How to Design Class Hierarchies

Matthias Felleisen
PLT
Northeastern University, Boston
The Team

Robert Findler
Matthew Flatt
Shriram Krishnamurthi

Kathy Gray
Viera Proulx
Teaching FP first is the ideal introduction to OOP.

A first year that teaches one semester of FP followed by another semester of OOP produces the best OO programmers.
Background

How to Design Programs

• 10 years of FP in first year & high schools

• “Structure & Interpretation of the Computer Science Curriculum” [FDPE’03, JFP’04]

• building the “bridge” to the “real world”

Aimed at what’s best for students in the long run
College Timeline

Year 1
Year 2
Year 3
Year 4
Year 5
first job

Co-op

Principles
Preparation for Industry
The First Year

Year 1

Principles:
- computation
- programming
- easy!

Year 2

Principles for OO:
- computation
- programming
- relevant
The First Year

Year 1
Principles:
- FP
- à la *HtDP*

Year 2
Principles:
- OOP
- à la *HtDCH*
& Java syntax
Part I: What is OOP? — A Quiz

Or, why you should believe that FP, our wonderful “church,” and OOP, the essence of evil “state,” can have anything to do with each other (from a 2004 conference)
Who Said This?

Though [it] came from many motivations, two were central. ... [T]he small scale one was to find a more flexible version of assignment, and then to try to eliminate it altogether.

(1993)
Who Said This?

Though [it] came from many motivations, two were central. ... [T]he small scale one was to find a more flexible version of assignment, and then to try to eliminate it altogether.

Who Said This?

Favor immutability.

(2001)
Who Said This?

Favor immutability.

Who Said This?

Use value objects when possible.

(2001)
Who Said This?

Use value objects when possible.

It is unfortunate that much of what is called “object-oriented programming” today is simply old style programming with fancier constructs. Many programs are loaded with “assignment-style” operations now done by more expensive attached procedures.

(1993)
It is unfortunate that much of what is called “object-oriented programming” today is simply old style programming with fancier constructs. Many programs are loaded with “assignment-style” operations now done by more expensive attached procedures.

Part II: How to Design Programs

Or, how should you teach FP in the first semester
(define-datatype tree tree?  
    [Leaf (value integer?)]  
    [Node (left tree?) (right tree?)])

; tree → integer  
; add up the numbers in the given tree  
(define (sum t)  
    (cases tree t  
      [Leaf   (v)   v]  
      [Node (l r) (+ (sum l) (sum r))])))

EoPL (2e) Scheme
Functional Programming is Obvious

(even for the parenthetically challenged)

type tree =
    Leaf of int
  | Node of tree * tree

(* tree → integer
    add up the numbers in the given tree *)

let rec sum(t) =
  match t with
    Leaf(i) -> i
  | Node(l,r) -> sum(l) + sum(r)
Is It Really for the Novice?

- What does a novice take away from this?
- What carries over to the industrial PLs (Java++, Perl)?
- Recursion? Types? Interactive exploration (repl)?
- How to write an interpreter?
- ... for a language you aren’t allowed to use?
A Great Novice Experience

• “I learned solid principles of programming.”
• “I know that this is useful, even if I didn’t ‘use’ it.”
• “Everything I learned after that is more popular, but not even remotely as convenient or powerful.”
• “It changed my life.”
How HtDP Produces Results

HtDP teaches

• The Design Recipe: data, data, data
• Abstraction as editing
• Organizing programs
# The Design Recipe

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Write a program to check whether an ant is at home.... An ant has a weight and a location in the zoo.... Home is the cartesian origin.

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“Real world”: **information**

“Computational world”: **representations**

Programmer’s job: pick a representation

⇒ determines rest of recipe
Write a program to check whether an ant is at home.... An ant has a weight and a location in the zoo.... Home is the cartesian origin.

<table>
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<th>structs</th>
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; A posn is
; (make-posn num num)
(define-struct posn (x y))

; An ant is
; (make-ant num posn)
(define-struct ant (weight loc))

(make-ant 0.001 (make-posn 4 5))
(make-ant 0.007 (make-posn 3 17))
; An ant is
;  (make-ant num posn)
(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; An ant is
; (make-ant num posn)
(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; Check whether ant a is home
(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; Check whether ant a is home
(define (ant-at-home? a) ...

## Data representation

- An ant is
- (make-ant num posn)

### Purpose & contract

- (define-struct ant (weight loc))

### Functional examples

- ant-at-home? : ant -> bool
- ; Check whether ant a is home

```scheme
(define (ant-at-home? a)
  ...
)
```

### Template (inventory)

### Body implementation

- (ant-at-home? (make-ant 0.001 (make-posn 0 0)))
- "should be" true

- (ant-at-home? (make-ant 0.001 (make-posn 1 1)))
- "should be" false

### Test (examples)
An ant is
(make-ant num posn)

(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; Check whether ant a is home
(define (ant-at-home? a)
  ...
  (ant-weight a)
  ...
  (ant-loc a) ...
)

(ant-at-home? (make-ant 0.001 (make-posn 0 0)))
"should be" true

(ant-at-home? (make-ant 0.001 (make-posn 1 1)))
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; An ant is
; (make-ant num posn)
(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; Check whether ant a is home
(define (ant-at-home? a)
  ...
  (ant-weight a)
  ...
  (posn-at-home? (ant-loc a)) ...
)

**data reference ⇒ template reference**
Add templates for referenced data, if needed, and implement body for referenced data

(ant-at-home? (make-ant 0.001 (make-posn 0 0)))
"should be" true
(ant-at-home? (make-ant 0.001 (make-posn 1 1)))
"should be" false
; An ant is
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(define-struct ant (weight loc))

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; Check whether ant a is home
(define (ant-at-home? a)
  ...
  (ant-weight a)
  ...
  (posn-at-home? (ant-loc a)) ...
)

(define (posn-at-home? p)
  ...
  (posn-x p) ...
  (posn-y p) ...
)

(ant-at-home? (make-ant 0.001 (make-posn 0 0)))
"should be" true
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; (make-ant num posn)
(define-struct ant (weight loc))

; ant-at-home? : ant -> bool
; Check whether ant a is home
;
; (define (ant-at-home? a)
; ... (ant-weight a)
; ... (posn-at-home? (ant-loc a)) ...)
; (define (posn-at-home? p)
; ... (posn-x p) ... (posn-y p) ...)
;
(define (ant-at-home? a)
  (posn-at-home? (ant-loc a)))
(define (posn-at-home? p)
  (and (= (posn-x p) 0) (= (posn-y p) 0)))

(ant-at-home? (make-ant 0.001 (make-posn 0 0))) "should be" true
(ant-at-home? (make-ant 0.001 (make-posn 1 1))) "should be" false
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; (make-ant num posn)
(define-struct ant (weight loc))

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; Check whether ant a is home
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; (define (ant-at-home? a)
;  ... (ant-weight a)
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(define (ant-at-home? a)
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Data representation

Purpose & contract

Functional examples

Template (inventory)

Body implementation

Test (examples)

; An ant is
; (make-ant num posn)

; A posn is
; (make-posn num num)

(define (ant-at-home? a)
  ... (ant-weight a)
  ... (posn-at-home? (ant-loc a)) ...)

(define (posn-at-home? p)
  ... (posn-x p) ... (posn-y p) ...)
1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 Test (examples)

```ocaml
type tree =
    Leaf of int
  | Node of tree * tree
```
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```ocaml
type tree =
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Data representation

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Test (examples)

type tree =
  Leaf of int
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(* tree → integer
  add up numbers in t *)
let rec sum(t) =
  match t with
    Leaf(i) -> ... i ...
  | Node(l,r) -> ... sum(l)
    ... sum(r) ...

40
Data representation

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type tree =
  Leaf of int
  | Node of tree * tree

(* tree → integer
  add up numbers in t *)
let rec sum(t) =
  match t with
    Leaf(i) -> ... i ...
  | Node(l,r) -> ... sum(l)
      ... sum(r) ...
Shapes of Data and Templates

; An animal is either
;  - snake
;  - dillo
;  - ant

; A snake is
; (make-snake sym num sym)

; A dillo is
; (make-dillo num bool)

; An ant is
; (make-ant num posn)

; A posn is
; (make-posn num num)

(define (feed-animal a)
  (cond
    [(snake? a) ... (feed-snake a) ...]
    [(dillo? a) ... (feed-dillo a) ...]
    [(ant? a) ... (feed-ant a) ...]))

(define (feed-snake s)
  ... (snake-name s) ... (snake-weight s)
  ... (snake-food s) ...)

(define (feed-dillo d)
  ... (dillo-weight d)
  ... (dillo-alive? d) ...)

(define (feed-ant a)
  ... (ant-weight d)
  ... (feed-posn (ant-loc d)) ...)

(define (feed-posn p)
  ... (posn-x p) ... (posn-y p) ...)
The Design Recipe

• Scales to mutually referential datatypes and hierarchies
• Supplemented by “iterative refinement”
• Students easily process files/directories, grammars, river systems, etc. after a few weeks.
Functional Abstraction

**map** is obvious:

; increase : (list-of num) → (list-of num)
; increase each number by one

(define (increase alon)
  (cond
    [(empty? alon) empty]
    [else (cons (add1 (first alon))
                 (increase (rest alon)))]))

⇒ (define (increase alon)
    (map add1 alon))
**Functional Abstraction**

map is **obvious**, even in OCaml:

\[
(* \text{increase} : \text{int list} \rightarrow \text{int list} \\
\text{increase each number by one *})
\]

\[
\begin{align*}
\text{let rec increase l =} & \\
\text{match l with} & \\
[\vphantom{\text{\}}] & [] \rightarrow [] \\
& [\vphantom{\text{\}}] \rightarrow [] \\
& | \text{first::rest} \rightarrow \\
& \quad \text{add1(first)::increase(rest)}
\end{align*}
\]

\[
\Rightarrow \quad \text{let increase l =} \\
\text{List.map add l}
\]
Functional Abstraction

Is abstraction really obvious?

• How do students create abstractions?
• How do they use this knowledge in C#?
• How do they know what abstractions exist in ML?
• How should this be of use in Java?
Abstraction as Editing

Programming is like writing — it needs editing

• Editing is called abstraction
• Recognize common patterns and abstract
• Learn to reuse abstractions
Abstraction as Editing

; (list-of num) -> (list-of num)
; increase each of the numbers by 1
(define (increase alon)
 (cond
   [(empty? alon) empty]
   [else (cons (add1 (first alon))
                 (increase (rest alon)))]))

; tests
(equal? (increase (list 1 2 3))
        (list 2 3 4))

; (list-of posn) -> (list-of num)
; extract the X coordinate from each
(define (extract alop)
 (cond
   [(empty? alop) empty]
   [else (cons (posn-x (first alop))
               (extract (rest alop)))]))

; tests
(equal? (extract (list (make-posn 2 3)))
        (list 2))
Abstraction as Editing

; (list-of num) -> (list-of num)
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; tests
(equal? (increase (list 1 2 3))
    (list 2 3 4))

; (list-of X) (X -> num) -> (list-of num)
; apply afun to each
(define (do-to-all alox afun)
    (cond
        [(empty? alon) empty]
        [else (cons (afun (first alon))
                    (do-to-all (rest alox)))]))

; (list-of posn) -> (list-of num)
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Abstraction as Editing

; (list-of num) -> (list-of num)
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(define (increase alon)
  (do-to-all add1 alon))

; (list-of posn) -> (list-of num)
; extract the X coordinate from each
(define (extract alop)
  (do-to-all posn-x alop))

; tests
(equal? (increase (list 1 2 3))
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Eventually, even novice programs get large

• Rules for how to create programs
• Rules for how to organize them

Design recipes *empower* students; programming rules *restrict* them
Program Organization

• One task, one function
• Keep functions small
• Keep like data together
• Name functions properly
Program Organization

(define-struct worm (head body))
; Worm = (make-worm Segment (Listof Segment))
; interpretation: head, followed by growth segments

; worm-move : Worm Direction -> Worm
; move the worm one step in the given direction

; worm-grow : Worm Posn -> Worm
; grow the worm by one body segment, head moves to Posn
; accumulator style

; worm-image : Worm -> Image
Program Organization

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; accumulator style

; worm-image : Worm -> Image

...and the same for worm Segments...
...and the same for for Food...
...and then the binary functions...
First Semester Summary

FP in the first semester is about data representations:

- Design systematically to data definition
- Abstract systematically and use abstractions
- Organize programs systematically
Part III: How to Design Data in OOP

Or, how should you transition from FP to OOP
Start with data:

```scheme
(define-struct posn (x y))
```

```java
class Posn {
    int x;
    int y;
    Posn(int x, int y) {
        this.x = x;
        this.y = y;
    }
}
```
From FP to OOP

Start with data:

```scheme
; A posn is
; (make-posn num num)
(define-struct posn (x y))
```

| Posn | int x | int y |
; An ant is
; (make-ant num posn)

; A posn is
; (make-posn num num)
; An animal is either
; - snake
; - dillo
; - ant

; A snake is
; (make-snake sym num sym)

; A dillo is
; (make-dillo num bool)

; An ant is
; (make-ant num posn)

; A posn is
; (make-posn num num)
From FP to OOP

type tree =
  Leaf of int
  | Node of tree * tree

Tree
  Leaf
  int val
  Node
  Tree left
  Tree right
From FP to OOP

type tree =
  Leaf of int
| Node of tree * tree

And so on (for mutually referential data definitions)...

Tree
  Leaf
  | int val
  | Node
  | Tree left
  | Tree right
From Functions to Methods

; An animal is either
; - snake
; - dillo
; - ant
; ...

; animal-is-lighter? : animal num -> bool
(define (animal-is-lighter? a n)
  (cond
   [(snake? a) (snake-is-lighter? s n)]
   [(dillo? a) (dillo-is-lighter? s n)]
   [(ant? a) (ant-is-lighter? s n)])

interface Animal {
    boolean isLighter(double n);
}

class Snake extends Animal {
    ...
    boolean isLighter(double n) { ... }
}

class Dillo extends Animal {
    ...
    boolean isLighter(double n) { ... }
}

class Ant extends Animal {
    ...
    boolean isLighter(double n) { ... }
}
From Functions to Methods

Data definition turns into class declarations

; An animal is either
; - snake
; - dillo
; - ant
; ...

; animal-is-lighter? : animal num -> bool
(define (animal-is-lighter? a n)
  (cond
    [(snake? a) (snake-is-lighter? s n)]
    [(dillo? a) (dillo-is-lighter? s n)]
    [(ant? a) (ant-is-lighter? s n)])

; snake-is-lighter? : snake num -> bool
(define (snake-is-lighter? s n) ...)

; dillo-is-lighter? : dillo num -> bool
(define (dillo-is-lighter? d n) ...)

; ant-is-lighter? : ant num -> bool
(define (ant-is-lighter? a n) ...)

interface Animal {
  boolean isLighter(double n);
}

class Snake extends Animal {
  ...
  boolean isLighter(double n) { ... }
}

class Dillo extends Animal {
  ...
  boolean isLighter(double n) { ... }
}

class Ant extends Animal {
  ...
  boolean isLighter(double n) { ... }
}
From Functions to Methods

Variant functions turn into variant methods — all with the same contract after the implicit argument

interface Animal {
    boolean isLighter(double n);
}

class Snake extends Animal {
    ...
    boolean isLighter(double n) { ... }
}

class Dillo extends Animal {
    ...
    boolean isLighter(double n) { ... }
}

class Ant extends Animal {
    ...
    boolean isLighter(double n) { ... }
}
From Functions to Methods

Function with variant-based **cond** turns into just an **abstract**
method declaration

```plaintext
; An animal is either
; - snake
; - dillo
; - ant
; ...

; animal-is-lighter? : animal num -> bool
(define (animal-is-lighter? a n)
  (cond
    [(snake? a) (snake-is-lighter? s n)]
    [(dillo? a) (dillo-is-lighter? s n)]
    [(ant? a) (ant-is-lighter? s n)]))

; snake-is-lighter? : snake num -> bool
(define (snake-is-lighter? s n) ...)  

; dillo-is-lighter? : dillo num -> bool
(define (dillo-is-lighter? d n) ...)  

; ant-is-lighter? : ant num -> bool
(define (ant-is-lighter? a n) ...)  

interface Animal {
  boolean isLighter(double n);
}

class Snake extends Animal {
  ...
  boolean isLighter(double n) { ... }
}

class Dillo extends Animal {
  ...
  boolean isLighter(double n) { ... }
}

class Ant extends Animal {
  ...
  boolean isLighter(double n) { ... }
}
```
How to Design Classes & Interfaces

• We (ought to) know this much
• Data types via interpreter/composite patterns
• Design recipe process produces instances of those patterns — students can tackle anything
• Students see FP mechanics (conditional) vs. OOP mechanics (dynamic dispatch)
Part IV: How to Design Hierarchies

Or, why the principles of FP à la *HtDP* produce class hierarchies
Method Abstraction

Duplication of code in method bodies:

<table>
<thead>
<tr>
<th>AClass</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{A\ m(B\ x)\ {\ \ldots\ \textcolor{red}{x}\ \ldots\ }}</td>
</tr>
<tr>
<td>\texttt{A\ n(B\ x,\ C\ y)\ {\ \ldots\ \textcolor{red}{x}\ \ldots\ }}</td>
</tr>
</tbody>
</table>
Method Abstraction

Duplication of code in method bodies:

- Handle as in FP

<table>
<thead>
<tr>
<th>AClass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A \ q(B \ x, \ D \ z) ) { \ldots \ x \ldots }</td>
</tr>
<tr>
<td>( A \ m(B \ x) ) { \text{return } q(x, \text{ new } D(42)) }; }</td>
</tr>
<tr>
<td>( A \ n(B \ x, \ C \ y) ) { \text{return } q(x, y.p()); }</td>
</tr>
</tbody>
</table>

Of course, it’s clumsy without \( \lambda \)...
Field Abstraction

Animal

Snake
- String name
- float weight
- String food

Dillo
- float weight
- boolean alive

Ant
- float weight
- Posn loc
  - Posn
    - int x
    - int y
Field Abstraction

- **Animal**
  - **Snake**
    - String name
    - Float weight
    - String food
  - **Dillo**
    - Float weight
    - Boolean alive
  - **Ant**
    - Float weight
    - Posn loc
      - Posn
      - Int x
      - Int y
Field Abstraction

Animal
- float weight

Snake
- String name
- String food

Dillo
- boolean alive

Ant
- Posn loc
  - Posn
    - int x
    - int y
Deep Hierarchies

```
Animal
  float weight
  
Snake
  String name
  String food

Dillo
  boolean alive

Ant
  Posn loc

Boa
  ...

Rattlesnake
  ...
```

Deep Hierarchies

Snake

... 

Boa

boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return a.smaller(this.weight*10)
    && a.slower(100)
    && yummy(a);
}

Rattlesnake

boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return a.smaller(this.weight*5)
    && a.slower(120)
    && yummy(a);
}
boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return a.smaller(this.weight*10)
    && a.slower(100)
    && yummy(a);
}

boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return a.smaller(this.weight*5)
    && a.slower(120)
    && yummy(a);
}
Deep Hierarchies

Boa

```java
boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return CanEatWFacts(a, 10, 100);
}
```

Rattlesnake

```java
boolean yummy(Animal a) { ... }
boolean CanEat(Animal a) {
    return CanEatWFacts(a, 5, 120);
}
```

Result: the **template-hook pattern** — via reasoning, not ad hoc process
More Abstraction for Class Hierarchies

• Abstraction inside of classes/hierarchies
• Abstraction from a client-only perspective
• Abstraction over traversals of collections (map, fold, etc.)

All of these steps yield code that is pattern-based

⇒ theory and practice coincide!
Part V: Encapsulated State

Or, without hiding and encapsulating state, it can’t be real OOP — right?
OOP proponents argue that OOP is about state:

- It is about hidden and encapsulated state
- It is about manipulating state

They’re right!
State: What’s Wrong with this Program?

// represent the world of a Worm Game: Worm, Food, and the Bounding Box
class WormWorld extends World {
  Worm w;
  Food f;
  Box b;
  WormWorld(Worm w, Food f, Box b) { ... }

  // what happens when the clock ticks
  World onTick() { return okWorld(w.nextWorld()); }

  // what happens when the player presses a key
  World onKeyEvent(String ke) { return okWorld(w.changeDirection(ke)); }

  // create a new world from the new worm, unless it ran into a wall
  // or ate itself
  World okWorld(Worm newWorm) {
    if (newWorm.canEat(this.f) && this.ate(newWorm))
      return new WormWorld(newWorm.eat(this.f),f.create(this.b),b)
    else ...
  }

  // did the worm encounter food and eat it?
  boolean ate(Worm w) { ... }
...
State: What’s Wrong with this Program?

// represent the world of a Worm Game: Worm, Food, and the Bounding Box
class WormWorld extends World {
    private Worm w;
    private Food f;
    private Box b;
    private WormWorld(Worm w, Food f, Box b) { ... }

    // override: what happens when the clock ticks
    public World onTick() { return okWorld(w.nextWorld()); }

    // override: what happens when the player presses a key
    public World onKeyEvent(String ke) { return okWorld(w.changeDirection(ke)); }

    // create a new world from the new worm, unless it ran into a wall
    // or ate itself
    private World okWorld(Worm newWorm) {
        if (newWorm.canEat(this.f) && this.ate(newWorm))
            return new WormWorld(newWorm.eat(this.f), f.create(this.b), b)
        else ...
    }

    // did the worm encounter food and eat it?
    private boolean ate(Worm w) { ... }
}

It’s missing some keywords
Encapsulation Means Privacy

• Hiding & encapsulating state means privacy
• Introduce when programs get large enough and students have a sense of invariants

Encapsulation does not imply a litany of assignment statements
Manipulating State: Methods produce Worlds

- Manipulating state means that some methods produce a new instance of the world

- Introduce this topic when you have an I/O library that doesn’t change state

Manipulating state does not imply a litany of assignment statements
State and “Real” Programs

• Our students regularly design interactive programs without a single assignment statement

```java
class WormWorld extends World {
    ...  
    // what happens when the player presses a key
    public World onKeyEvent(String ke) { ... }
    ...
}
```

• Schemers accept the occasional assignment statement as necessary — and that’s really OOP
Part VI: Experience
In the Classroom

- Development time: 3 years

- Test teaching at Northeastern: 6 semesters, 4 instructors (mostly Proulx)

- Test teaching at UChicago: 1 summer semester (Gray)

- Teacher/college workshops: 2 summers (Proulx & Gray)

- A dozen teachers in high schools, small colleges
Evaluation

Northeastern University:

• Four follow-up faculty have testified that the new crop of students are *vastly* better than the previous ones

• It works for several instructors, so it’s not the “enthusiasm of the inventor” (he doesn’t teach it)

High School:

• Teachers report strong AP results

Chicago:

• Too early for results
Objections

Common objection: it’s FP in Java syntax

Our reply:

• See quotes at the beginning of the talk — this is True OOP™
• We emphasize what OOP is all about for real programming:
  ◦ design of classes and hierarchies
  ◦ abstraction
  ◦ encapsulation
• Yes, the occasional assignment statement helps
Summary
What Doesn’t Work

• SICP-style approaches: teaching how to implement OO in an FP

• Cartwright (at Rice) approach: teaching how to interpret an FPL in an OOPL

Students must know such principles, but it doesn’t teach OOP
What Works

Take OOP seriously

• It’s about the systematic design of classes
• It’s about the systematic design of hierarchies
• It’s about server/provider vs. client/consumer
• It’s best seen as FP with grouping, privacy, and novel forms of abstraction
To produce the best OO programmers, teach FP, and then move on

*HtDP* and *HtDCH* demonstrate this approach with successful results

*Thanks!*