# Practical Program Analysis of Object-oriented Software
# Part 1

**Dr. Barbara G. Ryder**

**Rutgers University**

THE STATE UNIVERSITY OF NEW JERSEY
RUTGERS
PROLANGS
PROGRAMMING LANGUAGES RESEARCH GROUP

http://www.cs.rutgers.edu/~ryder

**September 2006**



# Outline

## Part 1

- What is program analysis for OOPLs?
- Reference analyses
  - Type-based
  - Flow-based
    - Flow sensitivity
    - Field sensitivity
    - Context sensitivity
      - 1-CFA, Object-sensitive

# Outline

## Part 2

- New results on accommodating reflection in points-to analysis
- Applications of analysis in software tools to increase programmer productivity
  - Using infeasibility analysis to enable better test coverage for recovery code
  - Combining static and dynamic analysis to report change impact of edits



# What is program analysis?

- Static program analysis extracts information about program semantics from code, without running it
  - E.g., Def-use analysis for dependences
  - Builds an abstract representation of the program and solves the analysis problem
- Dynamic program analysis extracts information from a program execution
  - E.g., Profiling, dynamic slicing
- Our focus: static reference analyses

# Object-oriented PL

- Characterized by data abstraction, inheritance, polymorphism
- Allows dynamic binding of method calls
- Allows dynamic loading of classes
- Allows querying of program semantics at runtime through reflection



# Reference Analysis

- *Determines information about the set of objects to which a reference variable or field may point during program execution*

# Reference Analysis

- OOPLs need type information about objects to which reference variables can point to resolve dynamic dispatch
- Often data accesses are indirect to object fields through a reference, so that the set of objects that might be accessed depends on which object that reference can refer at execution time
- Need to pose this as a compile-time program analysis with representations for reference variables/fields, objects and classes.



# Reference Analysis enables…

- Construction of possible calling structure of program
  - Dynamic dispatch of methods based on runtime type of receiver `x.f();`
- Understanding of possible dataflow in program
  - Indirect side effects through reference variables and fields `r.g=`

## Uses of Reference Analysis Information in Software Tools

- Program understanding tools (flow)
  - Semantic browers
  - Program slicers
- Software maintenance tools (type,flow)
  - Change impact analysis tools
- Testing tools (flow)
  - Coverage metrics



## Example Analyses

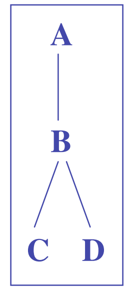
- Type hierarchy-based
  - CHA, RTA
- Incorporating flow
  - FieldSens (Andersen-based points-to)
- Incorporating flow and calling context
  - 1-CFA
  - Object-sensitive

cf Frank Tip, *OOPSLA'00*

# Example

```
static void main(){
   B b1 = new B();
   A a1 = new A();
   f(b1);
   g(b1);
}
static void f(A a2){
   a2.foo();
}
static void g(B b2){
   B b3 = b2;
   b3 = new C();
   b3.foo();
}
```

```
class A {
   foo(){..}
}
class B extends A{
   foo() {…}
}
class C extends B{
   foo() {…}
}
class D extends B{
   foo(){…}
}
```



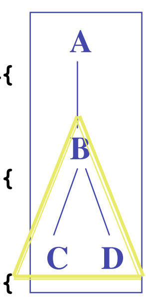



cf Frank Tip, *OOPSLA'00*

# CHA Example

```
static void main(){
   B b1 = new B();
   A a1 = new A();
   f(b1);
   g(b1);
}
static void f(A a2){
   a2.foo();
}
static void g(B b2){
   B b3 = b2;
   b3 = new C();
   b3.foo();
}
```

```
class A {
   foo(){..}
}
class B extends A{
   foo() {…}
}
class C extends B{
   foo() {…}
}
class D extends B{
   foo(){…}
}
```




Cone(Declared_type(receiver))

# CHA Characteristics

- Ignores program flow
- Calculates types that a reference variable can point to
- Uses 1 abstract reference variable per class throughout program
- Uses 1 abstract object to represent all possible instantiations of a class

J. Dean, D. Grove, C. Chambers, *Optimization of OO Programs Using Static Class Hierarchy*, ECOOP'95

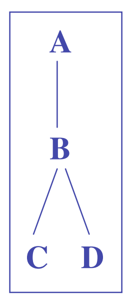


cf Frank Tip, OOPSLA'00

# RTA Example

```
static void main(){
   B b1 = new B();
   A a1 = new A();
   f(b1);
   g(b1);
}
static void f(A a2){
   a2.foo();
}
static void g(B b2){
   B b3 = b2;
   b3 = new C();
   b3.foo();
}
```

```
class A {
   foo(){..}
}
class B extends A{
   foo() {…}
}
class C extends B{
   foo() {…}
}
class D extends B{
   foo(){…}
}
```



# RTA Characteristics

- Only analyzes methods *reachable* from main(), on-the-fly
- Ignores classes which have not been instantiated as possible receiver types
- Uses 1 abstract reference variable per class throughout program
- Uses 1 abstract object to represent all possible instantiations of a class

D. Bacon and P. Sweeney, " Fast Static Analysis of C++ Virtual Function Calls", OOPSLA'96

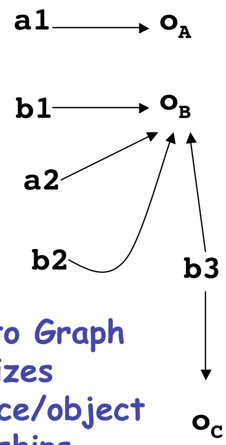


# Clients of CHA & RTA

- Call graph construction
  - Estimate dynamic dispatch targets
  - A pre-requisite for all static analyses of OOPLs that trace interprocedural flow
    - E.g., slicing, obtaining method coverage metrics for testing, understanding calling structure of legacy code, heap optimization, etc

# FieldSens Example

```
static void main(){
  B b1 = new B();
  A a1 = new A();
  f(b1);
  g(b1);
}
static void f(A a2){
  a2.foo();
}
static void g(B b2){
  B b3 = b2;
  b3 = new C();
  b3.foo();
}
```



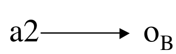

Points-to Graph summarizes reference/object relationships

cf Frank Tip, OOPSLA'00

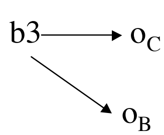


# FieldSens Example

```
static void main(){
  B b1 = new B();
  A a1 = new A();
  f(b1);
  g(b1);
}
static void f(A a2){
  a2.foo();
}
static void g(B b2){
  B b3 = b2;
  b3 = new C();
  b3.foo();
}
```




```
class A {
  foo(){..}
}
class B extends A{
  foo() {…}
}
class C extends B{
  foo() {…}
}
class D extends B{
  foo(){…}
}
```




cf Frank Tip, OOPSLA'00

## FieldSens Characteristics

- Only analyzes methods *reachable* from main()
  - On-the-fly call graph construction
- Keeps track of individual reference variables and fields
- Groups objects by their creation site
- Incorporates reference value flow in assignments and method calls

A. Rountev, A. Milanova, B. G. Ryder, "Points-to Analysis for Java Using Annotated Constraints". OOPSLA'01



## Some Clients of FieldSens

- Improving precision of call graphs with truly polymorphic call sites
- Calculating object read/write's through references
- Calculating objects escaping from their creation environment (e.g., a thread)

Rountev et.al, OOPSLA'01

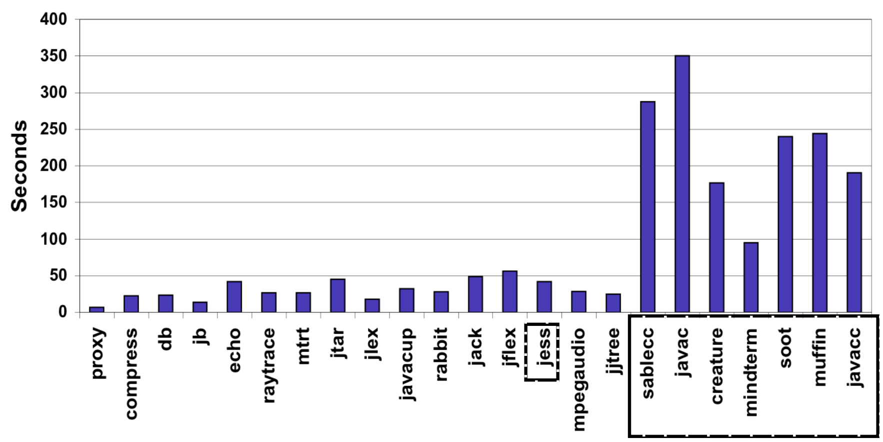
# Experiments

- 23 Java programs: 14 – 677 user classes, with 57K-1,070K bytecode
  - Added the necessary library classes (JDK 1.1)
  - Machine: 360 MHz, 512Mb SUN Ultra-60
- Cost measured in time and memory
- Points-to algorithm presented as an inclusion constraint solution problem
  - Migrated Andersen's points-to analysis for C to Java
- Precision (wrt usage in client analyses and transformations)
  - Call graph construction
  - Thread-local heap discovery
  - Object read-write information



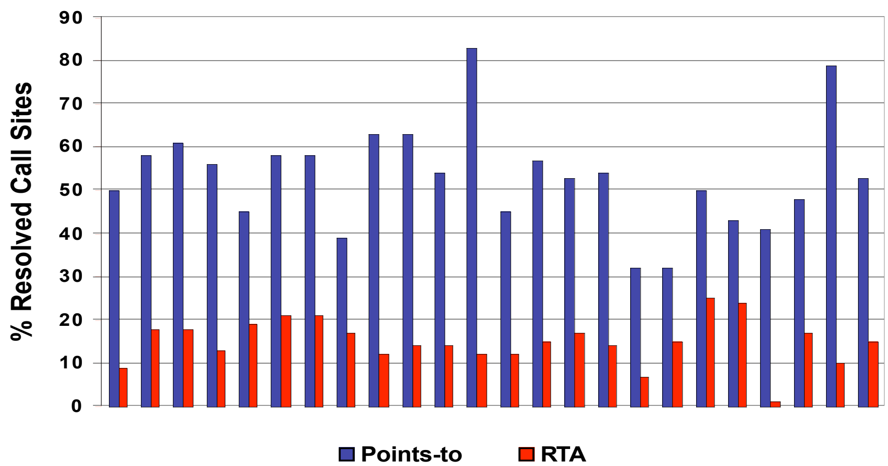
Rountev et.al, OOPSLA'01

# Analysis Time



Rountev et.al, OOPSLA'01

# Resolution of Virtual Call Sites




Call sites all reported as polymorphic by CHA



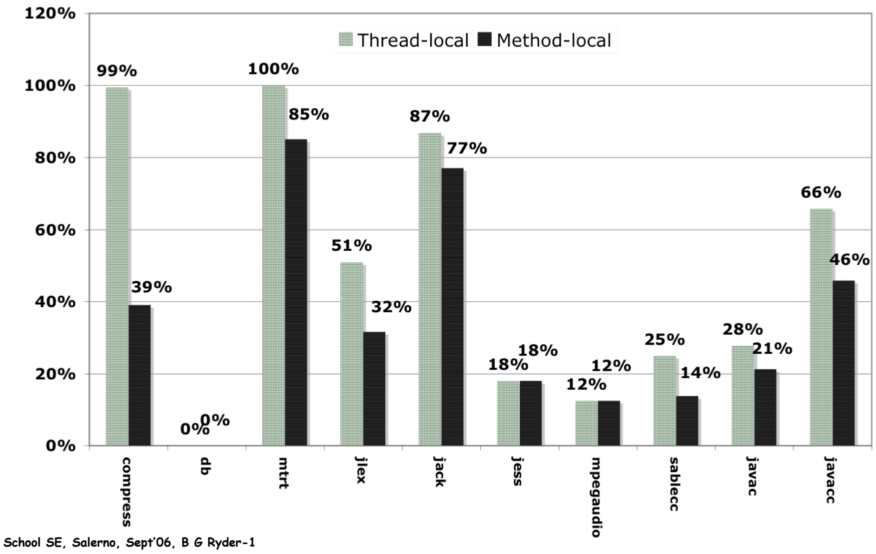
Rountev et.al, OOPSLA'01

# Number of Objects Created

| Program | Objects Created |
|---|---|
| compress | 456 |
| db | 154,325 |
| mtrt | 6,457,298 |
| jlex | 7,350 |
| jack | 1,340,919 |
| jess | 7,902,221 |
| mpegaudio | 2,025 |
| sablecc | 420,494 |
| javac | 3,738,777 |
| javacc | 43,265 |

Rountev et.al, *OOPSLA'01*

# Thread & Method-local new()'s




Intl School SE, Salerno, Sept'06, B G Ryder-1 25

Rountev et.al, *OOPSLA'01*

# Object Read-Write Info

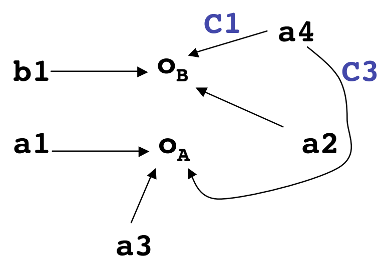
- Measured number of objects accessed on average at indirect reads/writes
  - More than 1/2 the accesses were to a single object (the lower bound) and
  - On average 81% were resolved to at most 3 objects

Intl School SE, Salerno, Sept'06, B G Ryder-1 26

# 1-CFA Analysis

**Improves on FieldSens by keeping track of calling context**

```
static void main(){
        B b1 = new B();//OB
        A a1 = new A();//OA
        A a2,a3;
C1:     a2 = f(b1);
C2:     a2.foo();
C3:     a3 = f(a1);
C4:     a3.foo();
}
public static A f(A a4){return a4;}
```




Points-to Graph

at C2, main calls B.foo()
at C4, main calls A.foo()



# 1-CFA Characteristics

- Only analyzes methods *reachable* from main()
- Keeps track of individual reference variables and fields
- Groups objects by their creation site
- Incorporates reference value flow in assignments and method calls
- Differentiates points-to relations for different calling contexts

Ryder, CC'03

# Dimensions of Precision

- Independent characteristics of a reference analysis which determines its precision
- Different combinations of these dimensions have already been explored in algorithms
- Need to understand what choices are available to design new analyses of appropriate precision for clients



# Dimensions of Precision

- Program representation - Call graph
  - Use hierarchy-based approximation
    - Do reference analysis based on an already built approximate call graph - Palsberg'91, Chatterjee'99, Sundaresan'00, Liang'01
  - Lazy on-the-fly construction
    - Only explore methods which are statically reachable from the main() (especially library methods)
    - Interleave reference analysis and call graph construction - Oxhoj'92, Razafimahefa'99, Rountev'01, Grove'01, Liang'01, Milanova'02, Whaley'02

# Dimensions of Precision

- Object Representation
  - Use one abstract object per class - Hierarchy-based analyses: Dean'95, Bacon'96; Flow-based analyses; Diwan'96, Palsberg'91, Sundaresan'00,Tip'00
  - Group object instantiations by creation site - Points-to analyses: Grove'01, Liang'01, Rountev'01, Milanova'02. Whaley'02
  - Finer-grained object naming - Oxhoj'92, Plevyak'94, Grove'01, Liang'02, Milanova'02



# Dimensions of Precision

Field Sensitivity

- Field-independent(fi)
  - Do not distinguish reference fields of an object, - Rountev'01, Lhotek & Hednren CC'03
- Field-based(fb)
  - Use one abstract field per field name (across all objects), -Lhotek & Hendren, CC'03
- Field-sensitive(fs)
  - Use one abstract field per field per abstract object (usually a creation site), -Rountev'01, Lhotek & Hednren CC'03

Lhotek & Hendren, CC'03

## Spark Experiments

- Precision measure incorporated unreachable dereferences and unique object reference targets
  - Precision of fb:fs was 57.7:60.0 on average
  - Time cost was very similar
  - Space cost of fb:fs was 86.6:138.4 on average
- Lesson learned: sometimes less precision is okay - need to know the client of the points-to info



## Dimensions of Precision

- Reference representation
  - Use one abstract reference per class - Dean'95, Bacon'96, Sundaresan'00
  - Use one abstract reference for each class per method - Tip'00
  - Represent reference variables or fields by their names program-wide - Sundaresan'00, Liang'01, Rountev'01, Milanova'02
  - XTA: example of one abstract reference for each class per method

# XTA Analysis

- Calculates set of classes that reach a method, incorporating (limited) flow
- Uses an on-the-fly constructed call graph
- Uses one abstract object per class with distinct fields
- Uses one abstract reference per class in each method

F. Tip and J. Palsberg, "Scalable Propagation-based Call Graph Construction Algorithms", OOPSLA'00



cf Frank Tip, OOPSLA'00

# Example of XTA

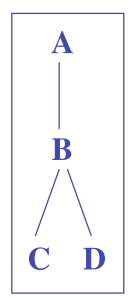
{A,B}

```
static void main(){
   B b1 = new B();
   A a1 = new A();
   f(b1);
   g(b1);
}
static void f(A a2){
   a2.foo();
}
static void g(B b2){
   B b3 = b2;
   b3 = new C();
   b3.foo();
}
```

{A,B}

{B,C}

```
class A {
   foo(){..}
}
class B extends A{
   foo() {…}
}
class C extends B{
   foo() {…}
}
class D extends B{
   foo(){…}
}
```



# Dimensions of Precision

- Directionality
  - How flow in reference assignments (`r=s`) is interpreted by the analysis
    - Symmetric (Unification): r and s have same points-to set after the assignment - Ruf'00, Liang'01
    - Directional (Inclusion): r's points-to set includes s's points-to set after the assignment - Sundarasen'00, Rountev'01, Liang'01, Milanova'02, Whaley'02



# Dimensions of Precision

- Flow sensitivity
  - Analyses which capture the sequential order of execution of program statements
    - Diwan'96,Chatterjee'99,Whaley'02
  - E.G.,

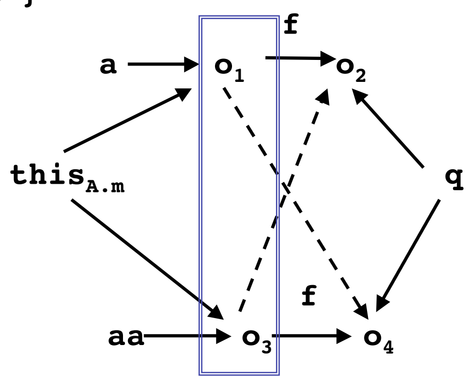
```
1. A s,t;
2. s = new A();//o1
3. t = s;
4. s = new A();//o2
```

<u>flow-sensitive</u>:
at 2., s refers to $o_1$
at 3., s,t refer to $o_1$
at 4., s refers to $o_2$
t refers to $o_1$
<u>flow-insensitive</u>:
s,t refer to $\{o_1\ o_2\}$

# Imprecision of Context Insensitivity

```
class Y extends X{ … }

class A{
    X f;
    void m(X q)
    { this.f=q;}
}
A a = new A();//o1
a.m(new X());//o2
A aa = new A();//o3
aa.m(new Y());//o4
```






# Dimensions of Precision

- Context sensitivity
  - Analyses which distinguish different calling contexts - Sharir/Pnueli'81
    - Call string - Palsberg'91,Grove'01
    - Functional approach- Plevyak'94,Agesen'95,Milanova'02
  - 1-CFA, example of call string approach
  - ObjSens, example of functional approach

## ObjSens Analysis

- Based on Andersen's points-to for C
- Uses receiver object to distinguish different calling contexts
- Groups objects by creation sites
- Represents reference variables and fields by name program-wide
- Flow-insensitive

A. Milanova, A. Rountev, B. G. Ryder, "Parameterized Object-sensitivity for Points-to and Side-effect Analyses for Java" ISSTA'02.

A. Milanova, A. Rountev, B.G. Ryder, "Parameterized Object Sensitivity for Points-to Analysis for Java", in *ACM Transactions on Software Engineering Methodology*, Volume 14, Number 1, pp 1-41, January 2005.

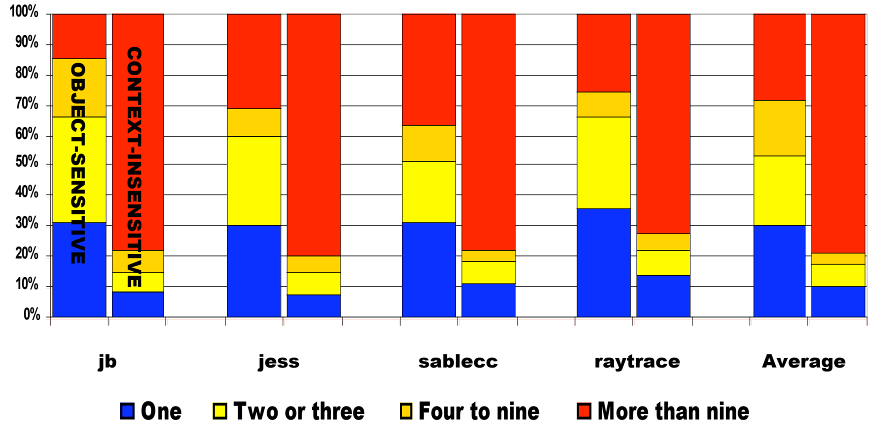


## ObjSens Analysis

- Shown to analyze to OO programming idioms well
  - Field encapsulation using set methods `this.f=x`
  - Superclass constructor setting subclass object fields
  - Uses of containers

# Side-effect Analysis: Modified Objects Per Statement

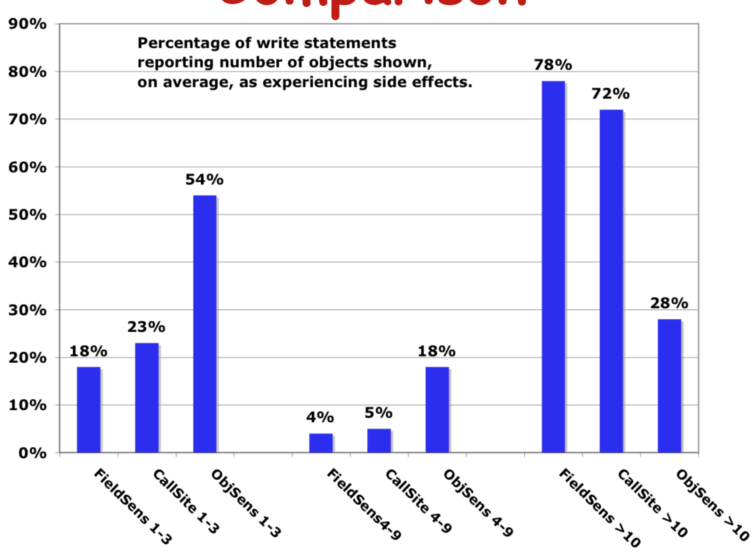
Milanova, ISSTA'02




Intl School SE, Salerno, Sept'06, B G Ryder-1 43

# Side Effect Analysis Comparison

Milanova, TOSEM05

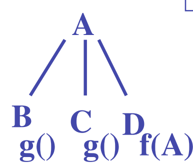


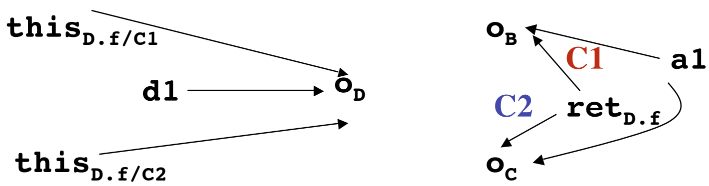

Intl School SE, Salerno, Sept'06, B G Ryder-1 44

# 1-CFA more precise than ObjSens

1-CFA

```
static void main(){
 D d1 = new D();
 if (…)C1: (d1.f(new B())).g();
 else  C2: (d1.f(new C())).g();
}
public class D
{ public A f(A a1){return a1;}
}
```



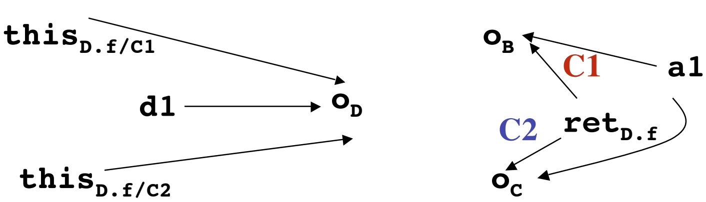



# 1-CFA more precise than ObjSens

1-CFA

```
static void main(){
 D d1 = new D();
 if (…)C1: (d1.f(new B())).g();
 else  C2: (d1.f(new C())).g();
}
public class D
{ public A f(A a1){return a1;}
}
```

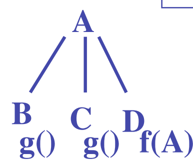
1-CFA distinguishes the two calling contexts of D.f at C1 and C2;
At C1, B.g() called;
At C2, C.g() called;

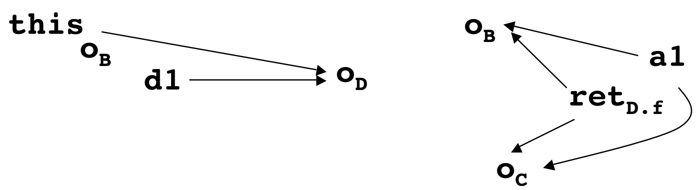


# 1-CFA more precise than ObjSens

ObjSens

```
static void main(){
 D d1 = new D();
 if (…)C1: (d1.f(new B())).g();
 else  C2: (d1.f(new C())).g();
}
public class D
{ public A f(A a1){return a1;}
}
```



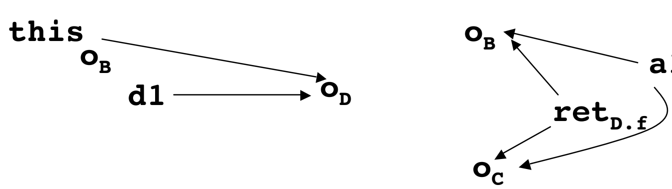



# 1-CFA more precise than ObjSens

ObjSens

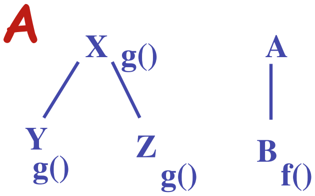
```
static void main(){
 D d1 = new D();
 if (…)C1: (d1.f(new B())).g();
 else  C2: (d1.f(new C())).g();
}
public class D
{ public A f(A a1){return a1;}
}
```

ObjSens groups the two calling contexts of D.f with the same receiver at C1 and C2;
Both B.g(),C.g() are called at C1 and C2;

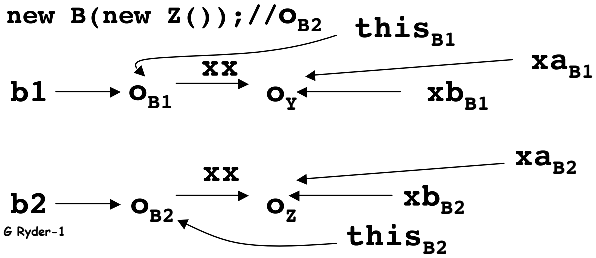


# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
   static void main(){
     X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
```



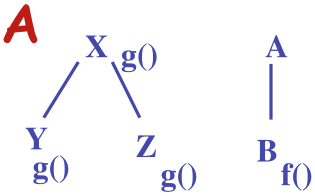

ObjSens

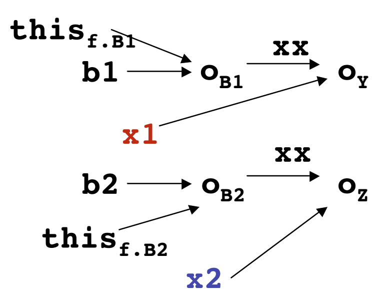





# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```

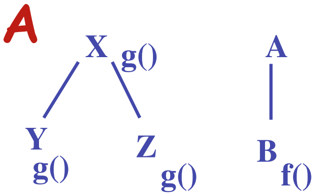



ObjSens

# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```

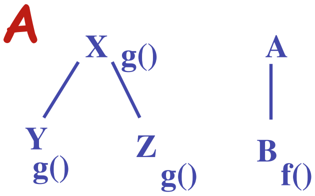



ObjSens finds
C4 calls Y.g() and
C5 calls Z.g()

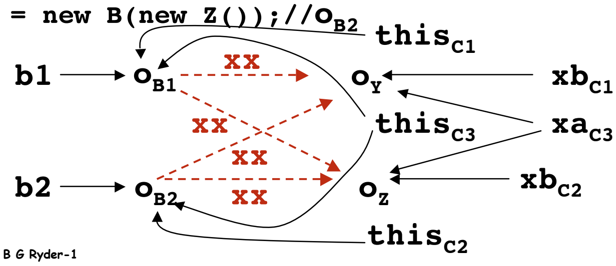


# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
    X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
```

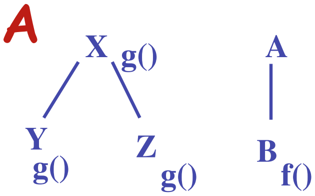



1-CFA

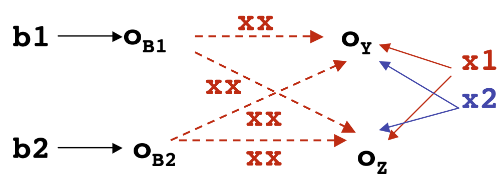


# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```



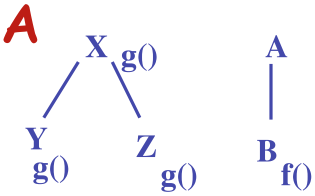

1-CFA






# ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B extends A
{ B (X xb){c3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```




1-CFA finds
C4 calls Y.g(), Z.g() and
C5 calls Y.g(), Z.g()

# Comparison Conclusion

- The call string and functional approaches to context sensitivity are incomparable!
- Neither is more powerful than the other
- Recent papers show that object-sensitive is effective in static analysis of race conditions (Aiken et. al, PLDI'06)



# Difficult Issues

- Use of reflection and dynamic class loading
  - Need whole program for a safe analysis
- Java native methods
  - Need to model possible effects
- Exceptions
- Incomplete programs
- Lack of benchmarks