Formal AOP: Opportunity Abounds

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Much of this talk reports on joint work with

Glen Bruns

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I will try to say something interesting.

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  - Limiting the power of AOP — Equational Reasoning

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- Cheese and Ham.
  - Class-based AOP and Weaving (with types)
  - “Pure” AOP

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- Waffle.
    - Limiting the power of AOP — Equational Reasoning
- Cheese and Ham.
    - Class-based AOP and Weaving (with types)
    - “Pure” AOP
- Waffle.
    - Increasing the power of AOP — Temporal Logics

Focus of attention: aspects as method/function call interceptors.

Opening Waffle

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The “Right” Abstractions

More complex programs require more expressive abstractions (ie, better tools).

- FORTRAN/ALGOL: expressions/recursive functions
- Structured Programming: first order control structures
- Labelled Break Statements/Exceptions: finally eliminate goto
- Higher-Order Programming: programmable control structures
- Modules/OO Programming: encapsulation of data and control
- Patterns: popularize higher-order OO
- AO Programming: encapsulation of “concerns” (Flavors)

Concerns

So what are we concerned about?

- Primary functionality (in its many aspects)
- Synchronization
- Persistence/Distribution
- User Interfaces
- Caching
- Security
- ...

How do we code using OOP/FP?

OOP/FP Solutions

- Hooks (Publish/Subscribe, Visitors) — must be placed ahead
- Wrappers (Decorators) — can be circumvented

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AOP to the Rescue

- Obliviousness — no need to plan ahead
- Quantification — no way to circumvent

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Why Aren’t We All Programming in Prolog?

Programming with quantification is a pain.

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Why Aren't We All Programming in Assembly Language?

Programming without equational reasoning is a pain.

Why Aren’t We All Programming in Prolog?

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Why Aren’t We All Programming in the Pi Calculus?

Same question.

Abstractions of the language need to support the way we work.

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AOP: The Declarative Imperative

Fillman and Friedman: *The cleverness of classical AOP is augmenting conventional sequentiality with quantification, rather than supplanting it wholesale.*

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- How can we reasonably quantify over programs?
- How can we reason about programs over which we quantify?

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AOP: The Declarative Imperative

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- How can we reasonably quantify over programs?
- How can we reason about programs over which we quantify?

Obliviousness is a two edged sword:

- Code providers should be oblivious to aspects — attach them where you like
- Code clients should be oblivious to aspects — assure that contracts will be validated

In both cases equational reasoning is essential.

Aspects Break Equational Reasoning: I

```
class C { void foo() { } }
class D1 extends C { }
class D2 extends C { void foo() { super.foo(); } }

aspect Diff {
   void around(): execution(D.foo()) {
      System.out.println("aspect in action");
   }
}
```

D1.foo() $\neq$ **D2.foo()**.

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Aspects Break Equational Reasoning: II

```
class E1 {
  void f() { f(); }
  void g() { g(); }
}
class E2 {
  void f() { g(); }
  void g() { f(); }
}
aspect Diff {
   void around(): execution(E.f()) {
      System.out.println("aspect in action");
   }
}
```

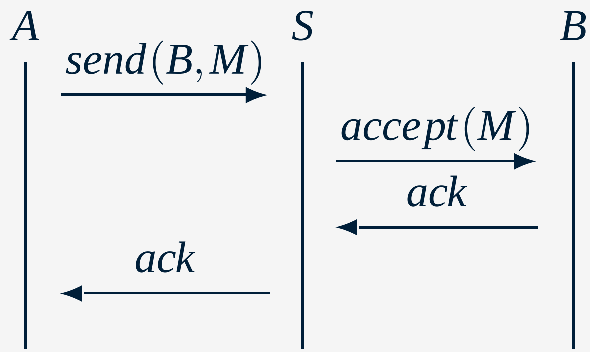
`E1.f()` $\neq$ **`E2.f()`**.

Also consider “jumping” and “vanishing” aspects.

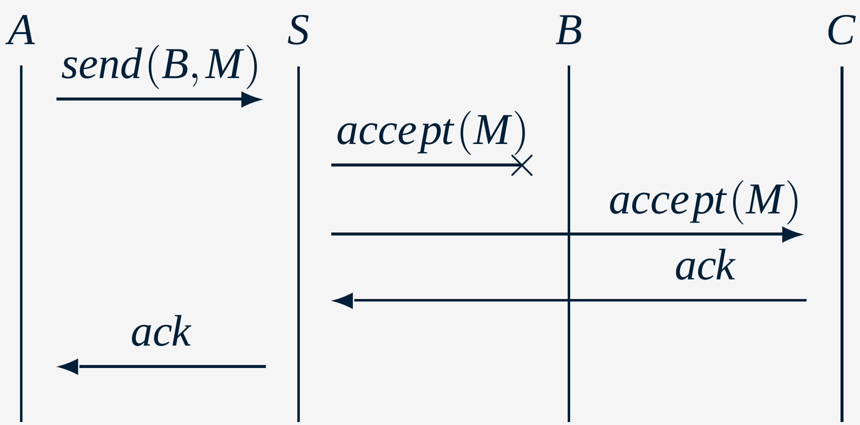
(example from Mitch Wand)

Aspects Interfere with Each Other

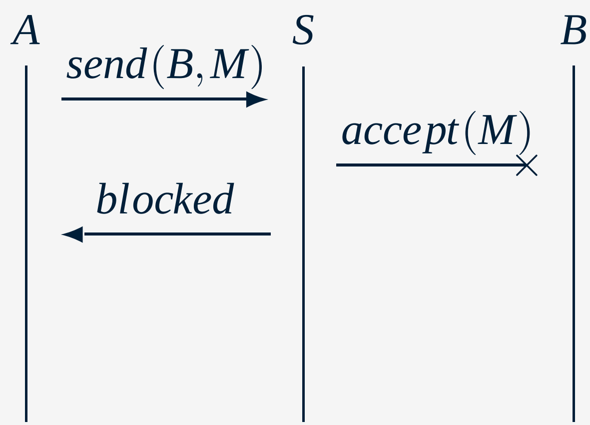
Alice calls Bob using a Server



Bob Forwards to Charlie



Bob blocks calls from Alice



WWDD?

Are aspects the new **`goto`**?

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WWDD?

Are aspects the new **`goto`**?

- **`goto`** problem “solved” by finding sufficiently expressive abstractions for control.
- Sanity of Hoare Logic mostly restored.
- Aspects will inevitably follow the same path. (Much work done in this direction, eg [Aldrich, thirty minutes ago].)
- [Wand ICFP 2003]: Need general support for domain-specific aspect languages. Need specification-level joint-point ontologies (AspectJ is implementation level.)
- Connections with behavioral types, behavioral subtyping.
- Contextual equivalence [Gordon’s applicative bisimulation] as useful tool. What are the observable events?

A Continuum of Approaches

- Meta-Object Protocols/Full-blown Introspection with Intercession
  - Compile-time
  - Load-time
  - Run-time
- Clearbox AOP (a lá AspectJ [Kiczales, et al])
- Blackbox AOP (a lá Composition Filters [Aksit, et al])
- Domain-Specific AOP
- Traditional OO/FP

What is the sweet spot?

AOP in the Wild Wild West

AOP is exploring its power.

Wither formal aspects of aspects?

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- Local sheriff — calls it like it is

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- School marm — drawing in the reigns

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- Local sheriff — calls it like it is
- School marm — drawing in the reigns
- Stranger without name — enabling new conquests

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AOP in the Wild Wild West

AOP is exploring its power.

Wither formal aspects of aspects?

- Local sheriff — calls it like it is
- School marm — drawing in the reigns
- Stranger without name — enabling new conquests
  - Hooker with heart of gold, if you prefer

Some Examples (Quickly)

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Lopes Example: Bounded Buffer

DJ	JAVA
see DJ code below	see Java code below

DJ

```
public class BoundedBuffer {
  private Object array[];
  private int putPtr = 0, takePtr = 0;
  private int usedSlots=0;

  public BoundedBuffer(int capacity) {
    array = new Object[capacity];
  }

  public void put(Object o) {
    array[putPtr] = o;
    putPtr = (putPtr + 1) % array.length;
    usedSlots++;
  }

  public Object take() {
    Object old = array[takePtr];
    array[takePtr] = null;
    takePtr = (takePtr + 1) % array.length;
    usedSlots--;
    return old;
  }
}

coordinator BoundedBuffer {
 selfex put, take;
 mutex {put, take};
 cond full = false, empty = true;
 put: requires !full;
   on_exit {
     empty = false;
     if (usedSlots == array.length)
          full = true;
   }
 take:  requires !empty;
     on_exit {
       full = false;
       if (usedSlots == 0) empty = true;
     }
}
```

JAVA

```
public class BoundedBuffer {
  private Object[] array;
  private int putPtr = 0, takePtr = 0;
  private int usedSlots = 0;

  public BoundedBuffer (int capacity) {
    array = new Object[capacity];
  }

  public synchronized void put(Object o) {
    while (usedSlots == array.length) {
      try {
        wait();
      }
      catch (InterruptedException e) {};
    }
    array[putPtr] = o;
    putPtr = (putPtr + 1) % array.length;
    }
    if (usedSlots++ == 0)
      notifyAll();
  }

  public synchronized Object take() {
    while (usedSlots == 0) {
      try {
        wait();
      }
      catch (InterruptedException e) {};
    }
    Object old = array[takePtr];
    array[takePtr] = null;
    takePtr = (takePtr+1) % array.length;
    }
    if (usedSlots-- == array.length)
      notifyAll();
    return old;
  }
}
```

Lopes Example: Distributed Book Locator

DJ

```
portal BookLocator {
 void register (Book book, Location l);
 Location locate (String title)
 default:
   Book: copy{Book only title,author,isbn;}
}
portal Printer {
  void print(Book book) {
    book: copy { Book only title,ps; }
  }
}

class Book {
  protected String title, author;
  protected int isbn;
  protected OCRImage firstpage;
  protected Postscript ps;
  // All methods omitted
}
class BookLocator {
  // books[i] is in locations[i]
  private Book     books[];
  private Location locations[];
  // Other variables omitted
  public void register(Book b, Location l){
    // Verify and add book b to database
  }
  public Location locate (String title) {
    Location loc;
    // Locate book and get its location
    return loc;
  }
  // other methods omitted
}
class Printer {
  public void print(Book b) {
    // Print the book
  }
}

coordinator BookLocator {
  selfex register;
  mutex {register, locate};
}
```

JAVA

```
interface Locator extends Remote {
 void register(String title,
               String author, int isbn,
               Location l)
      throws RemoteException;
 Location locate(String title)
      throws RemoteException;
}
interface PrinterService extends Remote {
  void print(String title, Postscript ps)
      throws RemoteException;
}
class Book {
  protected String title, author;
  protected int isbn;
  protected OCRImage firstpage;
  protected Postscript ps;
  // All methods omitted
}
class BookLocator
        extends UnicastRemoteObject
        implements Locator {
  // books[i] is in locations[i]
  private Book     books[];
  private Location locations[];
  // Other variables omitted
  public void register (String title,
                        String author,
                        int isbn,
                        Location l)
         throws RemoteException {
    beforeWrite(); //for synchronization
    Book b=new Book (title, author, isbn);
    // Verify and add book b to database
    afterWrite(); //for synchronization
  }
  public Location locate (String title)
         throws RemoteException {
    Location loc;
    beforeRead(); //for synchronization
    // Locate book and get its location
    afterRead(); //for synchronization
    return loc;
  }
  // other methods omitted
}
class Printer extends UnicastRemoteObject
              implements PrinterService {
  public void print(String title,
                    Postscript ps)
         throws RemoteException {
    // Print the book
  }
}
```

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Walker Example: Composable Security

```
fileNotNetwork =
{
  actions:  File.*, Network.*;
  policy:
    next →
      case ⋆ of
        File.* → run (filePolicy)
        Network.* → halt
      end
    done → ()
}
networkNotFile =
{
  actions:  File.*, Network.*;
  policy:
    next →
      case ⋆ of
        File.* → halt
        Network.* → run (networkPolicy)
      end
    done → ()
}
ChineseWall = fileNotNetwork ∨τ networkNotFile
```

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Aldrich Example: Dynamic Programming

```
val fib = fn x:int => 1
around call(fib) (x:int) =
    if (x > 2)
        then fib(x-1) + fib(x-2)
        else proceed x

(* advice to cache calls to fib *)
val inCache = fn ...
val lookupCache = fn ...
val updateCache = fn ...

pointcut cacheFunction = call(fib)
around cacheFunction(x:int) =
    if (inCache x)
        then lookupCache x
        else let v = proceed x
            in updateCache x v; v
```

Figure 2: The Fibonacci function written in `TinyAspect`, along with an aspect that caches calls to `fib`.

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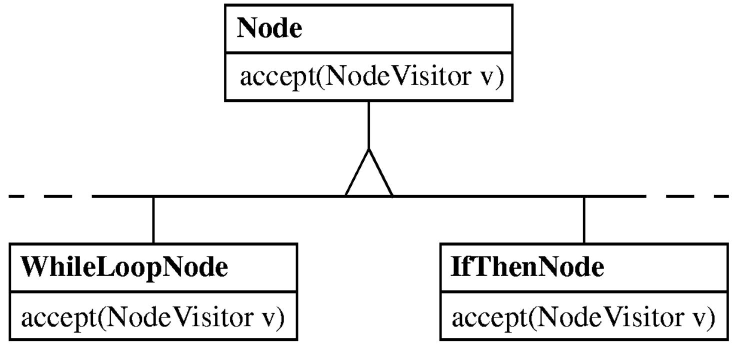
Clifton/Leavens Example: Visitors are Painful

```
public class WhileLoopNode extends Node {
  protected Node condition, body;
  /* ... */
  public void accept(NodeVisitor v) {
    v.visitWhileLoop(this);
  }
}
public class IfThenNode extends Node {
  protected Node condition, thenBranch;
  /* ... */
  public void accept(NodeVisitor v) {
    v.visitIfThen(this);
  }
}
```




```
public abstract class NodeVisitor {
  /* ... */
  public abstract void visitWhileLoop(WhileLoopNode n);
  public abstract void visitIfThen(IfThenNode n);
}
public class TypeCheckingVisitor extends NodeVisitor {
  /* ... */
  public void visitWhileLoop(WhileLoopNode n) { n.getCondition().accept(this); /* ... */ }
  public void visitIfThen(IfThenNode n) { /* ... */ }
}
```

Figure 1: Java code for some participants in the Visitor design pattern

```
// Methods for typechecking
public boolean Node.typeCheck()
  { /* ... */ }
public boolean WhileLoopNode.typeCheck()
  { /* ... */ }
public boolean IfThenNode.typeCheck()
  { /* ... */ }
```

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Flatt/Krishnamurthi/Felleisen Example: Mixins as Wrappers

```
class LockedDoor^c extends Door^c {
  boolean canOpen(Person^c p) {
    if (!p.hasItem(theKey)) {
      System.out.println("You don't have the Key");
      return false;
    }
    System.out.println("Using key...");
    return super.canOpen(p);
  }
}
class ShortDoor^c extends Door^c {
  boolean canPass(Person^c p) {
    if (p.height() > 1) {
      System.out.println("You are too tall");
      return false;
    }
    System.out.println("Ducking into door...");
    return super.canPass(p);
  }
}

/* Cannot merge for LockedShortDoor^c */
```

```
interface Door^i {
  boolean canOpen(Person^c p);
  boolean canPass(Person^c p);
}
mixin Locked^m extends Door^i {
  boolean canOpen(Person^c p) {
    if (!p.hasItem(theKey)) {
      System.out.println("You don't have the Key");
      return false;
    }
    System.out.println("Using key...");
    return super.canOpen(p);
  }
}
mixin Short^m extends Door^i {
  boolean canPass(Person^c p) {
    if (p.height() > 1) {
      System.out.println("You are too tall");
      return false;
    }
    System.out.println("Ducking into door...");
    return super.canPass(p);
  }
}
class LockedDoor^c = Locked^m(Door^c);
class ShortDoor^c = Short^m(Door^c);
class LockedShortDoor^c = Locked^m(Short^m(Door^c));
```

Fig. 9. Some class definitions and their translation to composable mixins

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Semantics

Understanding Pointcuts and Advice

Much work has been done.

- Connections with other things: Predicate Dispatching, Multimethods, MOPs, Reflection, Dynamically Scoped Functions, Subject Oriented Programming, *Coordination Languages?*, *Logic and constraint programming?*

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- Semantics: Denotational, Big-step operational, Small-step operational, Haskell, Scheme, Common Lisp. Eg, [de Meuter], [Andrews], [Douence Motelet Sudholt], [Lämmel], [Wand Kiczales Dutchyn], [Masuhara Kiczales Dutchyn], [Walker Zdancewic Ligatti]

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- Emphasis on understanding context-dependent pointcuts (**`cflow`**). Eg, [Wand Kiczales Dutchyn 2002].

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- Emphasis on understanding context-dependent pointcuts (**`cflow`**). Eg, [Wand Kiczales Dutchyn 2002].
- Our work: Emphasis on difference between pointcuts that fire before and after a call. Closest related work is [Lämmel 2002].

A Calculus of AO Programs (ECOOP 2003)

- Direct semantics of class-based and aspect-based languages.
- Small core of orthogonal primitives in ABL.
  - Only **`around`** advice — encode **`before`** and **`after`**
  - No method bodies — only advice bodies
  - Only call/execution pointcuts — and boolean connectives
- Concurrency and nested declarations are easy.
- Punted advice ordering: assume a global order on names.
- Specification of weaving and proof of correctness (in absence of dynamically arriving advice).

Specification of Weaving

No reductions are lost:

complete
$$
\begin{tikzcd}
P_{\mathrm{ABL}} \arrow[r, Rightarrow, "weave"] \arrow[d, -{Triangle[open]}] & P_{\mathrm{CBL}} \\
P'_{\mathrm{ABL}} &
\end{tikzcd}
$$
as
$$
\begin{tikzcd}
P_{\mathrm{ABL}} \arrow[r, Rightarrow, "weave"] \arrow[d, -{Triangle[open]}] & P_{\mathrm{CBL}} \arrow[d, -{Latex}] \\
P'_{\mathrm{ABL}} \arrow[r, Rightarrow, "weave"] & P'_{\mathrm{CBL}}
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P'_{\mathrm{ABL}} \arrow[r, Rightarrow, "weave"] & P'_{\mathrm{CBL}}
\end{tikzcd}
$$

($\rightarrow$ is OO reduction; $\rightarrowtriangle$ is AO reduction)

Example: s delegates to t

```
class S {
  void print() { out.print("I am a S"); }
  void foo(T t) { t.bar(); }
}
class T {
  void print() { out.print("I am a T"); }
  void bar() { }
}
advice A at call(T.bar()) {
  out.print("Aspect invoked");
  proceed();
}
```

$$\xrightarrow{\texttt{foo(t)}} \texttt{s:S} \xrightarrow[\textit{intercept}]{\texttt{bar()}} \texttt{A} \xrightarrow[\textit{proceed}]{\texttt{bar()}} \texttt{t:T}$$

A intercepts the message.

Call Advice

```
class S {
  void print() { out.print("I am a S"); }
  void foo(T t) { t.bar(); }
}
class T {
  void print() { out.print("I am a T"); }
  void bar() { }
}
protected S advice A at call(T.bar()) {
  this.print();
  target.print();
  proceed();
}
```

`s.foo(t)` prints “**`I am S; I am T`**”.

Call advice executed in the controlling context of the caller

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Exec Advice

```
class S {
  void print() { out.print("I am a S"); }
  void foo(T t) { t.bar(); }
}
class T {
  void print() { out.print("I am a T"); }
  void bar() { }
}
protected T advice A at exec(T.bar()) {
  this.print();
  target.print();
  proceed();
}
```

`s.foo(t)` prints “**`I am T; I am T`**”.

Exec advice executed in the controlling context of the callee

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The Class Calculus: Some Reductions

- Field get

$$\begin{array}{l}\mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\mathsf{f}=\mathsf{v}\ldots\}\\ \mathsf{thread}\ \{\mathsf{let}\ \mathsf{x}=\mathsf{o}.\mathsf{f};\vec{C}\}\end{array} \longrightarrow \begin{array}{l}\mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\mathsf{f}=\mathsf{v}\ldots\}\\ \mathsf{thread}\ \{\mathsf{let}\ \mathsf{x}=\mathsf{v};\vec{C}\}\end{array}$$

- Field set

$$\begin{array}{l}\mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\mathsf{f}=\mathsf{u}\ldots\}\\ \mathsf{thread}\ \{\mathsf{set}\ \mathsf{o}.\mathsf{f}=\mathsf{v};\vec{C}\}\end{array} \longrightarrow \begin{array}{l}\mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\mathsf{f}=\mathsf{v}\ldots\}\\ \mathsf{thread}\ \{\vec{C}\}\end{array}$$

- New declarations

$$\begin{array}{r}\mathsf{thread}\ \{\mathsf{new}\ \mathsf{class}\ \mathsf{c} <: \mathsf{d}\ \{\ldots\};\\ \mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\};\vec{C}\}\end{array} \longrightarrow \begin{array}{l}\mathsf{class}\ \mathsf{c} <: \mathsf{d}\ \{\ldots\}\\ \mathsf{object}\ \mathsf{o}:\mathsf{c}\ \{\ldots\}\\ \mathsf{thread}\ \{\vec{C}\}\end{array}$$

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The Class Calculus: Method call

$\mathsf{class}\ \mathsf{d} \mathbf{<:}\ \mathsf{Object}\ \{ \ldots \mathsf{m}\,\mathbf{(}\mathsf{x}\mathbf{)}\ \{\vec{B}\} \ldots \}$

$\mathsf{class}\ \mathsf{c} \mathbf{<:}\ \mathsf{d}\ \{ \ldots \}$

$\mathsf{object}\ \mathsf{o}\,\mathbf{:}\,\mathsf{c}\ \{ \ldots \}$

$\mathsf{thread}\ \{ \mathsf{o}\,\mathbf{.}\,\mathsf{m}\,\mathbf{(}\mathsf{v}\mathbf{)}\,\mathbf{;}\vec{C} \}$

$\longrightarrow$

$\mathsf{class}\ \mathsf{d} \mathbf{<:}\ \mathsf{Object}\ \{ \ldots \mathsf{m}\,\mathbf{(}\mathsf{x}\mathbf{)}\ \{\vec{B}\} \ldots \}$

$\mathsf{class}\ \mathsf{c} \mathbf{<:}\ \mathsf{d}\ \{ \ldots \}$

$\mathsf{object}\ \mathsf{o}\,\mathbf{:}\,\mathsf{c}\ \{ \ldots \}$

$\mathsf{thread}\ \{ \vec{B}[{}^{\mathsf{o}}/_{\mathsf{this}}, {}^{\mathsf{v}}/_{\mathsf{x}}]\,\mathbf{;}\vec{C} \}$

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The Aspect Calculus

- A pointcut ϕ is an element of the boolean algebra with atoms:
  - call $(c :: m)$
  - exec $(c :: m)$
- An advice declaration D binds message arguments $\vec{x}$ as well as this and target.
  - advice $a(\vec{x})$ at ϕ $\{\vec{C}\}$
- A class declaration D list the methods of the class (no code)
  - class c <: d $\{m_1, m_2 \ldots\}$
- New commands C are:
  - let $x = o[\overline{a}; \overline{b}](\vec{v})$; process call advice $\overline{a}$ and exec advice $\overline{b}$.
  - let $x =$ proceed $(\vec{v})$; proceed to next advice

Supporting Call advice

- To implement call advice a lá AspectJ, record the static type of object references on method calls:

$$\text{let } x \texttt{=} o\texttt{:}c\texttt{.}m\texttt{(}\vec{v}\texttt{);}$$

- To bind this in call advice, record the controlling object of a thread:

$$\text{thread } p \; \{ S \}$$

- These changes are required to implement the dynamic semantics.

Aspect Reduction: Context

$$\text{advice } a_0(x) : \text{call}(c :: m)\ \{\vec{C}_0\}$$

$$\text{advice } a_3(x) : \text{call}(d :: m)\ \{\vec{C}_3\}$$

$$\text{advice } b_1(x) : \text{exec}(c :: m)\ \{\vec{C}_1\}$$

$$\text{advice } b_2(x) : \text{exec}(d :: m)\ \{\vec{C}_2\}$$

$$\text{object } o : d\ \{\ldots\}$$

$$\text{class } d <: c\ \{\ldots\}$$

$$\text{thread } p\{\text{ let } x = o : c.m(v);\ \}$$

Actual type of o is d.

Declared type of o in thread is c.

Aspect Reduction: Fetching Advice

$$\text{advice } a_0(x) : \text{call}(c :: m)\ \{\vec{C}_0\}$$

$$\text{advice } a_3(x) : \text{call}(d :: m)\ \{\vec{C}_3\}$$

$$\text{advice } b_1(x) : \text{exec}(c :: m)\ \{\vec{C}_1\}$$

$$\text{advice } b_2(x) : \text{exec}(d :: m)\ \{\vec{C}_2\}$$

$$\text{object } o : d\ \{\ldots\}$$

$$\text{class } d <: c\ \{\ldots\}$$

$$\text{thread } p\{\text{let } x = o : c.m(v);\}$$

$$\rightarrow\!\triangleright$$

$$\text{thread } p\{\text{let } x = o.[a_0 ; b_1, b_2](v);\}$$

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Aspect Reduction: Call Advice

$$\text{advice } a_0(x) : \text{call}(c :: m)\ \{\vec{C}_0\}$$

$$\text{advice } a_3(x) : \text{call}(d :: m)\ \{\vec{C}_3\}$$

$$\text{advice } b_1(x) : \text{exec}(c :: m)\ \{\vec{C}_1\}$$

$$\text{advice } b_2(x) : \text{exec}(d :: m)\ \{\vec{C}_2\}$$

$$\text{object } o : d\ \{\ldots\}$$

$$\text{class } d <: c\ \{\ldots\}$$

$$\text{thread } p\{\text{let } x = o.[a_0 ; b_1, b_2](v);\}$$

$$\multimap\!\!\!\rhd$$

$$\text{thread } p\{\text{let } x = p\{\vec{C}_0[{}^{v}\!/\!_{x}, {}^{p}\!/\!_{\text{this}}, {}^{o}\!/\!_{\text{target}}, {}^{o.[\emptyset ; b_1, b_2]}\!/\!_{\text{proceed}}]\};\}$$

Controlling context is p.

Aspect Reduction: Exec Advice

$$\text{advice } a_0\,(x) : \text{call}(c :: m)\ \{\vec{C}_0\}$$

$$\text{advice } a_3\,(x) : \text{call}(d :: m)\ \{\vec{C}_3\}$$

$$\text{advice } b_1\,(x) : \text{exec}(c :: m)\ \{\vec{C}_1\}$$

$$\text{advice } b_2\,(x) : \text{exec}(d :: m)\ \{\vec{C}_2\}$$

$$\text{object } o : d\ \{\ldots\}$$

$$\text{class } d <: c\ \{\ldots\}$$

$$\text{thread } p\{\text{let } x = o.[\emptyset\,;\, b_1, b_2](v);\}$$

$$\rightarrow\!\triangleright$$

$$\text{thread } p\{\text{let } x = o\{\vec{C}_1[{}^{v}\!/\!_{x}, {}^{o}\!/\!_{\text{this}}, {}^{o}\!/\!_{\text{target}}, {}^{o.[\emptyset\,;\,b_2]}\!/\!_{\text{proceed}}]\};\}$$

Controlling context is o.

Encoding the CBL into the ABL

- Given a class:

$$\mathsf{class}\ c\ \mathbf{<:}\ \mathsf{Object}\ \{\ldots m\,\mathbf{(}\vec{x}\mathbf{)}\ \{\vec{C}_0\}\ldots\}$$

$$\mathsf{class}\ d\ \mathbf{<:}\ c\ \{\ldots m\,\mathbf{(}\vec{x}\mathbf{)}\ \{\vec{C}_1\}\ldots\}$$

- Create exec advice for each body:

$$\mathsf{advice}\ \mathsf{cbl\_}c\mathsf{\_}m\,\mathbf{(}\vec{x}\mathbf{)}\ \mathbf{:}\ \mathsf{exec}\,\mathbf{(}d\,\mathbf{::}\,m\mathbf{)}\ \{\vec{C}_0[{}^{\mathsf{proceed}}/_{\mathsf{super}\mathbf{.}m}]\}$$

$$\mathsf{advice}\ \mathsf{cbl\_}d\mathsf{\_}m\,\mathbf{(}\vec{x}\mathbf{)}\ \mathbf{:}\ \mathsf{exec}\,\mathbf{(}d\,\mathbf{::}\,m\mathbf{)}\ \{\vec{C}_1[{}^{\mathsf{proceed}}/_{\mathsf{super}\mathbf{.}m}]\}$$

- Ensure that $\mathsf{cbl\_}d\mathsf{\_}m$ has higher priority than $\mathsf{cbl\_}c\mathsf{\_}m$.
- More robust encoding of super uses static dispatch directly.

Weaving

- Programs that dynamically load advice affecting existing classes cannot be woven statically.
- For static advice, weaving is something like macro expansion:

$$\text{class } c \mathbf{<:} \, d \; \{ \, m\,\mathbf{[}\,\emptyset\,\mathbf{;}\, b_1, b_2\,\mathbf{]} \, \}$$

$$\text{advice } b_1\mathbf{(}\vec{x}\mathbf{)}\,\mathbf{:}\,\text{exec}\mathbf{(}d\,\mathbf{::}\,m\mathbf{)} \; \{ \, \vec{C}_1 \, \}$$

$$\text{advice } b_2\mathbf{(}\vec{x}\mathbf{)}\,\mathbf{:}\,\text{exec}\mathbf{(}d\,\mathbf{::}\,m\mathbf{)} \; \{ \, \vec{C}_2 \, \}$$

  is woven recursively as

$$\text{class } c \mathbf{<:} \, \ldots \; \{ \, m\mathbf{(}\vec{x}\mathbf{)} \; \{ \, \vec{C}_1 \left[{}^{\text{this}}\!/\!_{\text{target}}, {}^{\text{this}\mathbf{.}\mathbf{[}\emptyset\,\mathbf{;}\,b_2\mathbf{]}}\!/\!_{\text{proceed}}\right] \, \} \, \}$$

$$\text{advice } b_2\mathbf{(}\vec{x}\mathbf{)}\,\mathbf{:}\,\text{exec}\mathbf{(}d\,\mathbf{::}\,m\mathbf{)} \; \{ \, \vec{C}_2 \, \}$$

- The terminating version of this idea is now standard.

Weaving: Subtleties

- Extra parameter on call advice (for target object)
- Knowledge of controlling object required for call advice
- Must annotate advised method calls with method name (required for switch from call to exec advice)
- Introduce skip step to match advice lookups (required so that reductions match one-to-one)
- Theorem works modulo an equivalence on names (weaving must use actual method name, but aspect code uses name based on advice list)

complete $\begin{tikzcd} P_{\mathrm{ABL}} \arrow[r, Rightarrow, "\mathit{weave}"] \arrow[d] & P_{\mathrm{CBL}} \\ P'_{\mathrm{ABL}} & \end{tikzcd}$ as $\begin{tikzcd} P_{\mathrm{ABL}} \arrow[r, Rightarrow, "\mathit{weave}"] \arrow[d] & P_{\mathrm{CBL}} \arrow[d] \\ P'_{\mathrm{ABL}} \arrow[r, Rightarrow, "\mathit{weave}"] & \simeq \; P'_{\mathrm{CBL}} \end{tikzcd}$

The Full Untyped AOL

$a,..,z$	*Name*
$P,Q ::= (\overline{D} \vdash \overline{H})$	*Program*
$D,E ::=$	*Declaration*
class c **<:** d $\{\, \overline{M} \,\}$	Class
advice a**(**$\vec{x}$**)** **:** ϕ $\{\, \vec{C} \,\}$	Advice
$M ::= m$**[**$\overline{a}\,;\,\overline{b}$**]**	*Method*
$H,G ::=$	*Heap Element*
object o **:** c $\{\, \overline{F} \,\}$	Object
thread $o\{\, S \,\}$	Thread
$F ::= f$ **=** v	*Field*
$S,T ::=$	*Call Stack*
$\vec{C}$	Current Frame
let x**=**$o\{\, S \,\}$**;**$\vec{C}$	Pushed Frame

$C,B ::=$	*Command*
new $\overline{D}\,\overline{H}$**;**	New Declaration
return v**;**	Return
let x**=**v**;**	Value
let x**=**o**.**f**;**	Get Field
set o**.**f**=**v**;**	Set Field
let x**=**o**.**c**::**m**(**$\vec{v}$**);**	Static Message
let x**=**o**:**c**.**m**(**$\vec{v}$**);**	Dynamic Message
let x**=**o**.**m**[**$\overline{a}\,;\,\overline{b}$**](**$\vec{v}$**);**	Advised Message
let x**=**proceed**(**$\vec{v}$**);**	Proceed
$\phi,\psi ::=$	*Pointcut*
false	False
$\neg\phi$	Negation
$\phi \vee \psi$	Disjunction
call**(**c**::**m**)**	Call
exec**(**c**::**m**)**	Execution

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Types (Unpublished)

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Typing is Problematic

A symptom: the following code compiles in AspectJ1.1.

```
class D {
  public String m() { return "D"; }
}
aspect A {
  Object around(): call(* D.m()) {
    return new Integer(1);
  }
}
```

This looks like a bug.

Real issues: modular typechecking, variance, genericity.

We address only the first issue.

$$\text{if } \vdash P \text{ and } \vdash Q \text{ then } \vdash P \mid Q$$

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A Difference with AspectJ

- The set of call advice does not depend upon the type of the caller.
- To avoid locking entire heap on every method call, the declaration set is *closed* to precompute advice lists:

$$\text{class } c \mathbf{<:} \ldots \{ m\mathbf{[}\overline{a}\,\mathbf{;}\,\overline{b}\mathbf{]}, \ldots \}$$

- To allow modular typechecking and the use of this in call advice, must constrain the type of the caller.
- Method declarations have the form:

$$\text{class } c \mathbf{<:} \ldots \{ \text{protected } s \text{ method } m\mathbf{(}\vec{t}\mathbf{)}\mathbf{:}r\ \mathbf{[}\overline{a}\,\mathbf{;}\,\overline{b}\mathbf{]} \ldots \}$$

- **`protected`** is "protected c"; **`public`** is "protected Object".

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Another Difference

- In AspectJ, each advice list terminates in a call to a plain class, which cannot proceed.
- To capture this, we must distinguish two types of advice:

ρ ::=		*Placement*
	around	Around
	replace	Replace
D, E ::=	...	*Declaration*
	ρ advice $a(\vec{x}:\vec{t}):r$ at ϕ $\{\vec{C}\}$	Advice

Results for the Typed Calculus

The development is fairly standard

- Weaving still correct
- Weaving preserves types
- Reduction preserves types
- **`around`** advice no longer enough (**`before`** and **`after`** not encodable)

Lays the groundwork for

- Covariant return / Contravariant arguments
- Genericity
- Row polymorphism

The Full Typed AOL

$a,..,z$	*Name (& Type)*	C,B ::=	*Command*
X,Y,Z ::= n **:** t	*Typed Name*	new $\overline{D}\,\overline{H}$**;**	New
P,Q ::= $(\overline{D} \vdash \overline{H})$	*Program*	return v**;**	Return
ρ ::=	*Placement*	let X **=** v**;**	Value
around	Around	let X **=** o**.**f**;**	Get Field
replace	Replace	set o**.**f **=** v**;**	Set Field
D,E ::=	*Declaration*	let X **=** o**.**c**::**m**(**$\vec{v}$**);**	Static Message
class c **<:** d $\{\overline{F}\,\overline{M}\}$	Class	let X **=** o**:**c**.**m**(**$\vec{v}$**);**	Dynamic Msg
ρ advice a**(**$\vec{X}$**)** **:** r at φ $\{\vec{C}\}$	Advice	let X **=** o**:**c**.**m**[**$\overline{a}$**;**$\overline{b}$**](**$\vec{v}$**);**	Advised Msg
M ::= protected s method m**(**$\vec{t}$**)** **:** r **[**$\overline{a}$**;**$\overline{b}$**]**	*Method*	let X **=** proceed**(**$\vec{v}$**);**	Proceed
F ::= protected s field f **:** t**;**	*Field Type*	ϕ,ψ ::=	*Pointcut*
V ::= f **=** v**;**	*Field Value*	call**(**c**::**m**)**	Call
H,G ::=	*Heap Element*	exec**(**c**::**m**)**	Execution
object o **:** c $\{\overline{V}\}$	Object	¬call**(**c**::**m**)**	Not Call
thread o $\{S\}$	Thread	¬exec**(**c**::**m**)**	Not Execution
S,T ::=	*Call Stack*	true	True
$\vec{C}$	Current Frame	false	False
let X **=** $o\{S\}$**;**$\vec{C}$	Pushed Frame	$\phi \wedge \psi$	Conjunction
		$\phi \vee \psi$	Disjunction

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μABC

$P, Q, R \ ::=$	*Program*
$\mathsf{let}\, x = p \to q : \vec{m}; P$	Message
$\mathsf{return}\, v$	Return
$\mathsf{role}\, p < q; P$	New Role
$\mathsf{advice}\ a[\phi] = \sigma x\,.\,\tau y\,.\,\pi b\,.\,Q; P$	New Advice

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A Minimal Aspect-Based Calculus

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Design Choices

Goals

- Really really small.
- Straightforward compositional translation of class-based language.

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- Start with Abadi and Cardelli's object calculus (σ).
- Add object hierarchy (each object beneath its creator).
- Remove everything else. Call objects *roles*.

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Design Choices

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- Really really small.
- Straightforward compositional translation of class-based language.

Decisions

- Start with Abadi and Cardelli's object calculus (σ).
- Add object hierarchy (each object beneath its creator).
- Remove everything else. Call objects *roles*.
- Remove asymmetry of OO. Message send has the form:

$$p \to q : \vec{m}$$

send messages $\vec{m}$ from p to q

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Refactored Syntax

$f, \ldots, \ell, p, \ldots, z$	*Label or Role*
$a, \ldots, e$	*Advice name*
$m, n \ ::= \ell \mid a$	*Message*
$P, Q \ ::= \vec{B}; \mathsf{return}\, v$	*Program*
$B, C \ ::= \mathsf{let}\, x = p \rightarrow q : \vec{m} \mid D$	*Command*
$D, E \ ::=$	*Declaration*
$\quad \mathsf{role}\, p < q$	Role
$\quad \mathsf{advice}\, a[\phi] = \sigma x \,.\, \tau y \,.\, \pi b \,.\, Q$	Advice

Advice names are not first class.

Pointcuts

- Syntax

ϕ, ψ	$::=$	*Pointcut*
	$p \rightarrow q : \ell$	Call
	$\neg p \rightarrow q : \ell$	Not Call
	$\phi \wedge \psi \mid \mathsf{true}$	Conjunction
	$\phi \vee \psi \mid \mathsf{false}$	Disjunction
	$\forall x \leq p \,.\, \phi$	Universal
	$\exists x \leq p \,.\, \phi$	Existential

- Semantics

$$\vec{D} \vdash p \leq q$$

$$\vec{D} \vdash p \rightarrow q : \ell \ \mathsf{sat} \ \phi$$

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Dynamic Semantics

$$\vec{D}; \mathsf{let}\, z = p \rightarrow q : \vec{m}, \ell; P \quad \rightharpoonup \quad \vec{D}; \mathsf{let}\, z = p \rightarrow q : \vec{m}, \vec{a}; P$$

$$\text{where } \langle \vec{a} \rangle = \langle\, a \mid \vec{D} \ni \mathsf{advice}\, a[\phi] \cdots \text{ and } \vec{D} \vdash p \rightarrow q : \ell \ \mathsf{sat}\ \phi \,\rangle$$

$$\vec{D}; \mathsf{let}\, z = p \rightarrow q : \vec{m}, a; P \quad \rightharpoonup \quad \vec{D}; \vec{B}[{}^{p}/_{x}, {}^{q}/_{y}, {}^{\vec{m}}/_{b}]; P[{}^{v}/_{z}]$$

$$\text{where } \vec{D} \ni \mathsf{advice}\ a[\cdots] = \sigma x \,.\, \tau y \,.\, \pi b \,.\, \vec{B}; \mathsf{return}\, v$$

Pick the rightmost message (for consistency with declaration order).

Renaming required in second rule — $\mathsf{dom}(\vec{B})$ and $\mathsf{fn}(P)$ disjoint.

Dynamic Semantics

$$\vec{D}; \mathsf{let}\, z = p \to q : \vec{m}, \ell; P \;\; \longrightarrow\!\!\triangleright \;\; \vec{D}; \mathsf{let}\, z = p \to q : \vec{m}, \vec{a}; P$$

where $\langle \vec{a} \rangle = \langle\, a \mid \vec{D} \ni \mathsf{advice}\, a[\phi] \cdots$ and $\vec{D} \vdash p \to q : \ell$ sat $\phi \rangle$

$$\vec{D}; \mathsf{let}\, z = p \to q : \vec{m}, a; P \;\; \longrightarrow\!\!\triangleright \;\; \vec{D}; \vec{B}[{}^{p}\!/\!{}_{x}, {}^{q}\!/\!{}_{y}, {}^{\vec{m}}\!/\!{}_{b}]; P[{}^{v}\!/\!{}_{z}]$$

where $\vec{D} \ni \mathsf{advice}\; a[\cdots] = \sigma x \,.\, \tau y \,.\, \pi b \,.\, \vec{B}; \mathsf{return}\, v$

Pick the rightmost message (for consistency with declaration order).

Renaming required in second rule — $\mathsf{dom}(\vec{B})$ and $\mathsf{fn}(P)$ disjoint.

Garbage collection $P \overset{\mathrm{gc}}{\longrightarrow\!\!\triangleright} P'$ removes unused roles, advice, messages.

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Sugar

Sugar on programs:

$$
\begin{aligned}
x &\triangleq \mathsf{return}\, x \\
p \to q : \vec{m} &\triangleq \mathsf{let}\, x \mathbf{=} p \to q : \vec{m}; \mathsf{return}\, x \\
\mathsf{role}\, p &\triangleq \mathsf{role}\, p \mathbf{<} \mathsf{top}
\end{aligned}
$$

Sugar on pointcuts:

$$p\,.\,\ell \triangleq \exists x \leq \mathsf{top}\,.\,\exists y \leq p\,.\,x \to y : \ell$$

"$p\,.\,\ell$" fires when p or one of its subroles receives message ℓ.

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Call-by-value Lambda Calculus

$$
\begin{aligned}
\vec{D} \quad = \quad & \mathsf{role}\, f; \\
& \mathsf{advice}\ a[f\,.\,\mathsf{call}] = \tau y\,.\,\mathsf{let}\, x = y \to y : \mathsf{arg}; P; \\
& \mathsf{role}\, g < f; \\
& \mathsf{advice}\ b[g\,.\,\mathsf{arg}] = Q;
\end{aligned}
$$

$$
\begin{aligned}
(\lambda x\,.\,P)\,Q \quad & \twoheadrightarrow \quad \vec{D}; g \to g : \mathsf{call} \\
& \twoheadrightarrow \quad \vec{D}; g \to g : a \\
& \twoheadrightarrow \quad \vec{D}; \mathsf{let}\, x = g \to g : \mathsf{arg}; P \\
& \twoheadrightarrow \quad \vec{D}; \mathsf{let}\, x = g \to g : b; P \\
& \twoheadrightarrow \quad \vec{D}; \mathsf{let}\, x = Q; P \\
& \overset{\mathrm{gc}}{\twoheadrightarrow} \quad \mathsf{let}\, x = Q; P
\end{aligned}
$$

Cf. [Milner *Functions as Processes*]

Conditional

$$\begin{aligned}\textsf{if } p \le q \textsf{ then } R_1 \textsf{ else } R_2 \;\triangleq\; & \textsf{role}\, r; \\ & \textsf{advice } [\exists x \le \textsf{top} \,.\, x \to r : \textsf{if}] = R_2; \\ & \textsf{advice } [\exists x \le q \,.\, x \to r : \textsf{if}] = R_1; \\ & p \to r : \textsf{if}\end{aligned}$$

R_1 does not use its proceed variable. If R_1 fires, R_2 cannot fire.

$$\vec{D}; \textsf{if } p \le q \textsf{ then } R_1 \textsf{ else } R_2 \rightarrow^* \xrightarrow{\text{gc}} \begin{cases} R_1 & \text{if } \vec{D} \vdash p \le q \\ R_2 & \text{otherwise} \end{cases}$$

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Lambda Calculus with Advice

We encode primitives from core MinAML [Walker Zdancewic Ligatti 2003]. See also [Tucker Krishnamurthi 2003].

- new $p; P$ creates a new name p which acts as a hook.
- $\{p \,.\, z \to Q\} \ggg P$ attaches *after* advice $\lambda z \,.\, Q$ to hook p.
- $\{p \,.\, z \to Q\} \lll P$ attaches *before* advice $\lambda z \,.\, Q$ to hook p.
- $p\langle P \rangle$ evaluates P then runs advice hooked on p.

Not a full-blown translation. Eg, advice is first class in MinAML.

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Core MinAML Reduction

$$P \triangleq \mathsf{new}\ p; \{p\,.\,x_1 \to x_1 + 1\} \lll \{p\,.\,x_2 \to x_2 * 2\} \ggg p\langle 3 \rangle$$

$$\begin{aligned}
\vec{D} \triangleq\ & \mathsf{role}\ p; \\
& \mathsf{advice}\ a[p\,.\,\mathsf{hook}] = \lambda x_0\,.\,x_0; \\
& \mathsf{advice}\ b[p\,.\,\mathsf{hook}] = \tau z\,.\,\pi d\,.\,\lambda x_1\,.\,\mathsf{let}\ y_1 = x_1 + 1; (z \to z : d)(y_1); \\
& \mathsf{advice}\ c[p\,.\,\mathsf{hook}] = \tau z\,.\,\pi d\,.\,\lambda y_2\,.\,\mathsf{let}\ x_2 = (z \to z : d)(y_2); x_2 * 2;
\end{aligned}$$

$$\begin{aligned}
P &= \vec{D}; (p \to p : \mathsf{hook})\ 3 \\
&\rightarrowtriangle \vec{D}; (p \to p : a, b, c)\ 3 \\
\rightarrowtriangle^* &\xrightarrow{\mathsf{gc}}\!\!\!\!\rightarrowtriangle \vec{D}; \mathsf{let}\ x_2 = (p \to p : a, b)(3); x_2 * 2 \\
\rightarrowtriangle^* &\xrightarrow{\mathsf{gc}}\!\!\!\!\rightarrowtriangle \vec{D}; \mathsf{let}\ x_2 = (\mathsf{let}\ y_1 = 3 + 1; (p \to p : a)(y_1)); x_2 * 2 \\
\rightarrowtriangle^* &\xrightarrow{\mathsf{gc}}\!\!\!\!\rightarrowtriangle \vec{D}; \mathsf{let}\ x_2 = (p \to p : a)(4); x_2 * 2 \\
\rightarrowtriangle^* &\xrightarrow{\mathsf{gc}}\!\!\!\!\rightarrowtriangle \vec{D}; \mathsf{let}\ x_2 = 4; x_2 * 2 \\
\rightarrowtriangle^* &\xrightarrow{\mathsf{gc}}\!\!\!\!\rightarrowtriangle 8
\end{aligned}$$

Translating the CBL

$$[\![\text{advice } a[\phi](\vec{x})\ \{Q\}]\!] = \text{advice } a[[\![\phi]\!]] = \sigma\text{this} \,.\, \tau\text{target} \,.\, \pi\text{proceed} \,.\, \lambda\vec{x} \,.\, \text{this}[\![Q]\!]$$

$$[\![\text{class } t <: u\ \{\vec{M}\}]\!] = \text{role } t < u;\ \ t[\![\vec{M}]\!]$$

$$t[\![\text{method } \ell(\vec{x})\ \{Q\}]\!] = \text{advice } [t \,.\, \ell] = \tau\text{this} \,.\, \pi\text{super} \,.\, \lambda\vec{x} \,.\, \text{this}[\![Q]\!]$$

$$[\![\text{object } p : t\ \{\vec{F}\}]\!] = \text{role } p < t;\ \ p[\![\vec{F}]\!]$$

$$p[\![\text{field } f = v]\!] = \text{advice } a[\text{false}] = \text{return } v;$$

$$\text{advice } [p \,.\, f] = \sigma x \,.\, \tau y \,.\, \pi b \,.\, x \to y : a, b$$

$$p[\![\text{let } x = q.\ell(\vec{v}); P]\!] = \text{let } x = (p \to q : \ell)\,\vec{v}; p[\![P]\!]$$

Advice on fields; No call/exec distinction; No global advice order.

One step in CBL = Several steps in μABC (including garbage collection).

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Insight from μABC

- Advice + Names + Name Substitution = Enough!
- Not much more complicated than λ, π or σ.
- Paper includes spaghetti CPS translation of μABC into π.
- Essence of class-based AOP: role hierarchy + advice binding source, target, and proceed.
- Are pure aspects efficiently implementable?

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Closing Waffle

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Motivating Example: Resource Access Control

- Access Matrix Model [Lampson 1974].

$$\mathsf{Policy} \; : \; \mathsf{Subject} \times \mathsf{Object} \mapsto 2^{\mathsf{Rights}}$$

- Stack Inspection [Wallach et al 1997].

$$\begin{aligned}\mathsf{Stack} \; &: \; \overrightarrow{\mathsf{Subject}} \\ \mathsf{Policy} \; &: \; \mathsf{Stack} \times \mathsf{Object} \mapsto 2^{\mathsf{Rights}}\end{aligned}$$

- History-Based Access Control [Abadi Fournet 2003].

$$\begin{aligned}\mathsf{Event} \; &: \; \mathsf{Subject} \times \mathsf{Object} \times \mathsf{Value} \times \{\mathsf{call}, \mathsf{return}\} \\ \mathsf{History} \; &: \; \overrightarrow{\mathsf{Event}} \\ \mathsf{Policy} \; &: \; \mathsf{History} \times \mathsf{Object} \mapsto 2^{\mathsf{Rights}}\end{aligned}$$

Abadi/Fournet Example: Bad Plugin

```
// Trusted : static permissions contain all permissions.
public class NaiveProgram {
  public static void main() {
     String s = BadPlugIn.tempFile();
     new File(s).delete();
  }
}
// Mostly untrusted : static permissions don’t
// contain any FilePermission.
class BadPlugin {
  public static String tempFile() {
   return "..\\password";
  }
}
```

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Aspects for Resource Access Control

- Access Matrix Model: **`call`**
- Stack Inspection: **`call`** + **`cflow`**
- History-Based: ?

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A More General Notion of Past

- Connection between **`cflow`** and past-time eventuality operator $\Diamond\!\!\!-$ has been noted by many.
- **`cflow`**'s limitations are accepted on grounds of implementability.

How can we implement a more general notion of past?

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A More General Notion of Past

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- **`cflow`**'s limitations are accepted on grounds of implementability.

How can we implement a more general notion of past?

- Required in Firewalls and Intrusion Detection Systems.
- An elegant solution: Security Automata [Schneider 2000].
- Idea: automaton maintains an *abstraction* of the history.

Sketching a Logic of Temporal Pointcuts

A logic based on regular expressions and process algebraic operators:

ε	empty.
$\phi;\psi$	sequential composition of two traces.
$\phi*$	closure of sequential composition — $\varepsilon \vee (\phi;\phi*)$.
$\phi \parallel \psi$	parallel composition of two traces.
$\phi!$	closure of parallel composition — $\varepsilon \vee (\phi \parallel \phi!)$.

Some encodings:

$$\mathsf{balanced} = (\mathsf{call};\mathsf{return})!$$

$$\mathsf{semi{\cdot}balanced} = (\mathsf{balanced};\mathsf{call}*)*$$

$$\mathsf{cflow}\langle\phi\rangle = (\phi \wedge \mathsf{call}*) \parallel \mathsf{balanced}$$

Challenges for Temporal Pointcuts

- Whose past? thread? caller object? callee object? stack?
- How does one handle partially completed methods and advice? At what point, exactly, does a call begin or end?
- What logics are implementable?
- Compile-time weaving no longer an option.
- Dynamically loaded aspects attractive – requires rebuilding the automaton (a new kind of weaving).
- What if new aspects require information that has not been saved?

Putting the Waffles Together

- Logics should be powerful enough to capture join points that are not recorded in the stack.
- Join points are themselves resources, whose access must be managed.
- Interference between aspect policies an important issue.
- Work on Feature Interaction is relevant.

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Thank You!

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