Class Analysis

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

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 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

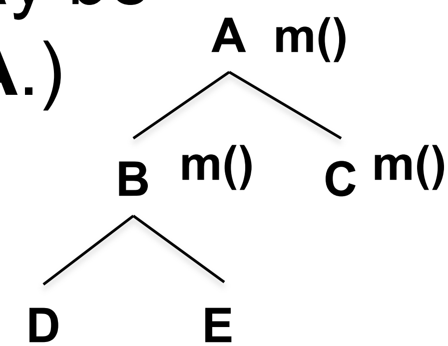
- Problem statement: What are the **classes** of objects that a (Java) **reference** variable may refer to at runtime?

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

Applications of Class Analysis

A r;
A is the declared type of r.
Also called static type or compile-time type.

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

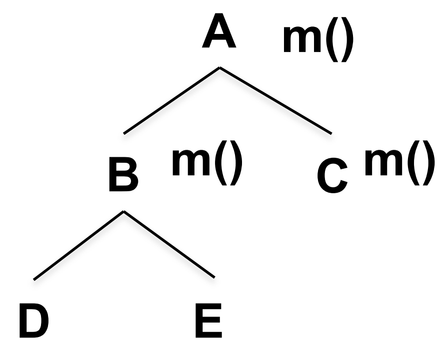


r : { D, E }
r.m() : B.m()

- Call graph
  - Nodes are methods
  - Edges represent calling relationships
  - 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%

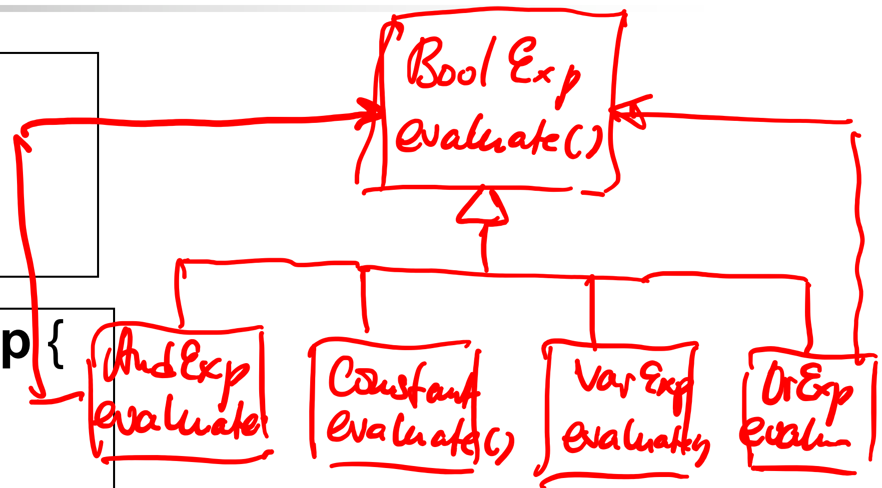


Boolean Expression Hierarchy

```
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);
    }
}
```

left : {Constant}
left.evaluate() : {Constant.evaluate()}

"Ground truth" given client on slide 11.

Boolean Expression Hierarchy

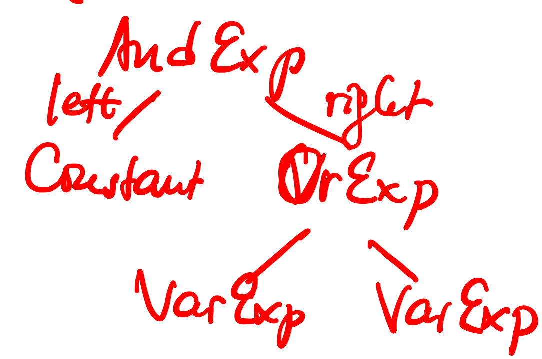
```
public class OrExp extends BoolExp {
   private BoolExp left;
   private BoolExp right;

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

left: {VarExp} } Ground truth
{VarExp.evaluate()}

A Client of the Boolean Expression Hierarchy

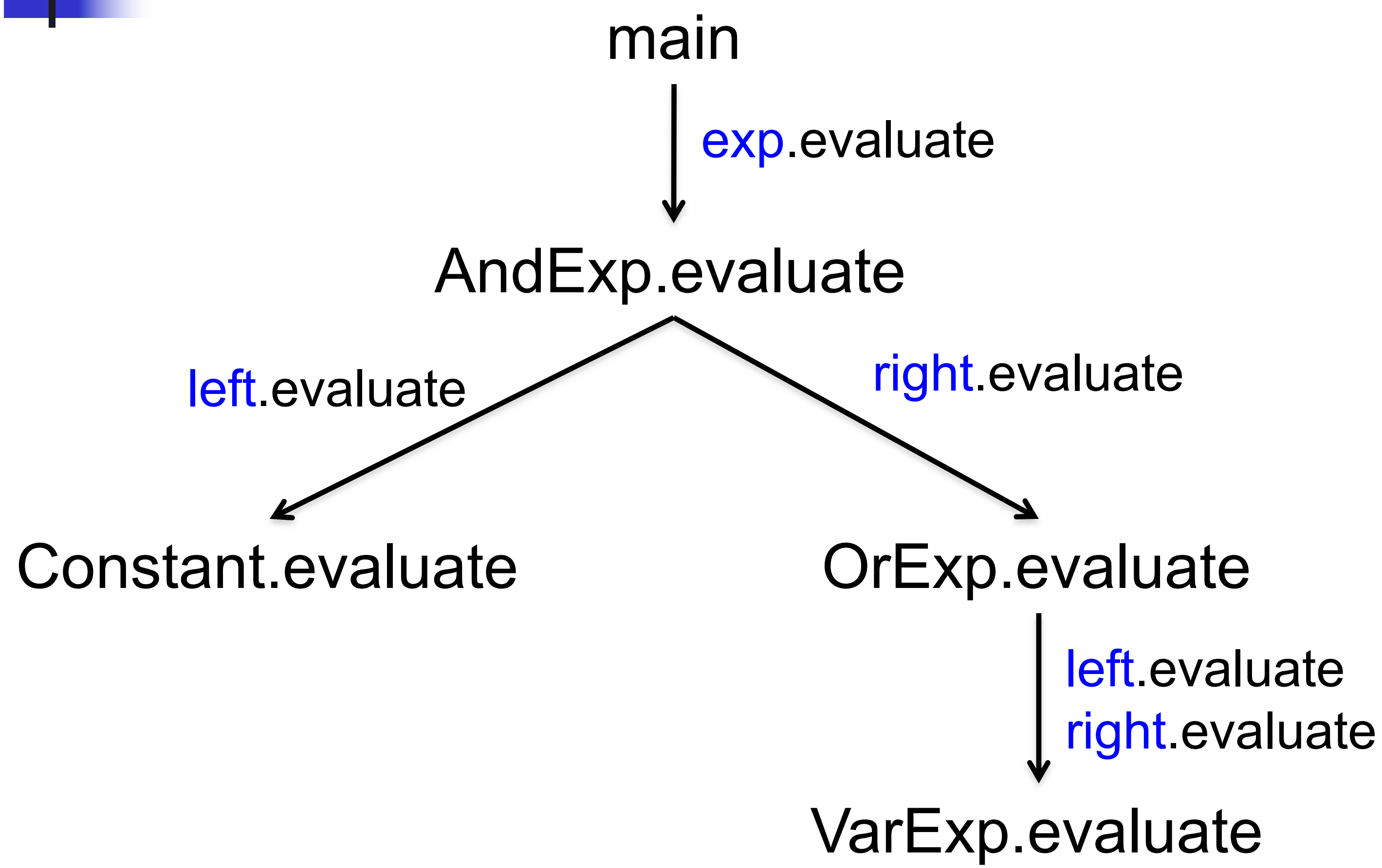
```
main() {
    Context theContext = new …
    BoolExp x = new VarExp("X");
    BoolExp y = new VarExp("Y");
    BoolExp exp = new AndExp(
                      new Constant(true), new OrExp(x, y) );
    theContext.assign(x, true);
    theContext.assign(y, false);
    boolean result = exp.evaluate(theContext);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



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!

Call Graph Example (Partial)



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

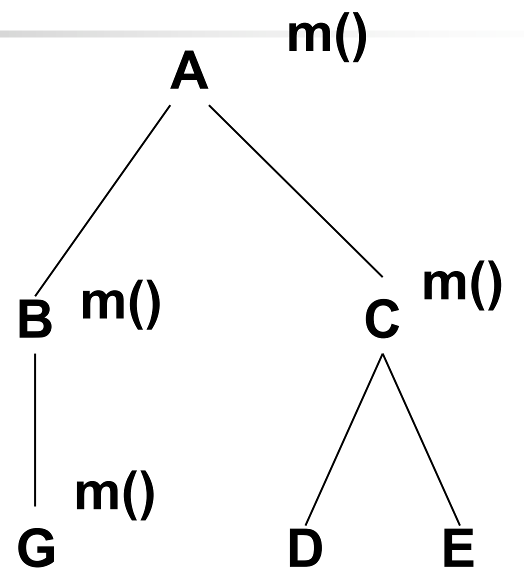
Class Hierarchy Analysis (CHA)

- 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 based on the hierarchy information

Example

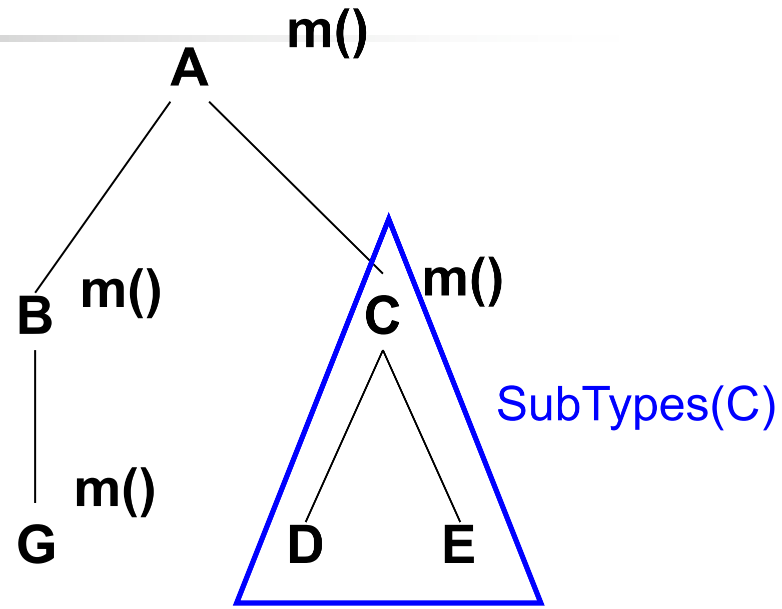
```
public class A {
    public static void main() {
        A a;
        D d = new D();
        E e = new E();
        if (…) a = d; else a = e;
        a.m();
    }
}
public class B extends A {
    public void foo() {
        G g = new G();
    }
} … // no other creation sites or calls in the program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

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



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();
    }
} …
```



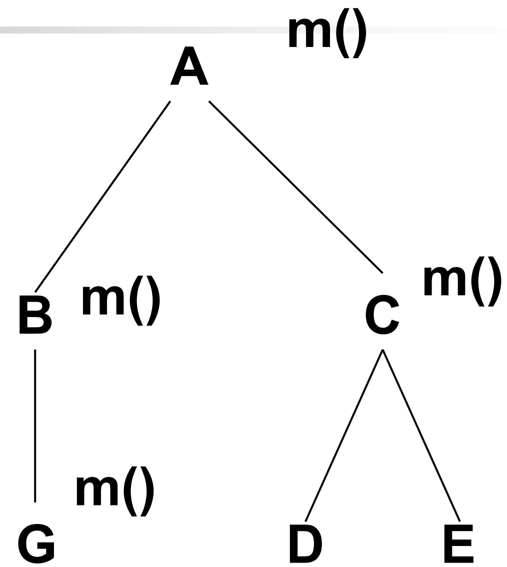
SubTypes(A) = **{ A, B, C, D, E, G }**

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

Example

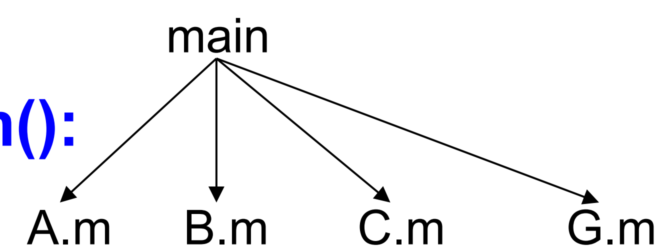
```
public class A {
    public static void main() {
        A a;
        D d = new D();
        E e = new E();
        if (…) a = d; else a = e;
        a.m();
    }
}
public class B extends A {
    public void foo() {
        G g = new G();
    }
} …
```

a.m() : {A.m(), B.m(), G.m(), C.m()}



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

a.m():



CHA as Reachability Analysis

R denotes the set of reachable methods

1. { main } $\sqsubseteq$ **R** // Algo: initialize **R** with **main**
2. for each method **m** $\in$ **R**,

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

{ **n'** } $\sqsubseteq$ **R** // Algo: add **n'** to **R**

(Practical concerns: must consider direct calls too!)

Rapid Type Analysis (RTA)

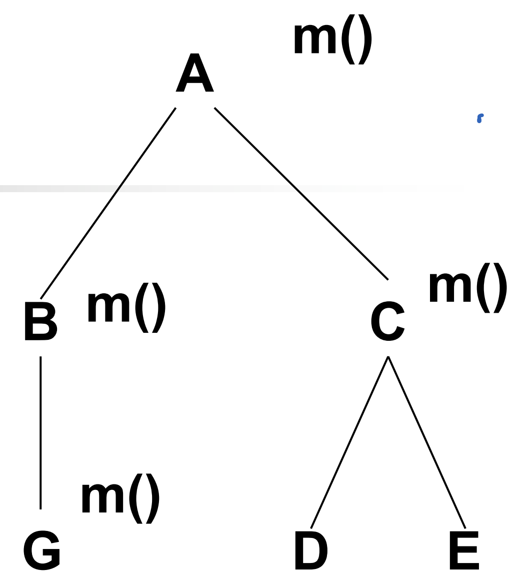
- Due to Bacon and Sweeney
  - David Bacon and Peter Sweeney, “Fast Static Analysis of C++ Virtual Function Calls”, OOPSLA ’96
- Improves on CHA
- Expands calls only if it has seen an **instantiated object** of the appropriate type!

Example

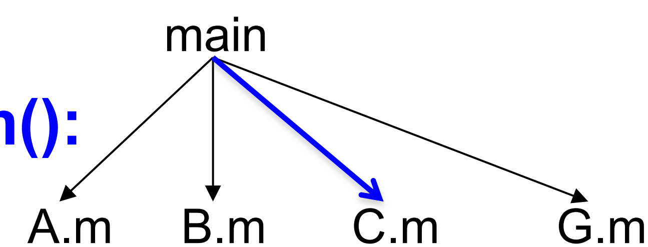
```
public class A {
    public static void main() {
        A a;
        D d = new D();
        E e = new E();
        if (…) a = d; else a = e;
        a.m();
    }
}
public class B extends A {
    public void foo() {
        G g = new G();
    }
}
```

I = {D, E}
R = {main, C.m}

RTA: a: {D, E}   a.m(): {C.m}
CHA: a: {A, B, C, D, E, G}



a.m():



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 **}** $\sqsubseteq$ **R** // Algo: initialize **R** with **main**

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

   { C } $\sqsubseteq$ **I** // Algo: add **C** to **I;** schedule
   // "successor" constraints

RTA

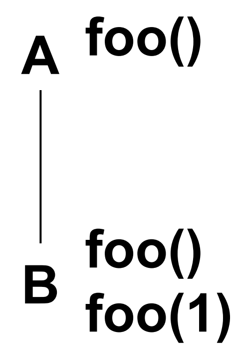
3. for each method **m** $\in$ **R**,
each virtual call **y.n(z)** in **m**,
each class **C** in **SubTypes(StaticType(y))** $\cap$ **I**,
and **n'**, where **n' = resolve(C,n)**

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

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();
}
```



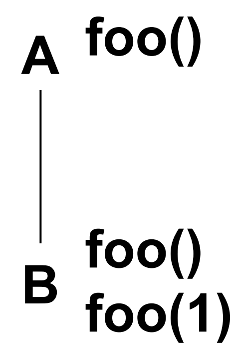
CHA resolves **result2** to **B.foo()**; however, it does not resolve **result3**.

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

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();
}
```



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);
}
```

I = All of them

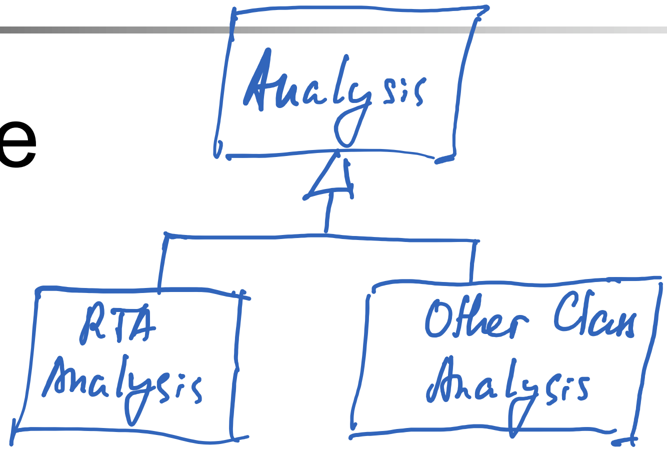
R =

exp: {VarExpr,Constant,OrExp,AndExp}

exp.evaluate() : { And.evaluate(), Or.Evaluate(), Constant.evaluate(), Var.evaluate() }

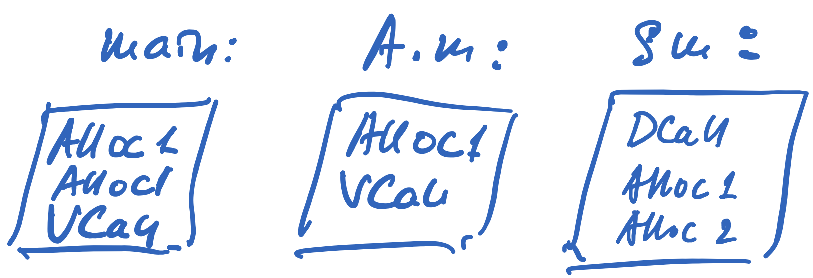
HW2 Class Analysis Framework

- Big picture



- Override hook methods to collect necessary transfer function info
  - You need hooks for Allocation (x=new A;), Virtual Call (x=y.m(2)) and direct call (e.g. sm()).
- Define classes to represent transfer functions (i.e. Constraints)

sootConstraints map:



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)`

      creates and registers a transfer function (i.e. constraint) for Allocation statement.
  - Transfer functions, i.e., Constraints
    - Add Constraint classes for certain statements
    - E.g., `class Alloc implements Constraint { … }`

      captures transfer function for Allocation statement
  - `sootConstraints` map
  - `resolve` function