abc: A workbench for Aspect-Oriented Programming Language and Compiler Research

Programming Tools Group, University of Oxford, UK
Sable Research Group, McGill University, Canada
Århus University, Denmark

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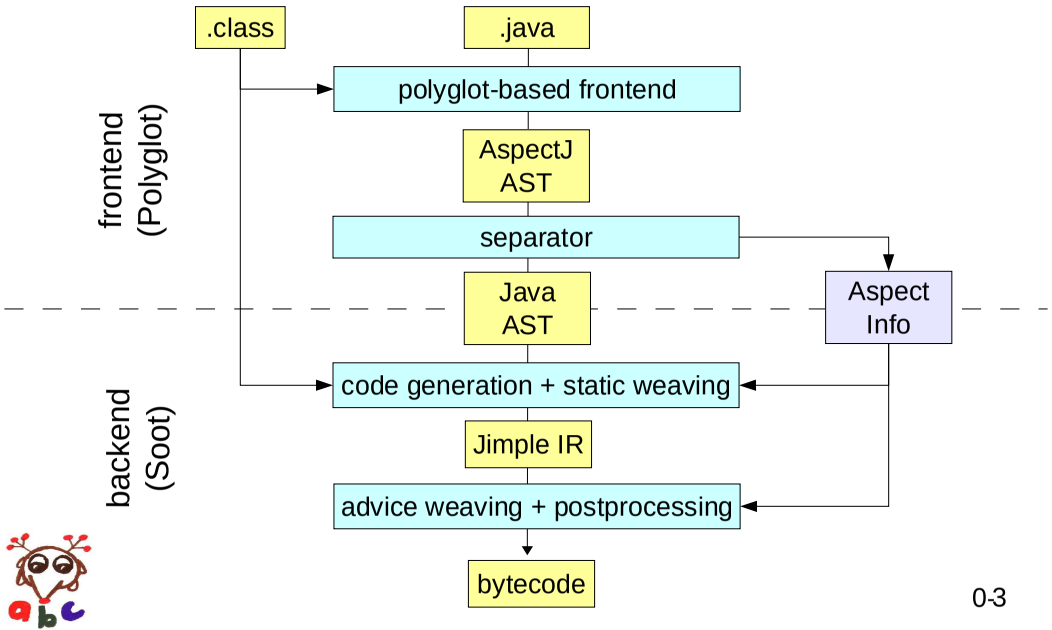
The need for a research compiler

- explore AOP language design space
- experiment with better code generation
- experiment with static analyses for safety checks and optimisations

side-benefit: clarify language definition

Architecture of abc



Schedule

9:00	overview
9:10	adding syntactic extensions to AspectJ
9:55	hands-on exercises
10:05	adding new joinpoints
10:50	hands-on exercises
11:00	break + continue hands-on exercises
11:30	introduction to Soot
12:00	optimisations and analysis
12:30	close

additions to frontend only: parse, check, transform to pure AspectJ

additions to frontend, AspectInfo, Weaver, Runtime

Soot's analysis framework; cflow optimisations

Let us help you with your extensions – we're here the whole week. Possibly have a BoF / dinner to discuss common development plans?

abc: Part I
Syntactic extensions

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Århus University, Denmark

Syntactic Extensions

- Introduction to Polyglot
- Example: global pointcuts

What is Polyglot?

An *extensible* Java compiler

Sample extensions:

- Jif : Java information flow and program partitioning
- PolyJ 2.0 : Java with parameterized types
- JMatch : Abstract iterable pattern matching for Java
- Jx: Nested inheritance in Java
- Jedd: BDD-based analyses
- JPred : Practical predicate dispatch

Produced by Andrew Myers, Nate Nystrom *et al.* at Cornell

How does Polyglot do it?

- Structured as a series of visitors
- Each visitor pass rewrites AST; about 15 such visitors
- Rigorous use of interfaces and factories makes it easy to change type system, environment, ...
- Delegates for overriding members of non-final AST classes (*cf.* intertype decls)

The AspectJ extension

Like any other Polyglot extension, five new packages:

- AST: new ast nodes (89 classes)
- Extension: overrides of existing Java AST nodes (13 classes)
- Parse: new lexer and grammar (2 files)
- Types: new types and type system (8 classes)
- Visit: new passes (35 classes)

- Includes Java/AspectInfo separator
- Many AST classes in pointcut language are light-weight
- The tricky bits are the type rules for ITDs, and the separator into Java & AspectInfo

plus new “driver” that controls pass order *etc*

Polyglot summary

- Extensible in all dimensions:
  - syntax, type system, visitors
- Potential merge problems with pure Java compiler only occur in extension dir and type system
- Extensions to *abc* have same structure as *abc* itself

Example extension: global pointcuts

global : <pattern> : <pc>;

add a new conjunct <pc>
to the pointcut
of each advice declaration
in any aspect that matches <pattern>

joinpoints in class C cannot be advised by aspects in subpackages of "special":

```
class C {
    global : special..* : !within(C);
    ...
}
```

aspect A only applies to classes in the package "foo.bar":

```
aspect A {
    global : A : within(foo.bar.*);
    ...
}
```

The translation we aim for

global pointcut declaration is turned into a named pointcut:

```
class C {
    pointcut  globalpc$7345() : !within(C);
    ...
}
```

every advice declaration in matching aspect gets extra conjunct in pointcut:

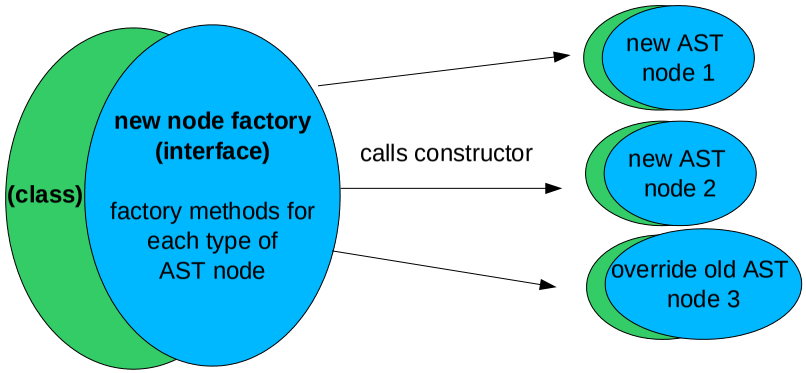
```
package special.bar.foos;
aspect Foo {
    before(int x) : call(* foo(int)) &&
                    args(x) && C.globalpc$7345()
    {...}

    after() :  call(* bar(..)) && C.globalpc$7345()
    {...}
}
```

Our task list

General	This example
• AST: new ast nodes	one for global pointcuts *GlobalPointcutDecl*
• Extension: overrides of existing AspectJ nodes	new method on AdviceDecl *EAJAdviceDecl*
• Parse: new lexer and grammar	new keyword: *global* new nonterminal new grammar rules
• Types: new types and type system	none
• Visit: new passes	to rewrite to pure AspectJ *GlobalPointcutVisitor*

extend AspectJ "driver" classes to use the above

abc node factory for an extension



each abc extension has a single node factory that extends abc.aspectj.ast.NodeFactory_c, and that implements abc.aspectj.ast.NodeFactory

global pointcut: new AST node

create in package abc.eaj.ast:	**extends in abc.aspectj.ast:**
interface GlobalPointcutDecl	PointcutDecl
class GlobalPointcutDecl_c	PointcutDecl_c
interface EAJNodeFactory	AspectJNodeFactory
class EAJNodeFactory_c	AspectJNodeFactory_c
with factory method for new node type	

contains declaration

```
public GlobalPointcutDecl GlobalPointcutDecl(
                        Position pos,
                        ClassnamePatternExpr aspect_pattern,
                        Pointcut pc)
  {
     return new GlobalPointcutDecl_c(pos, aspect_pattern, pc);
  }
```


New AST Class (1)

```
package abc.eaj.ast;

public class GlobalPointcutDecl_c extends PointcutDecl_c
                        implements GlobalPointcutDecl
{
   // pattern for aspects
   ClassnamePatternExpr aspect_pattern;
   // pointcut (declared in PointcutDecl_c)
   // Pointcut pc;
   // generated pointcut name  (declared in PointcutDecl_c)
   // String name;

   // constructor
   public GlobalPointcutDecl_c(Position pos,
                        ClassnamePatternExpr aspect_pattern,
                        Pointcut pc)
```


New AST class (2)

Polyglot implements all tree rewriting by “reconstruct” and “visitChildren” in each AST class

```
// construct new node if any of the children has changed
protected Node reconstruct(Node n, ClassnamePatternExpr aspect_pattern,Pointcut pc) ...
   (more detail on next slide)

// visit each of the children
public Node visitChildren(NodeVisitor v) ...
   (more detail two slides on)

// store (pattern,pointcut) pair in datastructure (of visitor) for later lookup during rewriting pass
public void registerGlobalPointcut(GlobalPointcuts visitor,
                        Context context,
                        EAJNodeFactory nf) ...

} // end of new AST class
```

New AST class: *reconstruct*

```
protected Node reconstruct(Node n,
                           ClassnamePatternExpr aspect_pattern,
                           Pointcut pc)
{
    // has one of the children changed?
    if (   aspect_pattern != this.aspect_pattern || pc != this.pc)
    {
        // then make a fresh copy of this node
        GlobalPointcutDecl_c new_n = (GlobalPointcutDecl_c) n.copy();
        new_n.aspect_pattern = aspect_pattern;
        new_n.pc = pc;

        return new_n;
    }
    return n;
}
```

New AST class: *visitChildren*

```
public Node visitChildren(NodeVisitor v)
{
    // visits pointcut
    Node n = super.visitChildren(v);

    ClassnamePatternExpr aspect_pattern =
          (ClassnamePatternExpr) visitChild(this.aspect_pattern, v);

    return reconstruct(n, aspect_pattern, pc);
}
```

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• Types: new types and type system	none
• Visit: new passes	to rewrite to pure AspectJ *GlobalPointcutVisitor*

extend AspectJ “driver” classes to use the above

Extension (override AspectJ)

```
package abc.eaj.extension;
...
public class EAJAdviceDecl_c extends AdviceDecl_c implements EAJAdviceDecl
{
    // constructor
    public EAJAdviceDecl_c(Position pos, Flags flags,
                           AdviceSpec spec, List throwTypes,
                           Pointcut pc, Block body) ...

    // add a new conjunct to the pointcut of an advice declaration
    public EAJAdviceDecl conjoinPointcutWith(GlobalPointcuts visitor, Pointcut global)
    {
        EAJAdviceDecl_c n = (EAJAdviceDecl_c) this.copy();
        n.pc = visitor.conjoinPointcuts(pc, global);
        return n;
    }
}
```

important:
rewrite must make *new copy*, not modify existing advice declaration

and override AdviceDecl factory method in EAJNodeFactory

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extend AspectJ “driver” classes to use the above

Parse: new grammar

a new production for an existing nonterminal

```
include "../../aspectj/parse/aspectj.ppg";
package abc.eaj.parse;

terminal Token GLOBAL;

non terminal GlobalPointcutDecl global_pointcut_decl;

extend class_member_declaration ::= global_pointcut_decl:a
    ... build AST...
  ;
extend interface_member_declaration ::= global_pointcut_decl:a
    ...
  ;

global_pointcut_decl ::=
    GLOBAL:x COLON classname_pattern_expr:a COLON pointcut_expr:b
    SEMICOLON:y
    {:
      Grm.parserTrace("GLOBAL type_pattern_expr, pointcut_expr");
      RESULT = parser.nf.GlobalPointcutDecl(parser.pos(x,y), a, b);
    :};
```

The abc Lexer

many new keywords:
aspect, privileged, pointcut, proceed, target...

minimise “stealing” of keywords from Java

stateful lexer:

Java:	aspect, privileged and pointcut
aspect:	after, around, before, declare, issingleton, percflow, percflowbelow, pertarget, perthis, pointcut, proceed
pointcut:	adviceexecution, args, call, cflow, cflowbelow, error, execution, get, handler, initialization, parents, precedence, preinitialization, returning, set, soft, staticinitialization, target, throwing, warning, within, withincode

New Lexer

“Driver” class to link in the new extension (new keywords, new joinpoints...)

```
package abc.eaj;

public class AbcExtension extends abc.main.AbcExtension
{
  ...other features of this class discussed later ...

  public void initLexerKeywords(AbcLexer lexer) {
    // Add the base keywords
    super.initLexerKeywords(lexer);

    // new keyword
    lexer.addGlobalKeyword("global",    // the lexeme
            new LexerAction_c(   new Integer(abc.eaj.parse.sym.GLOBAL),
                                 // token passed to parser
                              new Integer(lexer.pointcut_state())));
                                 // enter pointcut state
  }
}
```

add keywords to lexer states with:
addJavaKeyword
addAspectJKeyword
addPointcutKeyword
addGlobalKeyword
addAspectJContextKeyword

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extend AspectJ “driver” classes to use the above

Two new passes for global pointcuts

Pass 1:
Collect all global pointcuts, and store them in a mapping of (class pattern expression (cpe), pointcut (pc)) pairs

Pass 2:
for each aspect A:
  for each (cpe,pc) pair:
    if A matches cpe
    then for each advice declarations ad in A:
      ad.pointcut = ad.pointcut && reference to pc

one class for both visitors, store mapping in static data

New Visitor Class

```
package abc.eaj.visit;
...
public class GlobalPointcuts extends ContextVisitor
{
   // the two passes
   public final static int COLLECT = 1;
   public final static int CONJOIN = 2;
   private int pass;

   // mapping from cpe to pc
   static HashMap globalpcs = new HashMap();
   static int unmatchedCollectPasses = 0;

   // factory for constructing new nodes
   EAJNodeFactory nodeFactory;
```

Polyglot base class for visitors that need access to *context*: variables in scope, current class, *etc*.

New Visitor Class: key methods

called when entering AST node typically adjust context

```
public NodeVisitor enter(Node parent, Node n){
   if (pass == COLLECT && n instanceof GlobalPointcutDecl)
      ((GlobalPointcutDecl) n).registerGlobalPointcut(this, context(),
                                                      nodeFactory);
   return super.enter(parent, n);
}
```

called when leaving AST node this does the rewriting

```
public Node leave(Node parent, Node old, Node n, NodeVisitor v)
{
   n = super.leave(parent, old, n, v);
   if (pass == CONJOIN && n instanceof EAJAdviceDecl) {
      EAJAdviceDecl adviceDecl = (EAJAdviceDecl) n;
      PCNode aspct = PCStructure.v().getClass(context().currentClass());
      return applyMatchingGlobals(aspct, adviceDecl);
   }
   return n;
}
```

New visitor class: apply global pcs

```
protected EAJAdviceDecl applyMatchingGlobals(PCNode aspct,
                                             EAJAdviceDecl ad)
{
    Iterator i = globalpcs.keySet().iterator();

    while (i.hasNext()) {
        ClassnamePatternExpr pattern = (ClassnamePatternExpr) i.next();

        if (pattern.matches(aspct)) {
            Pointcut global = (Pointcut) globalpcs.get(pattern);
            ad = ad.conjoinPointcutWith(this, global);
        }
    }

    return ad;
}
```

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extend AspectJ “driver” classes to use the above

Driving *abc*

abc.eaj.AbcExtension. For registering

- new keywords
- new shadow and joinpoint types
- extended runtime

abc.eaj.ExtensionInfo:

- create lexer, parser, type system,...
- introduce new passes
- insert new passes between existing ones

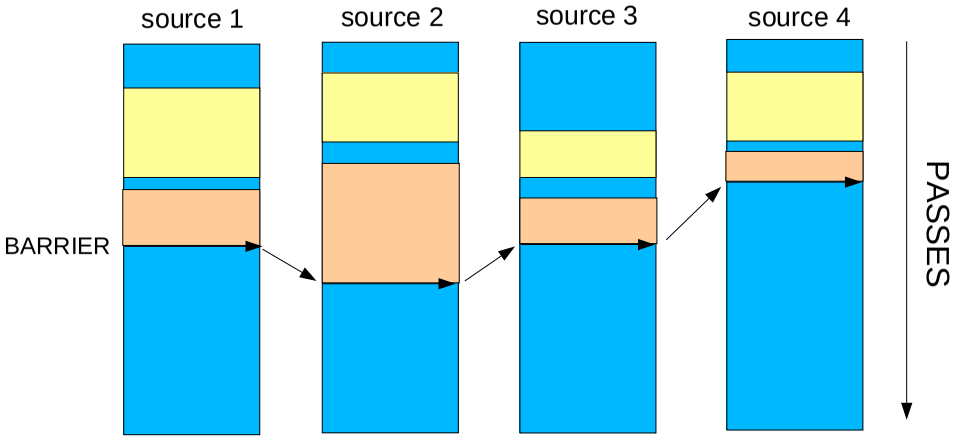
abc pass structure

new global pc passes go here

parse_and_clean	parse and build initial class hierarchy
patterns_and_parents	eval patterns; declare parents; eval patterns
precedence_relation	compute aspect precedences
disambiguate_signatures	inner/outer classes and method signatures
add_members	populate types with members
interface_ITDs	propagate interface ITDs to implementors
disambiguate_all	resolve all variable/method references
fold_and_checkcode	type checking; reachability etc
saveAST	make Soot connection
mangle_names	mangle names of private ITDs etc
aspectj_transforms	separate pure Java and AspectInfo
passes_jimple	mapping from classes to ASTs for Jimple

complex extension passes go after semantic checks

Barrier Passes



pass sequence is run independently for each source file;
barrier passes serve to ensure all files have reached the same stage before proceeding

Insert new passes

```
protected void passes_patterns_and_parents(List l, Job job)
  {
    super.passes_patterns_and_parents(l, job);

    l.add(new VisitorPass(COLLECT_GLOBAL_POINTCUTS,
                          job,
                          new GlobalPointcuts(GlobalPointcuts.COLLECT,
                                              job,
                                              (EAJTypeSystem) ts,
                                              (EAJNodeFactory) nf)));
    l.add(new GlobalBarrierPass(COLLECTED_GLOBAL_POINTCUTS, job));
    l.add(new VisitorPass(CONJOIN_GLOBAL_POINTCUTS,
                          job,
                          new GlobalPointcuts(GlobalPointcuts.CONJOIN,
                                              job,
                                              (EAJTypeSystem) ts,
                                              (EAJNodeFactory) nf)));
  }
```

barrier passes ensure that all source files reach this stage before proceeding

Our task list

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✔ Parse: new lexer and grammar	new keyword: *global* new nonterminal new grammar rules
✔ Types: new types and type system	none
✔ Visit: new passes	rewrite to pure AspectJ *GlobalPointcutVisitor*

it's as easy as abc!

Exercise: surround advice

runs before and after the joinpoint

surround(<formals>) : <pc> {beforeadvice}{afteradvice}

transforms to two pieces of normal advice

before(<formals>) : <pc> {beforeadvice}
after(<formals>) : <pc> {afteradvice}

consider advice precedence rules...

✔ extend AspectJ "driver" classes to use the above

abc: Part II
Adding new joinpoints

Programming Tools Group, University of Oxford, UK
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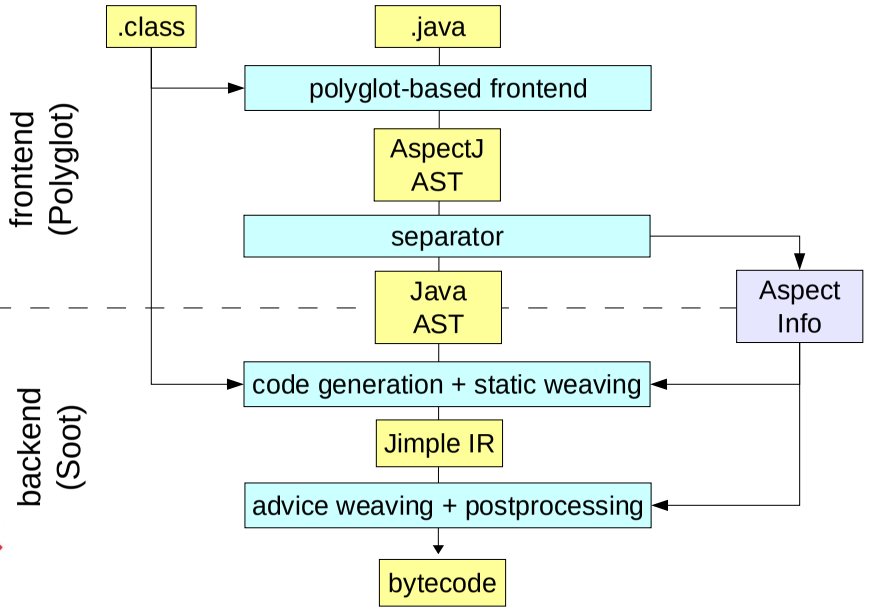
Adding new joinpoints

- AspectInfo
- matcher
- weaver

Architecture of abc



Example Java/aspects separation

```
aspect Aspect {
 private int C.count = 0;
 private void C.inc() {
       count++;
 }
 before(C x) : call(* foo(..)) &&
                target(x) {
       x.inc();
 }
}
```

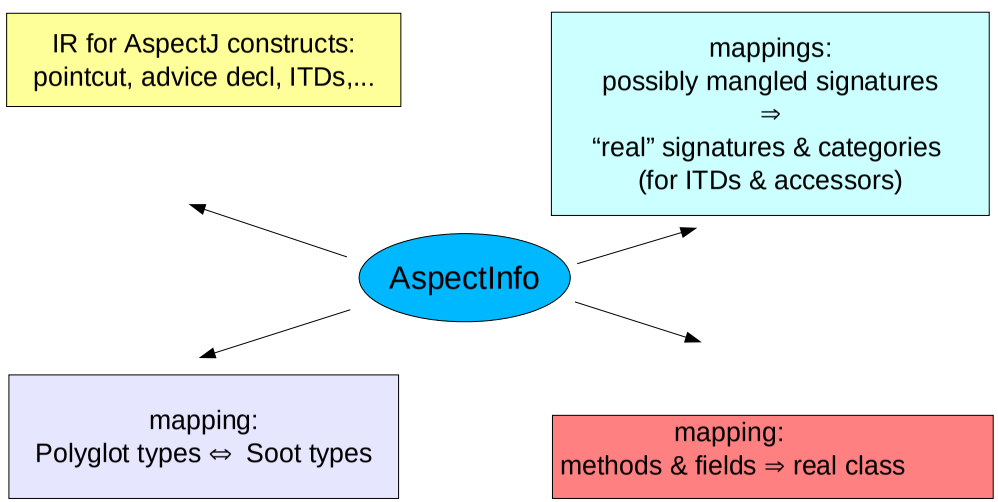
execution joinpoint:
- real name "inc"
- real parameters *none*
- real class "C"

```
public class Aspect {
  public static void Aspect$inc$5(final C this$6) {
    this$6.Aspect$count$3++;
  }

  public final void before$2(C x) { x.Aspect$inc$5(); }

  public Aspect() { super(); }

  public static int init$count$7(final C this$4) {
   return (int) 0; }

  public static Aspect aspectOf()
    throws
    org.aspectj.lang.NoAspectBoundException {
     return null;        // to be filled in later
  }

  public static boolean hasAspect() { return true; }
}
```

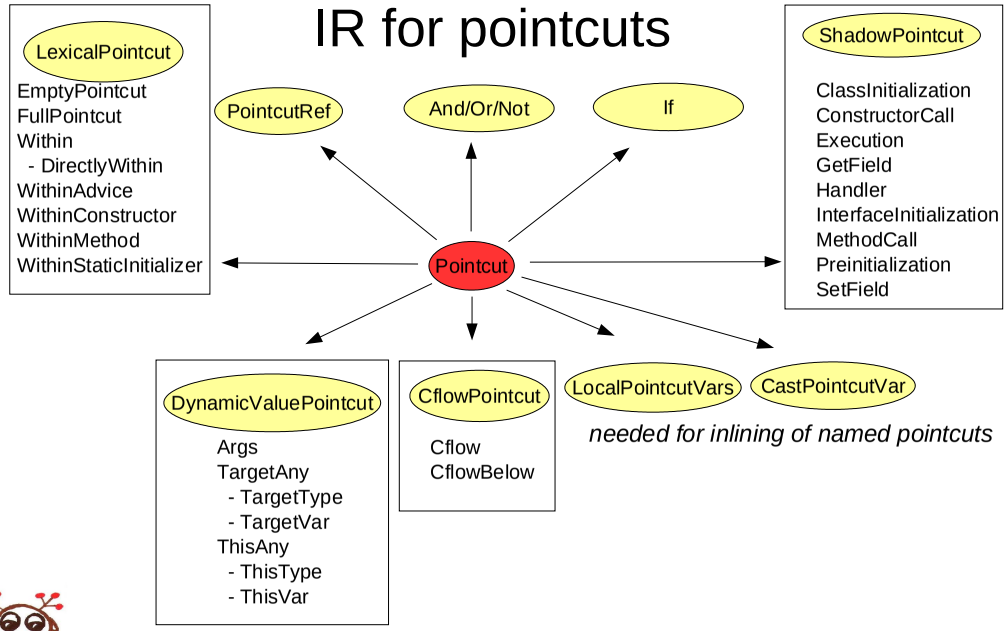
```
* intertype method inc
      host C
      implementation Aspect$inc$5
* before advice, pointcut
      call(* foo(..)) && target(x)
      method for body before$2(C x)
* intertype field count,
      host C
      initial value from init$count(C)
```

all the information that is not Java goes into AspectInfo

What's in AspectInfo?



IR for pointcuts

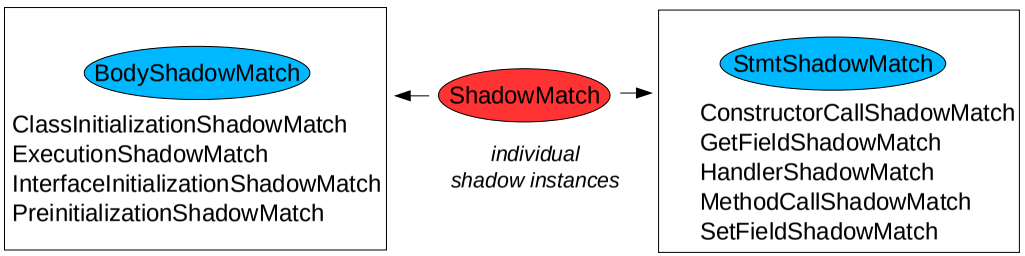


needed for inlining of named pointcuts

Examples: AspectJ pointcut to IR

AspectJ	**Intermediate Representation**
execution(int Foo.foo(char))	withinmethod(int Foo.foo(char)) && execution()
adviceexecution()	withinadvice() && execution()
call(Foo.new(int))	constructorcall(Foo.new(int))
initialization(Foo.new(..))	(withinconstructor(Foo.new(..)) && classinitialization()) || interfaceinitialization(Foo)

Shadow Kinds



individual shadow instances

for blocks of Jimple code

for single Jimple statements (or a pair, for constructor call)

and a singleton class for each kind named
<*kind*>ShadowType (a subtype of ShadowType)
with a method
ShadowMatch matchesAt(pos)
singleton instance of <*kind*>ShadowType created by
static <*kind*>ShadowMatch.newType()

Computing Advice Lists (simplified)

```
for each weavable class C
    for each method M in C
        for each "position" pos in M
            for each shadow type t
                ShadowMatch sm = t.matchesAt(pos);
                for each advice declaration ad
                    Pointcut pc = ad.getPointcut();
                    Residue r = pc.matchesAt(sm);
                    add (pos,ad,r) to "advice list" of M;
```

"positions" are defined in AbcExtension

Residue is an IR of the dynamic test to be inserted (e.g. for if, args, ...)

advice lists are applied in a separate weaving pass

[for non-statement shadows, pc.matchesAt(..) takes more parameters]

Example: Cast Pointcut

```
before(int i)
  cast(short) && args(i)
  && if (i < Short.MIN_VALUE   ||  i > Short.MAX_VALUE)
{
  System.err.println( “Warning: loss of “ +
                                “precision casting “ +
                                i   +  `` to a short.");
}
```

general syntax:

basic_pointcut_expr ::=
    PC_CAST LPAREN type_pattern_expr RPAREN

Our task list

General	This example
• extend parser, new AST nodes	as before...
• AspectInfo: IR for aspect-specific features	new class for cast pointcut
• Matcher: extend shadow matcher	how to match new pointcut
• New runtime	dynamic representation of cast joinpoint
• Extend driver classes to use new runtime	AbcExtension

New AST node

```
package abc.eaj.ast;
...
public class PCCast_c extends Pointcut_c
                      implements PCCast
{
   protected TypePatternExpr type_pattern;

   ... reconstruct, visitChildren ...

  // translate to AspectInfo
   public abc.weaving.aspectinfo.Pointcut makeAIPointcut()
   {
      return new abc.eaj.weaving.aspectinfo.Cast
          (type_pattern.makeAITypePattern(), position());
   }
}
```

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• Extend driver classes to use new runtime	AbcExtension

New AspectInfo Class

```
package abc.eaj.weaving.aspectinfo;
...
public class Cast extends ShadowPointcut
{
   private TypePattern pattern;
...
   protected Residue matchesAt(ShadowMatch sm)
   {
      if (!(sm instanceof CastShadowMatch)) return NeverMatch.v();
      Type cast_to = ((CastShadowMatch) sm).getCastType();

      if (!getPattern().matchesType(cast_to)) return NeverMatch.v();
      return AlwaysMatch.v();
   }
...
}
```

next step: define CastShadowMatch

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Shadow Matcher (1)

```
package abc.eaj.weaving;
...
public class CastShadowMatch extends StmtShadowMatch
{
   ..
   public static CastShadowMatch matchesAt(MethodPosition pos)
   {
      if (!(pos instanceof StmtMethodPosition)) return null;

      Stmt stmt = ((StmtMethodPosition) pos).getStmt();
      if (!(stmt instanceof AssignStmt)) return null;
      Value rhs = ((AssignStmt) stmt).getRightOp();
      if(!(rhs instanceof CastExpr)) return null;

      Type cast_to = ((CastExpr) rhs).getCastType();
      return new CastShadowMatch(pos.getContainer(), stmt, cast_to);
   }
```


Shadow Matcher (2)

```
public static ShadowType shadowType()
{
   return new ShadowType() {
      public ShadowMatch matchesAt(MethodPosition pos) {
         return CastShadowMatch.matchesAt(pos);
      }
   };
}

public List /*<ContextValue>*/ getArgsContextValues()
... return singleton of value being cast ...

public ContextValue getTargetContextValue()
... return null ...

public SJPInfo makeSJPInfo()
... make the relevant static joinpoint info ...
```

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• New runtime	dynamic representation of cast joinpoint
• Extend driver classes to use new runtime	AbcExtension

New Runtime (1)

```
package org.aspectbench.eaj.lang.reflect;

import org.aspectj.lang.Signature;

public interface CastSignature extends Signature
{
   public Class getCastType();
}
```

obvious implementation in
package org.aspectbench.eaj.runtime.reflect.CastSignatureImpl

New Runtime (2)

```
package org.aspectbench.eaj.runtime.reflect;

...

public class EajFactory extends Factory
{
   ...

   public CastSignature makeCastSig(String stringRep) {
      CastSignatureImpl ret = new CastSignatureImpl(stringRep);
      ret.setLookupClassLoader(lookupClassLoader);
      return ret;
   }

   ...
}
```

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✓ New runtime	dynamic representation of cast joinpoint
• Extend driver classes to use new runtime	AbcExtension

Use new runtime

```
package abc.eaj;
...
public class AbcExtension extends abc.main.AbcExtension
{
  ...
   // create list of shadow types that the weaver will iterate over
   protected List/*<ShadowType>*/ listShadowTypes()
   {
      List/*<ShadowType*/ shadowTypes = super.listShadowTypes();
      shadowTypes.add(CastShadowMatch.shadowType());
      return shadowTypes;
   }

   public String runtimeSJPFactoryClass() {
      return "org.aspectbench.eaj.runtime.reflect.EajFactory";
   }

  ...
}
```

Our task list

It's as easy as abc!

General	This example
✔ extend parser, new AST nodes	as before...
✔ AspectInfo: IR for aspect-specific features	new class for cast pointcut
✔ Matcher: extend shadow matcher	how to match new pointcut
✔ New runtime	dynamic representation of cast joinpoint
✔ Extend driver classes to use new runtime	AbcExtension

Exercise: array pointcuts

```
Bar around(Bar array[], int index) :
    arrayget() && target(array) && args(index) {
        Bar value=proceed(array,index);
        return value;
}
void around (Bar array[], Bar value, int index) :
    arrayset() && target(array) && args(value, index) {
        proceed(array,value,index);
}
```

general syntax:

```
basic_pointcut_expr ::=
    PC_ARRAYGET LPAREN RPAREN
  | PC_ARRAYSET LPAREN RPAREN
```

abc: Part III
Using Soot in the abc backend

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Using Soot in the abc backend

(See also: http://www.sable.mcgill.ca/soot)

Outline

- Introduction to Soot
  - What is Soot? What can it do?
  - Why do we use Soot in **abc**?
  - Soot's intermediate representations.
  - Intra-procedural analysis framework (analysis within method bodies).
  - Call graphs, points-to analysis and inter-procedural analysis.
  - Soot's **dava** decompiler.
- Using Soot for cflow optimizations in **abc**.

What is Soot? What can it do?

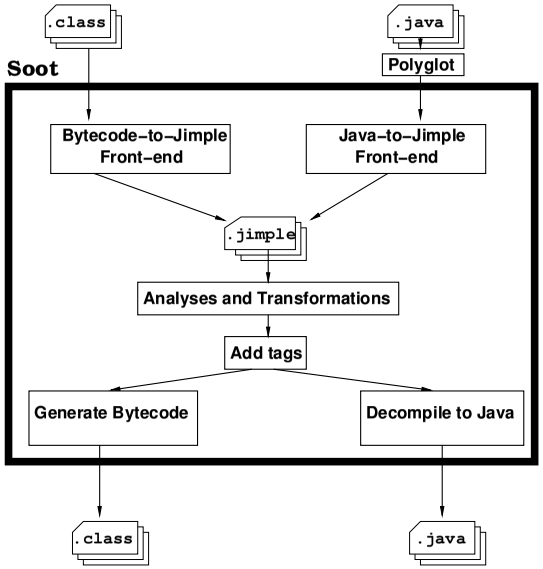
- Soot is a framework for analysing and transforming Java.
- Developed at McGill since 1998 - has been used in many research projects.
- Key features that Soot provides are:
  - Convenient IRs (mainly Jimple);
  - Existing analyses and transformations;
  - Framework for new analyses, transformations, code generation;
  - **Dava** decompiler;

www.sable.mcgill.ca/publications/

Why do we use Soot in abc?

- Provides a convenient basis for weaving, since its IR (Jimple) is simple, typed and stack-less.
- Use the existing bytecode optimizations to optimize the output of the weaver (**abc** has **-O** options).
- Develop AspectJ-specific analyses and transformations.
- Use existing whole program analyses and points-to frameworks to reason about call graphs and pointer/alias analyses.
- Enable efficient implementations of new, sophisticated pointcuts.

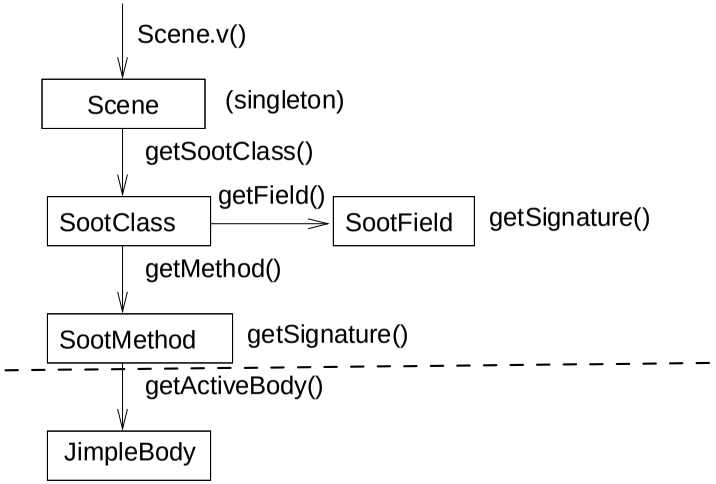
Soot



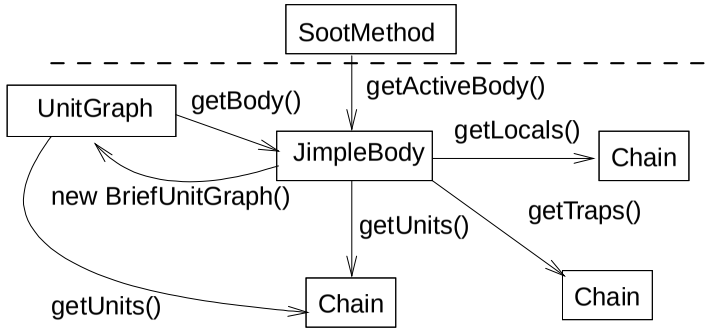
Soot Data Structure Basics

- Soot builds data structures to represent:
  - a complete environment (**`Scene`**)
  - classes (**`SootClass`**)
  - Fields and Methods (**`SootMethod`**, **`SootField`**)
  - bodies of Methods (come in different flavours, corresponding to different IR levels, ie. **`JimpleBody`**)
- These data structures are implemented using OO techniques, and designed to be easy to use and generic where possible.

Soot Classes



Body-centric View



Jimple

Jimple is:

- principal Soot Intermediate Representation
- 3-address code in a *control-flow graph*
- a *typed* intermediate representation
- *stackless*

Raja's Thesis, CASCON99, CC2000, SAS2000

Jimple example

Java:

```
public int bar(int a, int b) {
    return a+b;
}
```

Jimple:

```
public int bar(int, int) {
    Foo this;
    int a, b, $i0;

    this := @this;
    a := @parameter0;
    b := @parameter1;
    $i0 = a + b;
    return $i0;
}
```

Converting bytecode → Jimple → bytecode

- These transformations were relatively hard to design so that they produce correct, useful and efficient code.
- Worth the price, we **do** want a 3-addr typed IR.

raw bytecode	typed 3-address code (Jimple)
◦ each inst has implicit effect on stack	◦ each stmt acts explicitly on named variables
◦ no types for local variables	◦ types for each local variable
◦ $>$ 200 kinds of insts	◦ only 15 kinds of stmts

Bytecode → Jimple

- Naive translation from bytecode to untyped Jimple, using variables for stack locations.
- splits DU-UD webs (so many different uses of the stack do not interfere)
- types locals (SAS 2000)
- cleans up Jimple

Java → Jimple

- Input: Polyglot AST generated from .java sources
- Compile AST to Jimple
- Generate Jimple methods/classes for implicit Java features (initializers, inner class accessor methods, class literals, assertions)
- Output: Jimple to be analyzed/optimized, eventually converted to bytecode
- Combination of Polyglot, Java-to-Jimple, Jimple-to-Bytecode passes forms a complete Java compiler equivalent to javac.

This part is unchanged in abc.

Jimple → Bytecode

- A naive translation introduces many spurious stores and loads.
- Two approaches (CC 2000),
  - aggregate expressions and then generate stack code; or
  - perform store-load and store-load-load elimination on the naive stack code.

Weaving example – source

```
public class Foo {
    public int foo(int x, int y, int z) {
       return bar(x, y, z);
    }
    public int bar(int a, int b, int c) {
        return a+b+c;
    }
}
aspect A {
    before(Foo x) :
    call(int bar(int,int,int)) && target(x) {
        System.out.println(x);
    }
}
```

Weaving example – original bytecode

```
public int foo(int x, int y, int z)
0:    aload_0
1:    iload_1
2:    iload_2
3:    iload_3
4:    invokevirtual     Foo.bar (III)I (7)
7:    ireturn
```

Weaving example – weaving by hand

```
public int foo(int x, int y, int z)
0:    invokestatic      A.aspectOf ()LA; (14)
3:    aload_0
4:    invokevirtual     A.before$0 (LFoo;)V (20)
7:    aload_0
8:    iload_1
9:    iload_2
10:   iload_3
11:   invokevirtual     Foo.bar (III)I (9)
14:   ireturn
```

Weaving example – ajc weaving

```
public int foo(int x, int y, int z)
0:    aload_0
1:    iload_1
2:    iload_2
3:    iload_3
4:    istore            %4
6:    istore            %5
8:    istore            %6
10:   astore            %7
12:   invokestatic      A.aspectOf ()LA; (52)
15:   aload             %7
17:   invokevirtual     A.ajc$before$A$124 (LFoo;)V (56)
20:   aload             %7
22:   iload             %6
24:   iload             %5
26:   iload             %4
28:   invokevirtual     Foo.bar (III)I (37)
31:   ireturn
```

Weaving example – original Jimple

```
public int foo(int, int, int)
{
    Foo this;
    int x, y, z, $i0;

    this := @this;
    x := @parameter0;
    y := @parameter1;
    z := @parameter2;
    $i0 = this.bar(x, y, z);
    return $i0;
}
```

Weaving example – woven Jimple

```
public int foo(int, int, int)
{
    Foo this;
    int x, y, z, $i0;
    A theAspect;

    this := @this;
    x := @parameter0;
    y := @parameter1;
    z := @parameter2;
    theAspect = A.aspectOf();
    theAspect.before$0(this);
    $i0 = this.bar(x, y, z);
    return $i0;
}
```

Weaving example – bytecode from Jimple

```
public int foo(int x, int y, int z)
0:    invokestatic      A.aspectOf ()LA; (14)
3:    aload_0
4:    invokevirtual     A.before$0 (LFoo;)V (20)
7:    aload_0
8:    iload_1
9:    iload_2
10:   iload_3
11:   invokevirtual     Foo.bar (III)I (9)
14:   ireturn
```

Weaving details do matter!

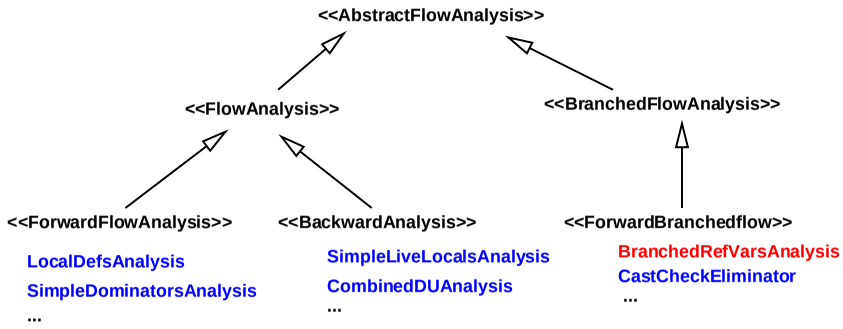
`lawOfDemeter.objectform.Pertarget.fieldIdentity`:

- ajc 1.2.0 used too many locals, too many cflow stacks.
  - ajc1.2.0: 616 locals 41 m, 38 s
  - ajc1.2.0+Soot: 3 locals 2 m, 56 s
- ajc 1.2.1 integrated abc's idea of cflow counters, and removed bug that generated too many cflow stacks.
  - ajc1.2.1: 38 locals 12.2 s
  - ajc1.2.1+Soot: 3 locals 12.2 s
- abc uses Soot's packing of locals, optimises cflow counters (still to come)
  - abc: 3 locals 8.7 seconds

Adding an intra-proc analysis/transform

- Soot provides:
  - An analysis framework.
  - Various control flow graph builders.
  - Various implementations of `FlowSet`.
  - Packs associated with different phases of Soot.
  - A large number of analyses and transforms already implemented.
- To add new analysis/transforms you can:
  - Extend an existing analysis and/or transform and add to a Pack (will see an example later); or
  - Implement a new analysis and/or transform and add to a Pack.

The `FlowAnalysis` Hierarchy



soot.toolkits.scalar

What you must provide...

A checklist of your obligations:

1. Subclass `*FlowAnalysis`
2. Implement abstraction: `merge()`, `copy()`
3. Implement flow function `flowThrough()`
4. Implement initial values: `newInitialFlow()` and `entryInitialFlow()`
5. Implement constructor
   (it must call `doAnalysis()`)

What Soot provides ...

- impls of abstraction domains (flow sets)
  - standard abstractions trivial to implement;
- an implemented solver, namely,
  - `doAnalysis()` method: executes intraprocedural analyses on a CFG using a worklist algorithm.

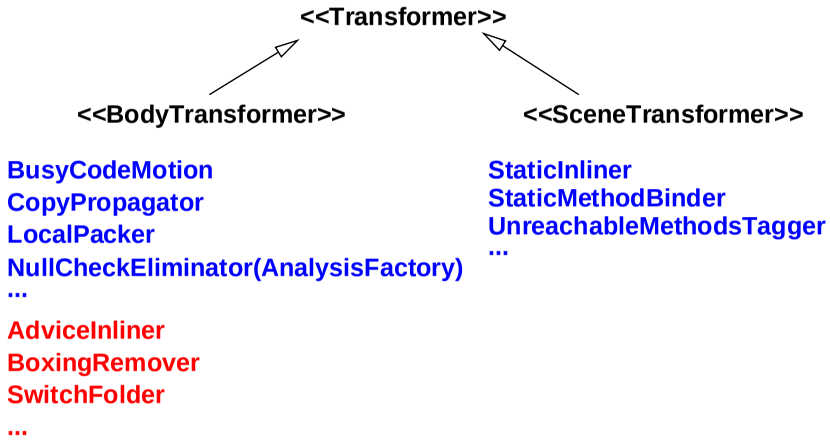
Enjoy: Flow Analysis Results

You can instantiate an analysis and collect results:

```
LiveVariablesAnalysis lv =
    new LiveVariablesAnalysis(g);

// retrieve analysis results for a stmt s:
lv.getFlowBefore(s);
lv.getFlowAfter(s);
```

Now you can use the results of your analysis in a transformation.

The `Transform` Hierarchy

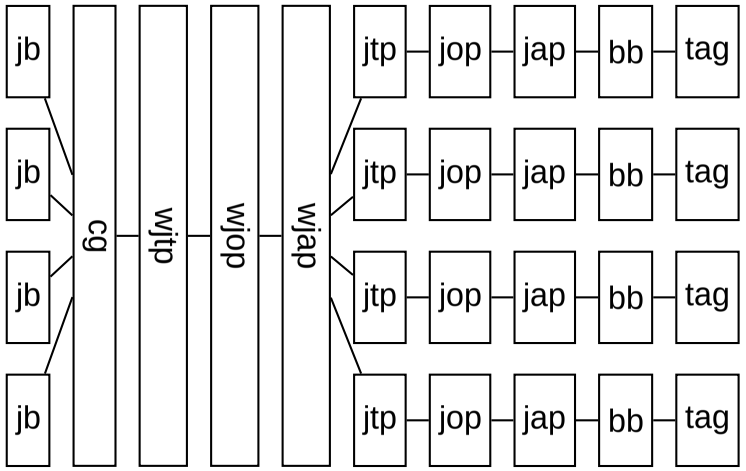


Adding transformations to Soot (easy way)

1. Implement a `BodyTransformer` or a `SceneTransformer`
   - `internalTransform` method does the transformation
2. Choose a pack for your transformation (usually `jtp`)
3. Add your transform to the pack.

```
Pack jtp = G.v().PackManager().getPack("jtp");
jtp.add(new Transform("jtp.nt",
                      new NullTransformer()));
```


Soot phases



Whole-program analyses

- CHA call graph based on class hierarchy
- VTA – more precise call graph (OOPSLA2000)
- Spark (stable): context-ins. points-to, call graph and side-effect analysis (CC2003)
- Paddle (current research): BDD-based framework for context-sensitive:
  - points-to analysis
  - call graph analysis
  - cflow analysis
  - type analysis (`instanceof` checks)
  - side-effect analysis (aspect purity)
  - escape analysis (`thisJoinPoint[StaticPart]`)

Soot has the SPARK points-to toolkit

If you want to know
... the types of the receiver o in the call: `o.m(...)`

1. Enable `cg.spark` so that points-to sets are computed.
2. Then use points-to information.

```
Local o;
PointsToAnalysis pa =
     Scene.v().getPointsToAnalysis();
PointsToSet ptset = pa.reachingObjects(o);
java.util.Set types = ptset.possibleTypes();
```

Call Graph

- Collection of edges representing all method invocations known to Soot
  - explicit method invocations
  - implicit invocations of static initializers
  - implicit calls of `Thread.run()`
  - implicit calls of finalizers
  - implicit calls by `AccessController`
  - ...
- `Filter` can be used to select specific kinds of edges

Call Graph Edges

- Each `Edge` contains
  - Source method
  - Source statement (if applicable)
  - Target method
  - Kind of edge

source m.	source stmt.	target m.	kind
●	●	●	VIRTUAL

```
foo() {                    bar() {
   o.bar();-------------->    /* */
}                          }
```

Querying Call Graph

`edgesOutOf(SootMethod)` iterator over edges with given source method

`edgesOutOf(Unit)` iterator over edges with given source statement

`edgesInto(SootMethod)` iterator over edges with given target method

main()	o.foo();	C1.foo()	VIRTUAL
main()	o.goo();	C1.goo()	VIRTUAL
main()	o.goo();	C2.goo()	VIRTUAL
bar()	o.foo();	C2.foo()	VIRTUAL

soot.jimple.toolkits.callgraph.CallGraph

Code Example

```
void mayCall( SootMethod src ) {
   CallGraph cg =
            Scene.v().getCallGraph();
   Iterator targets =
     new Targets(cg.edgesOutOf(src));

   while( targets.hasNext() ) {
      SootMethod tgt =
         (SootMethod) targets.next();
      System.out.println( ""+
        src+" may call "+tgt );
   }
}
```

Dava decompiler

```
public int foo(int x, int y, int z)
{
    A.aspectOf().before$0(this);
    return this.bar(x, y, z);
}
```

- Dava decompiles bytecode with strange aspect-generated control flow that breaks other decompilers.
- Dava is integrated with Soot and **abc**, use **abc `-dava <args>`** and decompiled output will be placed in a subdirectory called `dava/`.
- Very useful for debugging weavers.

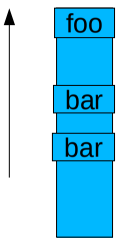
Optimisations in abc

- Intraprocedural Analyses using Soot
- Interprocedural Analysis
  - Analysing AspectJ Programs
  - Optimising *cflow*

Running Example: Optimising *cflow*

```
pointcut fooFromBar(int x) :
    call(* foo()) &&
    cflow( call(* bar(*)) && args(x) )
```

call stack:



bind x to the argument of the last call to bar

Obvious implementation:
maintain thread-local stack of bindings
- push before each call to bar
- pop after each call to bar
- check top upon each call to foo

Simple optimisations

no variable binders?
use an integer counter instead of stack

share stacks for multiple pointcuts:
e.g. unify cflows in
call(* bar(..)) && **cflow** (**call**(* foo(..)) && **args**(t,*,*))
call(* bar(..)) && **cflow** (**call**(* foo(..)) && **args**(*,s,*))
to
cflow(**call**(* foo(..)) && **args**(x,y,*))

Especially useful because of *inlining* of named pointcuts

Simple IR transformations: no need for dataflow analysis

Intraprocedural Optimisations

each cflow stack is local to a thread
want to retrieve it just once per method body
but never get the stack if it is not used

```
CflowStack threadLocalStack = null;
...
if (threadLocalStack == null)
    threadLocalStack = cflow.getThreadStack();
```

rely on Soot's null-check eliminator to remove this

getThreadStack() never returns null

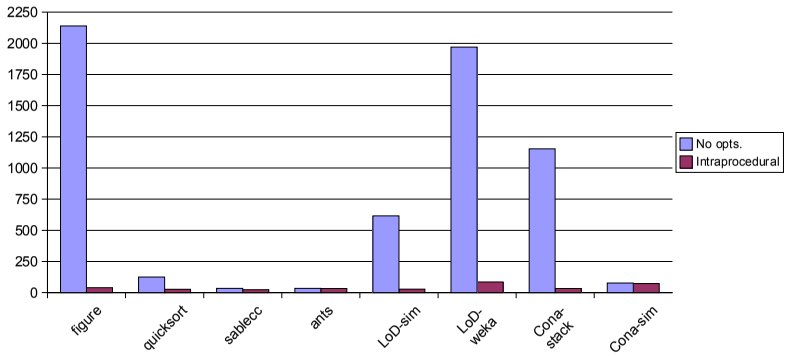
Intraprocedural Optimisations (2)

```
NullCheckEliminator.AnalysisFactory f =
   new NullCheckEliminator.AnalysisFactory() {
      (...)

         public boolean isAlwaysNonNull(Value v) {
            // Standard null-check eliminator
            if (super.isAlwaysNonNull(v)) return true;

            if (v instanceof InvokeExpr) {
               InvokeExpr ie = (InvokeExpr) v;
               SootMethodRef m = ie.getMethodRef();
               return CflowCodeGenUtils.isCflowGetMethod(m); }
            return false; }

   };
   // this should run before Dead Assignment Elimination
   PackManager.v().getPack("jop").insertBefore(
   new Transform("jop.nullcheckelim", new NullCheckEliminator(f)), "jop.dae");
```

Factory for constructing customised Null-Check eliminators

cflow-specific

Intraprocedural Optimisations: Summing Up



We have reduced, but not eliminated, overheads for cflow
Similar speedup for ajc 1.2 vs. 1.2.1 (some of the same opts)

see PLDI 2005 for detailed results

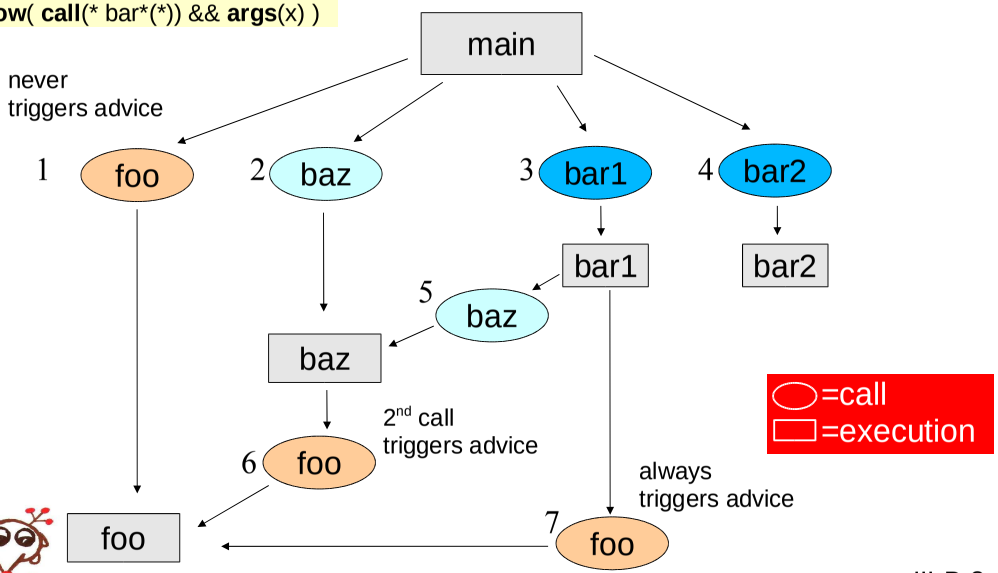
Optimising *cflow*

```
aspect Aspect {
   pointcut fooFromBar(int x) :
      call(* foo()) &&
      cflow( call(* bar*(*)) && args(x) );

   before(int x) : fooFromBar(x) {
      System.out.println("foo from bar, x="+x);
   }
}
```

```
public class Cflow {

   void foo() {}
   void bar1(int x) { foo(); baz(); }
   void bar2(int x) {}
   void baz() { foo(); }

   public static void main(String[] args) {
      Cflow c = new Cflow();
      c.foo();
      c.baz();
      c.bar1(3);
      c.bar2(4);
   }

}
```

Call Graph

```
call(* foo()) &&
cflow( call(* bar*(*)) && args(x) )
```



Interprocedural Optimisations

to implement cflow(p)

update shadow:
push/pop stack at each shadow matching p

query shadow:
test whether stack nonempty
bind formals from stack (if applicable)

at query shadow:
predict emptiness:
if yes or no, remove test

at update shadow:
predict whether observed by any query:
if not, remove push/pop

Optimising *cflow*

For each update shadow sh:

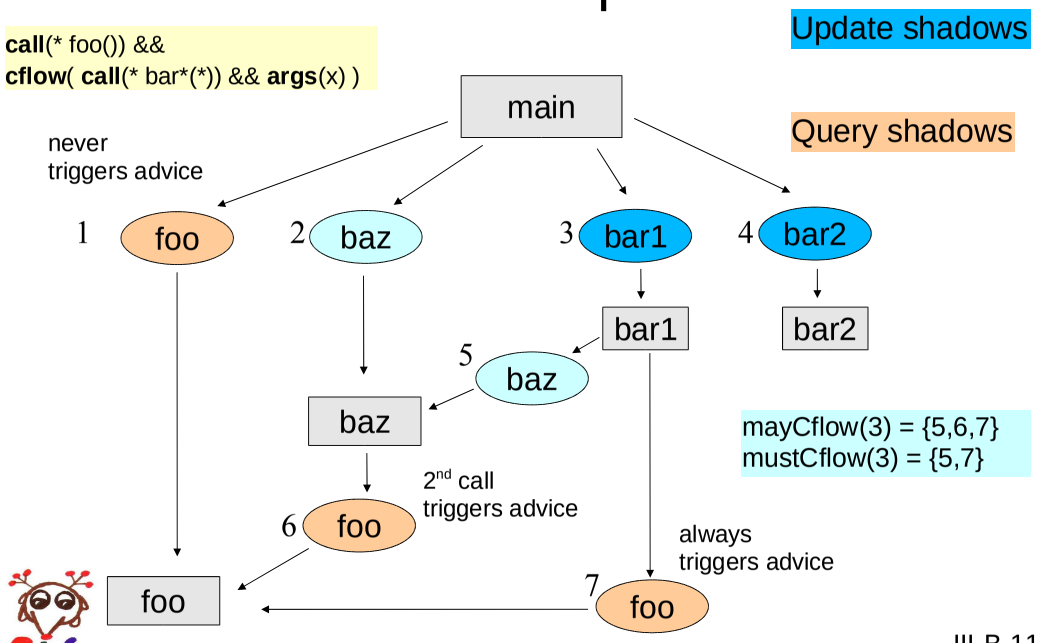
st ∈ *mayCflow*(sh) :
at statement st, we *may* be in the dynamic scope of sh

st ∈ *mustCflow*(sh) :
at statement st, we *must* be in the dynamic scope of sh

The set of statements that can be reached interprocedurally from sh

Call Graph

call(* foo()) &&
cflow(**call**(* bar*(*)) && **args**(x))



Optimising *cflow* (2)

At query shadow qsh:

If ¬(∃ upsh : qsh ∈ *mayCflow*(upsh))
qsh is *always false* and can be removed
If (∃ upsh : qsh ∈ *mustCflow*(upsh))
qsh is *always true* and can be removed

Only valid if no variables are bound

At update shadow upsh:

If ¬(∃ qsh ∈ mayCflow(upsh))
upsh is *never queried* and can be removed
If (∃ sh : upsh ∈ mustCflow(sh))
upsh is *guaranteed nonempty* and can be removed

Computing *cflow* information

computation of mayCflow(sh):

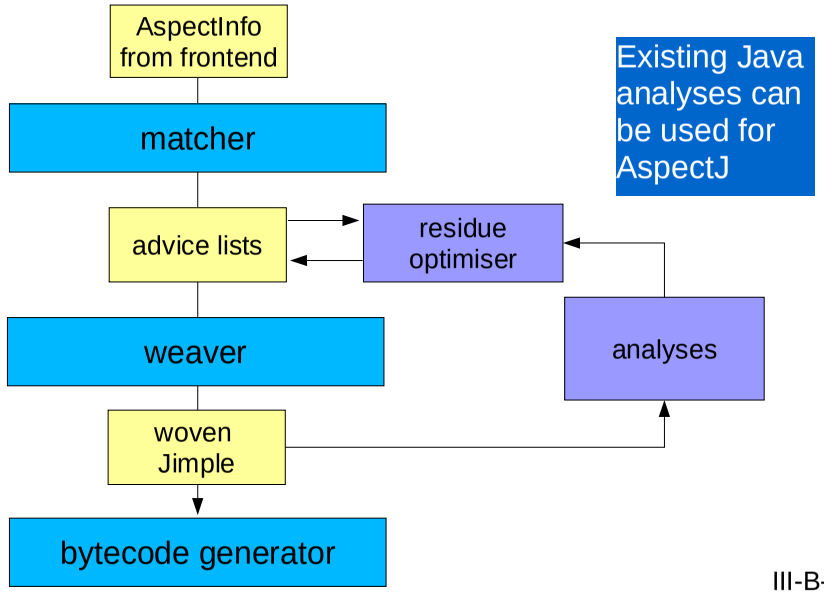
mayCflow ← { st | st is in intraprocedural shadow of sh}
repeat
  for all methods m | ∃ st ∈ mayCflow(sh) : st may call m *do*
    mayCflow ← mayCflow ∪ set of statements in m
until mayCflow does not change

computation of mustCflow(sh): dual

How is the "may call" relation computed?

- Call graph construction in Java is tricky
- AspectJ constructs (advice...) can affect the call graph of the base program

Reweaving: an analysis framework for AspectJ



cflow analysis: implementation

"may call" : use Paddle framework for callgraph construction
  still under active development

set representation: BDDs via Jedd
  (extension of Java for programming BDD-based analyses)

Implementing the analysis in Jedd:

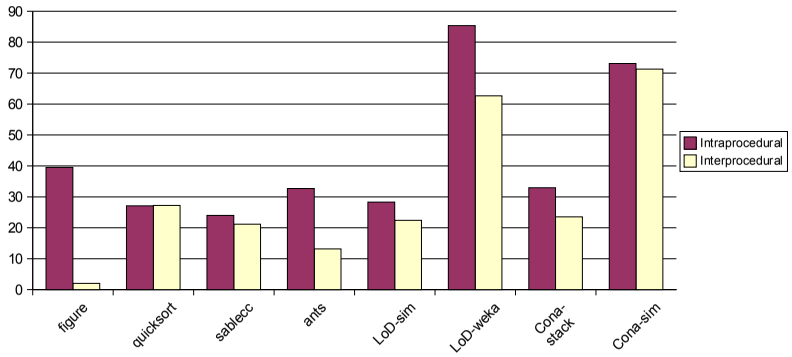
```
<stmt> mayCflow(Shadow sh) {
  <stmt> mayCflow = stmtsWithin(sh);
  <stmt> old;
  do {
    old = mayCflow;
    <method> targets = mayCflow(stmt) <> callTargets(stmt);
    mayCflow |= targets(method) <> stmtsIn(method);
  } while (mayCflow != old);
  return mayCflow;
}
```

cflow analysis: implementation (2)

Interface with abc: setting the *never valid* residues:

```
StackInfo si = stackInfo(stack);
BDDCflowStack bddcfs =
  new BDDCflowStack(cflowAnalysis, si.shadows, si.stmtMap.keySet(), si.bindsArgs );

for (Iterator stmtIt = bddcfs.neverValid(); stmtIt.hasNext();) {
  final Stmt stmt = (Stmt) stmtIt.next();

  for (Iterator rbIt = si.aa(stmt).getResidueBoxes().iterator(); rbIt.hasNext(); ) {
    final ResidueBox rb = (ResidueBox) rbIt.next();

    if (!(rb.getResidue() instanceof CflowResidue)) continue;
    CflowResidue cfr = (CflowResidue) rb.getResidue();
    if (cfr.setup() != stack) continue;

    rb.setResidue(NeverMatch.v()); }
}
```

Interprocedural Optimisations: Summing Up



All but one cflow *were static properties*
The analysis identified all of these

Send us *your* benchmarks!

Optimisations, Analyses and Beyond

- Statically determining properties:

```
declare error : uiCalls() && cflow(call(* EnterpriseBean+.*(..)))
      : "UI call from EJB";
```

  At each program point:

  - *Never matches*: no error
  - *Always matches*: error
  - *May match*: warning and runtime assert

Adapted from Laddad, *AspectJ in Action*

- *pcflow*(): analysis for precision
- Tracecuts: analysis crucial for efficiency