Dataflow Analysis: Class Analysis

Announcements

- HW2 out
- I've added a post on the forum on some common setup issues
- Post question on
  - Setup
  - Starter code, generic analysis framework and fixpoint interation algorithm
  - Soot

Outline of Today's Class

- Analysis scope and approximation
- Class analysis
- Class Hierarchy Analysis (CHA)
- Rapid Type Analysis (RTA)
- The XTA analysis family
- Other analyses: 0-CFA and PTA (next time)
- A brief overview of Soot

Outline of Today's Class

- Reading
- Jeff Dean, David Grove, and Craig Chambers, "Optimization of OO Programs Using Static Class Hierarchy Analysis", ECOOP'95
- David Bacon and Peter Sweeney, "Fast Static Analysis of C++ Virtual Function Calls", OOPSLA '96
- Frank Tip and Jens Palsberg, "Scalable Propagation-Based Call Graph Construction Algorithms", OOPSLA '00

Analysis Scope

- **Intra**procedural analysis
  - Scope is the CFG of a single subroutine
  - Assumes no call and returns in routine, or models calls and returns
  - What we did so far
- **Inter**procedural analysis
  - Scope of analysis is the ICFG (**Inter**procedural CFG), which models flow of control between routines

Analysis Scope

- **Whole-program** analysis
  - Usually, assumes entry point "main"
  - Application code + libraries
    - Intricate interdependences, e.g., Android apps
- **Modular** analysis
  - Scope either a library without entry point
  - or application code with missing libraries
  - … or a library that depends on other missing libraries

Approximations

- Once we tackle the "whole program" maintaining a solution per program point (i.e., in(j) and out(j) sets) becomes too expensive
- Dimensions of approximation
  - Transfer function space
  - Lattice
- Context sensitivity
- Flow sensitivity

Context Sensitivity

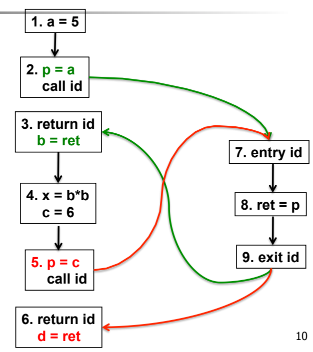
- So far, we studied **intraprocedural analysis**
- Once we extend to **interprocedural analysis** the issue of "context sensitivity" comes up
- Interprocedural analysis can be context-insensitive or context-sensitive
  - Today, we'll see some context-insensitive analyses
  - Next week, a lot more on context-sensitive analysis

Context Insensitivity

- Context-insensitive analysis makes one big CFG; reduces the problem to standard dataflow, which we know how to solve!
- Treats implicit assignment of actual-to-parameter and return-to-left_hand_side as explicit ones
  - E.g., **x = id(y)** where **id: int id(int p) { return p; }**
    adds **p = y**
    and **x = ret**
- Can be flow-sensitive or flow-insensitive

Context Insensitivity

```
int id(int p) {
  return p;
}
    a = 5;
  2: b = id(a);
    x = b*b;
    c = 6;
  5: d = id(c);
```



Flow Sensitivity

- Flow-sensitive vs. flow-insensitive analysis
- Flow-sensitive analysis maintains the CFG and computes a solution per each node in CFG (i.e. each program point)
  - Standard dataflow analysis is flow-sensitive
- For large programs, maintaining CFG and solution per program point does not scale

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!

Flow Insensitivity

- An "operational" definition. A worklist-like algorithm:

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

- Note that "successors" here does not refer to successor nodes in the CFG, but nodes **k** whose transfer function $\mathbf{f_k}$ may contribute to S as a result of the change by **j**

Your Homework

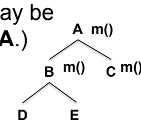
- A bunch of flow-insensitive, context-insensitive analyses for Java
  - RTA, XTA, and optionally other
  - Simple property space
  - Simple transfer functions
    - E.g., in fact, RTA gets rid of most CFG nodes, processes just 2 kinds of nodes
  - Millions of lines of code in seconds

Class Analysis

- Problem statement: What are the **classes** of objects that a (Java) **reference** variable may refer to?
- Class Hierarchy Analysis (CHA)
- Rapid Type Analysis (RTA)
- XTA
- 0-CFA (next time)
- Points-to Analysis (PTA) (next time)

Applications of Class Analysis

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



- 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}              right: {OrExp}
```

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} right: {VarExp}

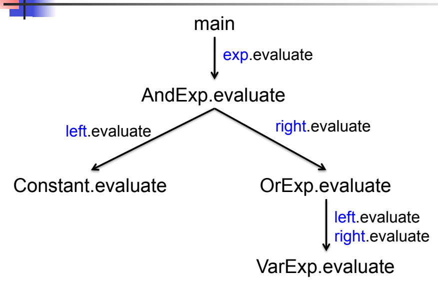
A Client of the Boolean Expression Hierarchy

```
main() {
  Context theContext;
  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)

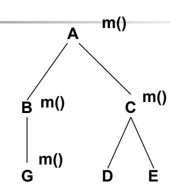
- Attributed to Dean, Grove and Chambers:
  - Jeff Dean, David Grove, and Craig Chambers, "Optimization of OO Programs Using Static Class Hierarchy Analysis", ECOOP'95
- Simplest way of inferring information about reference variables, simply look at class hierarchy!

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

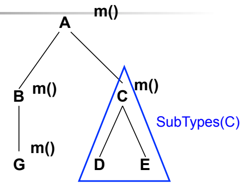
Example

```
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
```



Example

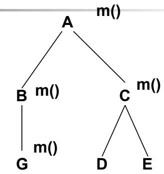
```
public class A {
    public static void main() {
        A a;
        D d = new D();
        E e = new E();
        if (...) a = d; else a = e;
        a.m();
    }
}
public class B extends A {
    public void foo() {
        G g = new G();
    }
} ...
```



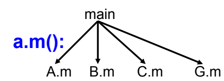
SubTypes(A) = { A, B, C, D, E, G }
SubTypes(B) = { B, G }

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



CHA as Reachability Analysis

R denotes the set of reachable methods

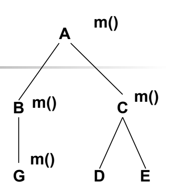
1. main∈ **R**
2. for each method **m**∈ **R**,
each virtual call **y.n(z)** in **m**,
each class **C** in **SubTypes(StaticType(y))** and
n', where **n'** = **resolve(C,n)**
n'∈**R**
(Practical concerns: must consider direct calls too!)

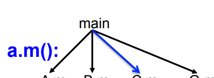
Rapid Type Analysis (RTA)

- 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();
    }
}
```





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**

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

RTA

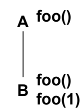
3. for each method **m** ∈ **R**,
each virtual call **y.n(z)** in **m**,
each class **C** in **SubTypes(StaticType(y))** ∩ **I**,
and **n'**, where **n'** = **resolve(C,n)**

  n' ∈ **R**

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.

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 storing more precise information about flow of class types

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 ∈ **R**

2. for each method **m** ∈ **R** and
   each new site **new C** in **m**
     C ∈ $\mathbf{S_m}$

XTA

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

  n' ∈ **R** **// add n' to R if not already there**
  C ∈ $\mathbf{S_{n'}}$ **// add C to** $\mathbf{S_{n'}}$ **if not already there**
  $\mathbf{S_m}$ ∩ **SubTypes(StaticType(p))** ⊑ $\mathbf{S_{n'}}$
  $\mathbf{S_{n'}}$ ∩ **SubTypes(StaticType(ret))** ⊑ $\mathbf{S_m}$

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

XTA

4. for each method **m** ∈ **R**,
each field read **x = y.f** in **m**
  $\mathbf{S_f}$ ⊑ $\mathbf{S_m}$

5. for each method **m** ∈ **R**,
each field write **x.f = y** in **m**
  $\mathbf{S_m}$ ∩ **SubTypes(StaticType(f))** ⊑ $\mathbf{S_f}$

Practical Concerns

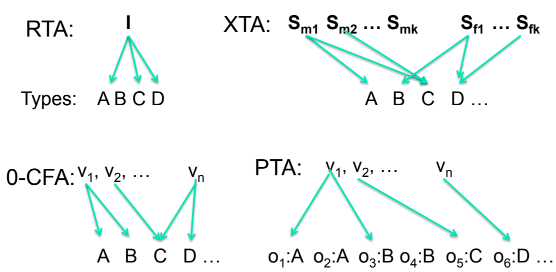
- Multiple parameters
- Direct calls
  - either static invoke calls or
  - special invoke calls
- Array reads and writes!
- Static fields

- See Tip and Palsberg for more

The Big Picture

- All fit into our monotone dataflow framework!
- Flow-insensitive, context-insensitive
  - Least solution of S = f_j(S) **V** 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



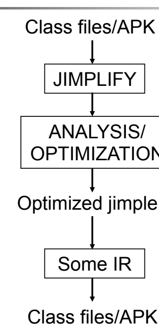
Soot: a framework for analysis and optimization of Java/Dalvik bytecode

- https://sable.github.io/soot/
- History
- Overview of Soot
  - From Java bytecode/Dalvik bytecode to **typed** 3-address code (**Jimple**)
  - 3-address code analysis and optimization
  - From Jimple to Java/Dalvik
- Jimple
- Analysis

History

- https://sable.github.io/soot/
- Started by Prof. Laurie Hendren at McGill
  - First paper on Soot came in 1999
  - Patrick Lam
  - Ondřej Lhoták
  - Eric Bodden
  - and other…
- Now actively developed by Eric Bodden and his group

Overview of Soot



Advantages of Jimple and Soot

- Jimple
  - Typed local variables
  - 16(!) simple 3-address statements (1 operator per statement). Bridges gap from analysis abstraction to analysis implementation
- Soot provides
  - Itraprocedural dataflow analysis framework
  - Points-to analysis
  - Context-sensitive analysis framework
  - Android taint analysis

Jimple

- Run soot: java soot.Main –jimple A (need paths)

```
public class A {
  main(String[] args) {
    A a = new A();
    a.m();
  }
  public void m() {
  }
}
```

```
public class A extends java.lang.Object
 {
  public void <init>() {
   A r0;
   r0 := @this: A;
   specialinvoke r0.
      <java.lang.Object: void <init>()>();
   return;
  }
  …
```

(continues on next slide…)

Jimple

Java:

```
public class A {
  main(String[] args) {
    A a = new A();
    a.m();
  }
  public void m() {
  }
}
```

Jimple:

```
…
public void m() {
     A r0;
     r0 := @this: A;
     return;
  }
…
```


Jimple

Java:

```
public class A {
  main(String[] args) {
    A a = new A();
    a.m();
  }
  public void m() {
  }
}
```

Jimple:

```
…
main(java.lang.String[]) {
    java.lang.String[] r0;
    A $r1, r2;
    r0 := @parameter0: java.lang.String[];
    $r1 = new A;
    specialinvoke $r1.<A: void <init>()>();
    r2 = $r1;
    virtualinvoke r2.<A: void m()>();
    return;
  }
}
```


Soot Abstractions. Look up API!

- Abstracts program constructs
- Some basic Soot classes and interfaces
  - **SootClass**
  - **SootMethod**
    - **SootMethod sm; sm.isMain(), sm.isStatic(),** etc.
  - **Local**
    - **Local l; … l.getType()**
  - **InstanceInvokeExpr**
    - Represents an instance (as opposed to static) invoke expression
    - **InstanceInvokeExpr iie; … receiver = iie.getBase();**

4 Kinds of Calls[1]

- Constructor/Super Call:

```
A a = new A();   =>   $r1 = new A;
                      specialinvoke $r1.<A: void <init>()>();
```

- Virtual Call:

```
a.m();   =>   virtualinvoke r2.<A: void m()>();
```

- Static Call:

```
sm();   =>   staticinvoke <A: void sm()>();
```

- Interface Call:

```
x.m();   =>   interfaceinvoke r0.<pack2.X: void m()>();
```

1. We should not need to worry about dynamicInvoke. (Soot does support it.)

Next class

- Catch up: points-to analysis
- Interprocedural Analysis
- Context sensitivity