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.
  - “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 $F : D \rightarrow D$
- Write $\text{Rec}(d).F(d)$ for the “least” fixed point of $F$.
  - I.e., if $a = \text{Rec}(d).F(d)$ 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

```java
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());
    }
}
```
First naive view of objects:

\[
\left[ \text{new Squares(...)\ldots} \right] = \left( \{ \text{outer} = \text{ref \ldots}, \right. \\
\left. \text{inner} = \text{ref \ldots} \}, \right.
\left. \{ \text{move} = \text{fun(dx,dy). this.outer.move(...)\ldots,} \right. \\
\left. \text{moveTo} = \text{fun(x,y). this.move(...) } \} \right)
\]

where this = (\{ \text{outer} = \ldots \},
\left. \{ \text{move} = \text{fun(dx,dy). this.outer.move(...)\ldots} \right. \)}}
Equivalently:

\[
\begin{align*}
\text{new Squares(...)} &= \text{Rec(this)}. \\
\{ & \text{outer} = \text{ref} ..., \text{// no mention of this} \\
\text{inner} = \text{ref} ... \}, \\
\{ & \text{move} = \text{fun(dx,dy). this.outer.move(...)} ..., \\
\text{moveTo} = \text{fun(x,y). this.move(...)} \}
\end{align*}
\]

*Defines mutually recursive methods*
Classes are Generators

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

\[ \llbracket \text{class}(i:i,I,m:M) \rrbracket = \lambda M' \llbracket M \rrbracket. \lambda IR' \llbracket I^\text{ref} \rrbracket. \]

\[ ([i], \lambda (this: IR' \times (IR' \rightarrow M')). [m]) \]

initial values of instance variables

methods
Semantics of Objects

\[ [\text{new Squares}(\ldots)] = \]
\[
\{ \text{outer} = \text{ref} \ldots, \text{inner} = \text{ref} \ldots \},
\]

\[
\text{Rec}(\text{fm} : [\text{ref}] \rightarrow [\text{M}]).
\]
\[
\lambda(\text{inst} : [\text{ref}]).
\]
\[
\{ \text{move} = \text{fun}(dx,dy).\ \text{inst}.\text{outer}\ldots,
\]
\[
\text{moveTo} = \text{fun}(x,y).\langle\text{inst, fm}\rangle.\text{move}(\ldots) \}
\]

Method suite can be shared between objects of same type.
Suppose $[\text{obj}] = \langle i, fm \rangle$

then $[\text{obj} \cdot p(\ldots)] = fm(i).p(\ldots)$

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

\[
\llbracket \text{class}(i:I,m:M) \rrbracket = \\
\Lambda M' <: [M]. \Lambda IR' <: [I^{\text{ref}}]. \\
([i], \lambda (\text{this} : IR' \times (IR' \rightarrow M')). [m])
\]

\[
\llbracket \text{Class}(I,M) \rrbracket = \\
\forall M' <: [M]. \forall IR' <: [I^{\text{ref}}]. \\
[I] \times (IR' \times (IR' \rightarrow M') \rightarrow [M])
\]

ThisClass_{int}
The Type of "this"

Inside methods

\[
\text{this} : \text{ThisClass}_{\text{int}}
\]

where \( \llbracket \text{ThisClass}_{\text{int}} \rrbracket = IR' \times (IR' \rightarrow M') \)

When return \text{this}, hide instance variables:

\[
\text{this} : \text{ThisClass}_{\text{ext}}
\]

where \( \llbracket \text{ThisClass}_{\text{ext}} \rrbracket = \exists X. X \times (X \rightarrow M') \)
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
public class Node {
    protected @ThisClass next;
    public Node(@ThisClass next) {
        this.next = next;
    }
    public void setNext(@ThisClass newNext) {
        this.next = newNext;
    }
    public @ThisClass getNext() {
        return next;
    }
}
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 $n.clone(): Node$
  - $m.setNext(m)$ 	extit{legal}, $n.setNext(m)$ 	extit{illegal}
Type of Objects

If get object from

\[
\text{class } C\{i:I(\text{ThisClass}), m:M(\text{ThisClass})\}
\]

Then meaning of type of objects is:

\[
\llbracket C \rrbracket = \text{Rec}(\text{ThisClass}). \exists X. X \times (X \rightarrow M(\text{ThisClass}))
\]
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.
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>
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 \( \{ C_1 = \text{Class}(\ldots, M_1(\text{ThisTG})), \ldots, 
C_n = \text{Class}(\ldots, M_n(\text{ThisTG})) \} \)

then types corresponding to TG given by:

\[
\text{Rec}(\text{ThisTG}). \{ C_1 = \exists X. X \times (X \to M_1(\text{ThisTG})) \ldots,
C_n = \exists X. X \times (X \to M_n(\text{ThisTG})) \} 
\]
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’
group GUIComponents {
    class Component {...}
    class Button extends ThisTG.Component {...}
    class Window extends ThisTG.Component {
        void addComp(@ThisTG.Component c){...}
    }
}
Extending ...

```java

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?