Class Analysis, conclusion

Announcements

- Quiz 2
- HW2
  - Post question on Submitty
    - I’m assuming you all have this set up locally
    - Starter code, class analysis framework and worklist algorithm
    - Soot
  - There are already many useful posts

Outline of Today's Class

- Rapid Type Analysis (RTA), last time

- HW2, Class analysis framework questions?

- The XTA analysis family
- 0-CFA
- Points-to analysis (PTA)

Class Analysis

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

A a; // declared type of a is A

...

$a \to A$
$a \to B$
$a \to C$

{A, B, C} is the run time type of a

- Applications
  - Call graph construction
    - Nodes are method
    - Edges represent calling relationships
    - Notion of methods reachable from **main**
  - Virtual call resolution

RTA, A Declarative Specification

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, A Declarative Specification

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"

4. for each direct call to n in m $\in$ R
$\{n\} \subseteq R$

Worklist Algorithm for Flow-Insensitive Analysis

- Flow-insensitive, context-insensitive analysis

$S = \langle R, I \rangle$

S = … /* initialize S, typically to empty, which is 0 of lattice */

W = { f_1, … f_n } /* initialize W with transfer functions in **main** */

while W ≠ Ø do {

  remove f_j from W

  S = f_j(S) /* f_j never "kills" */

  if S changed

    W = W U Successors

/* Successors includes all affected transfer functions; easy safe approximation for us: include all f_j's in reachable methods */

}

allocStmt

alloc = new Alloc()

addToMap(sootConstraints, endMethod, alloc);

class Alloc

new_class =

HashSet<Constraints> solve()

HW2 Class Analysis Framework

- Questions on HW2 class analysis framework?

XTA Analysis Family

- Due to Tip and Palsberg
  - Frank Tip and Jens Palsberg, “Scalable Propagation-Based Call Graph Construction Algorithms”, OOPSLA ’00
- Generalizes RTA
- Improves on RTA by keeping more info
  - What if we kept sets per method and per field rather than a “blob” I?

XTA

R is the set of reachable methods

$\mathbf{S_m}$ is the set of types that flow to method **m**

$\mathbf{S_f}$ is the set of types that flow to field **f**

1. **{** main **}** $\sqsubseteq$ **R**

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

   $\{ C \} \sqsubseteq S_m$

XTA

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

- $\{ \mathbf{n'} \} \sqsubseteq \mathbf{R}$ // add **n'** to **R** if not already there
- $\{ \mathbf{C} \} \sqsubseteq S_{n'}$ // add **C** to $S_{n'}$ if not already there
- $S_m \cap \mathbf{SubTypes(StaticType(p))} \sqsubseteq S_{n'}$ flow of act arg. to formal params
- $S_{n'} \cap \mathbf{SubTypes(StaticType(ret))} \sqsubseteq S_m$ flow of return to lhs

(**p** denotes the parameter of **n'**, and **ret** denotes the return of **n'**)

XTA

4. for each method **m** $\in$ **R**,
each field read **x = y.f** in **m**

$$S_f \sqsubseteq S_m$$

$S_f \subseteq S_m$

5. for each method **m** $\in$ **R**,
each field write **x.f = y** in **m**

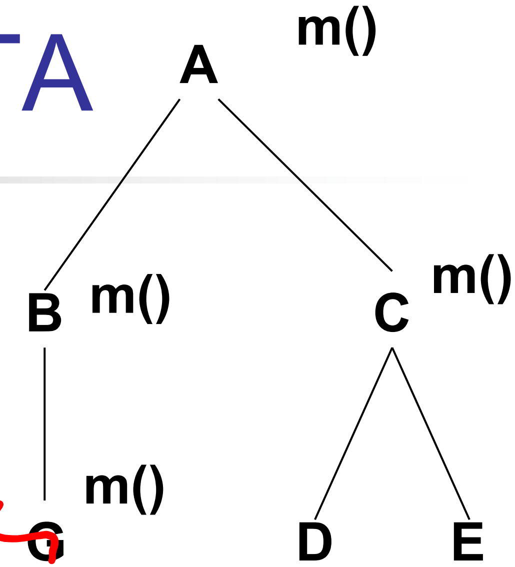
$$S_m \cap \textbf{SubTypes(StaticType(f))} \sqsubseteq S_f$$

Practical Concerns

- Multiple parameters
- Direct calls
  - either static invoke calls or
  - special invoke calls
- Array reads and writes!
- Static fields

- See Tip and Palsberg for more

Example: RTA vs. XTA




```
public class A {
    public static void main() {
        n1();
        n2();
    }
    static void n1() {
        A a1 = new B();
        a1.m();
    }
    static void n2() {
        A a2 = new C();
        a2.m();
    }
}
```

RTA:

a1: $cone(A) \cap \{B,C\} = \{B,C\}$

a1.m() : { B.m(), C.m() } imprecise

XTA:

a1: $cone(A) \cap \overbrace{S_{n1}}^{\{B\}} = \{B\}$

a1.m() : { B.m() }

Boolean Expression Hierarchy: RTA vs. XTA vs. “Ground Truth”

```
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) {
      private BoolExp l = this.left;
      private BoolExp r = this.right;
      return l.evaluate(c) && r.evaluate(c);
   }
}
```

AndExp.evaluate

~~AndExp.evaluate~~

Boolean Expression Hierarchy: RTA vs. XTA vs. "Ground Truth"

$S_{main} \subseteq S_{OrExp.OrExp}$

OrExp.OrExp

```
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) {
      private BoolExp l = this.left;
      private BoolExp r = this.right;
      return l.evaluate(c) || r.evaluate(c);
   }
}
```

$S_{OrExp.OrExp} \subseteq S_{OrExp.left}$ // field write

OrExp.evaluate

$S_{OrExp.left} \subseteq S_{OrExp.evaluate}$

XTA: C: {Constant, AndExp, OrExp, VarExp}

Boolean Expression Hierarchy: RTA vs. XTA vs. "Ground Truth"

declared type runtime

```
main() {
   Context theContext = new Context();
   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);
}
```

S_{main} = All

S_{main}

GT: exp: { AndExp }

RTA: exp: { VarExp, AndExp, OrExp, Constant } → All

XTA: exp: cone (BoolExp) ∩ S_{main} = All

Outline of Today's Class

- Rapid Type Analysis (RTA), last time
- HW2, Class analysis framework questions?
- The XTA analysis family
- 0-CFA
- Points-to analysis (PTA)

0-CFA

- Described in Tip and Palsbserg's paper
- 0-CFA stands for 0-level Control Flow Analysis, where "0-level" stands for context-insensitive analysis
  - Will see 1-CFA, 2-CFA, … k-CFA later
- Improves on XTA by storing even more information about flow of class types

0-CFA

R is the set of reachable methods

$\mathbf{S_v}$ is the set of types that flow to variable **v**

$\mathbf{S_f}$ is the set of types that flow to field **f**

1. **{** main **}** $\sqsubseteq$ **R**

2. for each method $\mathbf{m} \in \mathbf{R}$ and
   each new site **x = new C** in **m**
   $\{\ \mathbf{C}\ \} \sqsubseteq \mathbf{S_x}$

0-CFA

3. for each method $\mathbf{m} \in \mathbf{R}$,
each virtual call $\mathbf{x = y.n(z)}$ in $\mathbf{m}$,
each class $\mathbf{C}$ in S_y
and $\mathbf{n'}$, where $\mathbf{n' = resolve(C,n)}$

- $\{ n' \} \sqsubseteq R$
- $\{ C \} \sqsubseteq S_{this}$
- $S_z \cap \mathbf{SubTypes(StaticType(p))} \sqsubseteq S_p$

flow from ~~act~~ arguments to formal params

- $S_{ret} \cap \mathbf{SubTypes(StaticType(x))} \sqsubseteq S_x$

flow from return variable to lhs of call x.

(**this** is the implicit parameter of **n'**, **p** is the parameter of **n'**, and **ret** is the return of **n'**)

0-CFA

4. for each method **m** $\in$ **R**,
each field read **x = y.f** in **m**

$$S_f \cap \textbf{SubTypes(StaticType(x))} \sqsubseteq S_x$$

5. for each method **m** $\in$ **R**,
each field write **x.f = y** in **m**

$$S_y \cap \textbf{SubTypes(StaticType(f))} \sqsubseteq S_f$$

0-CFA

$\{A\} \subseteq S_x$ | $x = new\ A;$

$S_x \subseteq S_y$ | $y = x;$

$S_y \subseteq S_z$ | $z = y;$

$S_x = S_y = S_z = \{A\}$

6. for each method **m** $\in$ **R**, each assignment **x = y** in **m**

$$S_y \cap \textbf{SubTypes(StaticType(x))} \sqsubseteq S_x$$

Example: XTA vs. 0-CFA

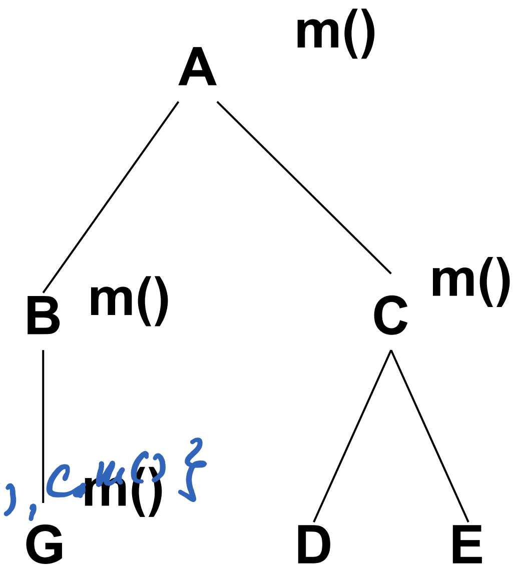
```
public class A {
   public static void main() {
      A a1 = new B();
      a1.m();

      A a2 = new C();
      a2.m();
   }
}
```

XTA:

a1: {B, C}

a1.m(): {B.m(), C.m()}



0-CFA:

a1: {B}

a1.m(): {B.m()}

Boolean Expression Hierarchy: XTA vs. 0-CFA

```
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) {
       private BoolExp l = this.left;
       private BoolExp r = this.right;
       return l.evaluate(c) && r.evaluate(c);
    }
}
```

Boolean Expression Hierarchy: XTA vs. 0-CFA

```
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) {
      private BoolExp l = this.left;
      private BoolExp r = this.right;
      return l.evaluate(c) || r.evaluate(c);
   }
}
```

$S_{OrExp.OrExp.left} \subseteq S_{OrExp.left}$

$S_{OrExp.left} \subseteq S_{OrExp.evaluate.l}$

0-CFA: l : {VarExp}

Boolean Expression Hierarchy: XTA vs. 0-CFA

```
main() {
   Context theContext = new Context();
   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);
}
```

- c = new Constant();
- o = new OrExp();
- exp = new AndExp(c, o);

$S_x \subseteq S_{OrExp.orExp.left}$

XTA: exp : All

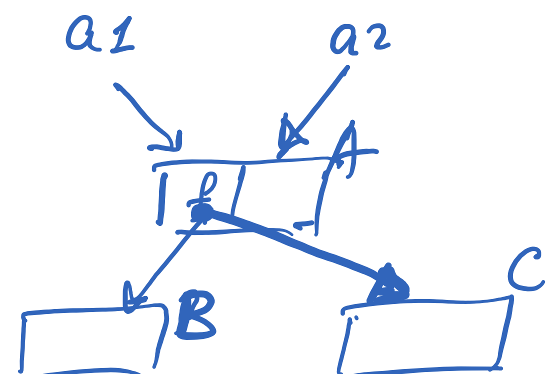
0-CFA: exp : {AndExp}

Outline of Today's Class

- Rapid Type Analysis (RTA), last time
- HW2, Class analysis framework questions?
- The XTA analysis family
- 0-CFA
- Points-to analysis (PTA)

PTA

- Widely referred to as Andersen's points-to analysis for Java



- Improves on 0-CFA by storing information about **objects**, not classes
  - A a1 = new A(); // $\mathbf{o_1}$
  - A a2 = new A(); // $\mathbf{o_2}$

PTA

R is the set of reachable methods

Pt(v) is the set of objects that **v** may point to

Pt(o.f) is the set of objects that field **f** of object **o** may point to

1. **{** main **}** $\sqsubseteq$ **R**

2. for each method **m** $\in$ **R** and
   each new site **i: x = new C** in **m**
   { o_i } $\sqsubseteq$ Pt(x) // instead of C, we have o_i

PTA

class_of(o) returns the class of object **o**

3. for each method $\mathbf{m} \in \mathbf{R}$,
each virtual call **x = y.n(z)** in **m**,
each class $\mathbf{o_i}$ in **Pt(y)**
and **n'**, where **n'** = **resolve(class_of($\mathbf{o_i}$),n)**

- $\{ \mathbf{n'} \} \sqsubseteq \mathbf{R}$
- $\{ \mathbf{o_i} \} \sqsubseteq \mathbf{Pt(this)}$
- $\mathbf{Pt(z)} \cap \mathbf{SubTypes(StaticType(p))} \sqsubseteq \mathbf{Pt(p)}$
- $\mathbf{Pt(ret)} \cap \mathbf{SubTypes(StaticType(x))} \sqsubseteq \mathbf{Pt(x)}$

actuals to formals

(**this** is the implicit parameter of **n'**, **p** is the parameter of **n'**, and **ret** is the return of **n'**)

PTA

4. for each method **m** $\in$ **R**,
each field read **x = y.f** in **m**
  for each object **o** $\in$ **Pt(y)**
    Pt(o.f) $\cap$ **SubTypes(StaticType(x))** $\sqsubseteq$ **Pt(x)**

5. for each method **m** $\in$ **R,**
each field write **x.f = y** in **m**
  for each object **o** $\in$ **Pt(x)**
    Pt(y) $\cap$ **SubTypes(StaticType(f))** $\sqsubseteq$ **Pt(o.f)**

PTA

6. for each method **m** $\in$ **R**,
each assignment stmt **x = y** in **m**

Pt(y) $\cap$ **SubTypes(StaticType(x))** $\sqsubseteq$ **Pt(x)**

Example: 0-CFA vs. PTA

```java
public class A {
    public static void main() {
        X x1 = new X();   // o1
        A a1 = new B();   // o2
        x1.f = a1;  // o1.f points to o2
        A a2 = x1.f;  // a2 points to o2
        a2.m();
```

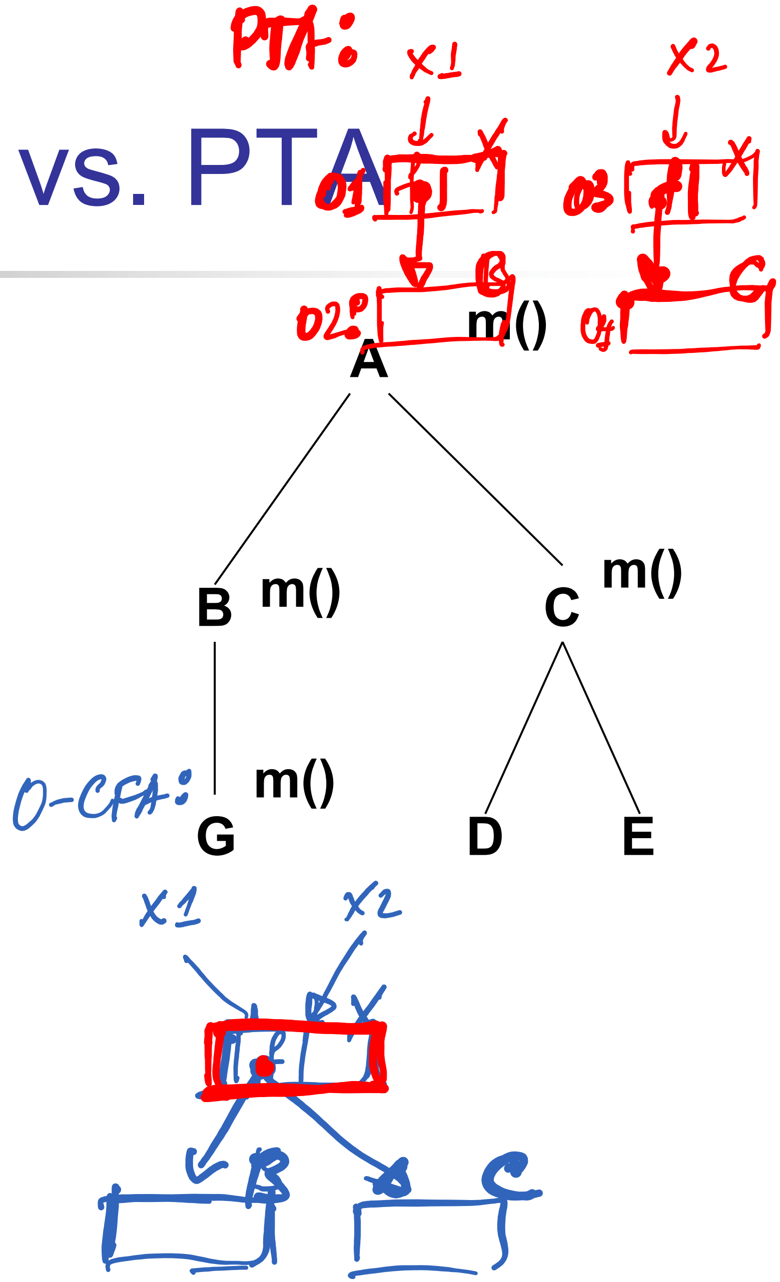
a2: {B, C}

PTA: a2: {B}

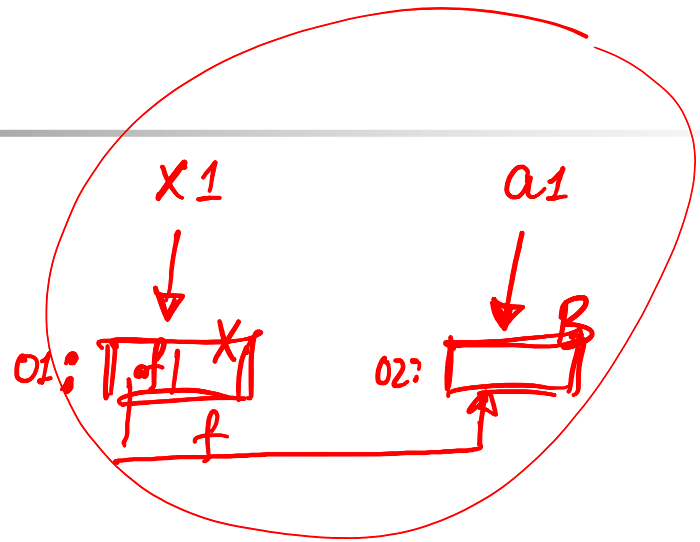
```java
        X x2 = new X();   // o3
        A a3 = new C();   // o4
        x2.f = a3;  // o3.f points to o4
        A a4 = x2.f; // a4 points to o4
        a4.m();
```

a4: {B, C}

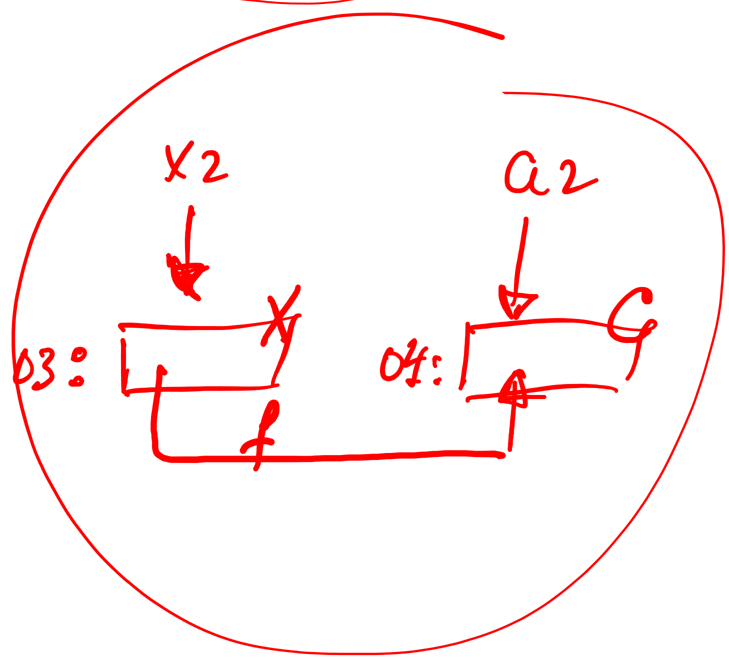
```java
    }
}
```



```
x1 = new X(); // o1
a1 = new B(); // o2
x1.f = a1;
```




```
x2 = new X() // o3
a2 = new C() // o4
x2.f = a2
```



The Big Picture

- All fit into our monotone dataflow framework!
- Flow-insensitive, context-insensitive
  - Compute single solution S
- Algorithms differ mainly in “size” of S
  - RTA: only 2 kinds of statements; Lattice?
  - XTA: expands to all statements; Lattice?
  - 0-CFA: all statements; Lattice?
  - PTA (Points-to analysis): all statements; Lattice elements are points-to graphs

The Big Picture