SHIP?
DISPLAY
CLOCK-TICK
EXPLODE

PLANET
position:
POSITION
PLANET?
CLOCK-TICK
DISPLAY

Instance Diagram



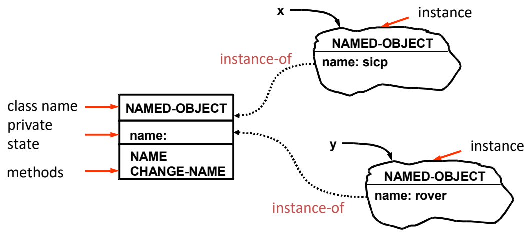
SHIP
position:
velocity:
num-torps:
POSITION
VELOCITY
MOVE
ATTACK

instance of ship
enterprise
SHIP
pos: (vec 10 10)
vel: (vec 5 0)
num-torps: 3

war-bird
SHIP
pos: (vec 10 10)
vel: (vec 5 0)
num-torps: 3
instance of ship

Abstract View – Class/Instance Diagrams

Class Diagram **Instance Diagram**



x
instance
NAMED-OBJECT
name: sicp
instance-of

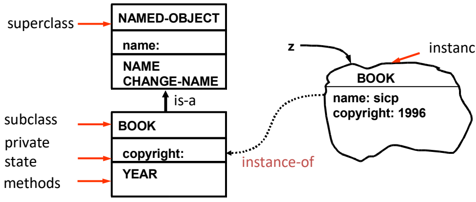
class name
private state
methods

NAMED-OBJECT
name:
NAME
CHANGE-NAME

y
instance
NAMED-OBJECT
name: rover
instance-of

Abstract View – with Inheritance

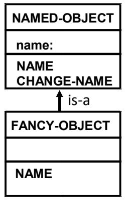
Class Diagram **Instance Diagram**



superclass
NAMED-OBJECT
name:
NAME
CHANGE-NAME
is-a
subclass
private state
methods
BOOK
copyright:
YEAR

z
instance
BOOK
name: sicp
copyright: 1996
instance-of

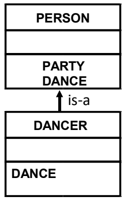
Abstract View – with Inheritance



- NAME method is overridden
- Might want to call superclass'

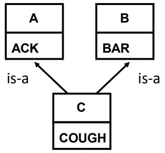
A FANCY-OBJECT reports its name with hearts and stars before and after it

Abstract View – with Inheritance



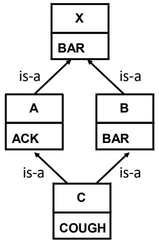
- Suppose the PARTY method calls the DANCE method
- If we override DANCE, and then ask an instance of DANCER to PARTY, which DANCE method runs?

Abstract View: Multiple Inheritance



- Superclass & Subclass
  - A is a **superclass** of C
  - C is a **subclass** of both A & B
    - C "is-a" B
    - C "is-a" A
- A subclass **inherits** the state and methods of its superclasses
  - Class C has methods **ACK**, **BAR**, and **COUGH**

Abstract View: Multiple Inheritance



- Diamond Inheritance Problem
  - Which BAR do you get from C?
  - Should this be allowed?

Different Views of an Object-Oriented System

- An **abstract view**
  - class and instance diagrams
  - terminology: methods, inheritance, superclass, subclass, abstract class, interfaces, traits, mixins...
- Scheme OO system **user view**
  - conventions on how to write Scheme code to:
    - define classes
      - inherit from other classes
    - create instances
    - use instances (invoke methods)
- Scheme OO system **implementer view**
  - How do instances, classes, inheritance, and types work?

Object-Oriented Design & Implementation

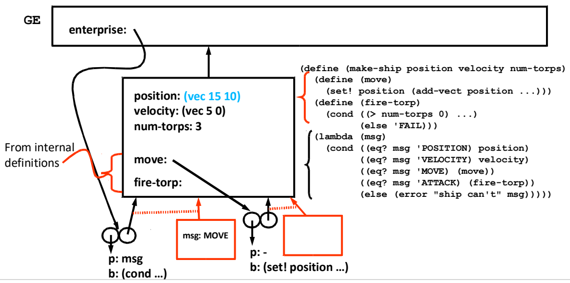
- Focus on classes
  - Relationships between classes
  - Kinds of interactions that need to be supported between instances of classes
- Careful attention to behavior desired
  - Inheritance of methods
  - Explicit use of superclass methods
  - Shadowing of methods to override default behaviors

Implementation #1

- A procedure has
  - **parameters** and **body** as specified by λ expression
  - **environment** (which can hold name-value bindings!)
- Encapsulate data, and provide controlled access
  - Applying a procedure creates a private environment
  - Need access to that environment
    - constructor, accessors, mutators, predicates, operations
    - mutation: changes in the private state of the procedure

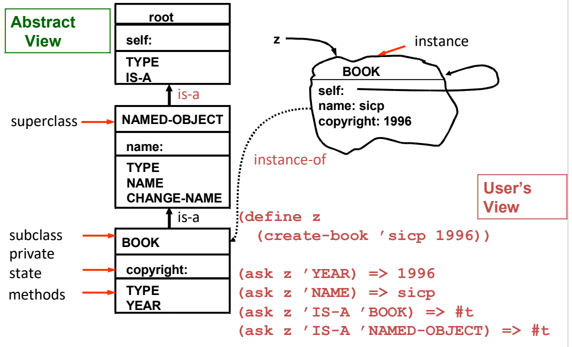
Environment Diagram

```
(define enterprise
  (make-ship (make-vect 10 10) (make-vect 5 0) 3))
(enterprise 'MOVE)
```



```
(define (make-ship position velocity num-torps)
  (define (move)
    (set! position (add-vect position ...)))
  (define (fire-torp)
    (cond ((> num-torps 0) ...)
          (else 'FAIL)))
  (lambda (msg)
    (cond ((eq? msg 'POSITION) position)
          ((eq? msg 'VELOCITY) velocity)
          ((eq? msg 'MOVE) (move))
          ((eq? msg 'ATTACK) (fire-torp))
          (else (error "ship can't" msg)))))
```

OO System View in Scheme with Inheritance



```
(define z
  (create-book ’sicp 1996))

(ask z ’YEAR) => 1996
(ask z ’NAME) => sicp
(ask z ’IS-A ’BOOK) => #t
(ask z ’IS-A ’NAMED-OBJECT) => #t
```

A Space-Ship Object

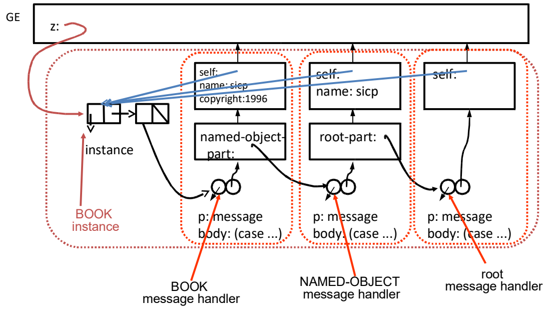
```
(define (make-ship position velocity num-torps)
  (define (move)
    (set! position (add-vect position ...)))
  (define (fire-torp)
    (cond ((> num-torps 0) ...)
          (else 'FAIL)))
  (lambda (msg)
    (cond ((eq? msg 'POSITION) position)
          ((eq? msg 'VELOCITY) velocity)
          ((eq? msg 'MOVE) (move))
          ((eq? msg 'ATTACK) (fire-torp))
          (else (error "ship can't" msg)))))
```

Missing elements

- What about inheritance?
- How do I call another method on myself?
  - Or from my superclass?

Implementer’s View of this in Environment Model

(define z (create-book ’sicp 1996))



Implementation #1 Summary

- Implemented with procedures doing message dispatch
- All methods are public
- All state is private
- Could support multiple inheritance
- Objects are first class
- Classes are not

User view: Class Definition

- Classes are created by applying
  `make-class`

```
(define named-object
   (make-class 'NAMED-OBJECT '(name) root-object
        (make-methods
               'CONSTRUCTOR
               (lambda (self super name)
                      (write-state! self 'name name))
               'NAME
               (lambda (self super)
                      (read-state self 'name)))))
```

- This means classes are first-class objects

User View: Object Instantiation

- Apply **`make-instance`** to instantiate an object
- Extra arguments are passed to the CONSTRUCTOR method

```
(define sicp
  (make-instance book 'SICP 1996))
```

Implementation #2

- Simple data structure approach
  - Easier for user to use, in some ways
  - Easier for implementer to implement
    - And to play with!
  - May be more/less/differently powerful

User view: Class Definition

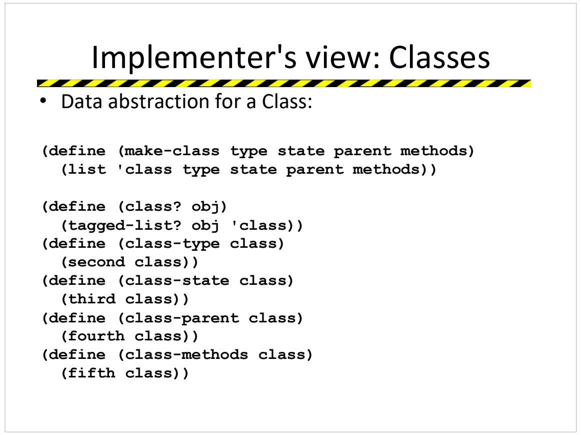
- Call methods with "invoke" on "self"
- Shadowed methods accessed via "super"

```
(define book
   (make-class 'BOOK '(copyright) named-object
        (make-methods
               'CONSTRUCTOR
               (lambda (self super name year)
                    (super 'CONSTRUCTOR name)
                    (write-state! self 'copyright year))
               'YEAR
               (lambda (self super)
                    (read-state self 'copyright))
               'NAME
               (lambda (self super)
                    (list (super 'NAME)
                          'Copyright
                          (invoke self 'YEAR))))))
```

User View: Method invocation

- Use the `invoke` procedure with method name and optional parameters

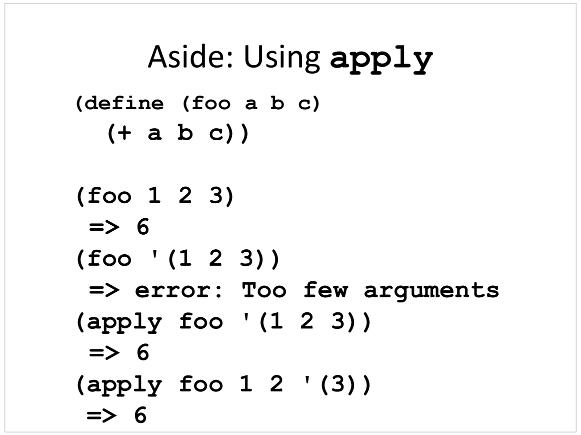
```
  (invoke sicp 'YEAR)

=> 1996
```



Implementer's view: Classes

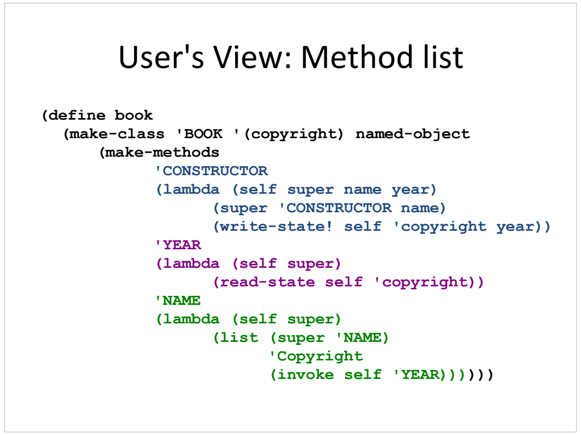
- Data abstraction for a Class:

```
(define (make-class type state parent methods)
  (list 'class type state parent methods))

(define (class? obj)
  (tagged-list? obj 'class))
(define (class-type class)
  (second class))
(define (class-state class)
  (third class))
(define (class-parent class)
  (fourth class))
(define (class-methods class)
  (fifth class))
```



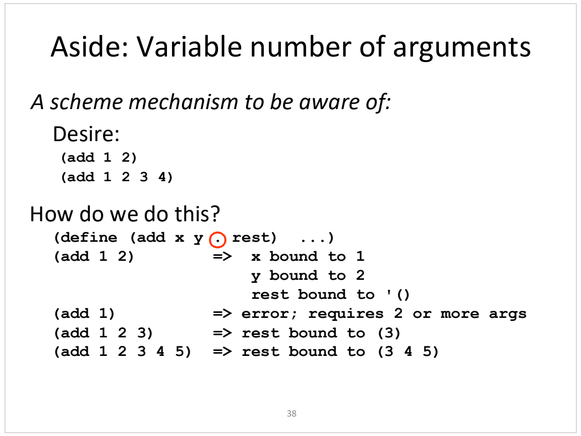
Aside: Using `apply`

```
(define (foo a b c)
  (+ a b c))

(foo 1 2 3)
 => 6
(foo '(1 2 3))
 => error: Too few arguments
(apply foo '(1 2 3))
 => 6
(apply foo 1 2 '(3))
 => 6
```



User's View: Method list

```
(define book
  (make-class 'BOOK '(copyright) named-object
      (make-methods
           'CONSTRUCTOR
           (lambda (self super name year)
                 (super 'CONSTRUCTOR name)
                 (write-state! self 'copyright year))
           'YEAR
           (lambda (self super)
                 (read-state self 'copyright))
           'NAME
           (lambda (self super)
                 (list (super 'NAME)
                       'Copyright
                       (invoke self 'YEAR))))))
```



Aside: Variable number of arguments

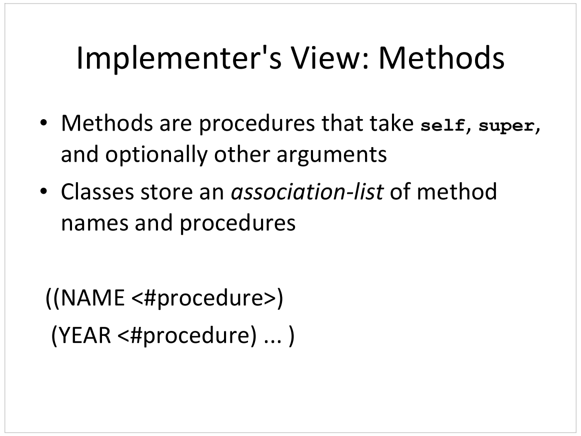
A scheme mechanism to be aware of:

Desire:

```
(add 1 2)
(add 1 2 3 4)
```

How do we do this?

```
(define (add x y . rest)  ...)
(add 1 2)         =>  x bound to 1
                      y bound to 2
                      rest bound to '()
(add 1)           => error; requires 2 or more args
(add 1 2 3)       => rest bound to (3)
(add 1 2 3 4 5)   => rest bound to (3 4 5)
```

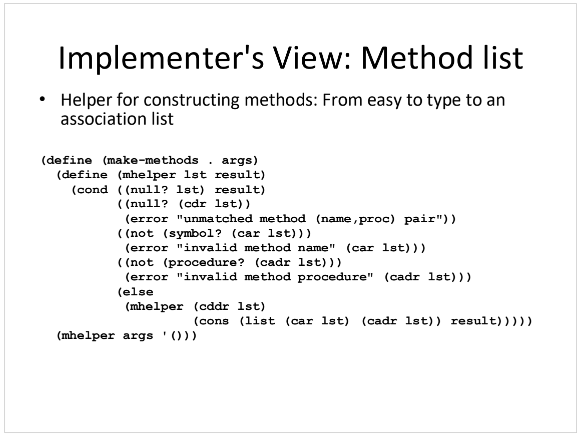


Implementer's View: Methods

- Methods are procedures that take **`self`**, **`super`**, and optionally other arguments
- Classes store an *association-list* of method names and procedures

((NAME <#procedure>)

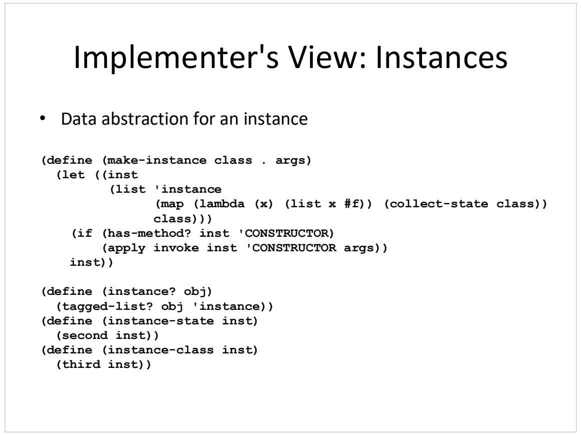
(YEAR <#procedure) ...)



Implementer's View: Method list

- Helper for constructing methods: From easy to type to an association list

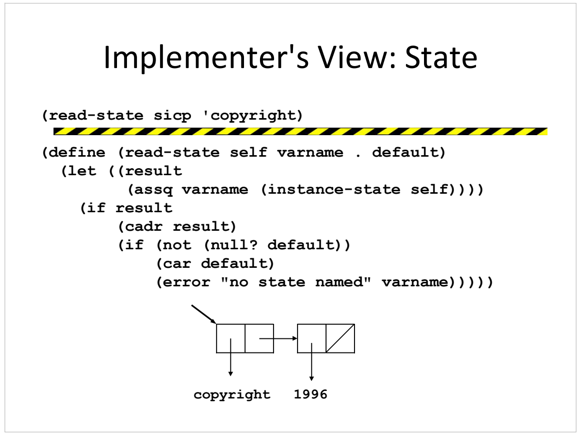
```
(define (make-methods . args)
  (define (mhelper lst result)
    (cond ((null? lst) result)
          ((null? (cdr lst))
           (error "unmatched method (name,proc) pair"))
          ((not (symbol? (car lst)))
           (error "invalid method name" (car lst)))
          ((not (procedure? (cadr lst)))
           (error "invalid method procedure" (cadr lst)))
          (else
           (mhelper (cddr lst)
                    (cons (list (car lst) (cadr lst)) result)))))
  (mhelper args '()))
```



Implementer's View: Instances

- Data abstraction for an instance

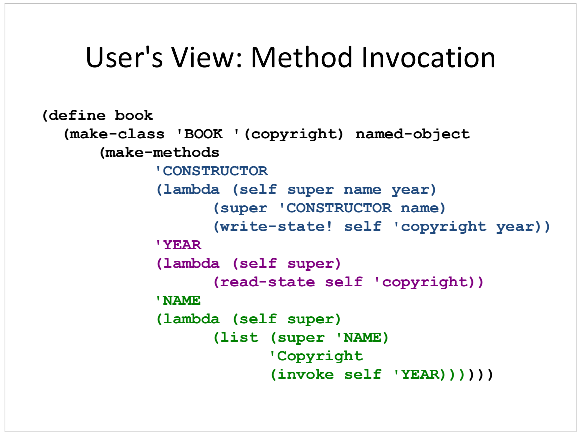
```
(define (make-instance class . args)
  (let ((inst
         (list 'instance
               (map (lambda (x) (list x #f)) (collect-state class))
               class)))
    (if (has-method? inst 'CONSTRUCTOR)
        (apply invoke inst 'CONSTRUCTOR args))
    inst))

(define (instance? obj)
  (tagged-list? obj 'instance))
(define (instance-state inst)
  (second inst))
(define (instance-class inst)
  (third inst))
```



Implementer's View: State

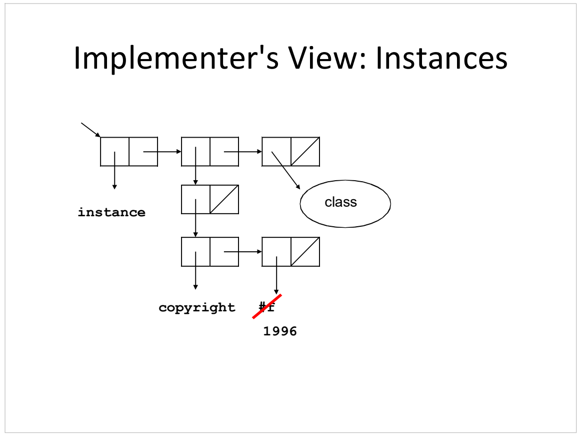
```
(read-state sicp 'copyright)
```

```
(define (read-state self varname . default)
  (let ((result
          (assq varname (instance-state self))))
    (if result
        (cadr result)
        (if (not (null? default))
            (car default)
            (error "no state named" varname)))))
```

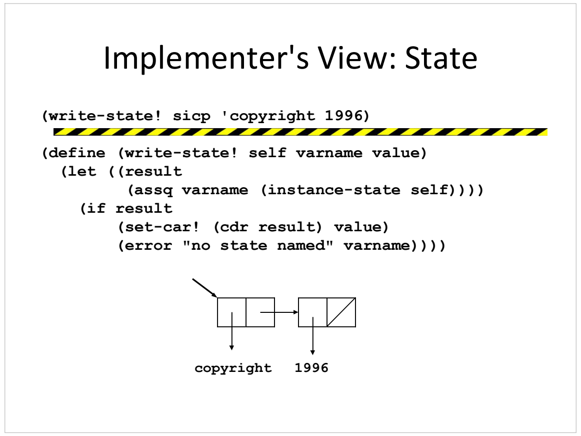


User's View: Method Invocation

```
(define book
  (make-class 'BOOK '(copyright) named-object
     (make-methods
            'CONSTRUCTOR
            (lambda (self super name year)
                   (super 'CONSTRUCTOR name)
                   (write-state! self 'copyright year))
            'YEAR
            (lambda (self super)
                   (read-state self 'copyright))
            'NAME
            (lambda (self super)
                   (list (super 'NAME)
                         'Copyright
                         (invoke self 'YEAR))))))
```



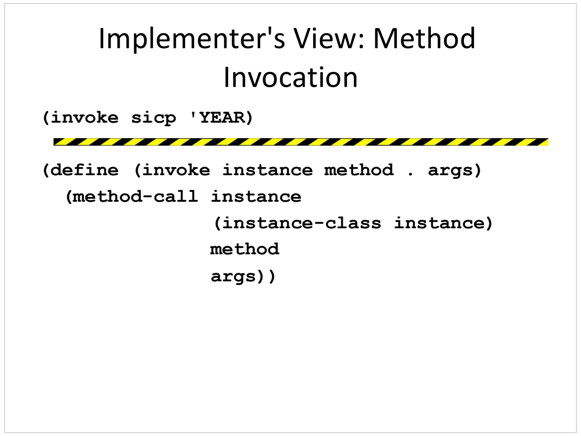
Implementer's View: Instances



Implementer's View: State

```
(write-state! sicp 'copyright 1996)
```

```
(define (write-state! self varname value)
  (let ((result
          (assq varname (instance-state self))))
    (if result
        (set-car! (cdr result) value)
        (error "no state named" varname))))
```



Implementer's View: Method Invocation

```
(invoke sicp 'YEAR)
```

```
(define (invoke instance method . args)
  (method-call instance
               (instance-class instance)
               method
               args))
```

Implementer's View: Method Invocation

```
(define (method-call self class method args)
  (if (class? class)
    (let ((proc (find-class-method method class))
          (super (make-super class self)))
      (if proc
          (apply proc self super args)
          (method-call self (class-parent class) method
                            args)))
    (error "no such method" method)))


(define (make-super class self)
   (lambda (method . args)
     (method-call self (class-parent class) method args)))
```

Implementer's view: State

```
(read-state      'copyright)
```

```
(define (read-state      varname . default)
  (let ((result
           (assq varname (instance-state self))))
    (if result
        (cadr result)
        (if default
            (car default)
            (error "no state named" varname)))))
```

Dynamic scoping

- Want to have dynamic scoping just for **`self`** and **`super`**
- We want to bind specific values for the duration of the method invocation only
- Could we define **`self`** and **`super`** in the GE and then change it before a method call and reset it after?

Implementation oddities

- All methods are public
- All state is public
  - Would be easy to violate the abstraction barrier
  - Would be better if **`read-state`**/**`write-state!`** only worked from within method bodies

Implementation oddities

- Methods require explicit **`self`** and **`super`**
  - Why can't **`self`** and **`super`** just "have the right value" while the method is executing?
  - We want to be able to refer to these free variables in our methods without passing them around
  - Actual value depends on the calling context, not the program text

Dynamic scoping: Actually useful

```
(define self #f)
(define super #f)

(define (invoke instance method . args)
  (fluid-let ((self instance))
    (method-call (instance-class instance)
                 method
                 args)))
```

Before

```
(define (method-call self class method args)
  (if (class? class)
    (let ((proc (find-class-method method class))
          (super (make-super class self)))
       (if proc
          (apply proc self super args)
          (method-call self
                       (class-parent class)
                       method
                       args)))
    (error "no such method" method)))
```

After

```
(define (method-call class method args)
  (if (class? class)
      (let ((proc (find-class-method method class)))
        (if proc
            (fluid-let ((super (make-super class)))
                 (apply proc args))
            (method-call (class-parent class)
                         method
                         args)))
      (error "no such method" method)))
```

Where do we go from here?

- Current idea provides a “library” of procedures to give OOP behavior
- What if you wanted it to be part of the language itself, with custom syntax?
  - Macros **`(define-syntax ...)`**
  - Extend m-eval **(Problem Set 4)**
    - Do better than **`read-state`** and **`write-state!`**

Before

```
(define (method-call self class method args)
  (if (class? class)
    (let ((proc (find-class-method method class))
          (super (make-super class self)))
       (if proc
          (apply proc self super args)
          (method-call self
                       (class-parent class)
                       method
                       args)))
    (error "no such method" method)))
```

User view: Class Definition

- With our dynamic **`self`** and **`super`**

```
(define book
   (make-class 'BOOK '(copyright) named-object
       (make-methods
              'CONSTRUCTOR
              (lambda (name year)
                   (super 'CONSTRUCTOR name)
                   (write-state! 'copyright year))
              'YEAR
              (lambda ()
                   (read-state 'copyright))
              'NAME
              (lambda ()
                   (list (super 'NAME)
                         'Copyright
                         (invoke self 'YEAR))))))
```

Where do we go from here?

- What other features might you want?
  - Allow some public state access?
  - Private/protected methods?
  - Metaobject protocol?

MetaObject Procotol (MOP)

- Gives programmer access to objects and classes
  - Introspection: Look up fields, methods
  - Intercession: Modify the behavior of an object
- Metaclass
  - The “class of a class” (i.e. classes are objects)
  - Can expose how the OOP system works

Recitation Time!

- Problem Set 4 released after class
  - Implement an OO system in m-eval
  - Text Adventure Game
  - It will take a good deal of time
  - Lots of room for optional exploration