Class Analysis

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Announcements

- HW2
  - Post question on Submitty
    - Setup, please do set this up as soon as possible!
    - Starter code, class analysis framework and worklist algorithm
    - Soot

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Flow Insensitivity

- Flow-insensitive analysis discards CFG edges and computes a single solution S
- A "declarative" definition, i.e., specification:
  - Least solution S of equations S = $f_j(S) \vee S$
  - Points-to analysis is an example where such a solution makes sense!

E.g., Flow-Sensitive vs. Flow-Insensitive Constant Propagation

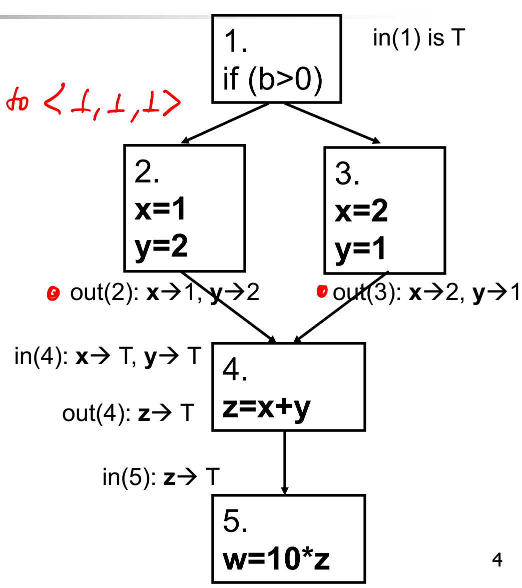
Assume we can initialize S to <⊥,⊥,⊥>

1. **x=1**
2. **y=2**
3. **x=2**
4. **y=1**
5. **z=x+y**
6. **w=10*z**

<1,⊥,⊥>

...

S = <T,T,T>



Example

- There are variations, but typically, in a flow-insensitive analysis f_j refer to statement j, not basic block j
- IRs mitigate flow insensitivity

x y z w
S = ⟨⊥, ⊥, ⊥, ⊥⟩

```
1. x=1
2. x=2
3. y=1
4. z=x+y
5. w=10*z
```

S = ⟨T, 1, T, T⟩

x1 x2 y z w
S = ⟨⊥, ⊥, ⊥, ⊥, ⊥⟩

```
1. x1=1
2. x2=2
3. y=1
4. z=x2+y
5. w=10*z
```

S = ⟨1, 2, 1, 3, 30⟩

Flow Insensitivity

- An "operational" definition. A worklist algorithm: 0 of the lattice

```
S = 0, W = { 1, 2, … n } /* all nodes */
while W ≠ Ø do {
  remove j from W
  S = fj(S) V S
  if S changed then
    W = W U { k | k is "successor" of j }
}
```

if S changed add all f_i to W

- "successor" is not CFG successor nodes, but more generally, nodes **k** whose transfer function $\mathbf{f_k}$ may be affected as a result of the change in S by **j**

Outline of Today's Class

- Class analysis
- Class Hierarchy Analysis (CHA)
- Rapid Type Analysis (RTA)

- HW2 class analysis framework

- XTA analysis family (next week)
- 0-CFA (next week)

Your Homework

- A bunch of flow-insensitive, context-insensitive analyses for Java
  - RTA in HW2, other analyses in later homework
  - Simple property space
  - Simple transfer functions
    - E.g., in fact, RTA gets rid of most CFG nodes, processes just 3 kinds of statements (i.e., CFG nodes)

  - Millions of lines of code in seconds

Class Analysis

- Problem statement: What are the **classes** of objects that a (Java) **reference** variable may refer to at runtime?

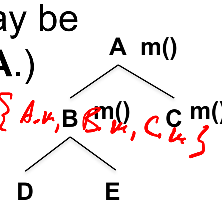
- Class Hierarchy Analysis (CHA)
- Rapid Type Analysis (RTA)
- XTA family of analyses
- 0-CFA
- Points-to Analysis (PTA)

Applications of Class Analysis

- Call graph construction
  - At virtual call **r.m()**, what methods may be called? (Assuming **r** is of static type **A**.)

r: {A, B, C, D, E} r.m() = {A.m, B.m, C.m}

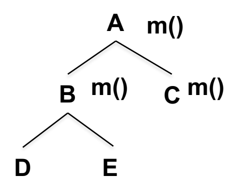
r: {D, E} r.m() = {B.m}



- Call graph
  - Nodes are methods
  - Edges represent calling relationships m1 → m2
  - Notion of methods reachable from **main**

Applications of Class Analysis

- Virtual call resolution
  - If analysis proves that a virtual call has a single target, it can replace it with a direct call
  - An OOPSLA'96 paper by Holzle and Driesen reports that C++ programs spend 5% of their time in dispatch code. For "all virtual", it is 14%

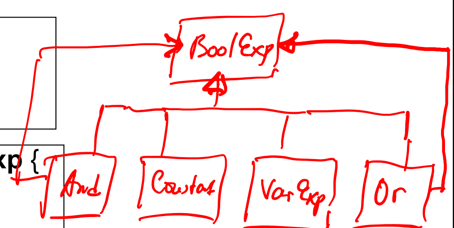


Boolean Expression Hierarchy

```
public abstract class BoolExp {
   public boolean evaluate(Context c);
}
```

```
public class Constant extends BoolExp {
   private boolean constant;
   public boolean evaluate(Context c) {
     return constant;
   }
}
```

```
public class VarExp extends BoolExp {
    private String name;
    public boolean evaluate(Context c) {
        return c.lookup(name);
    }
}
```



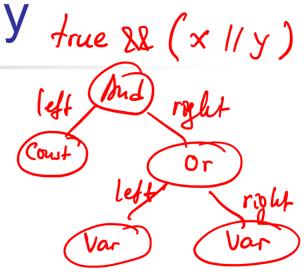
Boolean Expression Hierarchy

```
public class AndExp extends BoolExp {
  private BoolExp left;
  private BoolExp right;

  public AndExp(BoolExp left, BoolExp right) {
    this.left = left;
    this.right = right;
  }
  public boolean evaluate(Context c) {
     return left.evaluate(c) && right.evaluate(c);
   }
}
```


Boolean Expression Hierarchy

```
public class OrExp extends BoolExp {
  private BoolExp left;
  private BoolExp right;

  public OrExp(BoolExp left, BoolExp right) {
    this.left = left;
    this.right = right;
  }
  public boolean evaluate(Context c) {
    return left.evaluate(c) || right.evaluate(c);
  }
}
```

A Client of the Boolean Expression Hierarchy




```
main() {
   Context theContext = new …
   BoolExp x = new VarExp("X");
   BoolExp y = new VarExp("Y");
   BoolExp exp = new AndExp(
                    new Constant(true), new OrExp(x, y) );
   theContext.assign(x, true);
   theContext.assign(y, false);
   boolean result = exp.evaluate(theContext);
}
```

exp: {AndExp}

At runtime, exp can refer to an object of class AndExp,
but it cannot refer to objects of class OrExp, Constant or VarExp!

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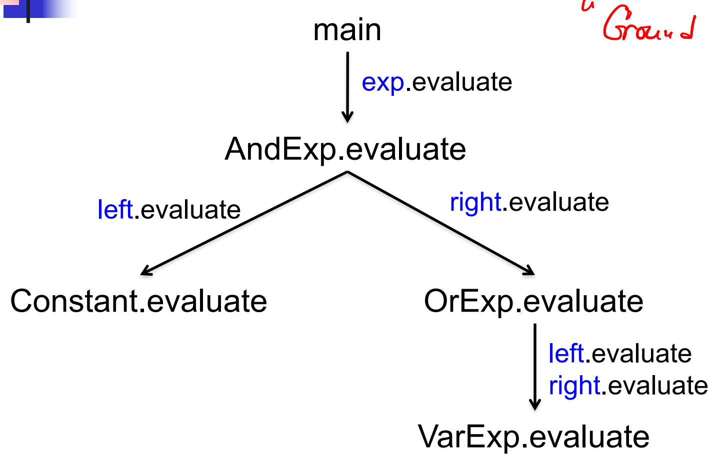
Call Graph Example (Partial)

"Ground Truth"



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Class Hierarchy Analysis (CHA)

- Attributed to Dean, Grove and Chambers:
  - Jeff Dean, David Grove, and Craig Chambers, "Optimization of OO Programs Using Static Class Hierarchy Analysis", ECOOP'95
- Simplest way of inferring information about reference variables --- just look at class hierarchy

A r;

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Class Hierarchy Analysis (CHA)

- In Java, if a reference variable **r** has type **A**, **r** can refer only to objects that are concrete subclasses of **A**. Denoted by **SubTypes(A)**
  - Note: refers to Java subtype, not true subtype
  - Note: **SubTypes(A)** notation due to Tip and Palsberg (OOPSLA'00)
- At virtual call site **r.m(),** we can find what methods may be called using the hierarchy information

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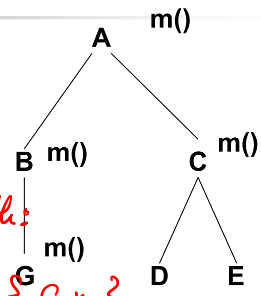
Example

```
public class A {
   public static void main() {
         A a;
         D d = new D();
         E e = new E();
         if (…) a = d; else a = e;
         a.m();
   }
}
public class B extends A {
   public void foo() {
         G g = new G();
   }
} … // no other creation sites or calls in the program
```

Ground truth: a: {D, E} a.m(): {C.m}



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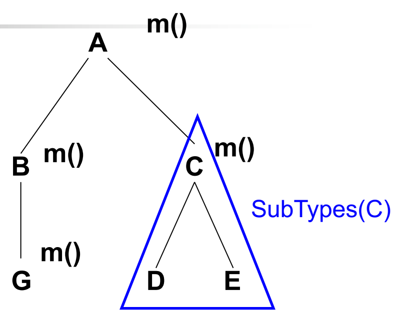
Example

```
public class A {
   public static void main() {
         A a;
         D d = new D();
         E e = new E();
         if (…) a = d; else a = e;
         a.m();
   }
}
public class B extends A {
   public void foo() {
         G g = new G();
   }
} …
```



SubTypes(A) = **{ A, B, C, D, E, G }**

SubTypes(B) = **{ B, G }**

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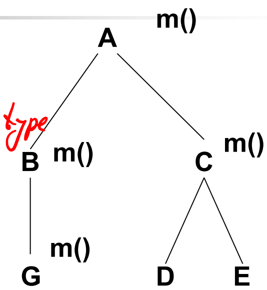
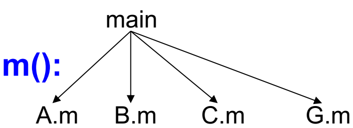
Example

```
public class A {
   public static void main() {
        A a;   Static type, also declared type
        D d = new D();
        E e = new E();
        if (…) a = d; else a = e;
        a.m();
   }
}
public class B extends A {
   public void foo() {
        G g = new G();
   }
} …
```



a: **SubTypes(StaticType(a)) = SubTypes(A)**
= { A, B, C, D, E, G }

a.m():



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CHA as Reachability Analysis

R denotes the set of reachable methods

1. { main } ⊑ **R**   // Algo: initialize **R** with **main**

2. for each method **m** ∈ **R**,
each virtual call **y.n(z)** in **m**,
each class **C** in **SubTypes(StaticType(y))** and
n', where **n'** = **resolve(C,n)**

   { **n'** } ⊑ **R**   // Algo: add **n'** to **R**

   (Practical concerns: must consider direct calls too!)

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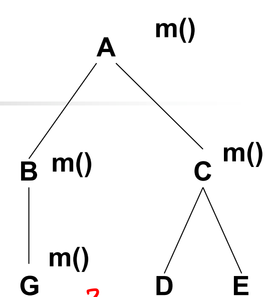
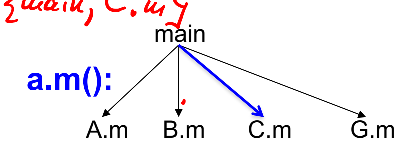
Rapid Type Analysis (RTA)

- Due to Bacon and Sweeney
  - David Bacon and Peter Sweeney, “Fast Static Analysis of C++ Virtual Function Calls”, OOPSLA ’96
- Improves on CHA
- Expands calls only if it has seen an **instantiated object** of the appropriate type!

Example

```
public class A {
   public static void main() {
        A a;
Alloc   D d = new D();     I = {D, E}
Alloc   E e = new E();     R = {main, C.m}
        if (…) a = d; else a = e;
VCall   a.m();
   }
}
public class B extends A {
   public void foo() {
        G g = new G();
   }
}
```





RTA starts at **main**.
Records that **D** and **E** are instantiated.
At call **a.m()** looks at all CHA targets.
Expands only into target **C.m()**!
Never reaches **B.foo()**, never records **G** as being instantiated.

RTA

R is the set of reachable methods

I is the set of instantiated types

1. **{** main **}** ⊑ **R**   // Algo: initialize **R** with **main**

2. for each method **m** ∈ **R** and
   each new site **new C** in **m**

   { C } ⊑ **I**   // Algo: add **C** to **I;** schedule
   // "successor" constraints

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RTA

3. for each method **m** ∈ **R**,
each virtual call **y.n(z)** in **m**,
each class **C** in **SubTypes(StaticType(y))** ∩ **I,**
and **n'**, where **n'** = **resolve(C,n)**

   { n' } ⊑ **R** // Algo: add target **n'** to **R**, if not already
   // there. Schedule "successors"

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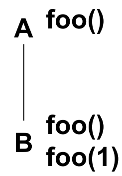
Comparison

Bacon-Sweeny, OOPSLA' 96

```
class A {
public :
   virtual int foo() { return 1; };
};
class B: public A {
public :
   virtual int foo() { return 2; };
   virtual int foo(int i) { return i+1; };
};
void main() {
   B* p = new B;
   int result1 = p->foo(1);
   int result2 = p->foo();
   A* q = p;
   int result3 = q->foo();
}
```



CHA resolves **result2** to **B.foo()**; however, it does not resolve **result3**.

RTA resolves **result3** to **B.foo()** because only **B** has been instantiated.

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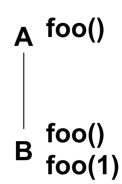
Caveat

Bacon-Sweeny, OOPSLA' 96

```
class A {
public :
   virtual int foo() { return 1; };
};
class B: public A {
public :
   virtual int foo() { return 2; };
   virtual int foo(int i) { return i+1; };
};
void main() {
   void* x = (void*) new A;
   B* q = (B*) x;
   int result3 = q->foo();
}
```



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RTA Example with Boolean Expression Hierarchy

```
main() {
   Context theContext = new …
   BoolExp x = new VarExp("X");
   BoolExp y = new VarExp("Y");
   BoolExp exp = new AndExp(
                      new Constant(true), new OrExp(x, y) );
   theContext.assign(x, true);
   theContext.assign(y, false);
   boolean result = exp.evaluate(theContext);
}
```

R = { main, VarExp.evaluate, … }
I = { VarExp, AndExp, Constant, OrExp }

{ VarExp, AndExp, OrExp, Constant }

for each C = cone(BoolExp) ∩ I
ds' = resolve(C, evaluate())
// { VarExp.evaluate, … }
change = true

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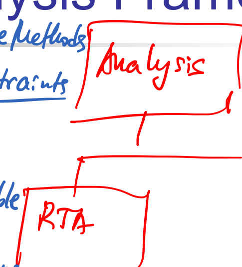
HW2 Class Analysis Framework

- Big picture

readableMethods
sootConstraints

worklist "hooks"

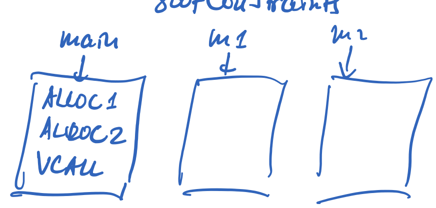


define hooks

1. Run soot
→ Soot traverses all CHA-reachable methods
→ Creates this sootConstraints map

2. Run worklistSolve

sootConstraints



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HW2 Class Analysis Framework

- Let’s take a moment (or two, or more) to go over HW2 class analysis framework
  - Hooks
    - E.g., `void allocStmt(SootMethod enclMethod, int allocSiteId, Node lhs, Node alloc)`
  - Transfer functions, i.e., Constraints
    - Add Constraint classes for certain statements
    - E.g., `class Alloc implements Constraint { … }`
  - `sootConstraints` map
  - `resolve` function