How to Design Class Hierarchies

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Thesis

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.

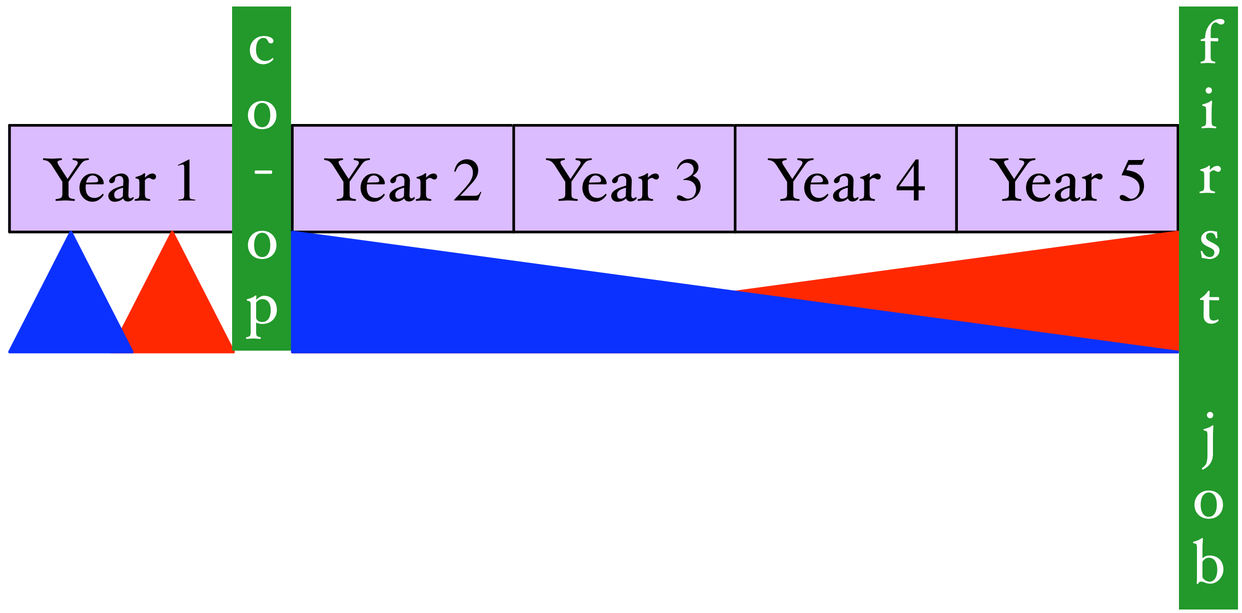
Background

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

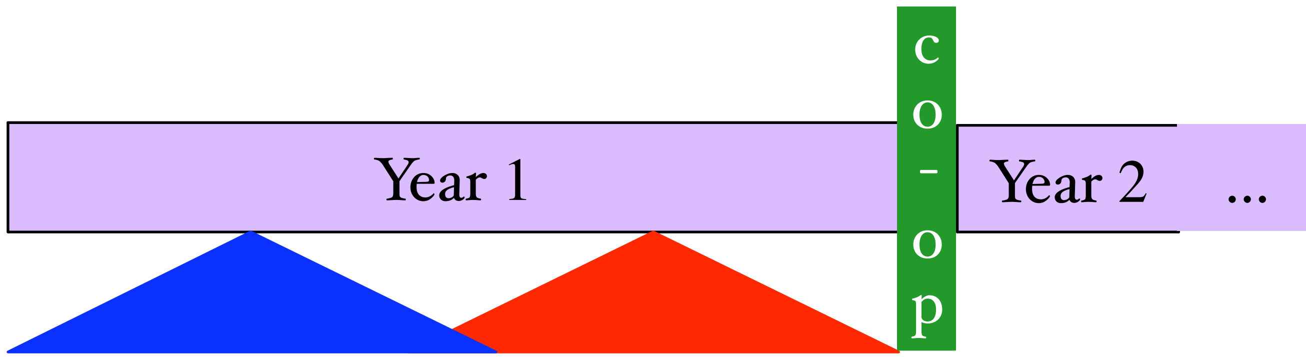
College Timeline



Principles

Preparation for Industry

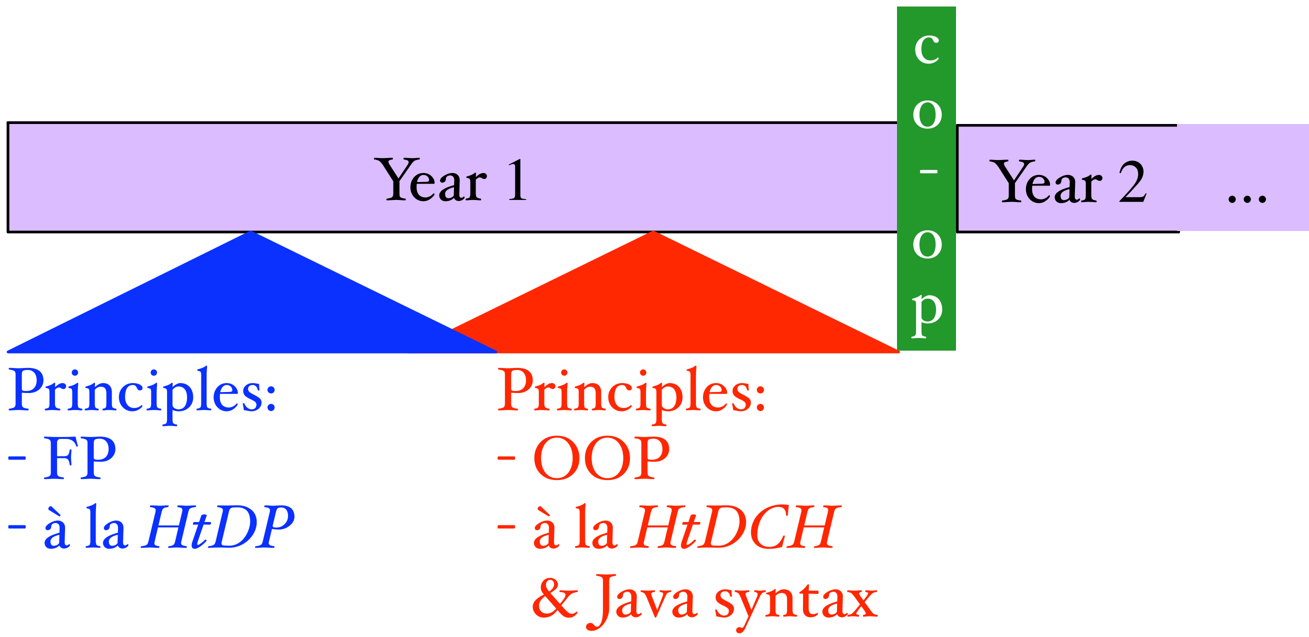
The First Year



Principles:
- computation
- programming
- easy!

Principles for OO:
- computation
- programming
- relevant

The First Year



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?

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Alan Kay, *History of Smalltalk* (1993)

Who Said This?

Favor immutability.

(2001)

Who Said This?

Favor immutability.

Joshua Bloch, *Effective Java* (2001)

Who Said This?

Use value objects when possible.

(2001)

Who Said This?

Use value objects when possible.

Kent Beck, *Test Driven Development* (2001)

Who Said This?

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)

Who Said This?

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.

Alan Kay, *History of Smalltalk* (1993)

Part II: How to Design Programs

Or, how should you teach FP in the first semester

Functional Programming is Obvious

```
(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)
```

OCaml

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

1 Data representation
2 Purpose & contract
3 Functional examples
4 Template (inventory)
5 Body implementation
6 Test (examples)

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.

1. Data representation
2. Purpose & contract
3. Functional examples
4. Template (inventory)
5. Body implementation
6. Test (examples)

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.

1 Data representation

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6 Test (examples)

“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.

	atomic data	intervals / enumerations	structs	unions	...
1 Data representation					
2 Purpose & contract					
3 Functional examples					
4 Template (inventory)					
5 Body implementation					
6 Test (examples)					

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.

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 Test (examples)

```
; 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
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 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
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 Test (examples)

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 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)
  ...)
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 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-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
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 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)))
"should be" false
```

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

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 Test (examples)

```
; 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
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

5 Body implementation

6 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)
  ... (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
(ant-at-home? (make-ant 0.001 (make-posn 1 1)))
"should be" false
```

1 Data representation

2 Purpose & contract

3 Functional examples

4 Template (inventory)

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6 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)
;    ... (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
```

1 Data representation

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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)) ...)
; (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
```

1 Data representation

2 Purpose & contract

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5 Body implementation

6 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)

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6 Test (examples)

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

1 Data representation

2 Purpose & contract

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4 Template (inventory)

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```
type tree =
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  | Node of tree * tree
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1 Data representation

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3 Functional examples

4 Template (inventory)

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6 Test (examples)

```
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) ...
```

1 Data representation

2 Purpose & contract

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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:

```
(* increase : int list → int list
   increase each number by one *)
```

```
let rec increase l =
  match l with
     [] -> []
   | first::rest ->
       add1(first)::increase(rest)
```

⟹

```
let increase l =
  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)
; 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))
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Abstraction as Editing

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(equal? (increase (list 1 2 3))
        (list 2 3 4))
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```
; (list-of posn) -> (list-of num)
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(define (extract alop)
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    [else (cons (posn-x (first alop))
                (extract (rest alop)))]))

; tests
(equal? (extract (list (make-posn 2 3)))
        (list 2))
```

```
; (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 alox))
                (do-to-all (rest alox)))]))
```

Abstraction as Editing

```
; (list-of num) -> (list-of num)
; increase each of the numbers by 1
(define (increase alon)
  (do-to-all add1 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)
  (do-to-all posn-x alop))
```

```
; tests
(equal? (extract (list (make-posn 2 3)))
        (list 2))
```

```
; (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 alox))
                (do-to-all (rest alox)))]))
```

Program Organization

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

```
(define-struct worm (head body))
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Program Organization

```
(define-struct worm (head body))
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; 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
```

...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

From FP to OOP

Start with data:

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

```
class Posn {
  int x;
  int y;
  Posn(int x, int y) {
    this.x = x;
    this.y = y;
  }
}
```

From FP to OOP

Start with data:

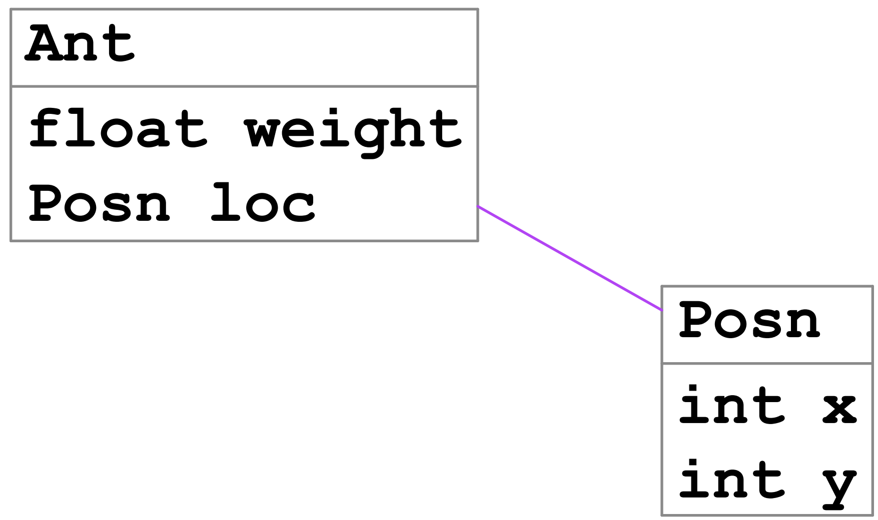
```
; A posn is
;   (make-posn num num)
(define-struct posn (x y))
```

Posn
int x int y

From FP to OOP

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

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



From FP to OOP

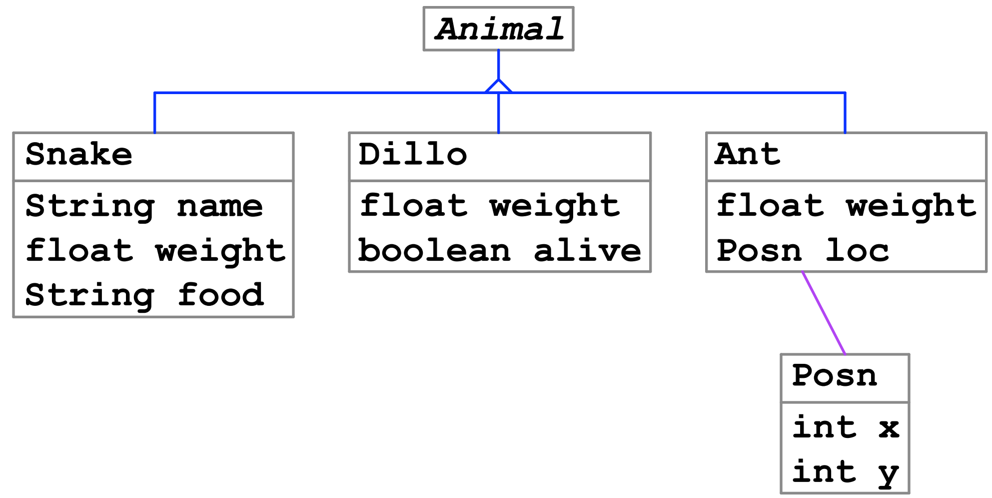
```
; An animal is either
;  - snake
;  - dillo
;  - ant

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

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

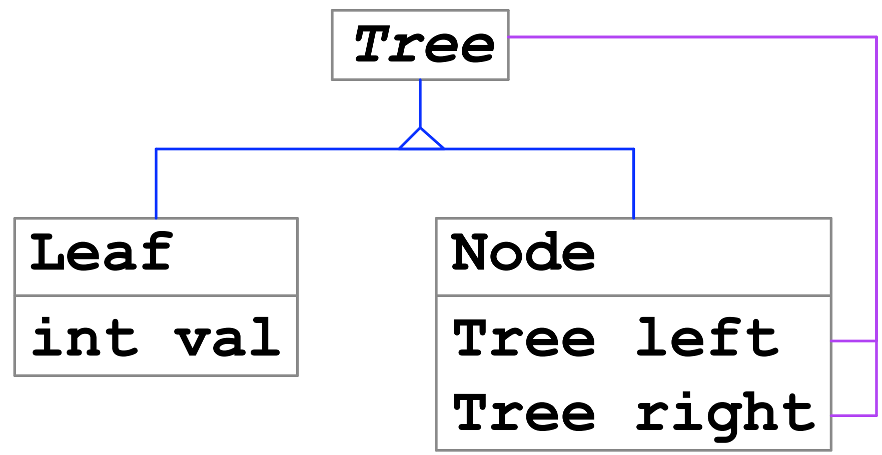
; An ant is
; (make-ant num posn)

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



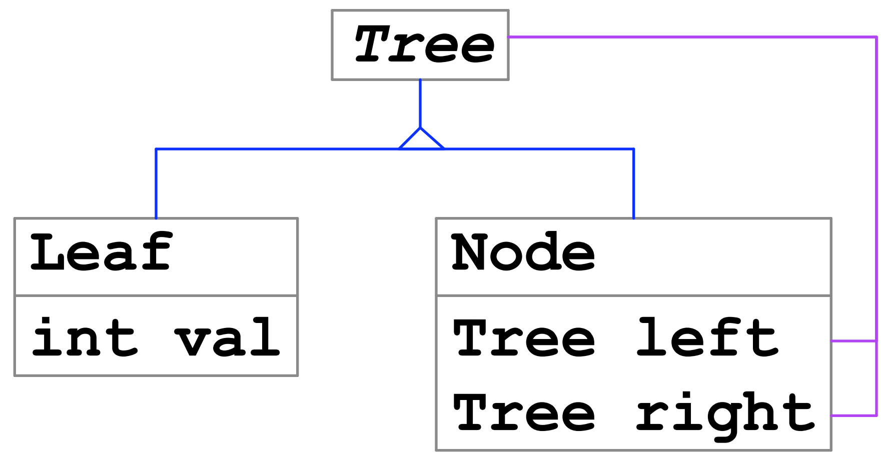
From FP to OOP

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



From FP to OOP

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



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

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-ligheter? 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

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-ligheter? 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

```
; 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-ligheter? 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) ...)
```

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

```
; 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-ligheter? 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) ...)
```

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

```
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:

```
AClass
---------------------------------------
A m(B x) { ... x ... }
A n(B x, C y) { ... x ... }
```

Method Abstraction

Duplication of code in method bodies:

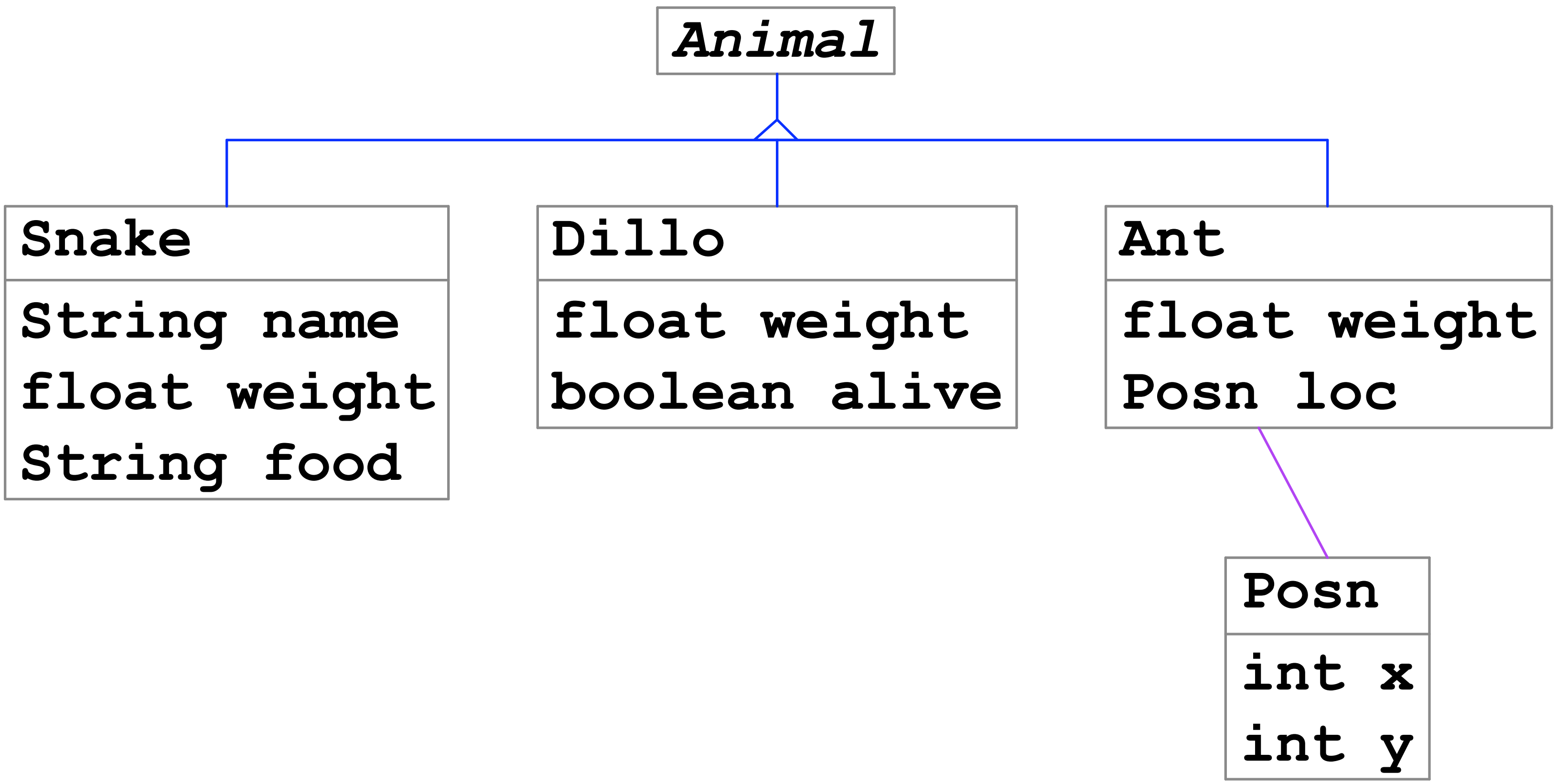
- Handle as in FP

```
AClass

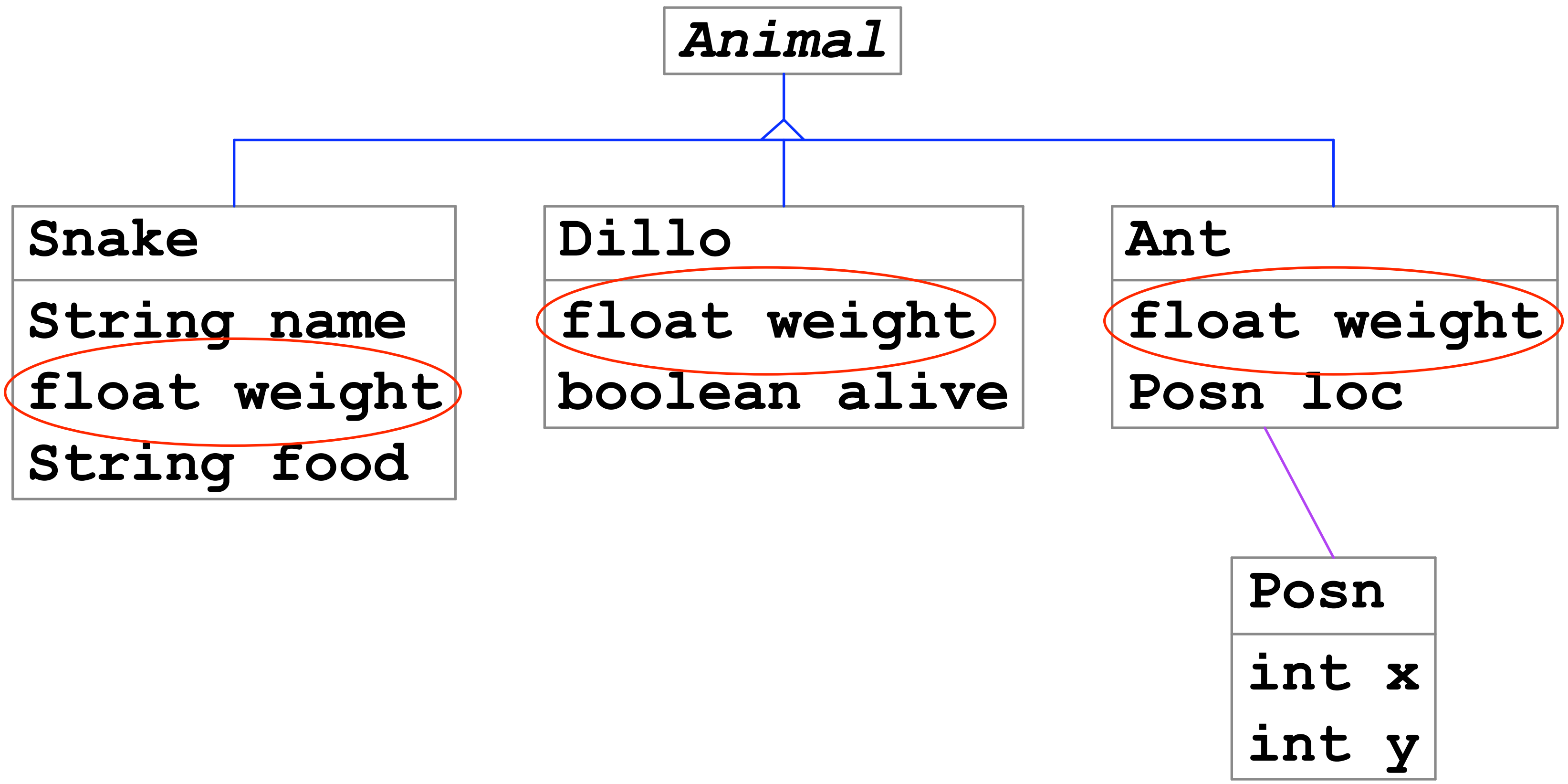
A q(B x, D z) { ... x ... }
A m(B x) { return q(x, new D(42)); }
A n(B x, C y) { return q(x, y.p()); }
```

Of course, it's clumsy without λ...

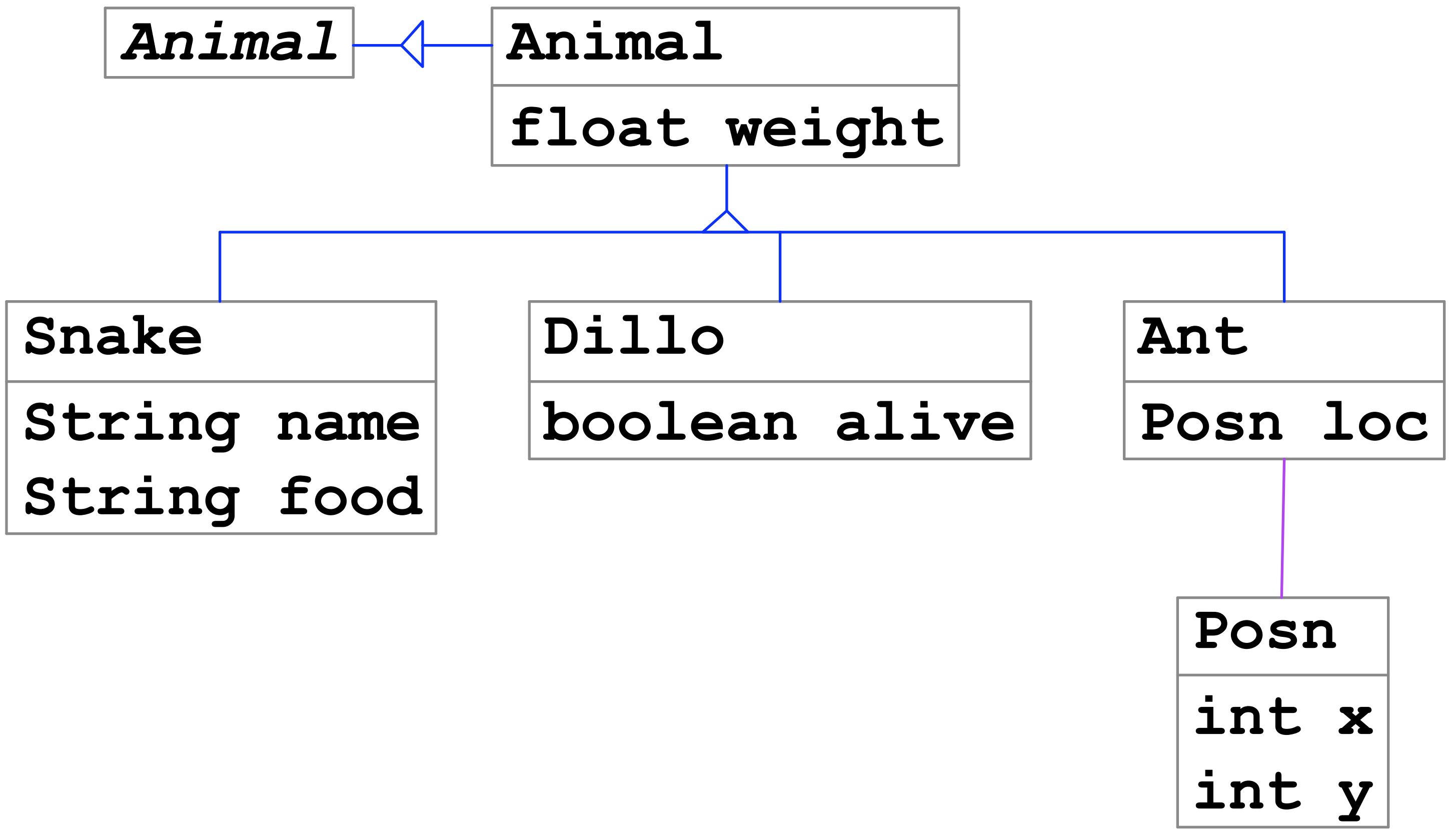
Field Abstraction



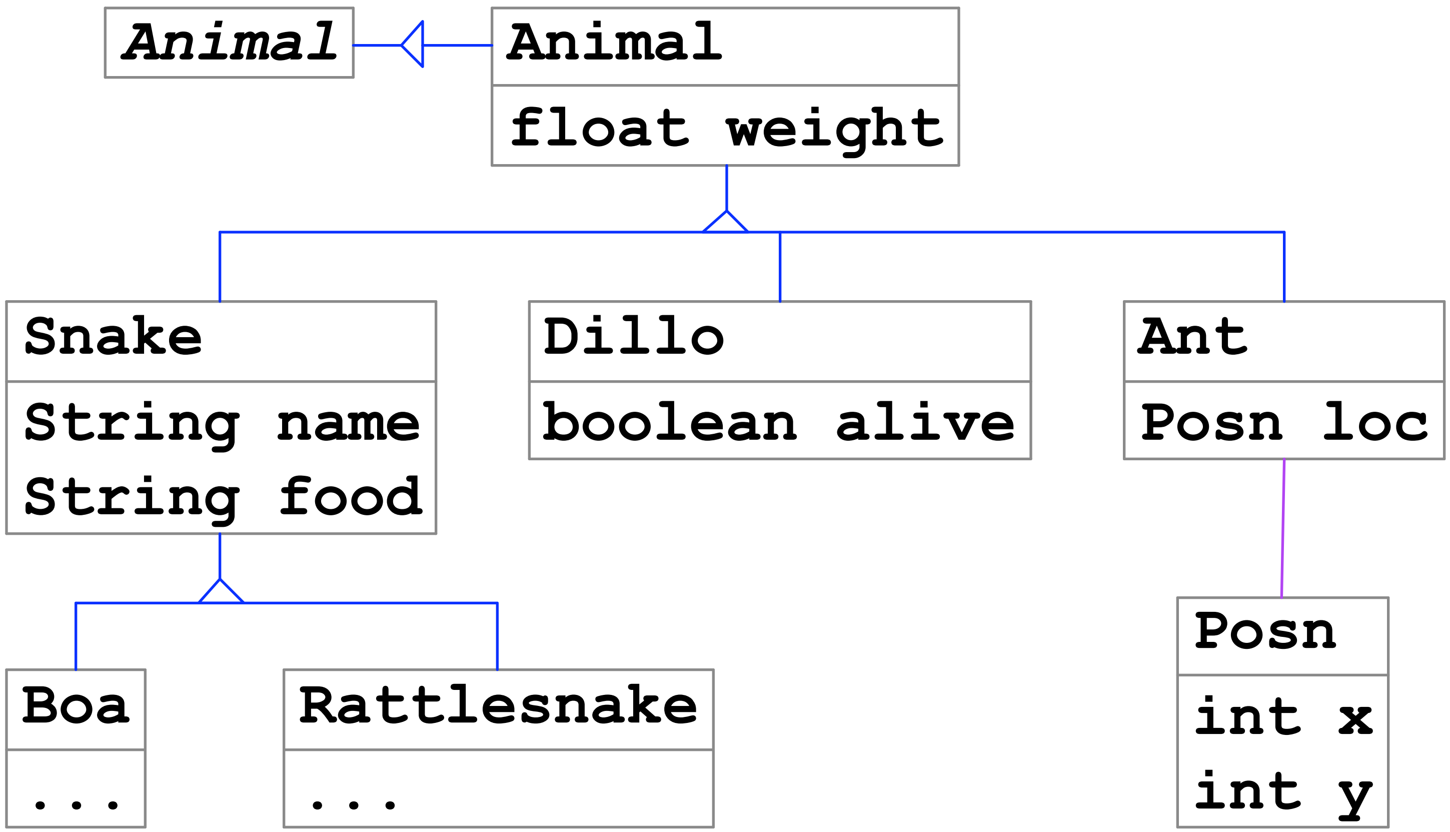
Field Abstraction



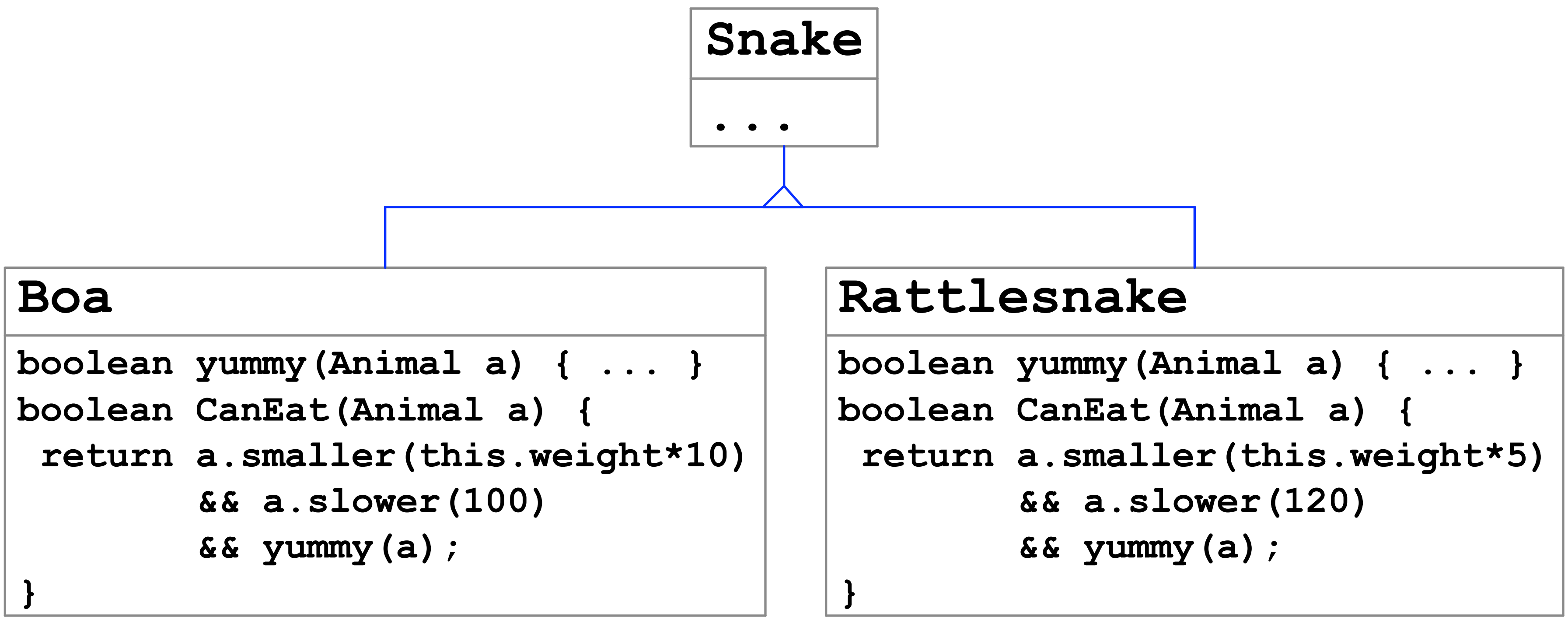
Field Abstraction



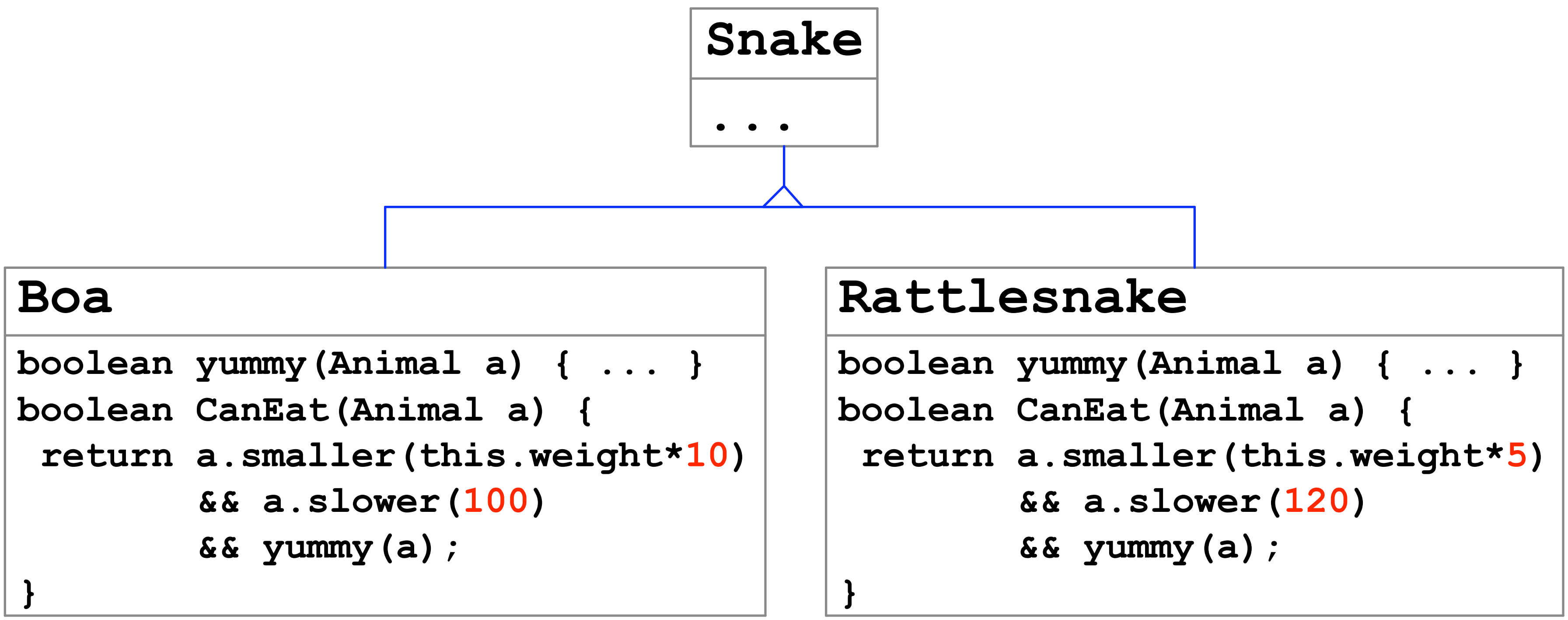
Deep Hierarchies



Deep Hierarchies



Deep Hierarchies



Deep Hierarchies

```
Snake
...
abstract boolean yummy(Animal a);
boolean CanEatWFacts(Animal a, int wf, int sd) {
 return a.smaller(this.weight*wf)
        && a.slower(sd)
        && yummy(a);
}
```

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

```
Rattlesnake
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

$\Rightarrow$ theory and practice coincide!

Part V: Encapsulated State

Or, without hiding and encapsulating state, it can't be real OOP — right?

Encapsulated State

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

```
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!