Object-Oriented Languages, Fixed Points, and Systems of Objects

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Based on work with Leaf Petersen, Joe Vanderwaart, and Nate Foster

FOOL History

- FOOL 1 - Stanford University in October 1993.
- FOOL 2 - Paris in July 1994.
  - *"On binary methods" w/ 8 co-authors*
- FOOL 3 - New Brunswick, New Jersey on July 1996.
- FOOL 4 - Paris in January 1997 w/ POPL

Outline

- History of Semantics of OO Languages
- Objects, Classes, and Fixed Points
- Problems When No Fixed Points
- Mutually Recursive Fixed Points

Restrict attention to class-based languages.

Early Semantics

- Cardelli
  - Objects as records of functions
- Cook & Palsberg, Reddy
  - Objects as fixed points of records
- Abel group
  - Typed semantics of objects and classes using fixed points *(no instance variables)*
- Kamin (untyped), Mitchell (typed)
  - Operational semantics using self-application

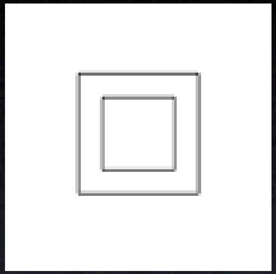
More early semantics

- Pierce, Bruce semantics with instance vbles
  - Both used existentials, differed in fixed points of types
- Abadi & Cardelli
  - operational semantics of object calculus
  - with Viswanathan, using fixed points on types
    - allows method updates in objects
- See “Comparing object encodings” by Bruce, Cardelli, & Pierce.

Fixed-point notation

- Let F: D → D
- Write Rec(d).F(d) for the "least" fixed point of F.
  - I.e., if a = Rec(d).F(d) then a = F(a).
- Say F is a generator of the fixed point
- We will interpret "this" or "self" in object-oriented languages as a fixed point.

A simple example



```
public class Squares {
    private FramedRect outer, inner;

    public Squares(Location upleft, int size,
        DrawingCanvas canvas){...}

    public void move(int dx, int dy) {
        this.outer.move(dx,dy);
        this.inner.move(dx,dy);
    }

    public void moveTo(int x, int y) {
        this.move(x - this.outer.getX(),  y - this.outer.getY());
    }
}
```

Understanding Objects

First naive view of objects:

```
⟦new Squares(...)⟧ =
    ({ outer = ref ...,              // no mention of this
       inner = ref ... },
     { move = fun(dx,dy). this.outer.move(...)...,
       moveTo = fun(x,y). this.move(...) })

where this = ({ outer = ...},
              { move = fun(dx,dy).
                    this.outer.move(...)...})
```

Understanding Objects

Equivalently:

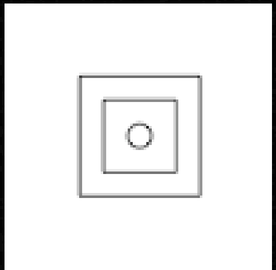
```
⟦new Squares(...)⟧ = Rec(this).
           ({ outer = ref ..., // no mention of this
              inner = ref ... },
            { move = fun(dx,dy). this.outer.move(...)...,
              moveTo = fun(x,y). this.move(...) })
```

Defines mutually recursive methods

Classes are Generators

- Classes serve many roles:
  - Types
  - Generators of new objects
- *Extensible* via subclasses to form new generators

Subclass



```
public class OvalSquares extends Squares {
    private FramedOval center;

    public OvalSquares(Location upleft,
            int size, DrawingCanvas canvas) {
        super(upleft, size, canvas);
        this.center = new FramedOval(...);
    }
    public void move(int dx, int dy) {
        super.move(dx, dy);  // old move
        this.center.move(dx, dy);
    }
}
```

What happens to moveTo?

Classes Are Generators of Fixed Points

- Meaning of *this* is not bound in classes
- Semantics of moveTo changes (indirectly) in OvalSquares:
  - someSquares = Rec(*this*). SQ(*this*)
  - someOvalSquares = Rec(*this'*). OSQ(*this'*) where OSQ extends SQ.
- Objects formed as *fixed points* of SQ and OSQ.

Semantics of Classes?

Methods must be meaningful in all possible subclasses.

$[\![$`class(i:I,m:M)`$]\!] =$

$$\Lambda\, M' <: [\![\mathtt{M}]\!].\ \Lambda\, IR' <: [\![\mathtt{I}^{ref}]\!].$$

$$(\,[\![\mathtt{i}]\!]\ ,\ \lambda(this : IR' \times (IR' \rightarrow M')).\ [\![\mathtt{m}]\!]\,)$$

initial values of instance variables

methods

Semantics of Objects

$[\![\texttt{new Squares(...)}]\!] =$

$(\{\ \mathit{outer} = \mathit{ref}\ ...,\ \mathit{inner} = \mathit{ref}\ ...\ \},$

$\mathrm{Rec}(\mathit{fm} : [\![\texttt{I}^{\mathit{ref}}]\!] \rightarrow [\![\texttt{M}]\!]).$

$\lambda(\mathit{inst} : [\![\texttt{I}^{\mathit{ref}}]\!]).$

$\{\ \mathit{move} = \mathit{fun}(dx,dy).\ \mathit{inst}.\mathit{outer}...,$

$\mathit{moveTo} = \mathit{fun}(x,y).\langle \mathit{inst},\mathit{fm} \rangle.\mathit{move}(...)\ \})$

Method suite can be shared between objects of same type.

Sending Messages

Suppose $[\![\texttt{obj}]\!] = \langle \texttt{i}, \texttt{fm} \rangle$

then $[\![\texttt{obj.p(...)}]\!] = \mathit{fm}(i).p(\ldots)$

In objects, methods fixed -- parameterized by suite of instance variables, not this.

Summary of Semantics

- *Fixed points* are key to understanding O-O languages.
- Classes are *extensible generators* of fixed points.
- Objects are formed as *fixed points*.

Type of Class

$$[\![\texttt{class(i:I,m:M)}]\!] =$$

$$\Lambda\, M' <: [\![\texttt{M}]\!].\, \Lambda\, IR' <: [\![\texttt{I}^{ref}]\!].$$

$$(\, [\![\texttt{i}]\!]\, ,\, \lambda(this : IR' \times (IR' \rightarrow M')).\ [\![\texttt{m}]\!]\,)$$

$$[\![\texttt{Class(I,M)}]\!] =$$

$$\forall\, M' <: [\![\texttt{M}]\!].\, \forall\, IR' <: [\![\texttt{I}^{ref}]\!].$$

$$[\![\texttt{I}]\!] \times (\underline{IR' \times (IR' \rightarrow M')} \rightarrow [\![\texttt{M}]\!])$$

$ThisClass_{int}$

The Type of "this"

Inside methods

this : ThisClass_{int}

where $[\![\text{ThisClass}_{int}]\!] = IR' \times (IR' \rightarrow M')$

When return this, hide instance variables:

this : ThisClass_{ext}

where $[\![\text{ThisClass}_{ext}]\!] = \exists X.\, X \times (X \rightarrow M')$

ThisClass as a Type

Can declare:

clone: () → @ThisClass

If obj has type @T, then value of obj can have type T, but not a subtype.

Subsumption: e: @T ⇒ e: T

Also examples with parameters of type ThisClass -- called *binary methods*

LOOJ Example

(Bruce & Foster, ECOOP '04)

```
public class Node {
   protected @ThisClass next;
   public Node(@ThisClass next) {
     this.next = next;
   }

   public void setNext(@ThisClass newNext) {
     this.next = next;
   }

   public @ThisClass getNext() {
     return next;
   }
}
```

binary method

Subclasses

```
public class DbleNode extends Node {
   protected @ThisClass prev;
   public DbleNode(@ThisClass next,
                   @ThisClass prev) {
     super(next);
     this.prev = prev;
   }
   public void setNext(@ThisClass newNext) {
     super.setNext(newNext);
     newNext.setPrev(this);
   }
   public void setPrev(@ThisClass newPrev) {
     this.prev = newPrev;
   }
   ...
}
```

Type-Checking

- Can only send binary message to object if know its exact type - @C.
- If o: @C and m: U then o.m: U[C/ThisClass]
- If o: C then o.m: U[C/@ThisClass, ThisClass]
  - If m: @Node then m.clone(): @Node
  - If n: Node then n.clone(): Node
  - m.setNext(m) *legal*, n.setNext(m) *illegal*

Type of Objects

If get object from

```
class C{i:I(ThisClass),
        m:M(ThisClass)}
```

Then meaning of type of objects is:

$$[\![C]\!] = \mathit{Rec}(\mathit{ThisClass}).\ \exists X.\ X \times (X \to M(\mathit{ThisClass}))$$

Type-Checking Classes

- Type-check modularly.
- Type-check methods of class C under assumptions that hold in all extensions!
  - this : ThisClass
  - ThisClass extends C

Can prove soundness of type system. (ECOOP '04)

F-bounded Polymorphism

- F-bounded polymorphism introduced by Mitchell and the Abel group (similar to other proposals). *Now in Java 5.*
- Very expressive, but not work smoothly with inheritance hierarchy.

F-bounded Polymorphism

```
abstract class ComparableF<T> {
   boolean lessThan(T other); }

class BinTree<T extends ComparableF<T>>
 {...}

class Point extends ComparableF<Point>{
   boolean lessThan(Point other){...} }

class ColorPoint extends Point {...}
```

Is `BinTree<ColorPoint>` *legal?*

In some situations need `T = ComparableF<T>`

Fixed w/ ThisClass

```
abstract class Comparable {
   boolean lessThan(ThisClass other); }

class BinTree<T extends Comparable>
 {...}

class Point implements Comparable{
   boolean lessThan(ThisClass other){...} }

class ColorPoint extends Point {...}
```

`BinTree<ColorPoint>` *is legal!*

Interacting Systems

- Expression problem
  - *See solution in §6 of my WOOD 2003 paper.*
  - *Scala solution later today*
- Subject-Observer pattern

Virtual Classes

```
class Observer {
  typedef SType as Subject;
  typedef EType as Event;
  void notify (SType subj, EType e) {…};
}

class Subject {
  typedef OType as Observer;
  typedef EType as Event;
  OType[] observers;        ...
  void notifyObservers(EType e) {
    for (obs:observers)
      obs.notify(this,e);
  }
}
```

Specializing Virtual Classes

```
class MenuObserver extends Observer {
  typedef SType as MenuSubject;
  typedef EType as MenuEvent;
  void notify (SType subj, EType e) {
    … subj.getSelectedLabel() …};
}

class MenuSubject extends Subject {
  typedef OType as MenuObserver;
  typedef EType as MenuEvent;
  void getSelectedLabel(){…}
    …
}
```

Mutually Recursive Groups

```
group SubjectObserver{
  class Observer {
    void notify (@ThisTG.Subject subj,
                 @ThisTG.EventType e) {…};
  }
  class Subject {
    void notifyObservers(@ThisTG.EventType e) {
      for (obs:observers)
        obs.notify(this,e);
    }
  }
  class Event {…}
}
```

Extending Groups

```
group MenuSubObs extends SubjectObserver{
  class Observer {
    void notify (@ThisTG.Subject subj,
                @ThisTG.EventType e) {
        … subj.getSelectedLabel()…};
  }
  class Subject {
    String[] labels;
    String getSelectedLabel() {…};
  }
  …
}
```

Semantics of Groups

If group TG {C_1 = Class(…,M_1(ThisTG)), …,

C_n = Class(…,M_n(ThisTG)) }

then types corresponding to `TG` given by:

$$Rec(ThisTG).\{C_1 = \exists X.\, X \times (X \rightarrow M_1(ThisTG))\ldots,$$

$$C_n = \exists X.\, X \times (X \rightarrow M_n(ThisTG))\ \}$$

Type-Checking Rules

- ... similar to as before.
  - Need exact types for receiver of methods with ThisTG in parameter positions.
  - Type-check under weak assumptions on ThisTG
  - Proof of type-safety similar
    - *done for extension of LOOM, not LOOJ*

Even More ...

- Groups can preserve relations between classes
  - If class A extends B in group G, and G' extends G, then A also extends B in G'

Example

Borrowed from Jiazzi

```
group GUIComponents {
   class Component {...}
   class Button extends ThisTG.Component {...}
   class Window extends ThisTG.Component {
      void addComp(@ThisTG.Component c){...}
   }
}
```

Extending ...

```
group ColorGUIComponents
                          extends Components {
   class Component {
      Color currentColor;
      void setColor(Color clr){...}
   }
}
```

All extensions of Component gain Color.

Type error if conflicts!

Polymorphism Works

```
@ColorComponents.Window clrWindow;
@ColorComponents.Button clrButton;

clrWindow.addComponent(clrButton);
      // because Button still extends Window

<G extends GUIComponents>
  void doGUIStuff (@G.Button button,
                   @G.Window window) {
      ... window.addComponent(button)... }
```

Type-checking rules ensure safety!

ThisTG vs. ThisType

- ThisType as fixed point:
  - Works well, but complications because of exact types and binary methods.
- ThisTG as mutually recursive fixed point
  - Works better, especially if default is exact group.
  - Generalization may be more fundamental than original.

Related Work

- Beta's Virtual Types and proposed Java extensions by Thorup and Torgersen
- Bruce & Vanderwaart '99
  - w/weaker type system
- Family Polymorphism - Erik Ernst
- Scala - Odersky et al - dependent types
- Nested Inheritance - Nystrom, Chong, & Myers *(restricted to exact types)*

More Related Work

- Hand-rolled fixed points:
  - Units & Mixins - Findler and Flatt
  - Jiazzi (Java extension) - McDirmid, Flatt, and Hsieh
  - Collaborations - Smaragdakis and Batory
- OCAML - Remy & Vouillon
  - Type inference and row types

Questions?