Dimensions of Precision in Reference Analysis of Object-oriented Programming Languages

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Outline

- What is reference analysis of OOPLs and what is it used for?
- Examples of reference analyses
  - Hierarchy-based: CHA, RTA
  - Incorporating flow: FieldSens
  - Context-sensitive: 1-CFA
- Dimensions of analysis
  - More examples and categorization of analysis algorithm choices
- Conclusions

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 run-time 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 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 Compilers

- Side-effect analysis, dependence analysis (flow)
- Devirtualization & inlining (hierarchy)
- Synchronization removal (flow)
- Stack-based object allocation (flow)

Uses of Reference Analysis Information in Software Tools

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

Example Analyses

- Hierarchy-based
  - CHA, RTA
- Incorporating flow
  - FieldSens (Andersen-based points-to)
- Incorporating flow and calling context
  - 1-CFA

Example

cf Frank Tip, OOPSLA'00

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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();
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class A {
   foo(){..}
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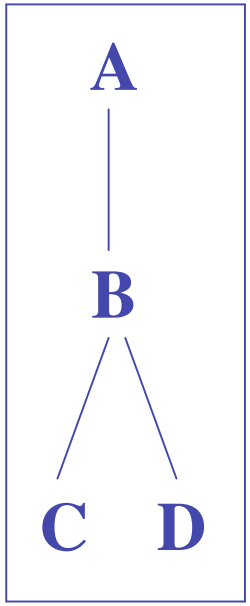

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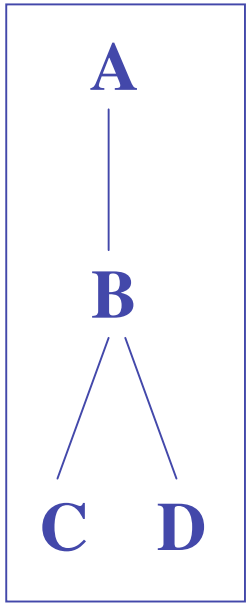

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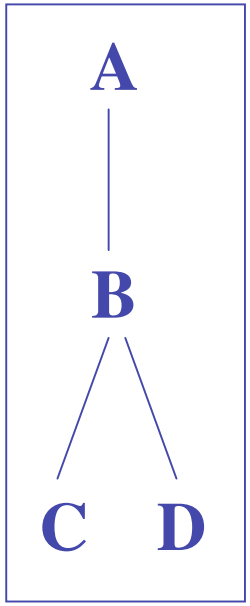

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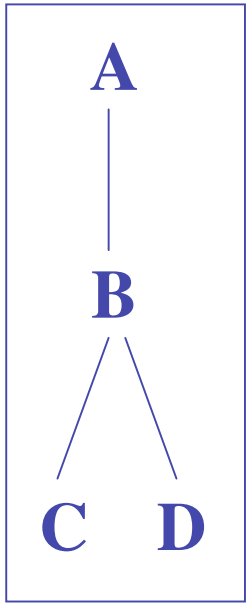

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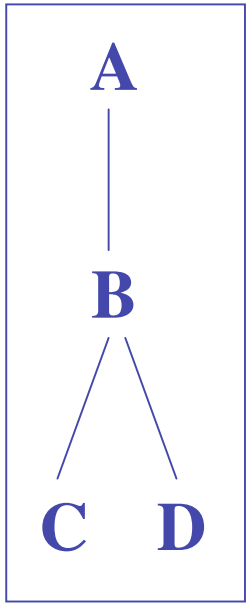

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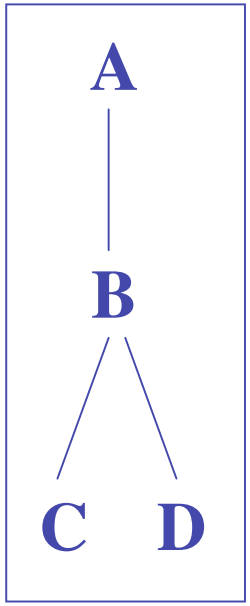

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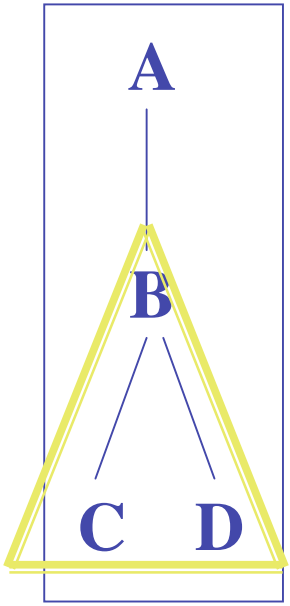

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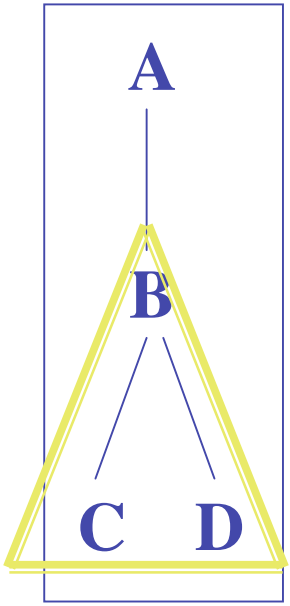

Cone(Declared_type(receiver))

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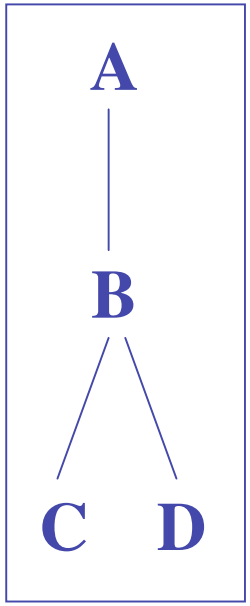

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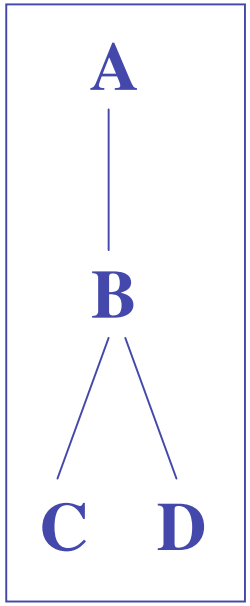

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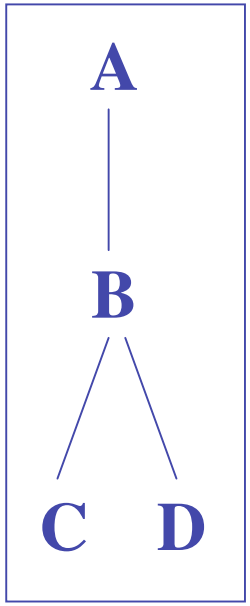

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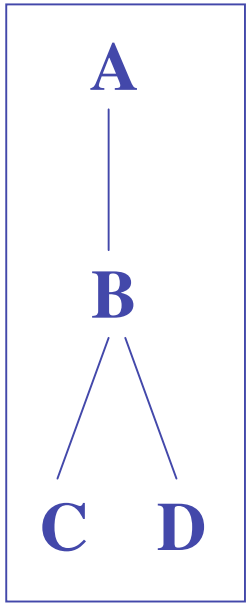

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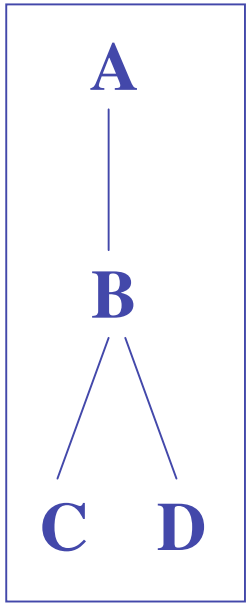

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CHA Characteristics

- 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

RTA Example

cf Frank Tip, OOPSLA'00

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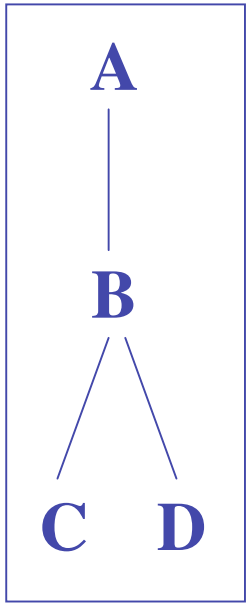

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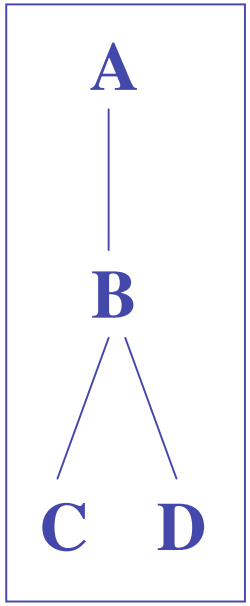

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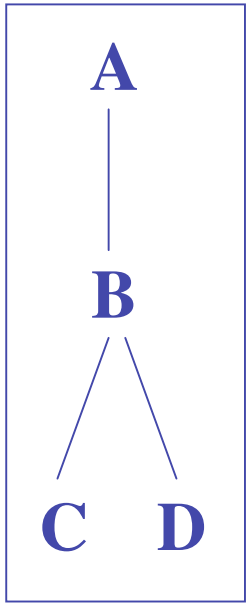

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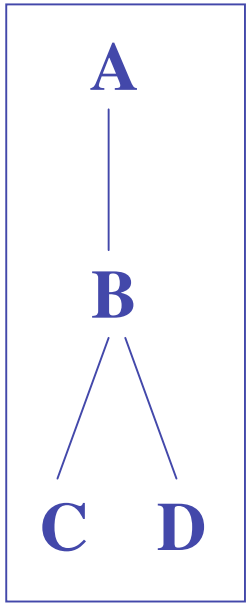

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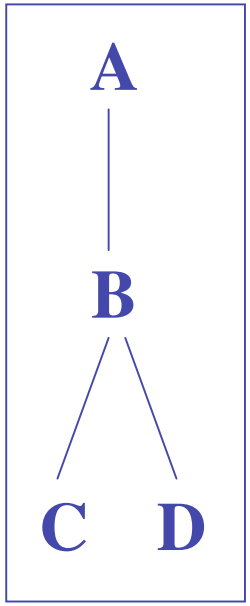

RTA Characteristics

- 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

FieldSens Example

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Points-to Graph summarizes reference/object relationships

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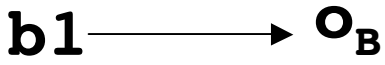

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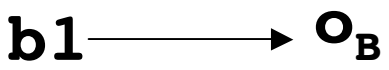

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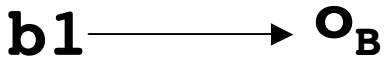

Points-to Graph summarizes reference/object relationships

FieldSens Example

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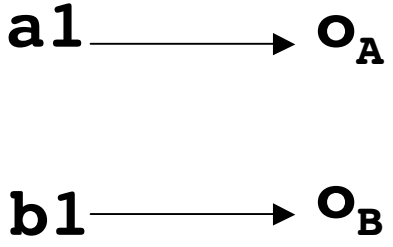

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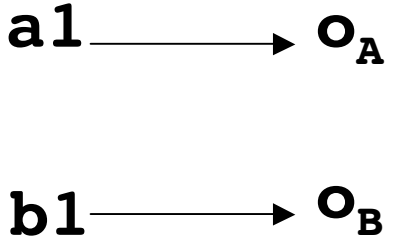

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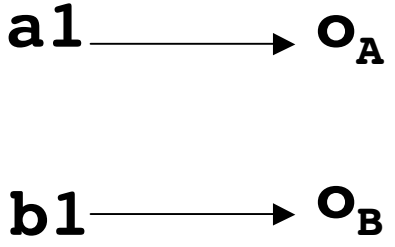

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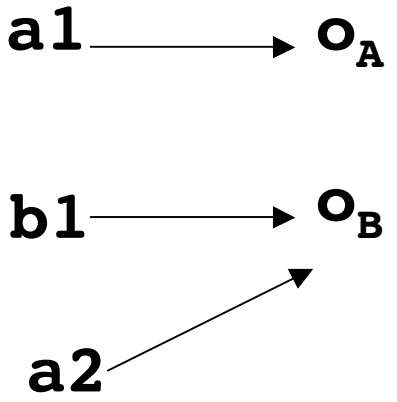

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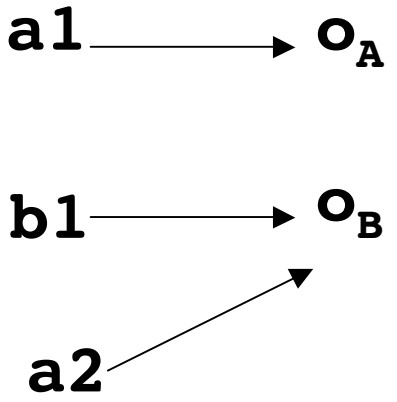

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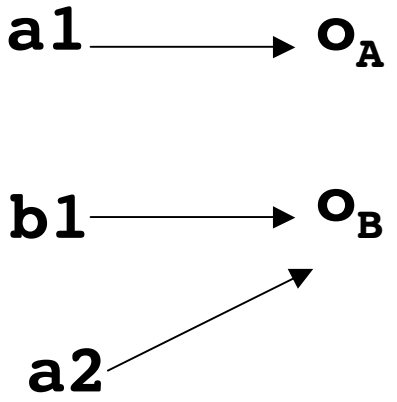

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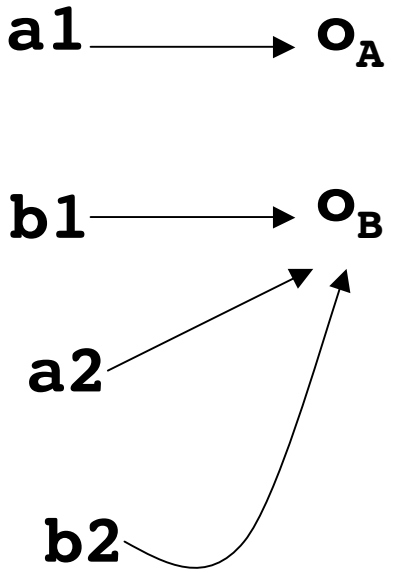

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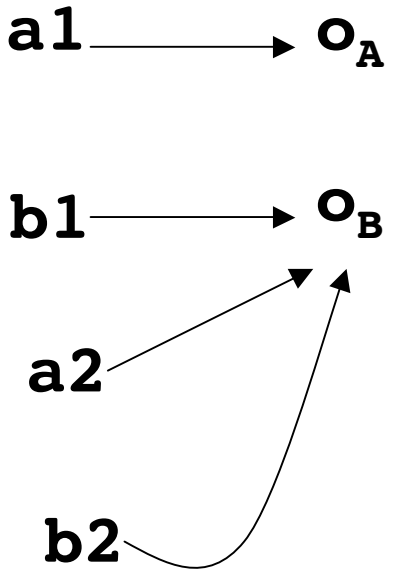

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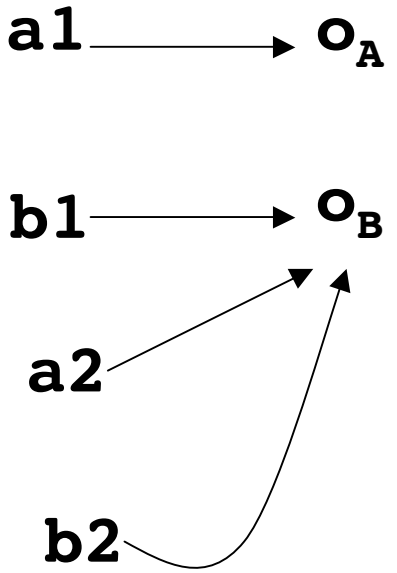

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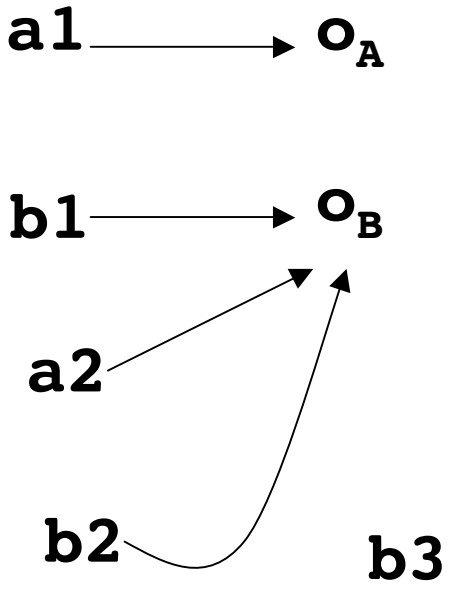

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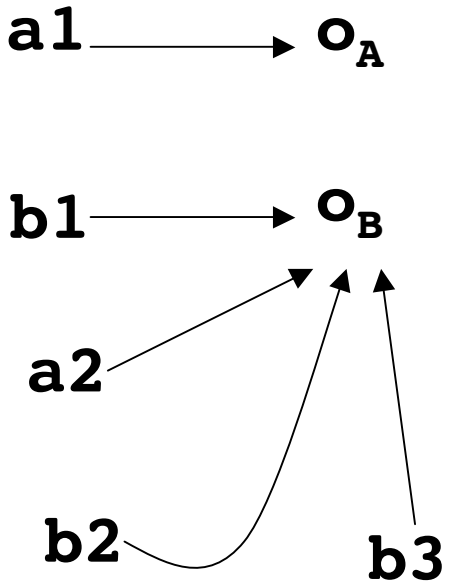

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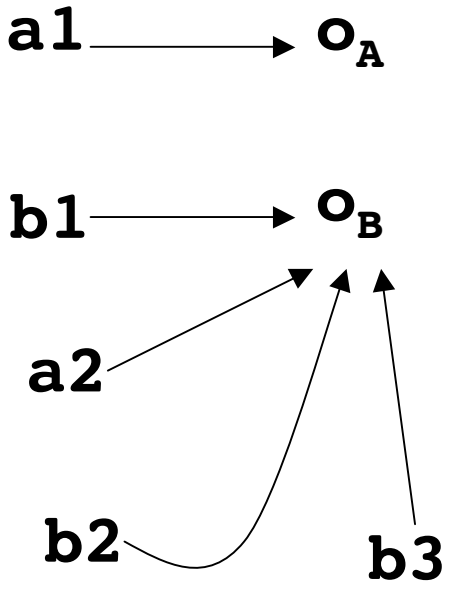

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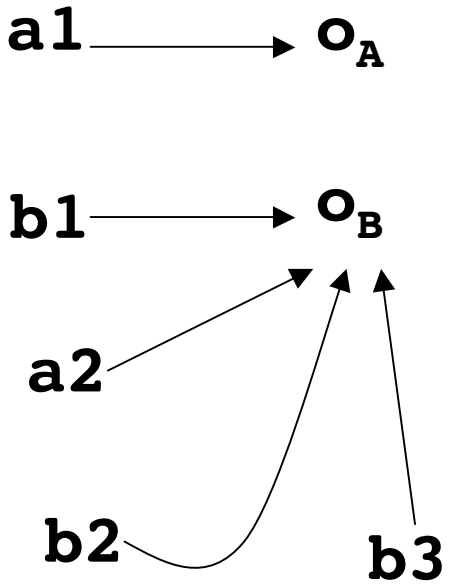

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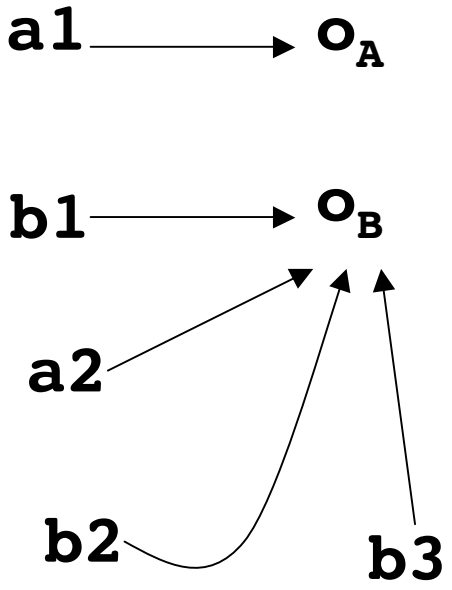

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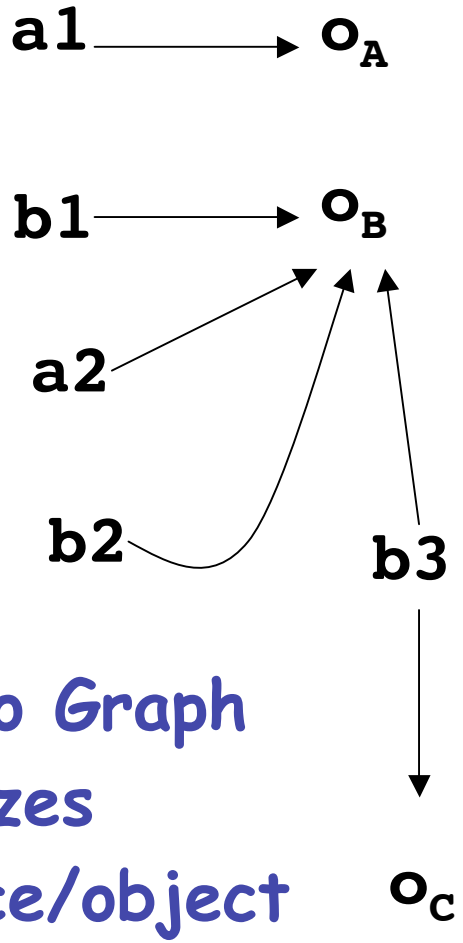

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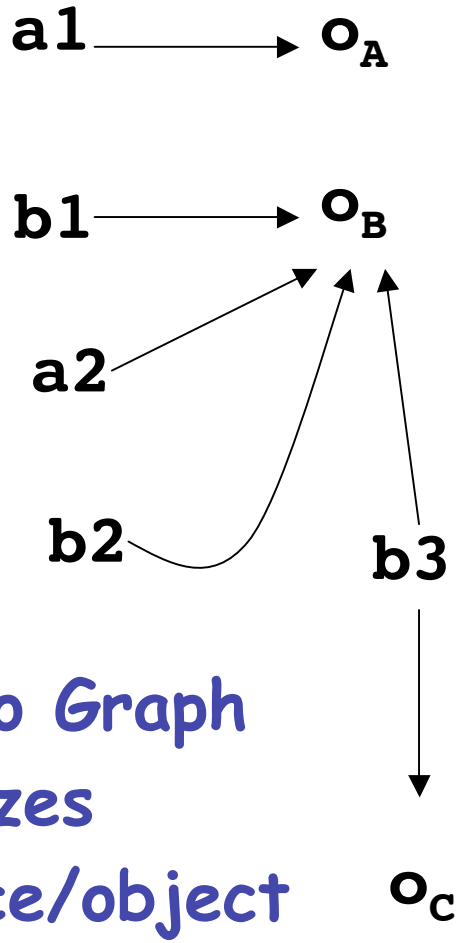

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cf Frank Tip, OOPSLA'00

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```
class A {
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}
class B extends A{
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}
class C extends B{
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}
class D extends B{
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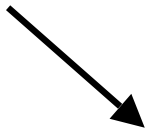

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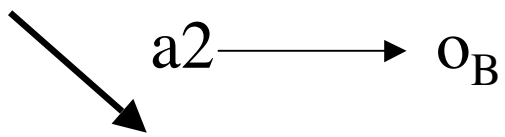


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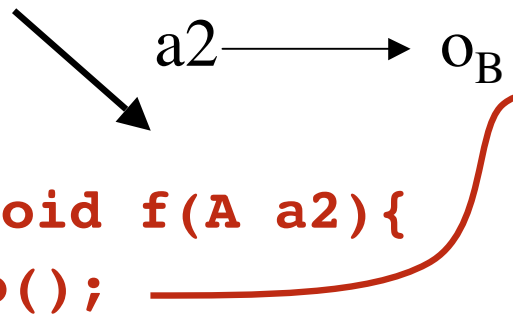


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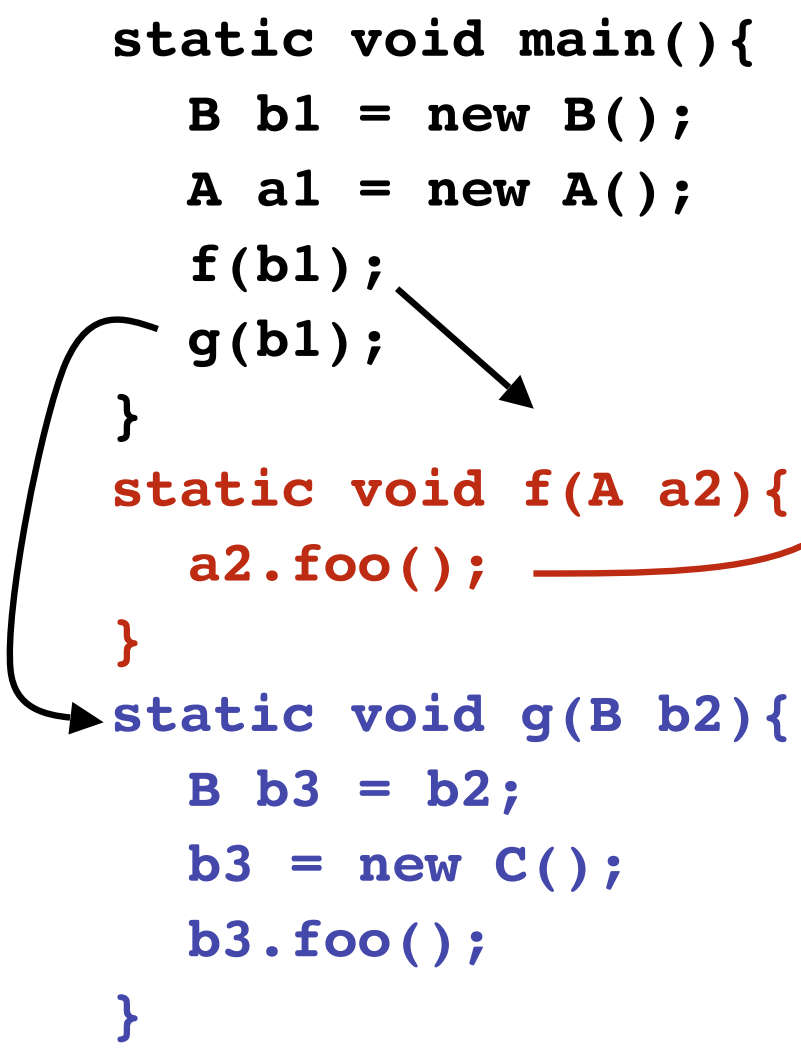

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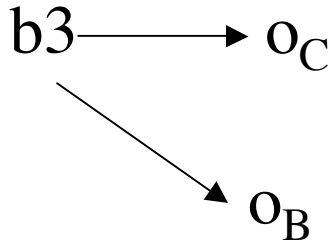

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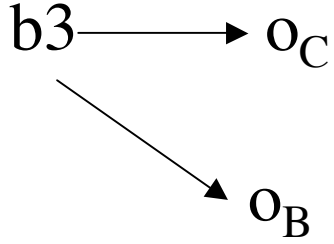

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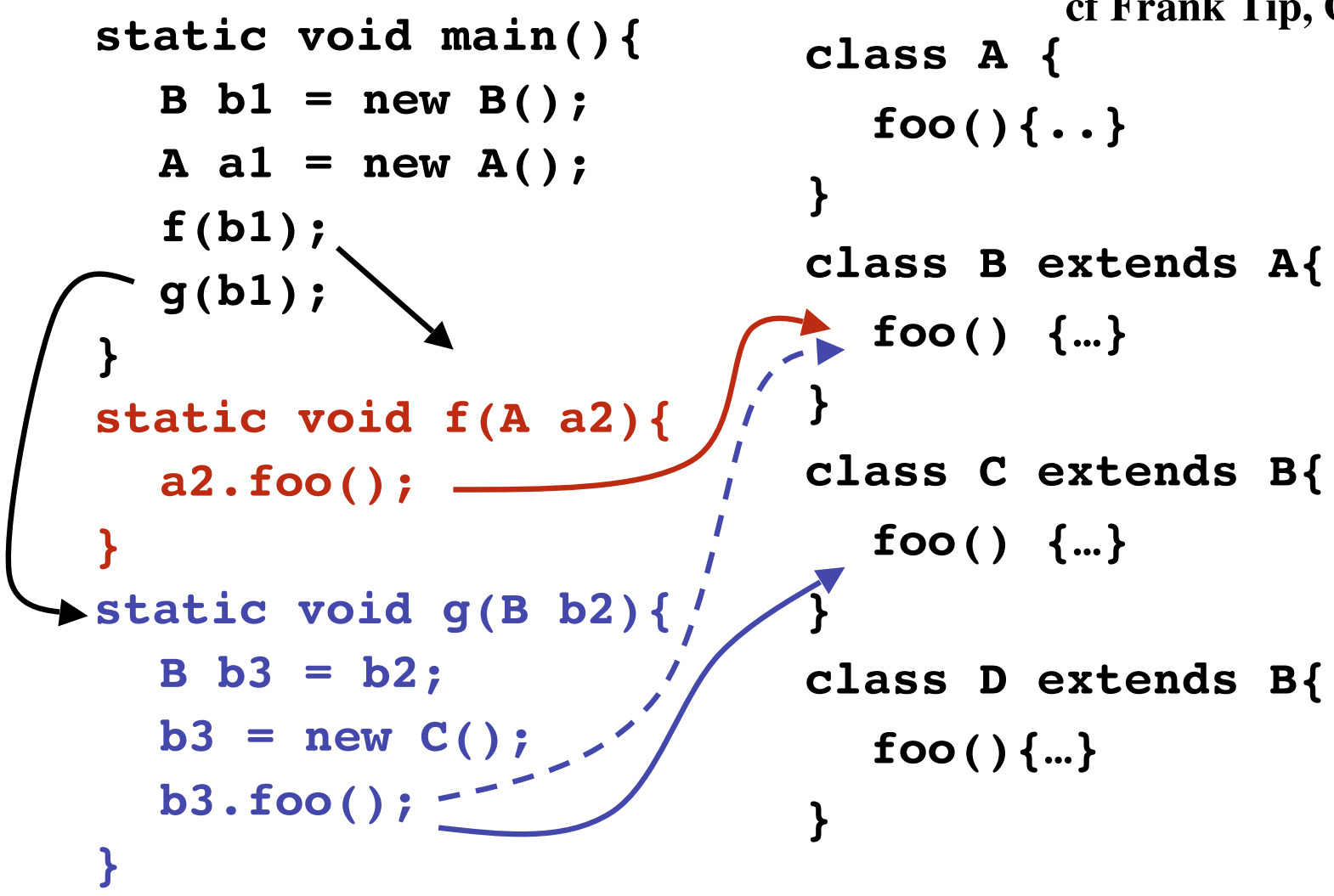

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FieldSens Characteristics

- 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

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

1-CFA Analysis

- Improves on FieldSens by keeping track of calling context

```
static void main(){
      B b1 = new B();//O_B
      A a1 = new A();//O_A
      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;}
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Points-to Graph

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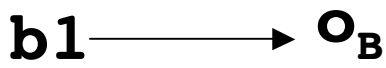

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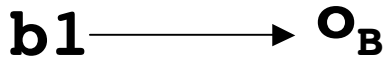

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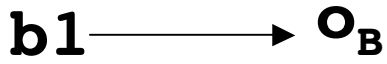

Points-to Graph

1-CFA Analysis

- Improves on FieldSens by keeping track of calling context

```
static void main(){
      B b1 = new B();//O_B
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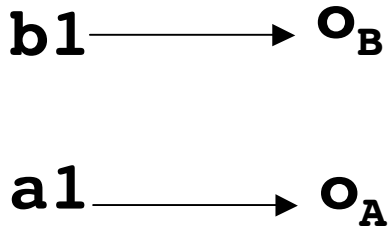

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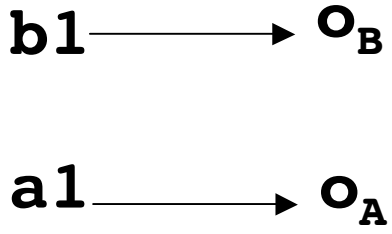

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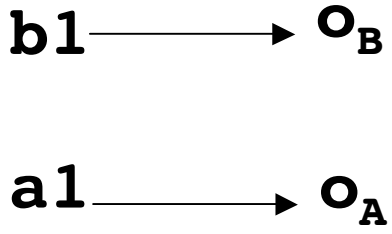

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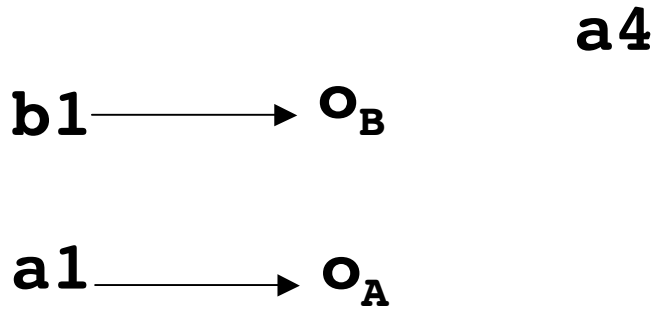

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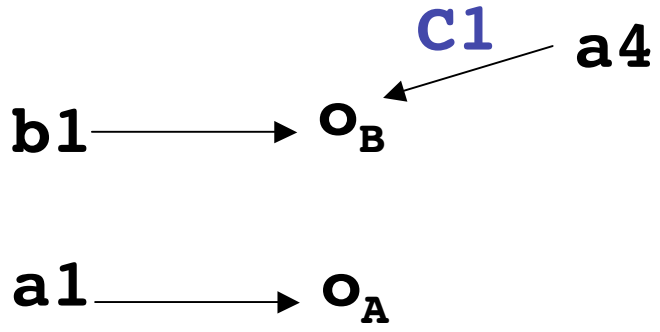

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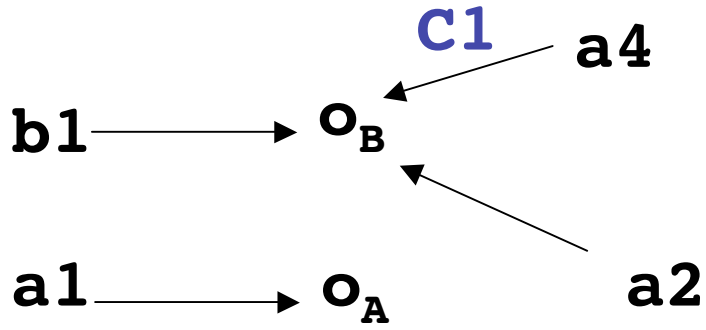

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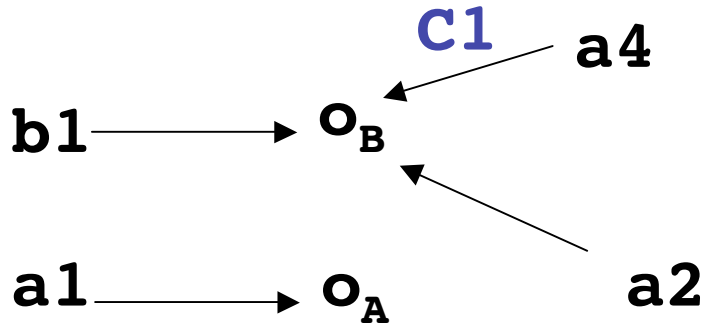

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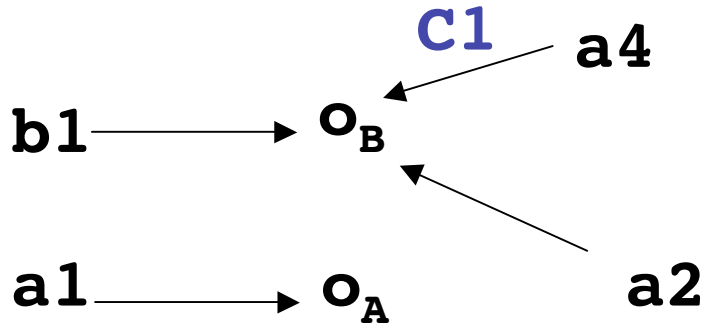

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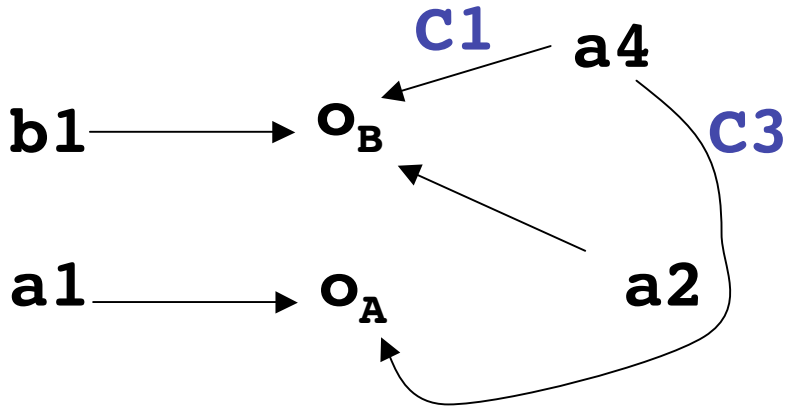

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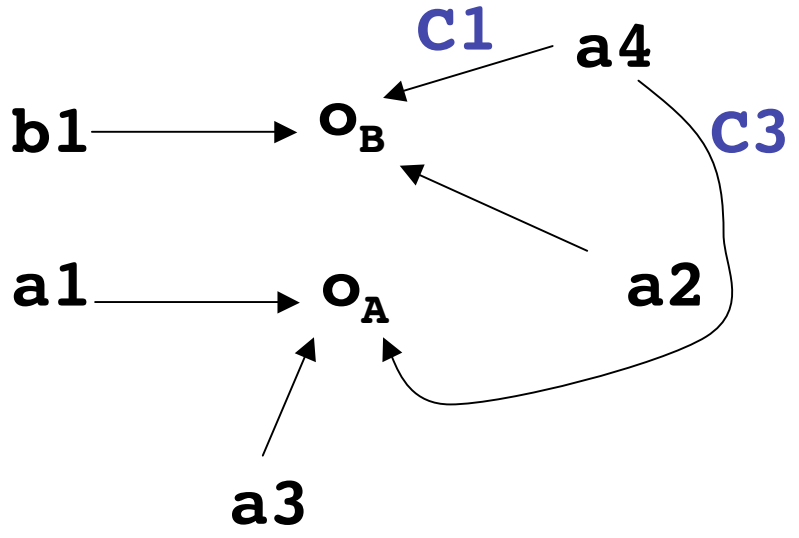

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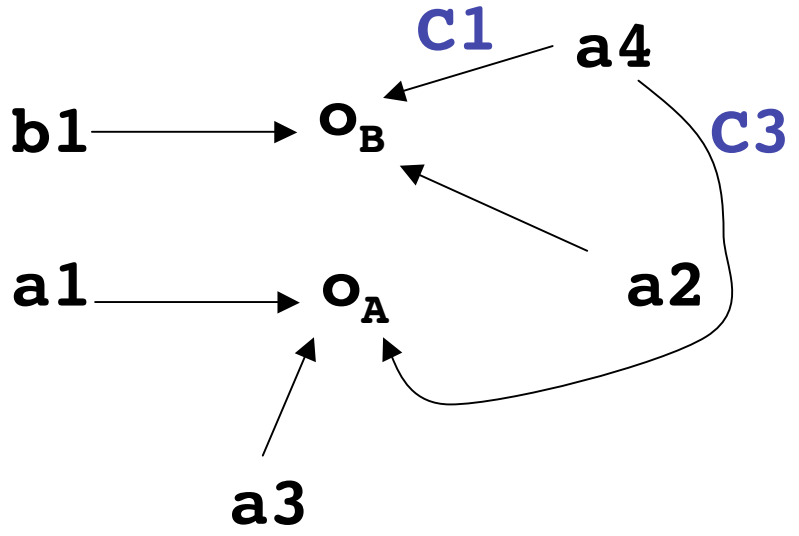

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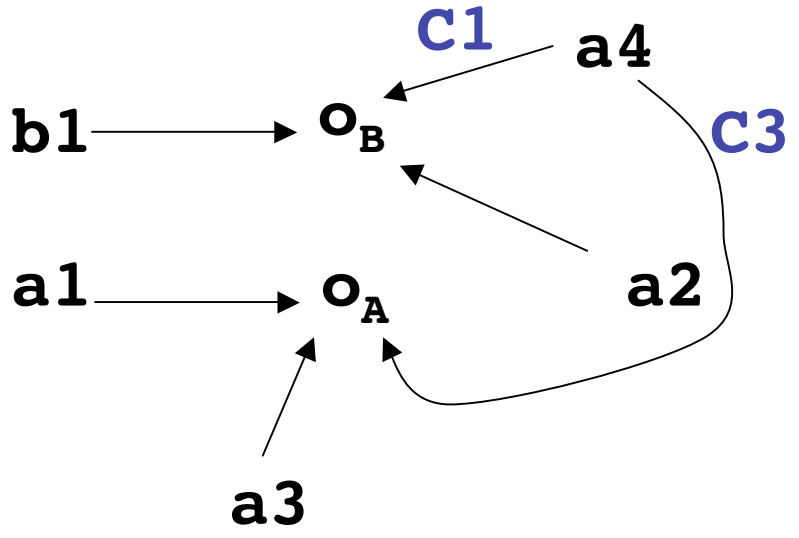

Points-to Graph

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

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
- Field Sensitivity
  - May or may not distinguish fields -Rountev'01

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

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

Example of XTA

cf Frank Tip, OOPSLA'00

```
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(){…}
}
```

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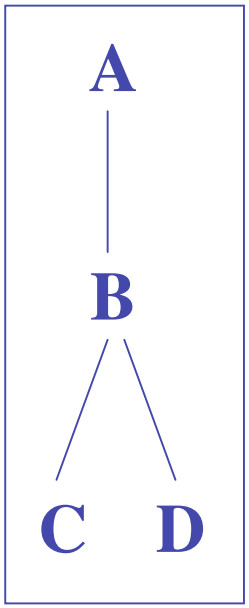

Example of XTA

{A,B}

```
static void main(){
   B b1 = new B();
   A a1 = new A();
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static void f(A a2){
   a2.foo();
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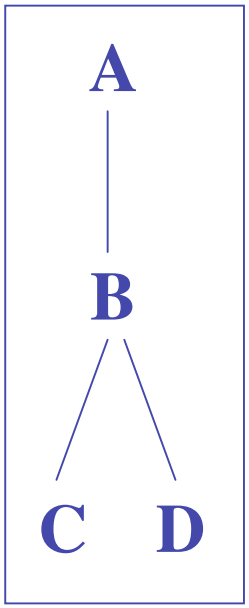

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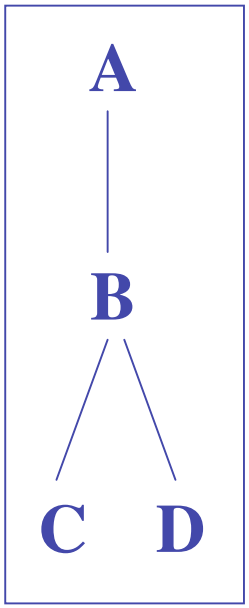

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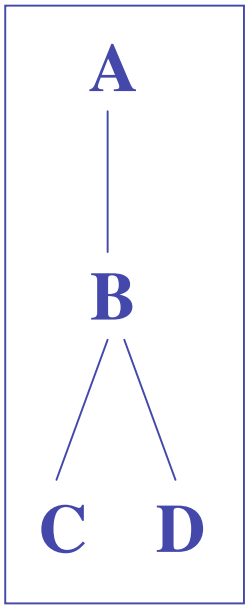

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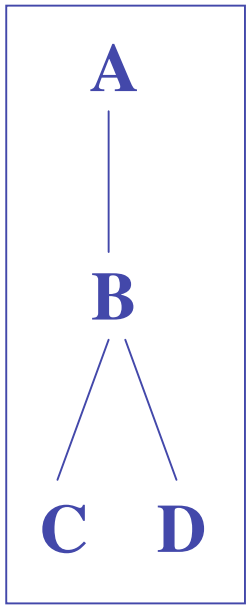

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}                          {A,B}
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   a2.foo();
}                          {B,C}
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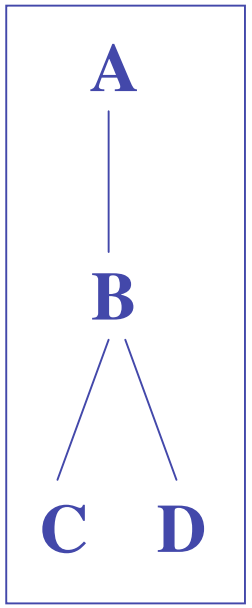

Dimensions of Precision

- 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
```

flow-sensitive:
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
flow-insensitive:
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
```

a o1 o2

this$_{A.m}$ q

aa o3 o4

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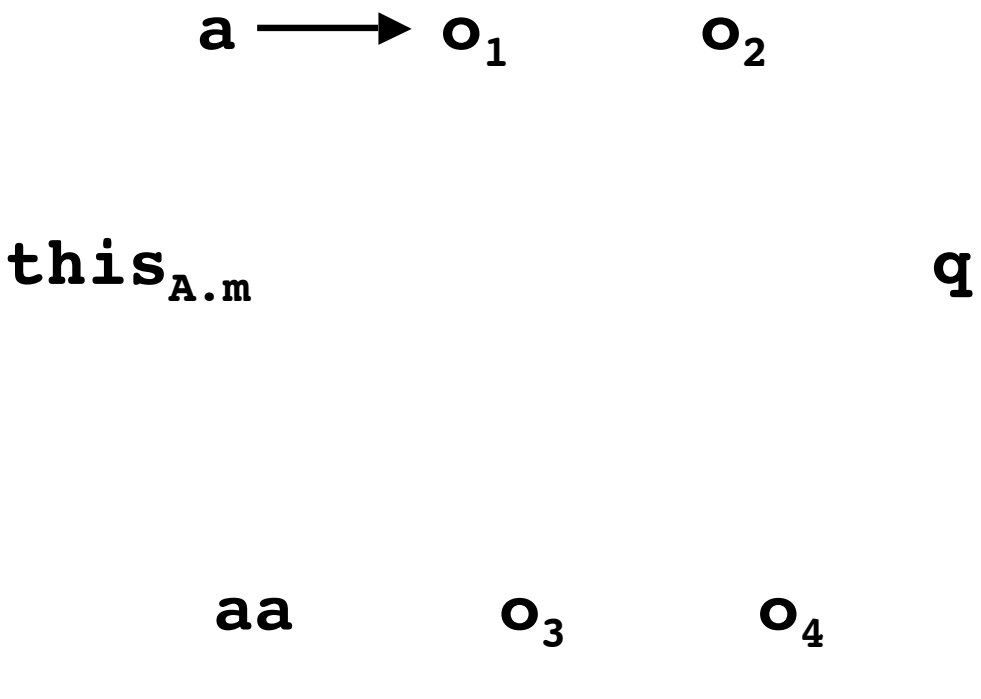

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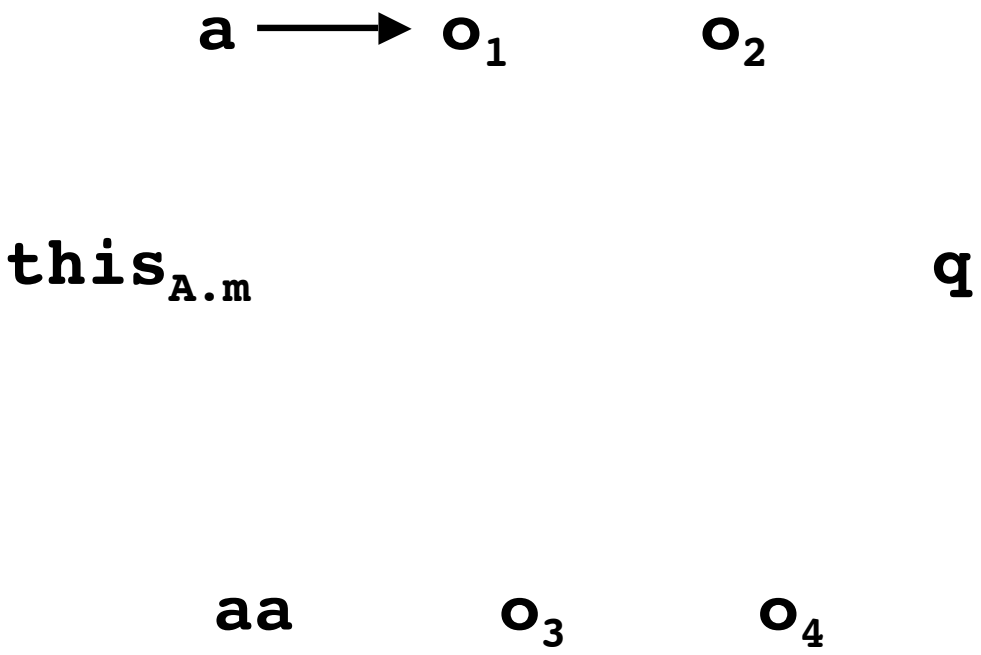

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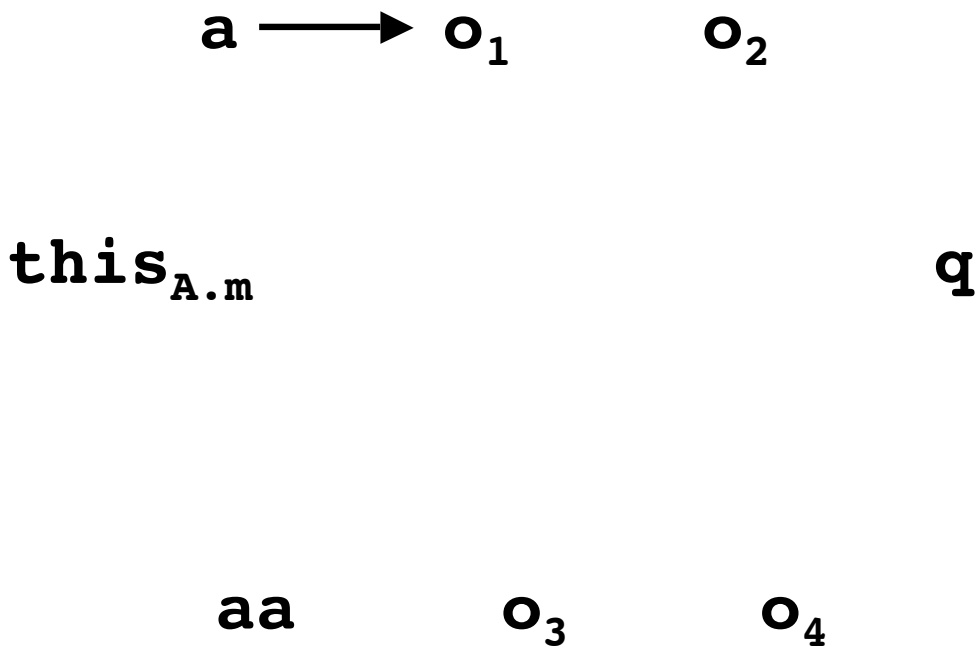

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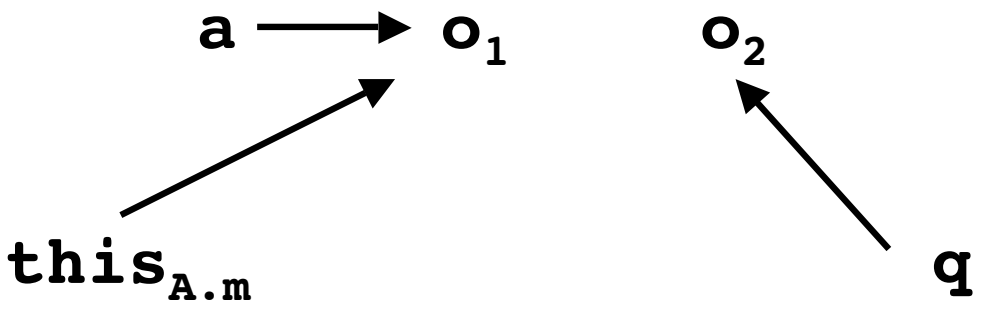

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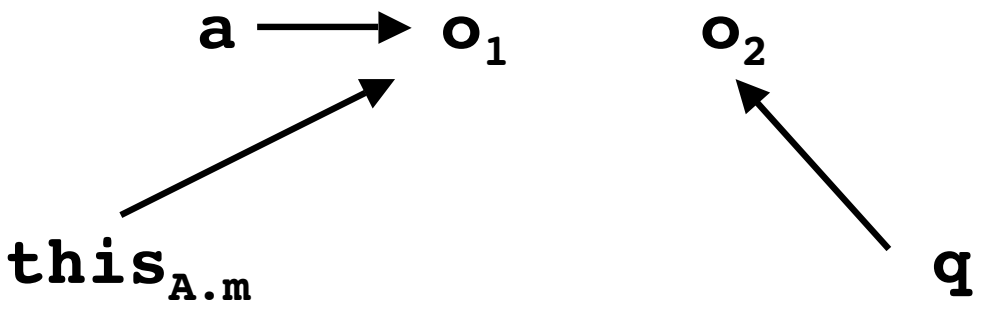

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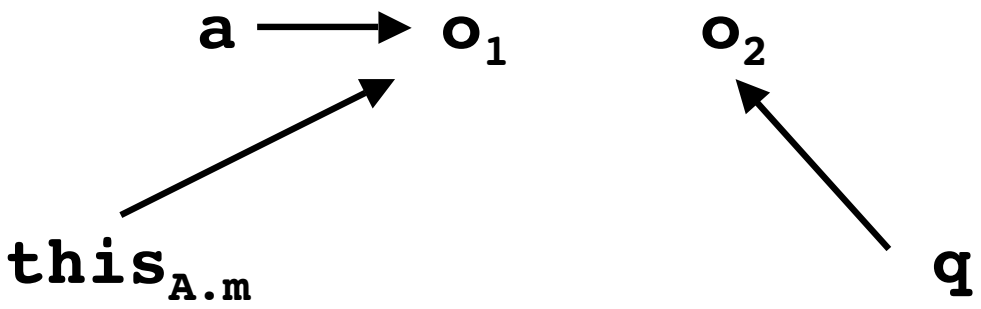

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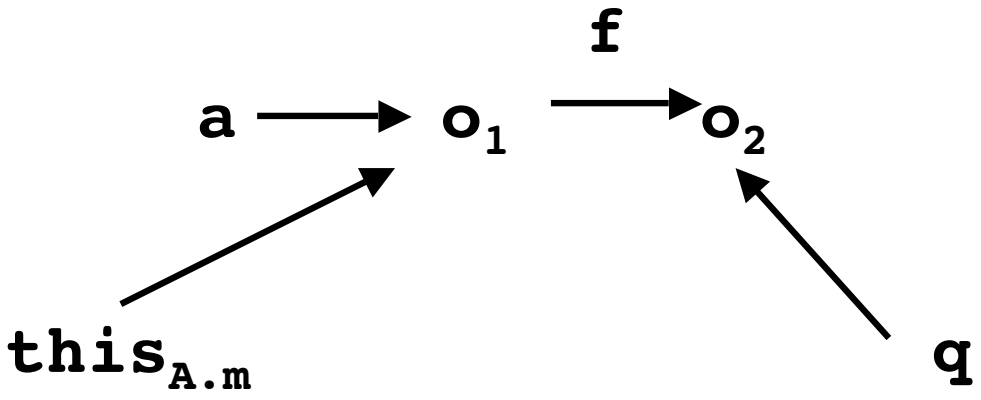

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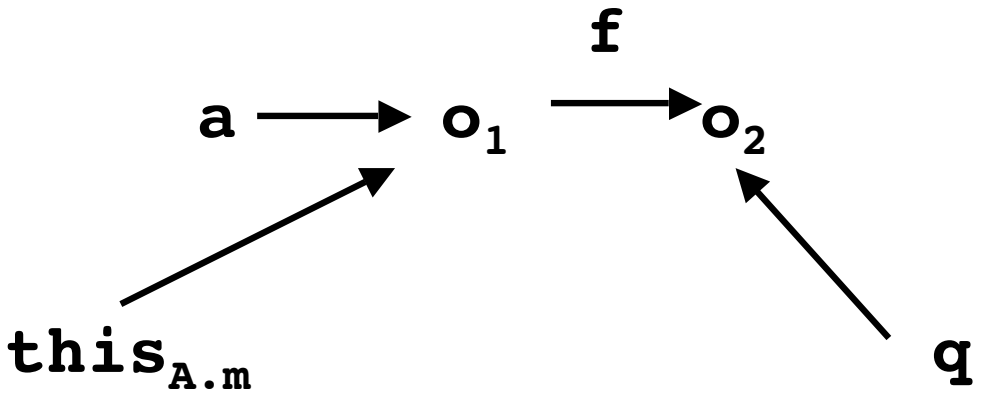

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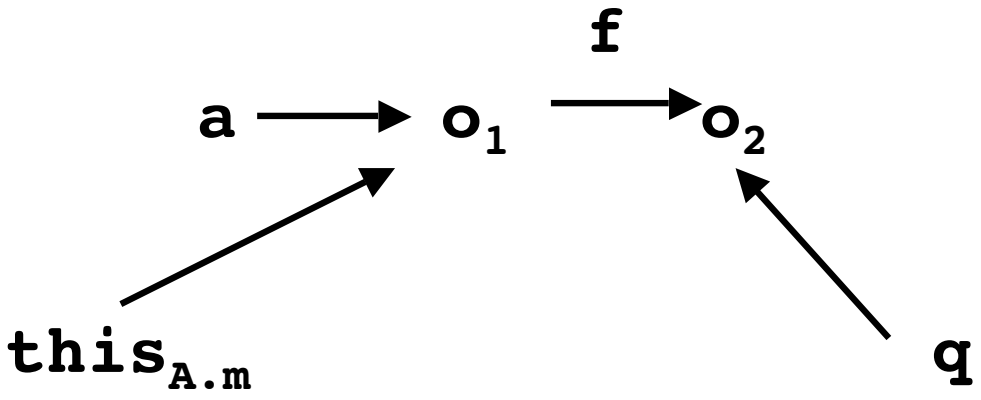

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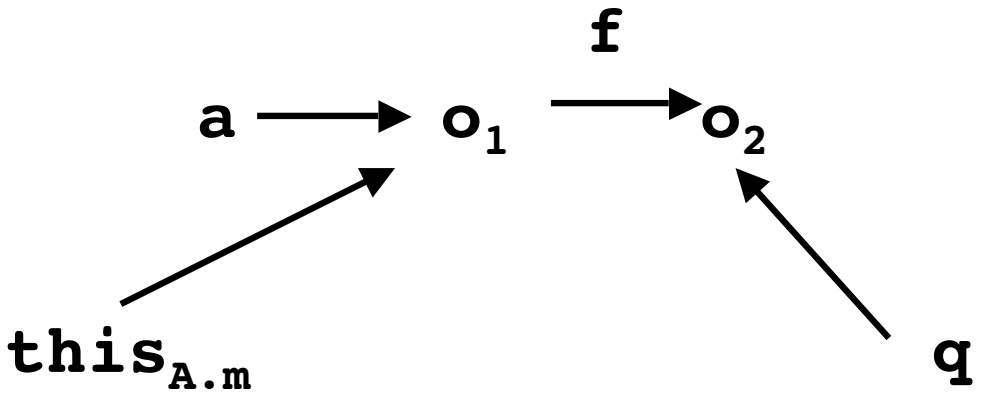

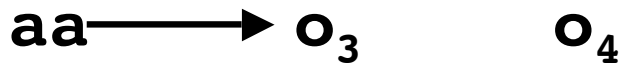

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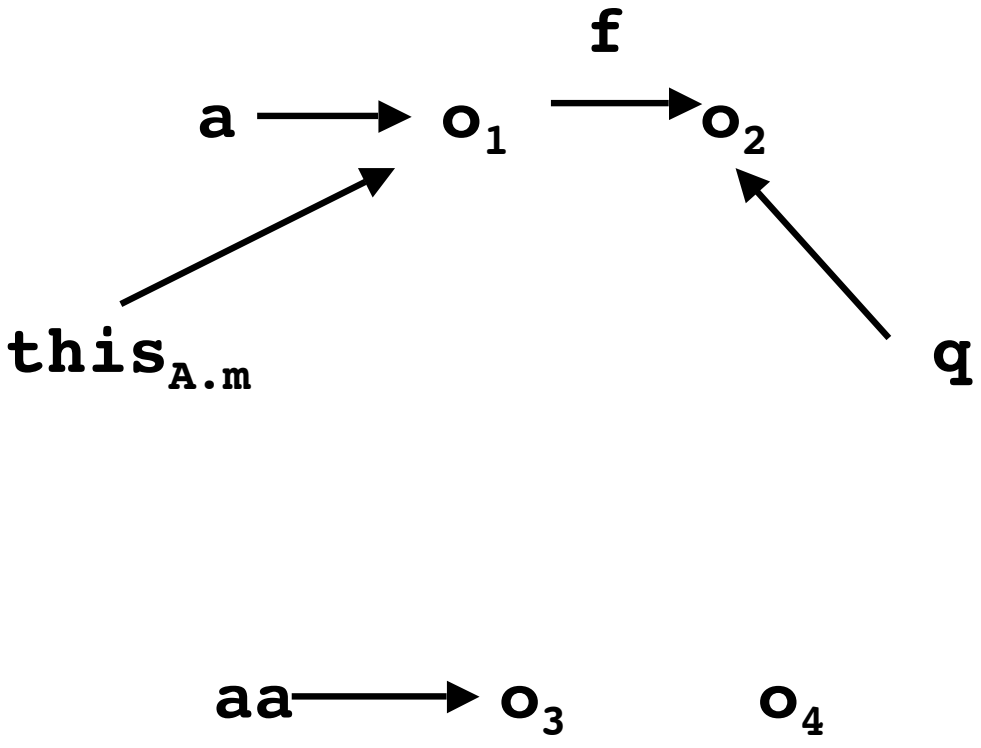

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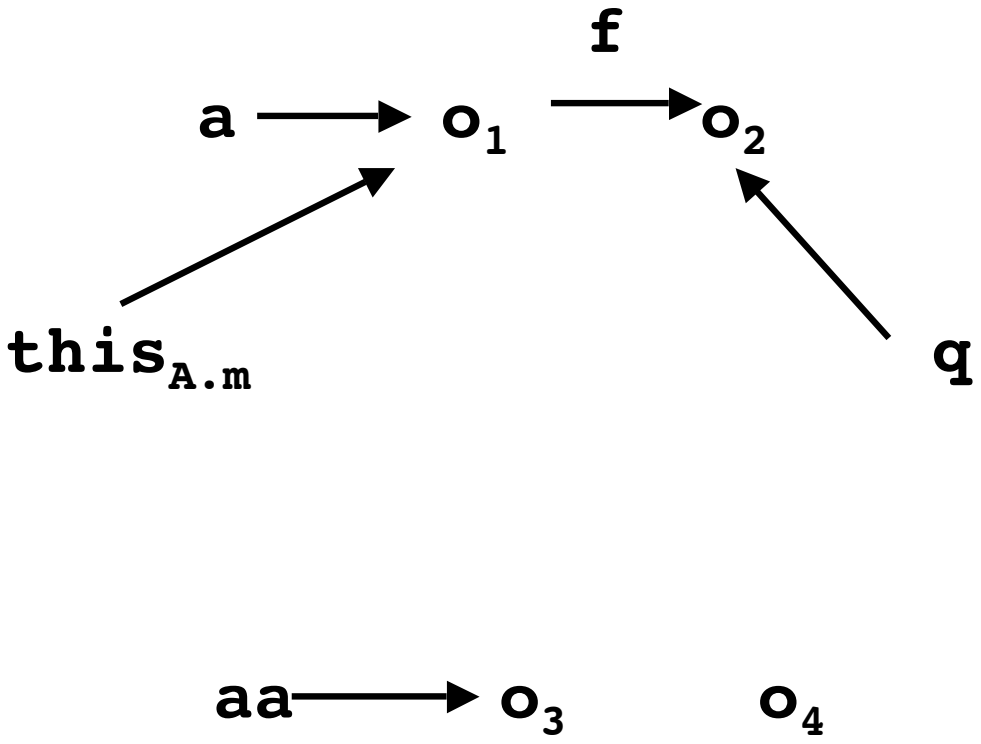

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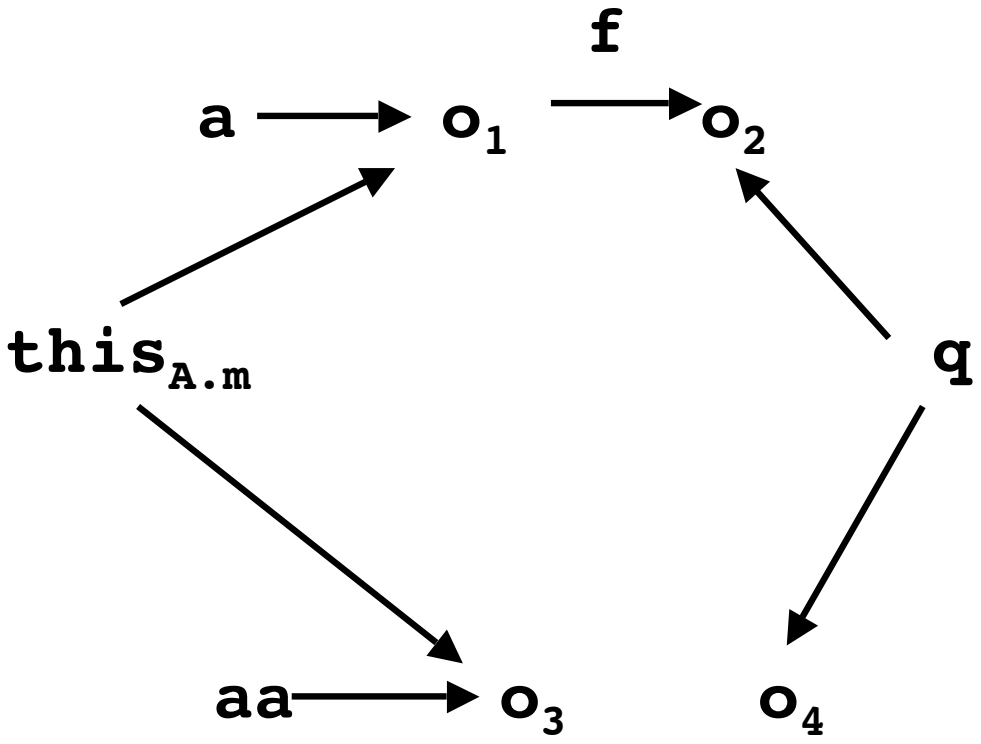

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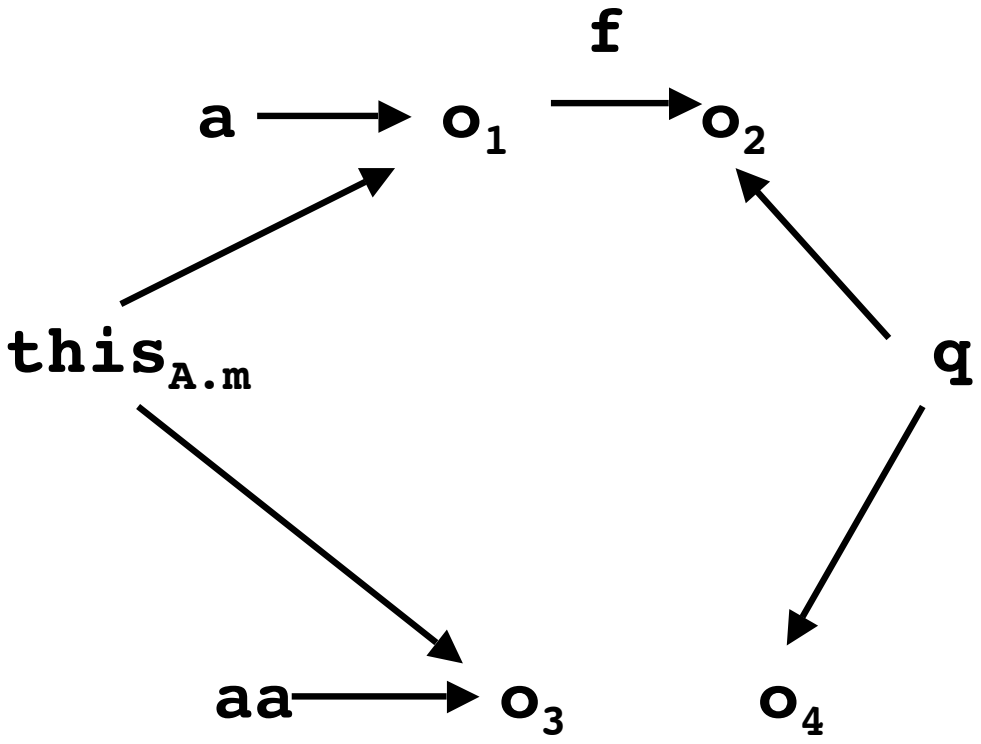

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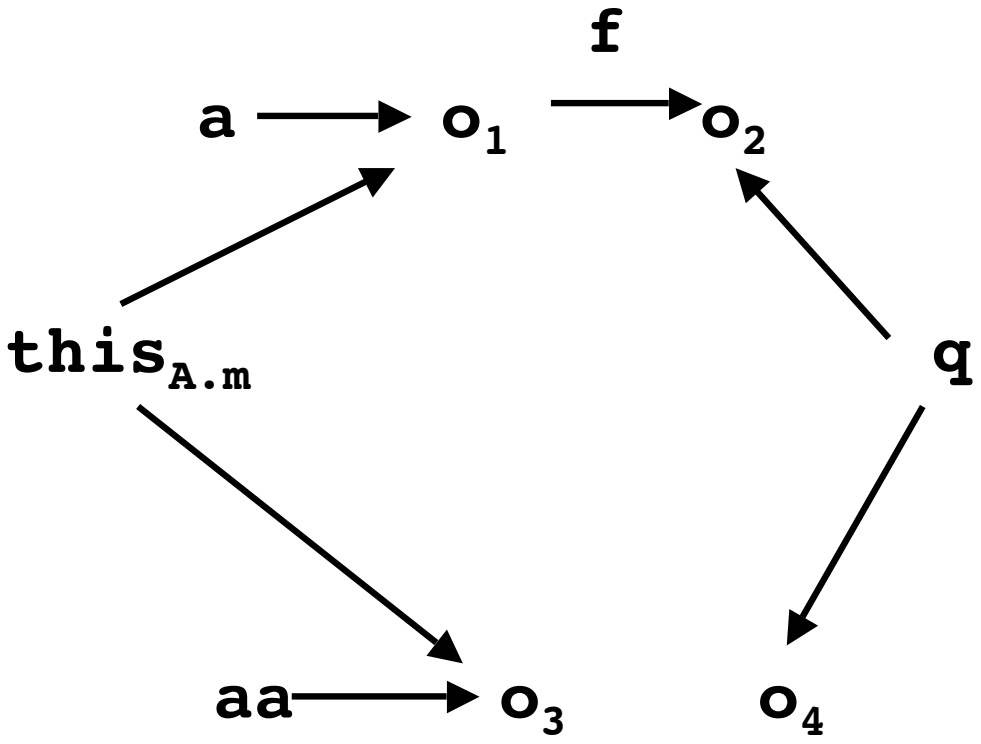

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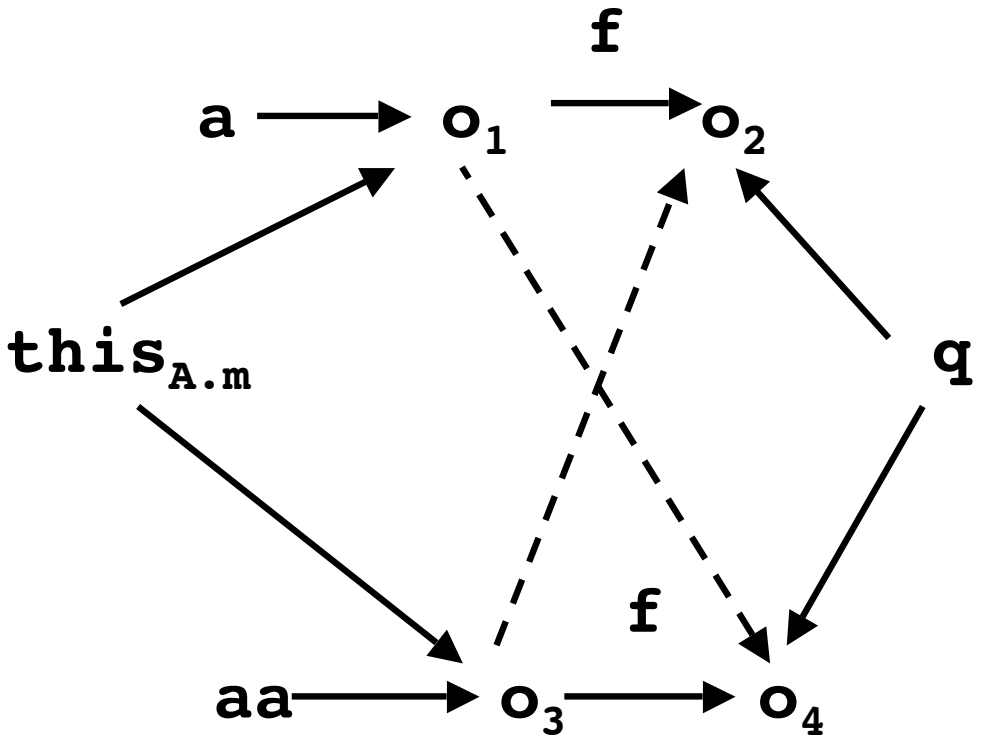

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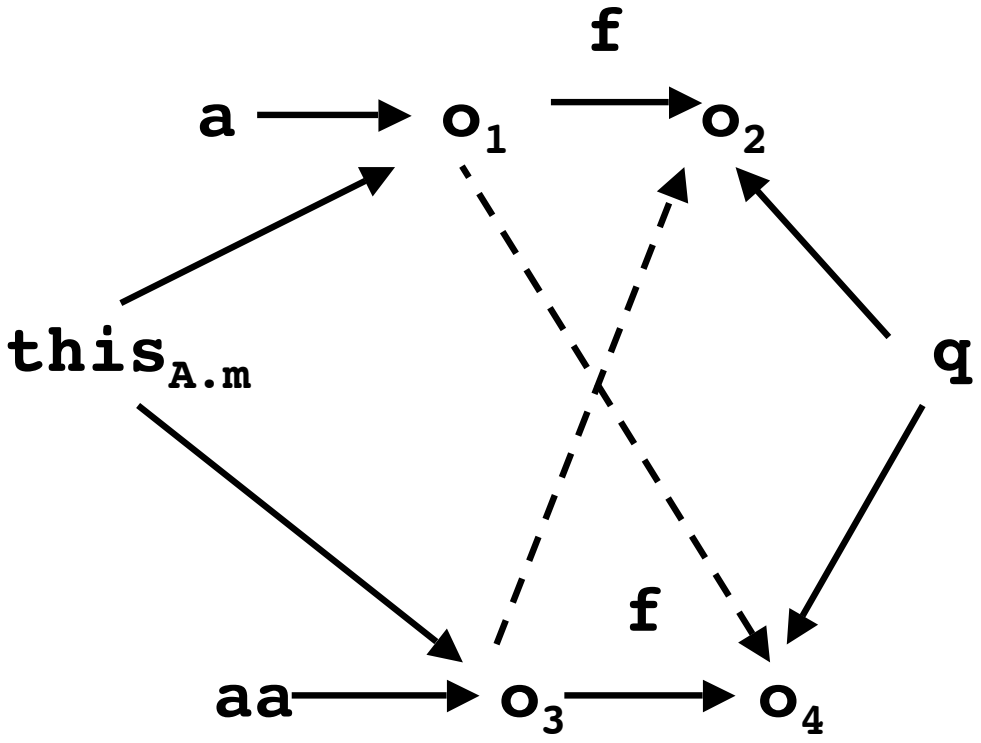

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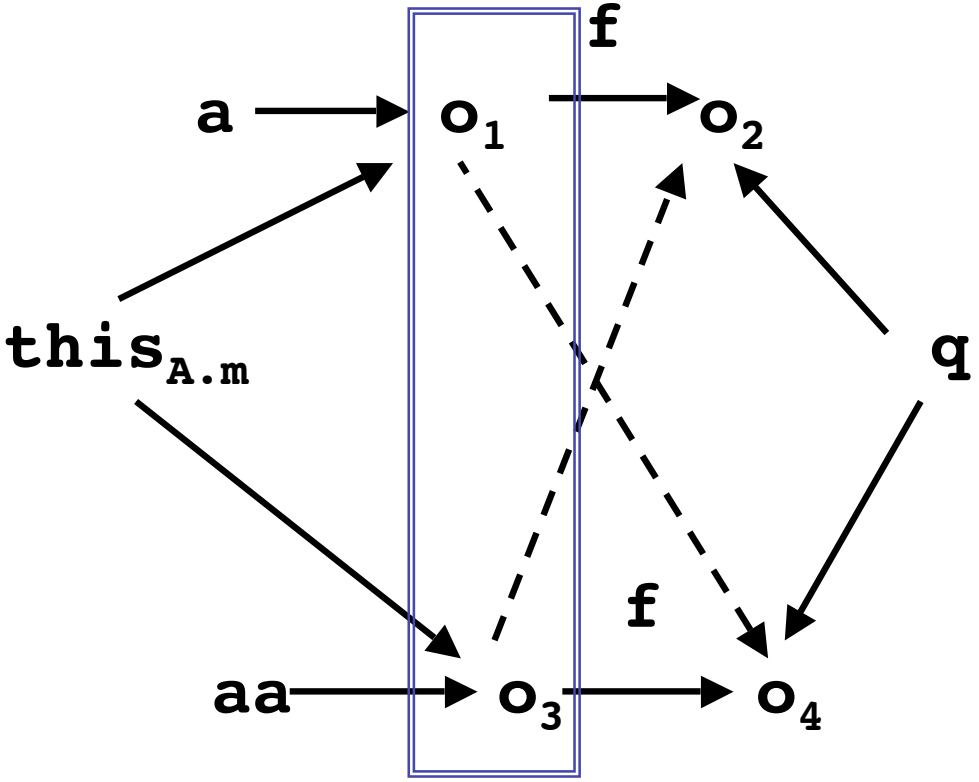

Dimensions of Precision

- 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

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

1-CFA more precise than ObjSens

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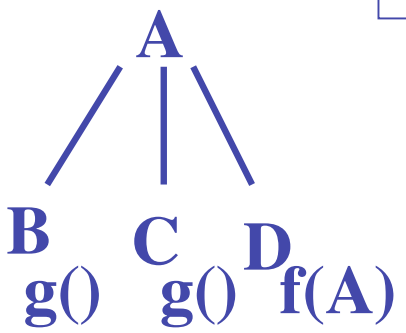

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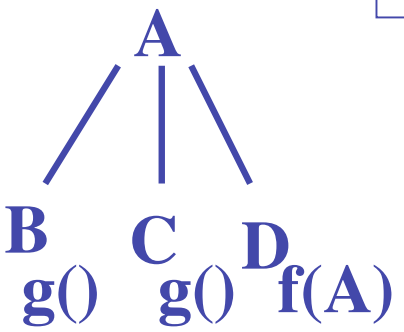

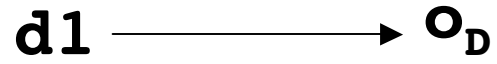

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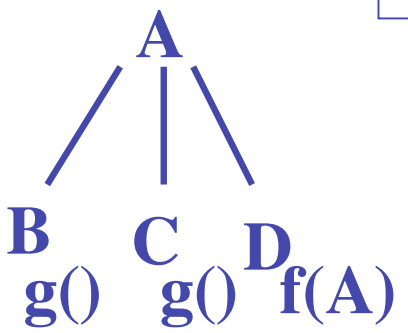

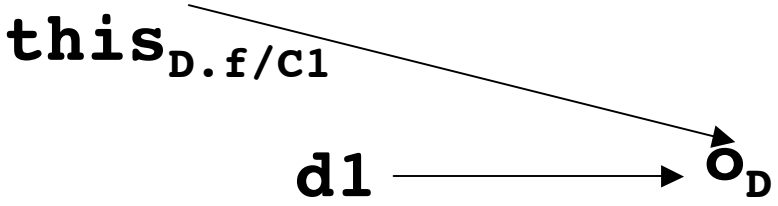

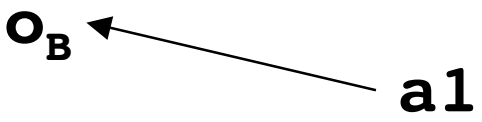

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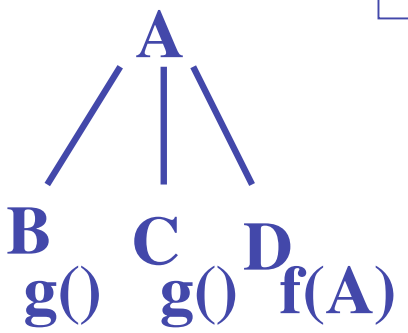

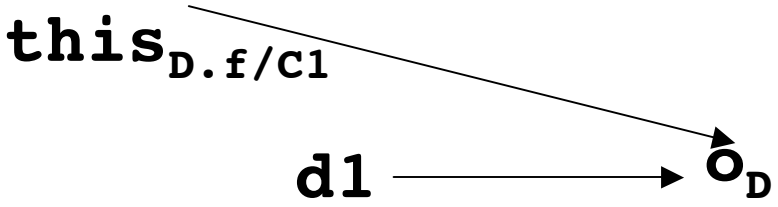

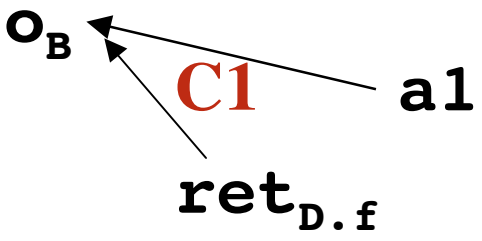

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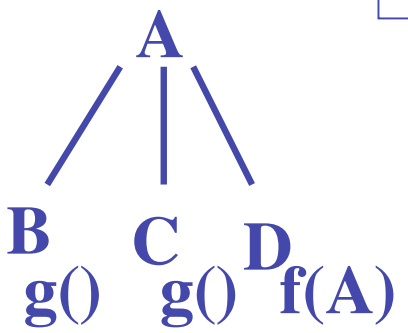

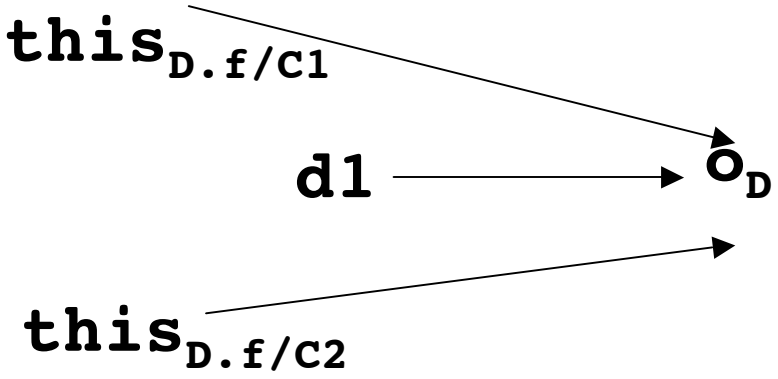

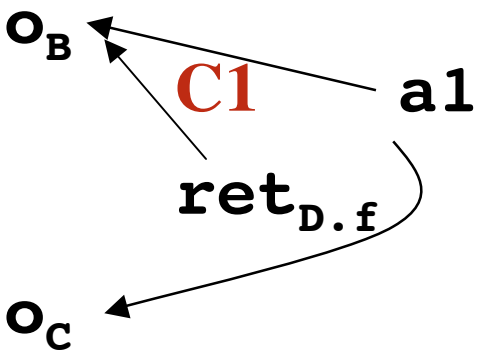

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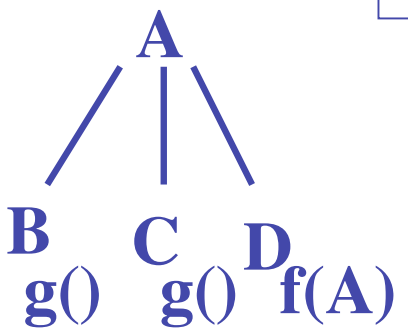

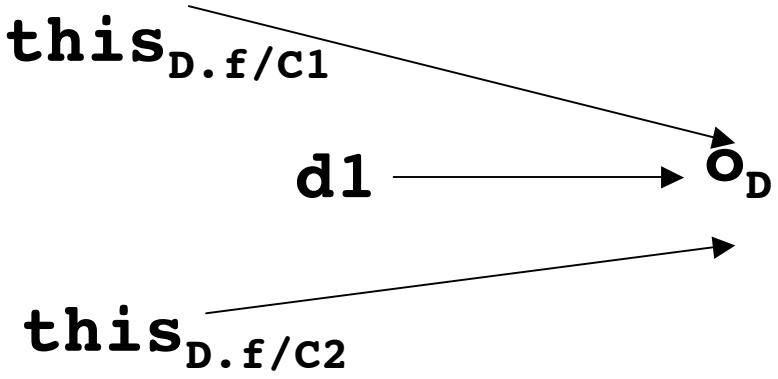

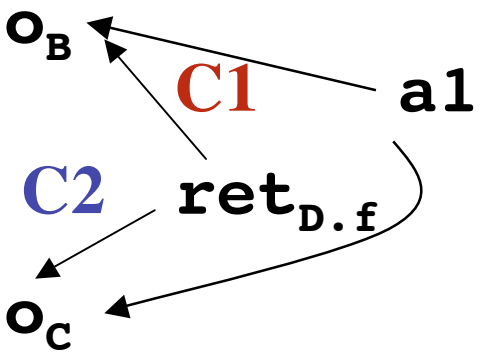

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1-CFA

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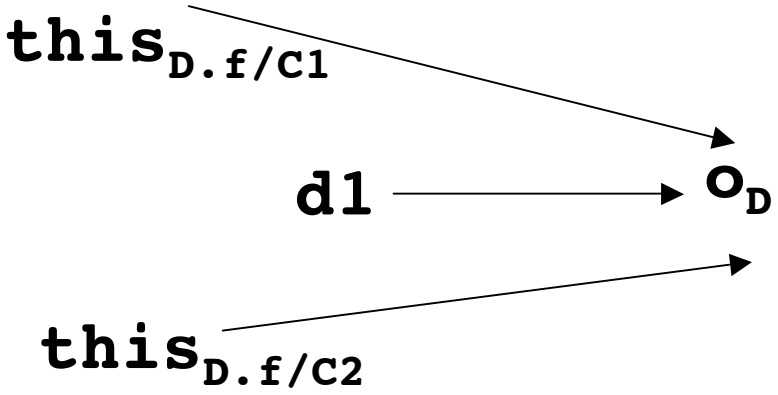

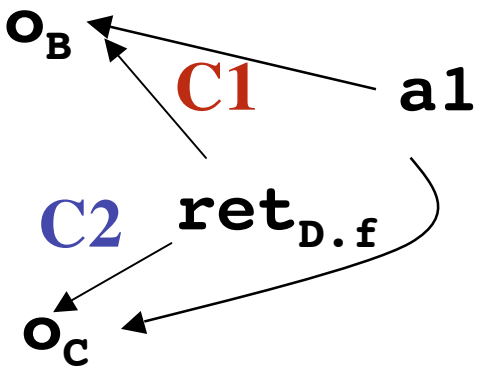

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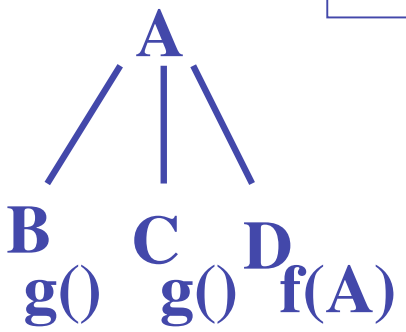

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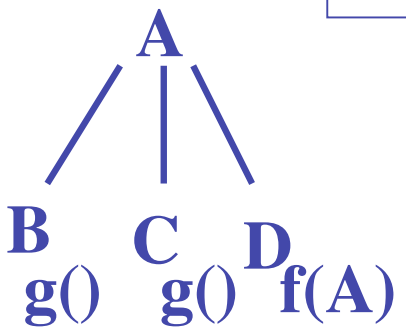

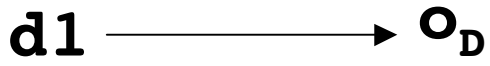

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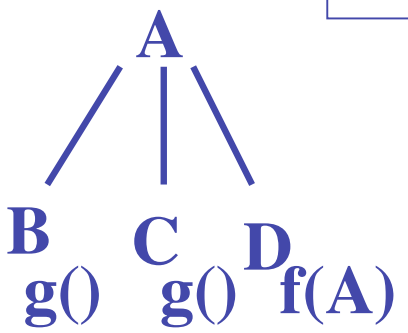

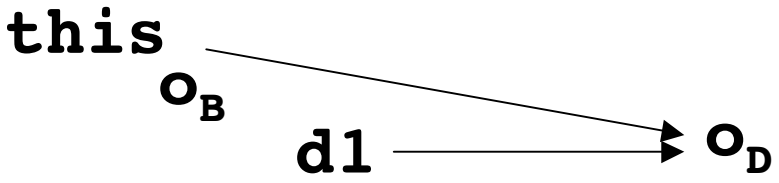

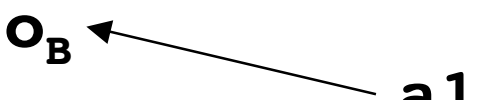

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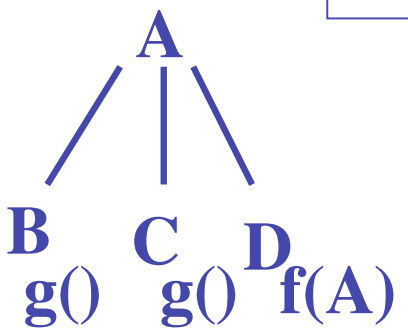

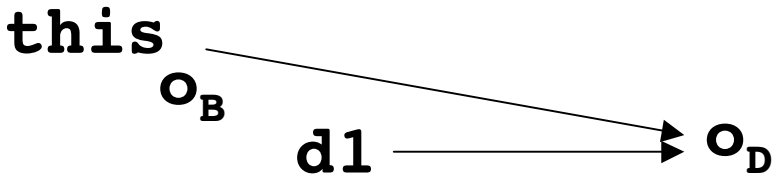

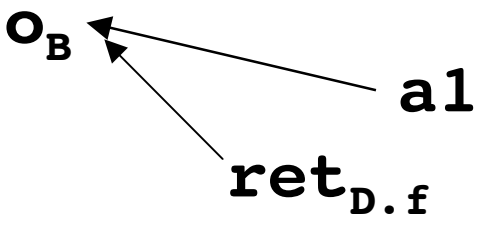

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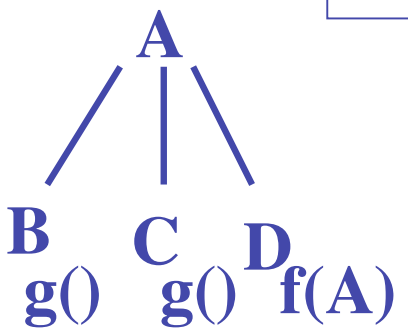
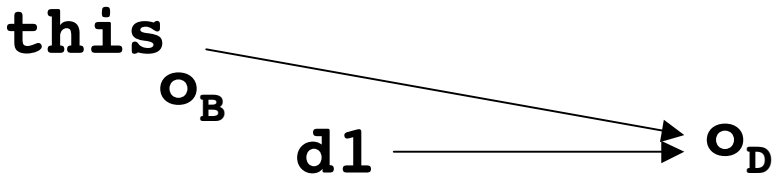
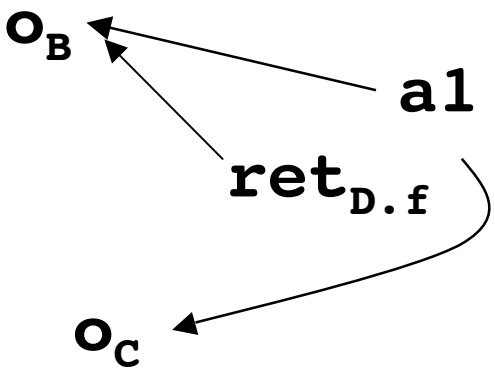
ObjSens



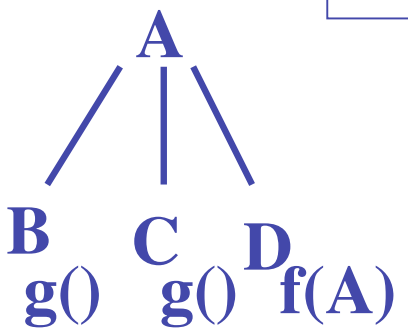


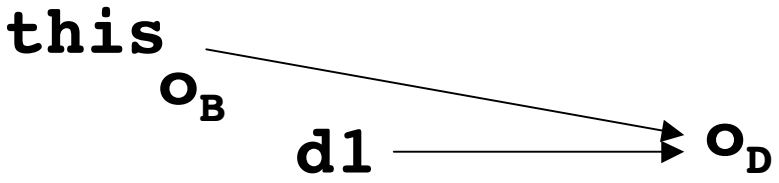


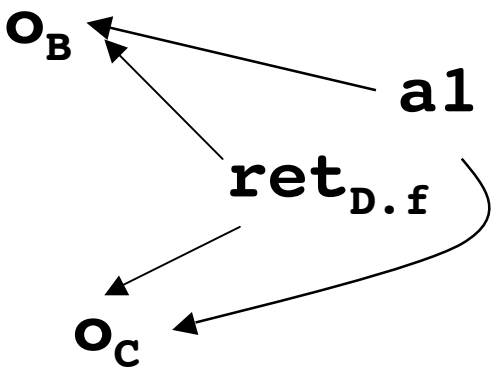
1-CFA more precise than ObjSens

```
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





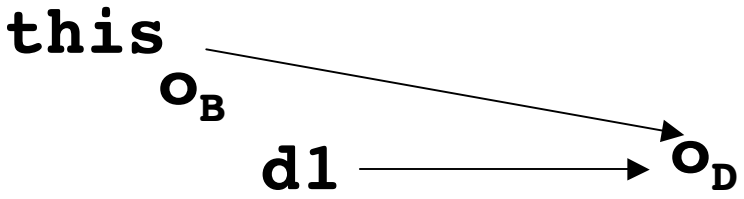


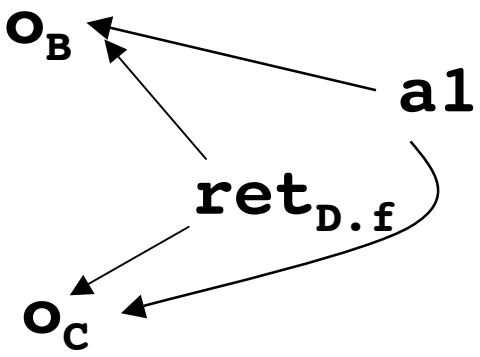
1-CFA more precise than ObjSens

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;}
}
```

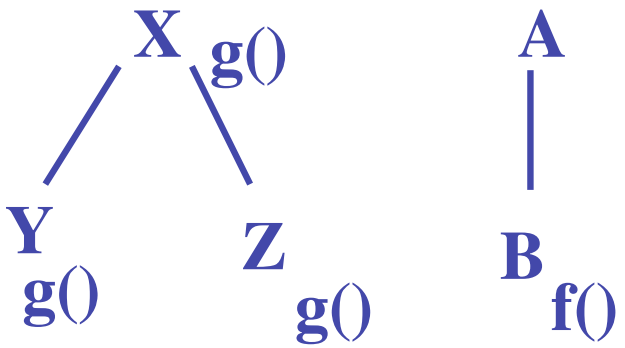
ObjSens groups the two calling contexts of D.f with the same receiver at C1 and C2;
Both B.g(),C.g() are called at C1 and C2;





ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ 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());//O_B1
   C2: B b2 = new B(new Z());//O_B2
```



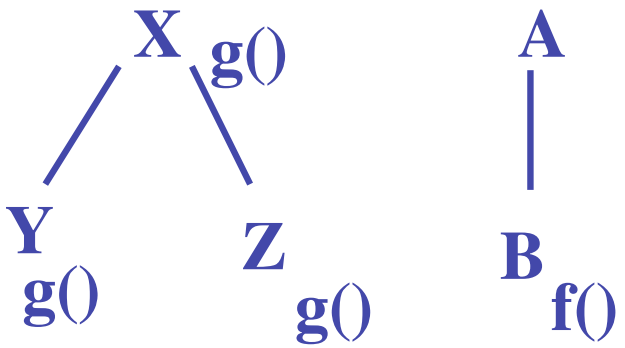
ObjSens

O_{B1} O_Y

O_{B2} O_Z

ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ 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());//O_B1
   C2: B b2 = new B(new Z());//O_B2
```



ObjSens

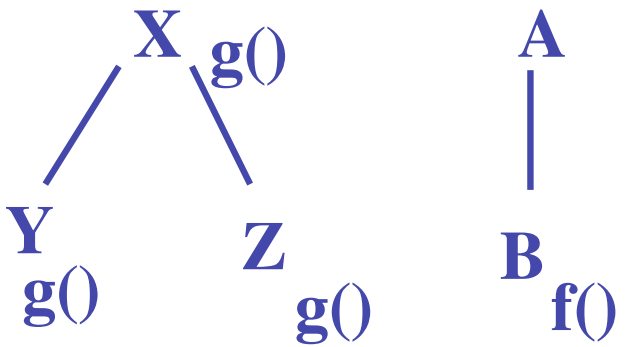
$this_{B1}$

O_{B1} O_Y

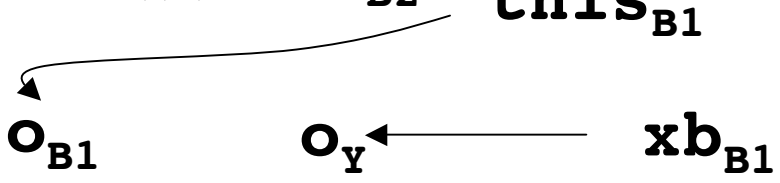
O_{B2} O_Z

ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ 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
```



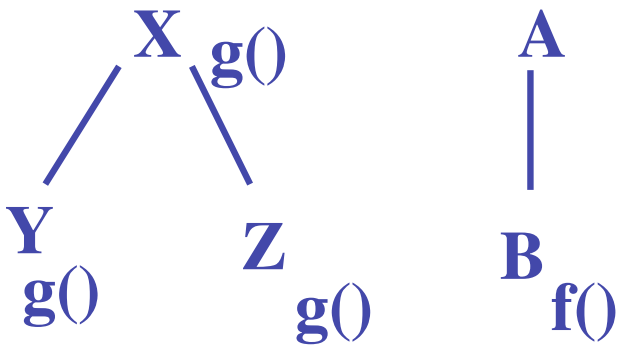
ObjSens



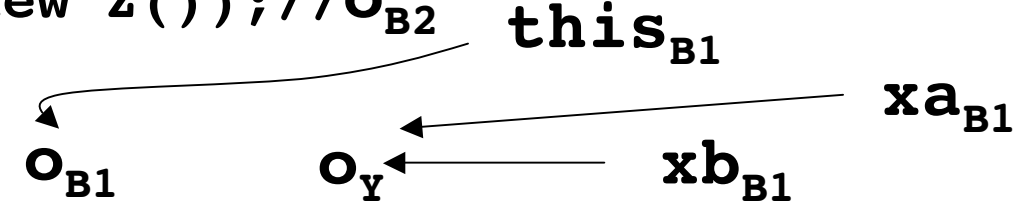
oB2 oZ

ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ 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



o B2 o Z

ObjSens more precise than 1-CFA

```
public class A
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
   static void main(){
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   C1: B b1 = new B(new Y());//oB1
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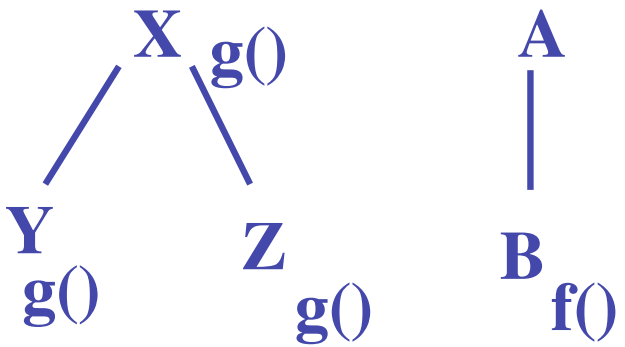
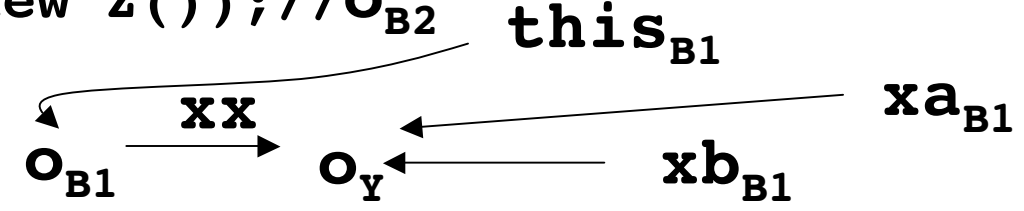


ObjSens



oB2 oZ

ObjSens more precise than 1-CFA

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}
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{ 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
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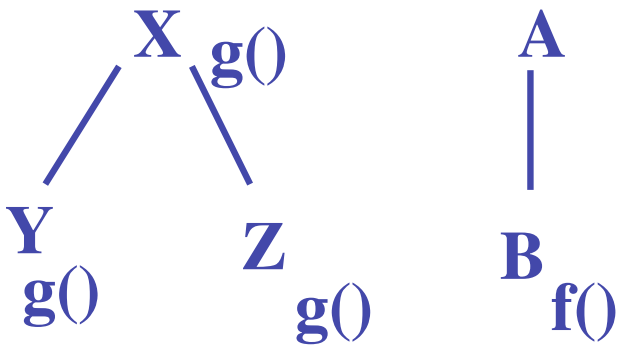
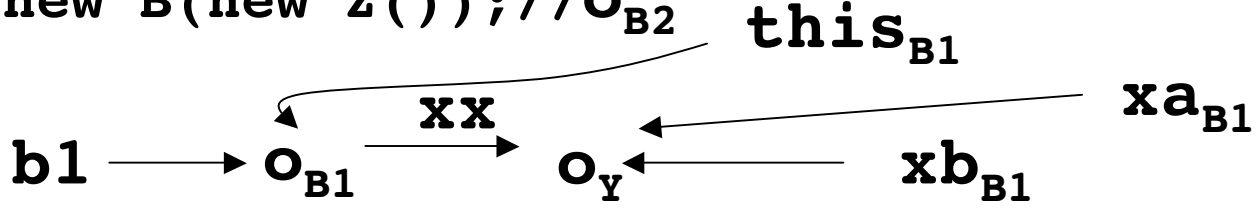
```



ObjSens



oB2 oZ

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   C1: B b1 = new B(new Y());//oB1
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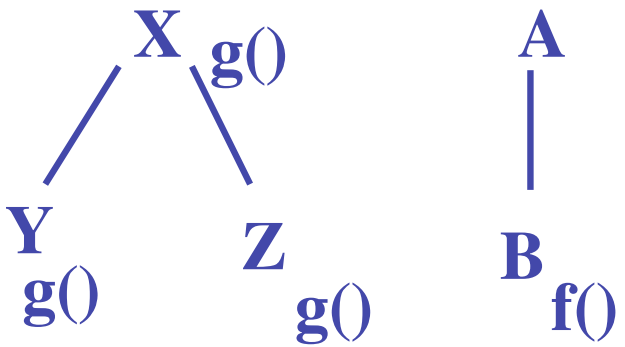
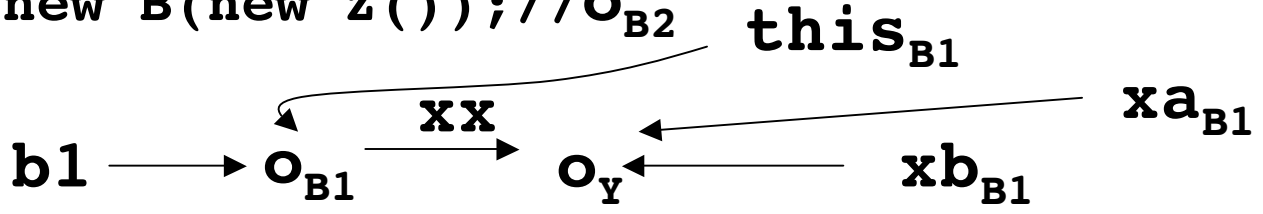
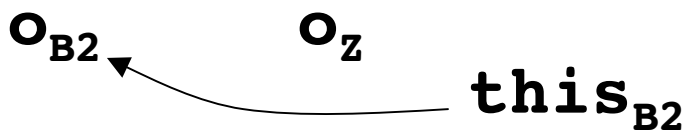
```



ObjSens





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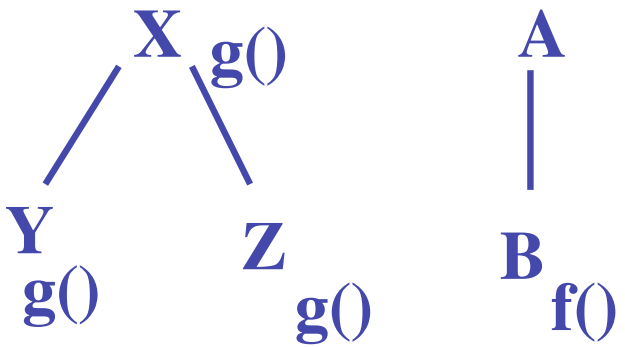
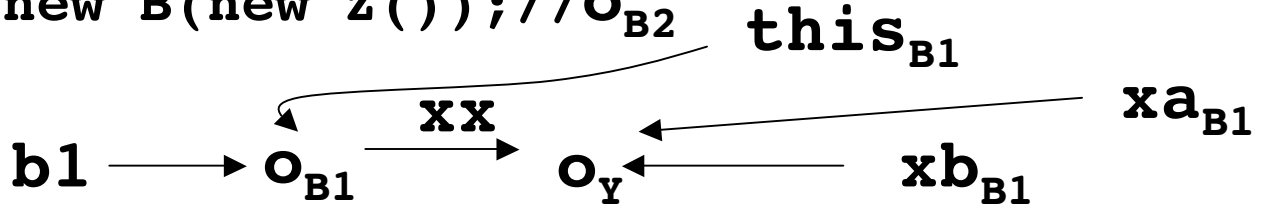
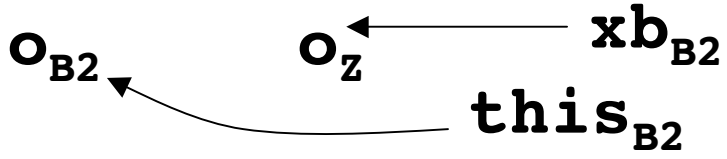


ObjSens





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  A (X xa){ this.xx=xa;}
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{ B (X xb){C3: super(xb);}
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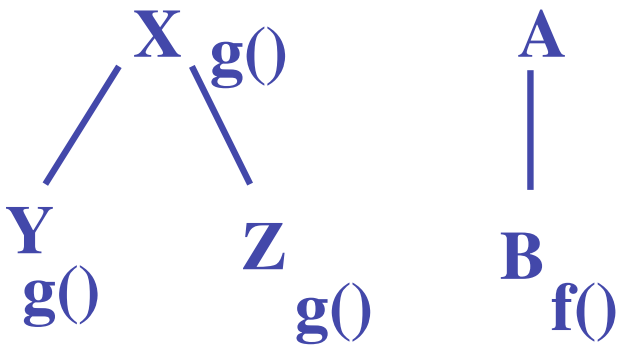
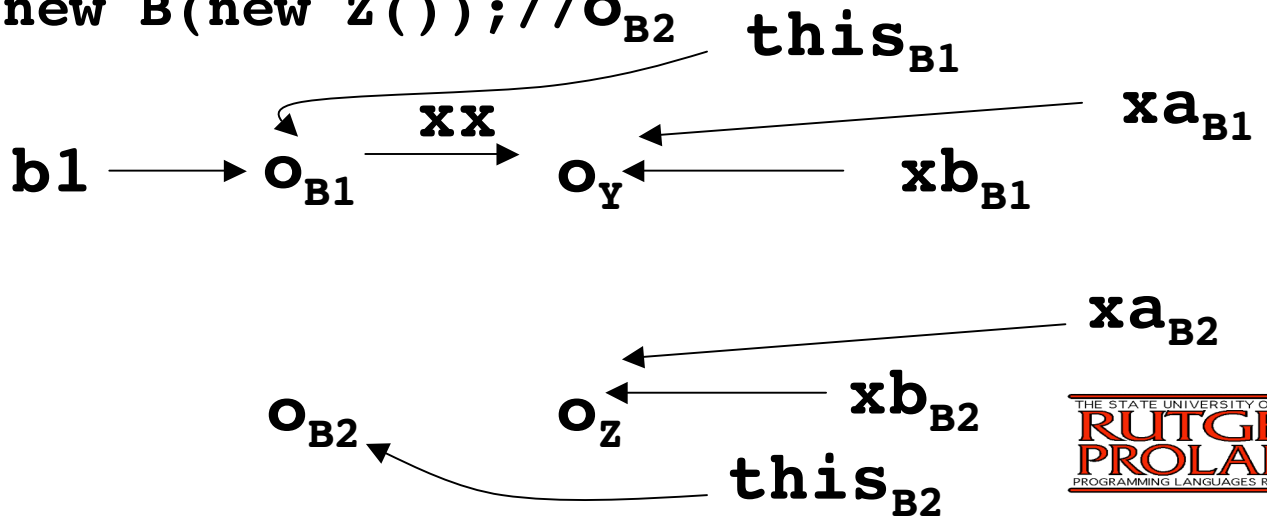
```



ObjSens



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   C1: B b1 = new B(new Y());//oB1
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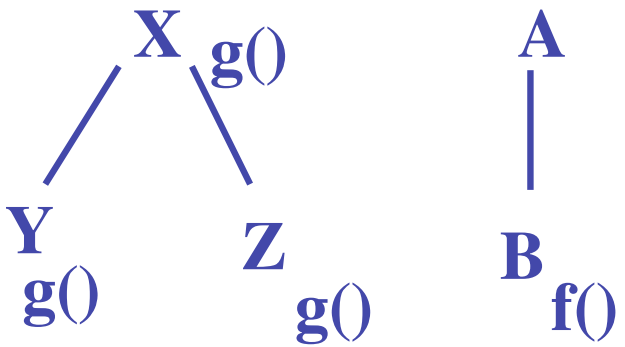
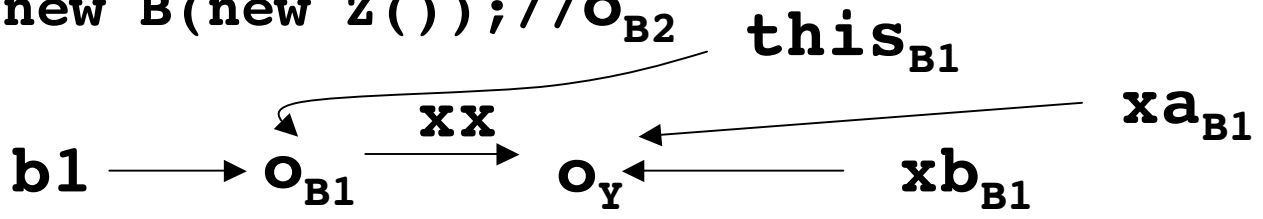
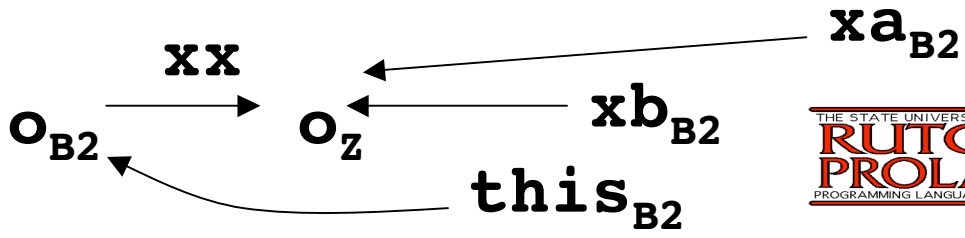


ObjSens





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   static void main(){
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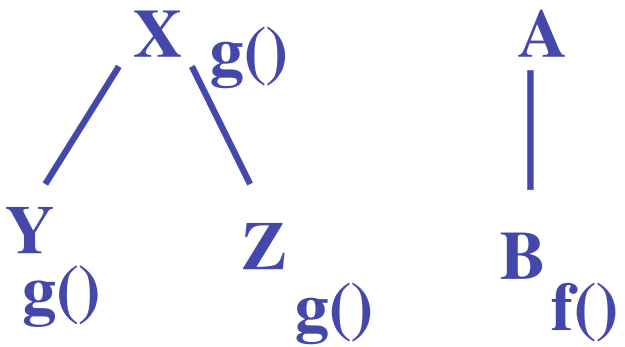
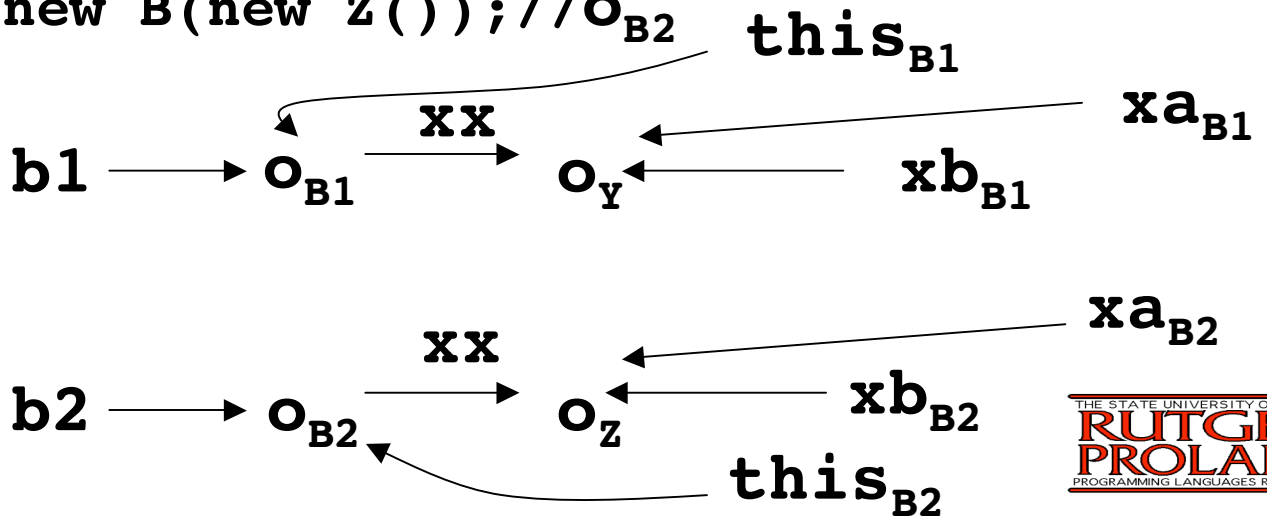
   C1: B b1 = new B(new Y());//oB1
   C2: B b2 = new B(new Z());//oB2
```



ObjSens



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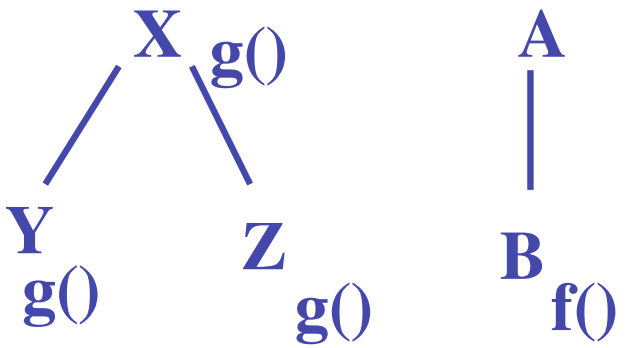
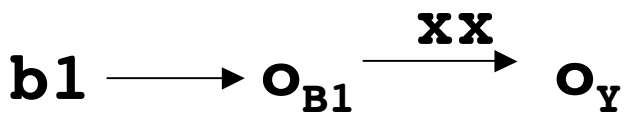
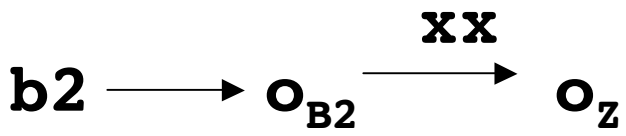
{ X xx;
  A (X xa){ this.xx=xa;}
}
public class B
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```







ObjSens

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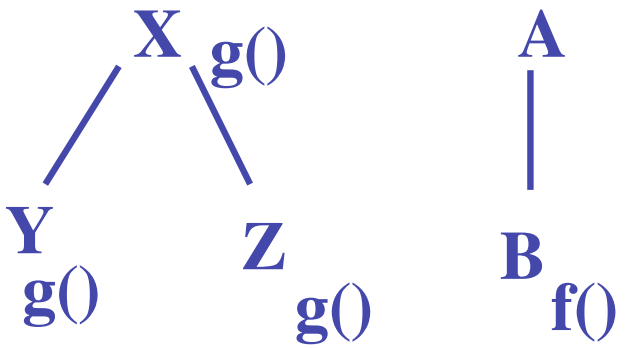
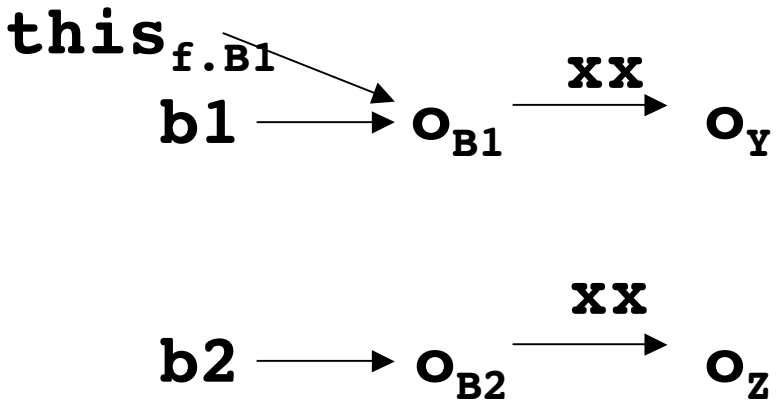
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```





ObjSens

ObjSens more precise than 1-CFA

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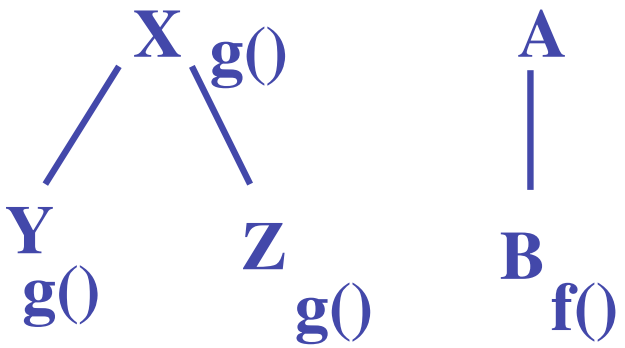
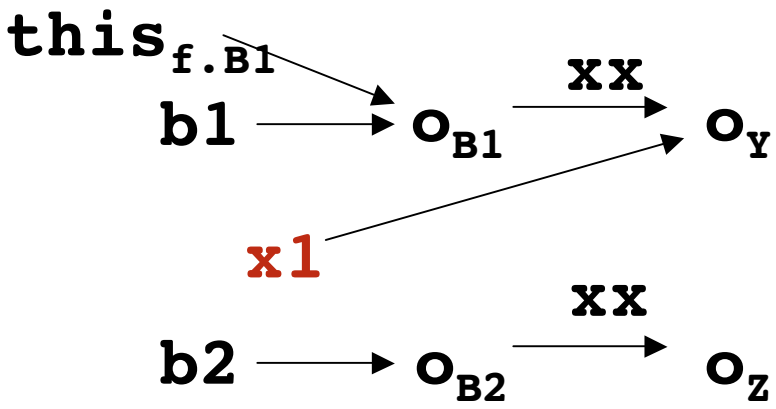
public class B
{ B (X xb){C3: super(xb);}
  public X f() {return this.xx;}
  static void main(){
   X x1,x2;
  C1: B b1 = new B(new Y());//oB1
  C2: B b2 = new B(new Z());//oB2
     x1=b1.f();
C4: x1.g();
     x2=b2.f();
C5: x2.g();
}
```





ObjSens

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  C1: B b1 = new B(new Y());//oB1
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     x1=b1.f();
C4: x1.g();
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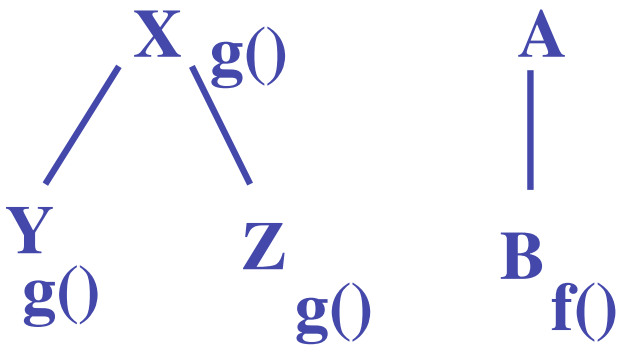
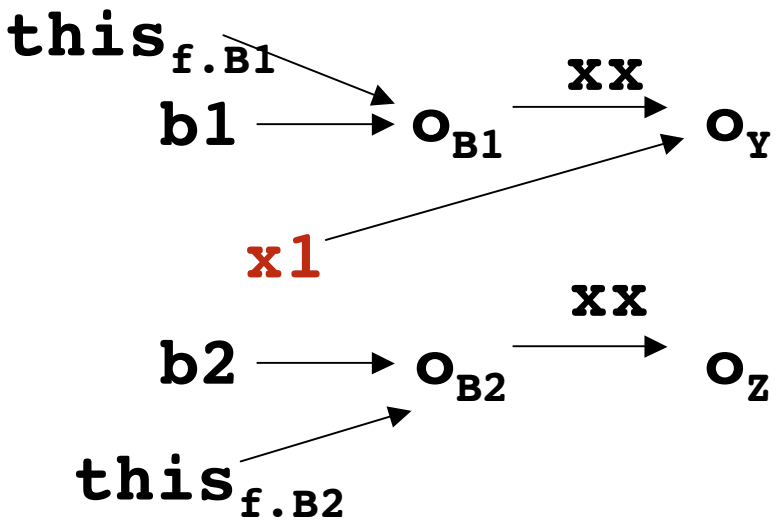
```





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     x1=b1.f();
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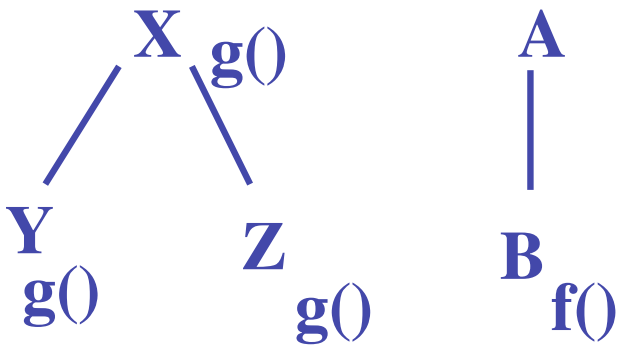
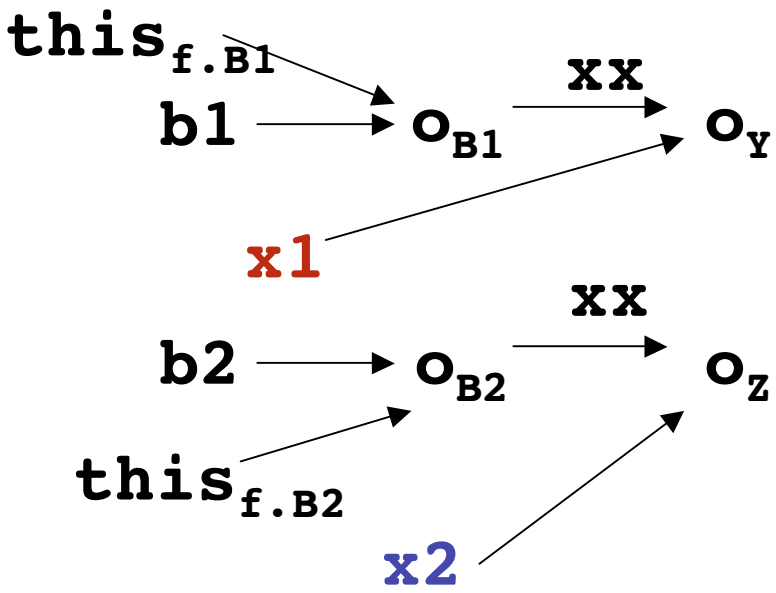
```





ObjSens

ObjSens more precise than 1-CFA

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     x1=b1.f();
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     x2=b2.f();
C5:  x2.g();
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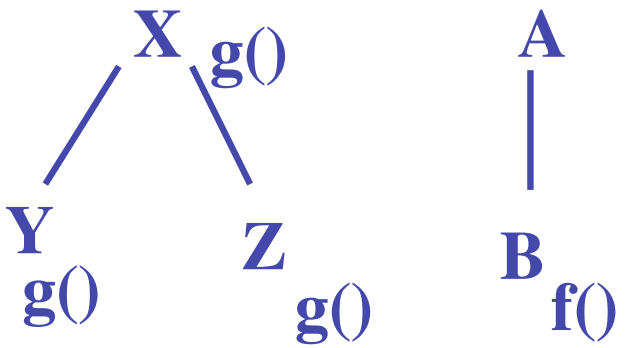

ObjSens finds
C4 calls Y.g() and
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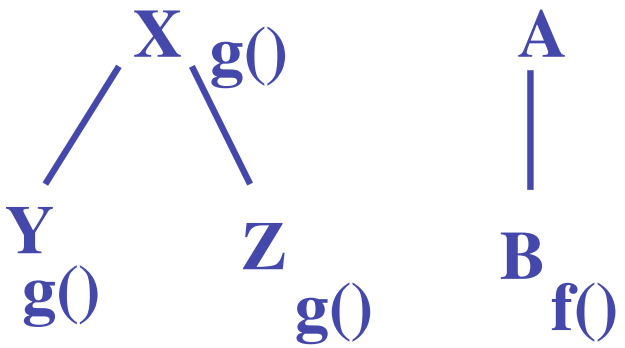

1-CFA

O_{B1} O_Y

O_{B2} O_Z

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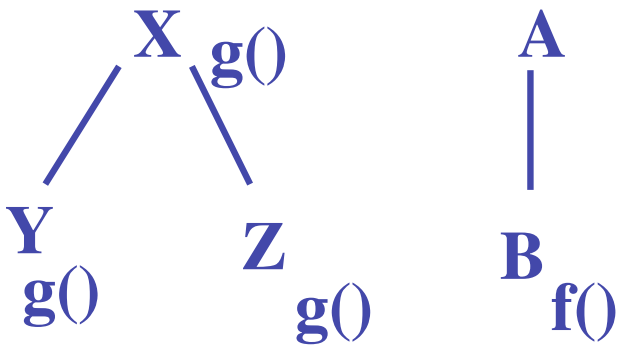

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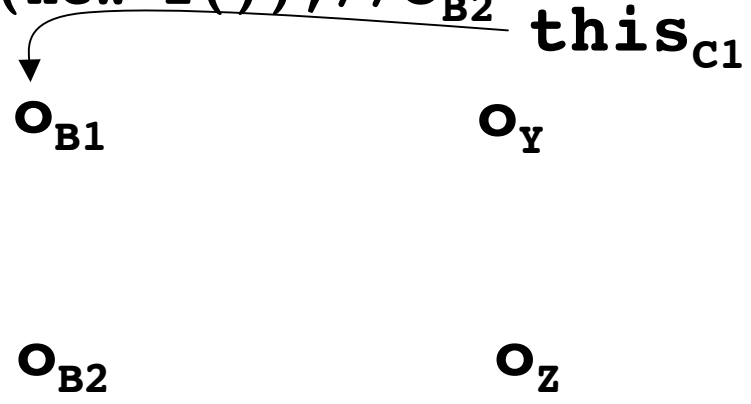

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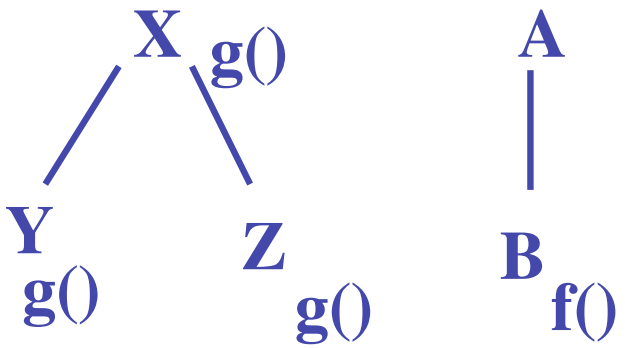

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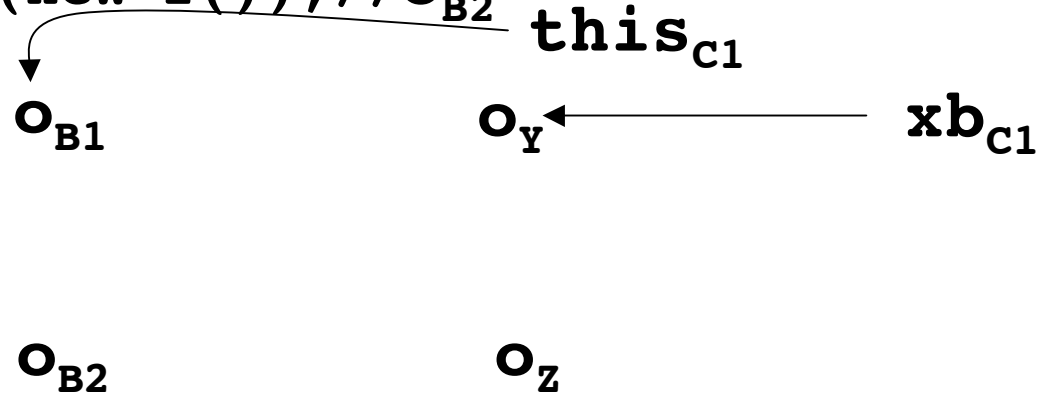

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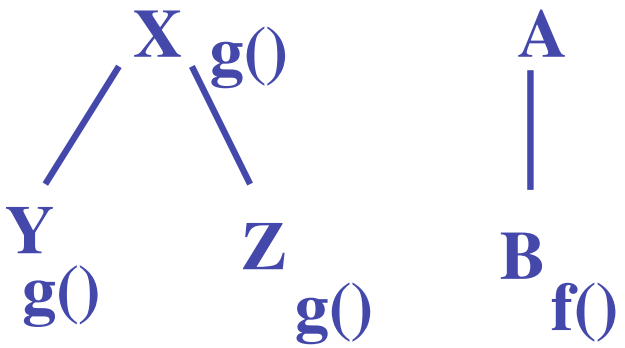

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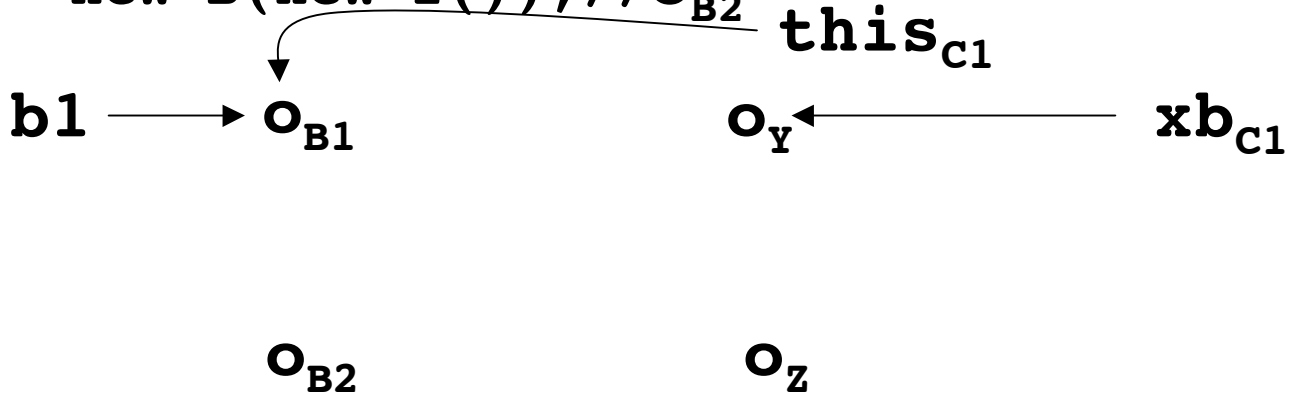

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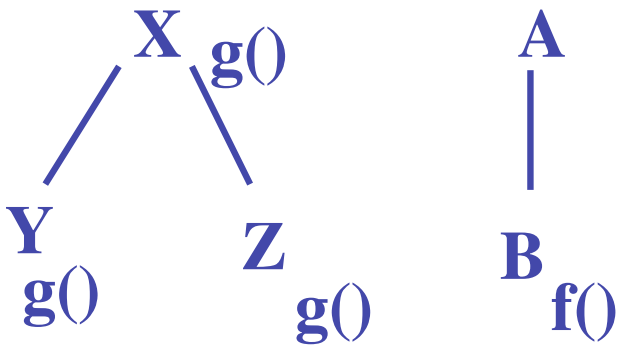

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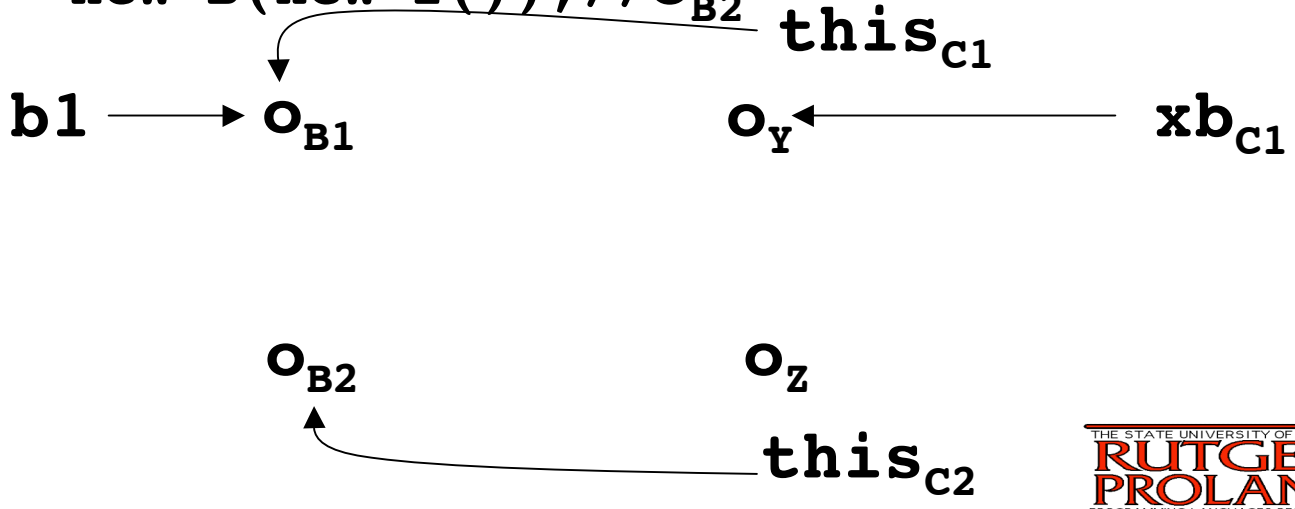

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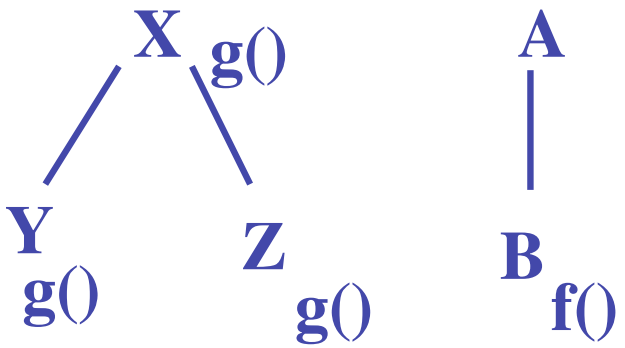

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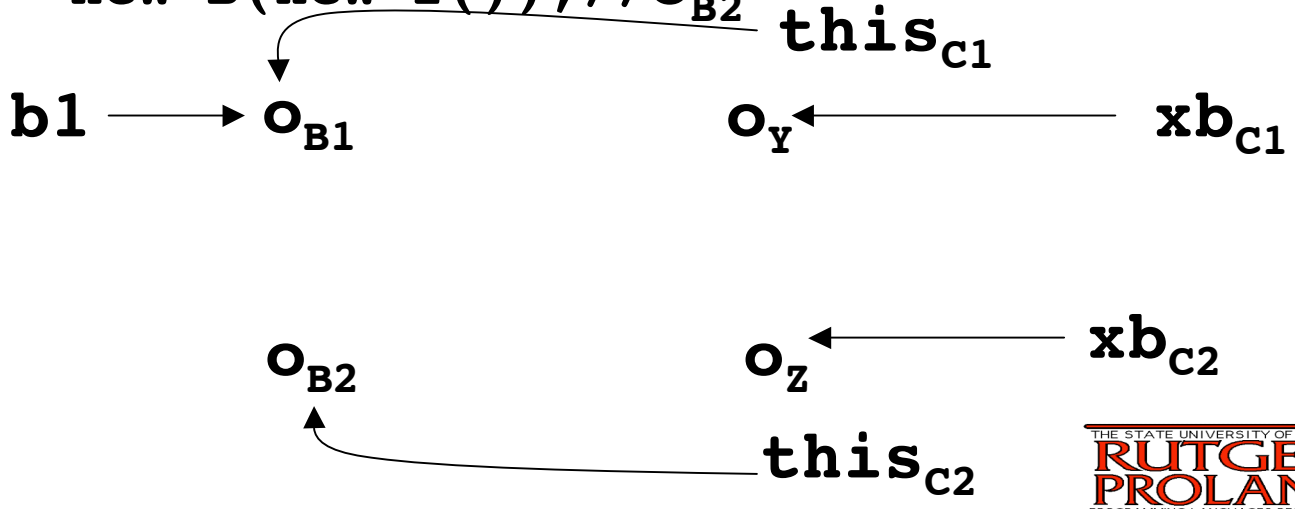

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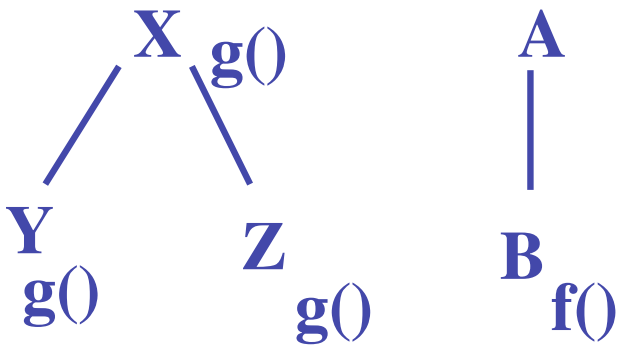

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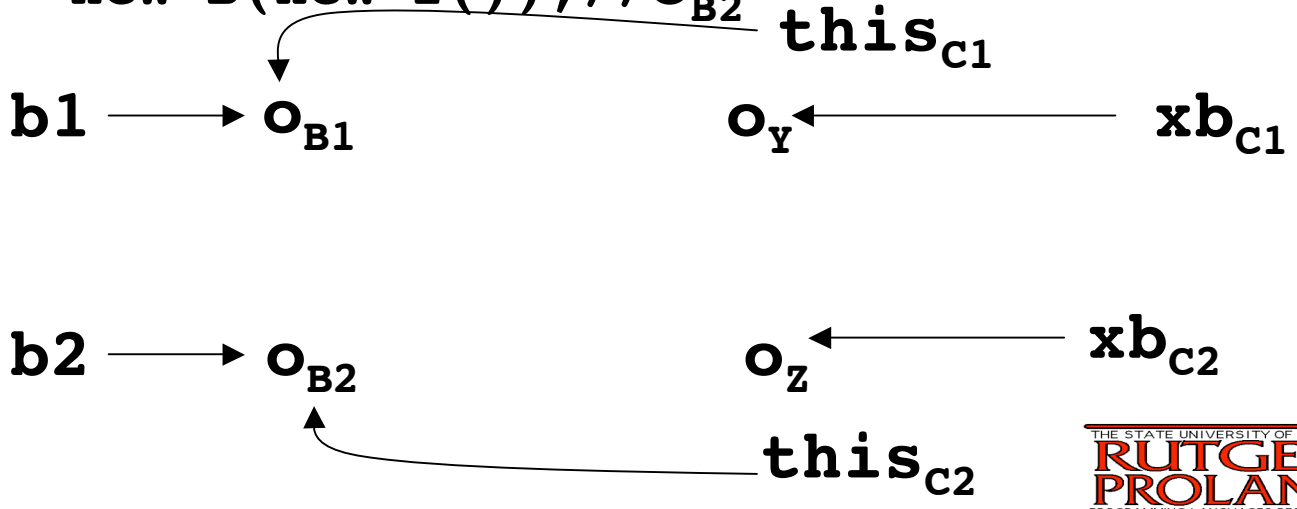

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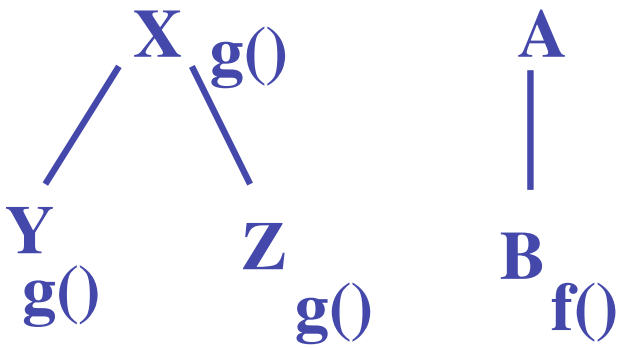

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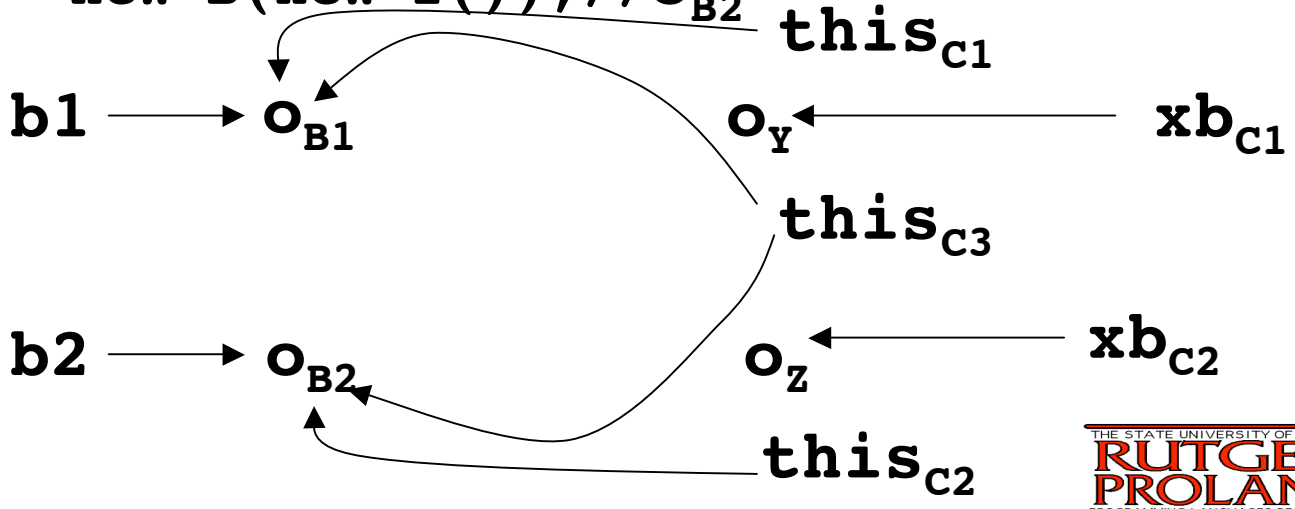

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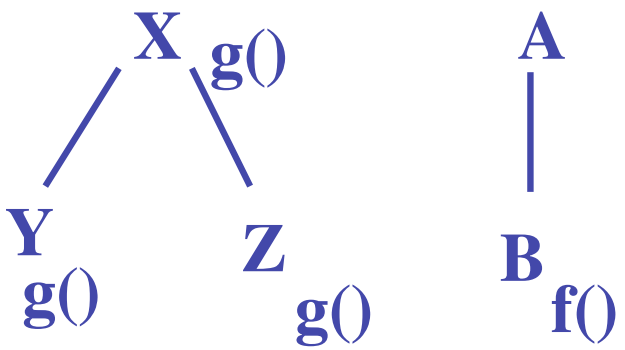

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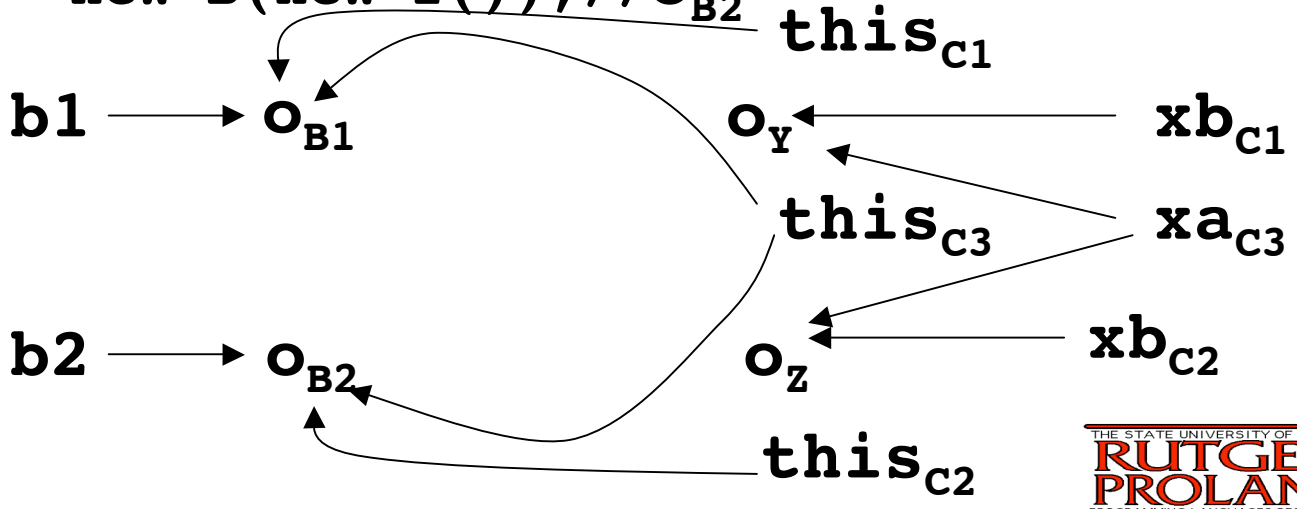

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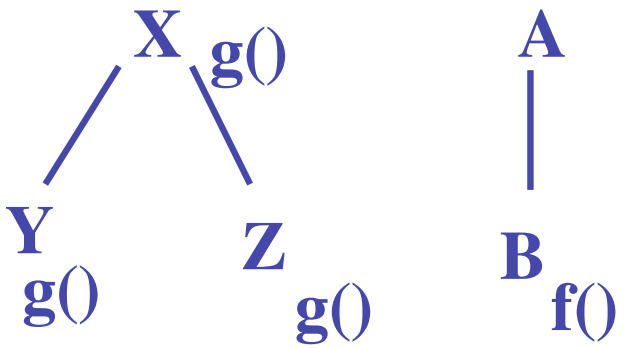

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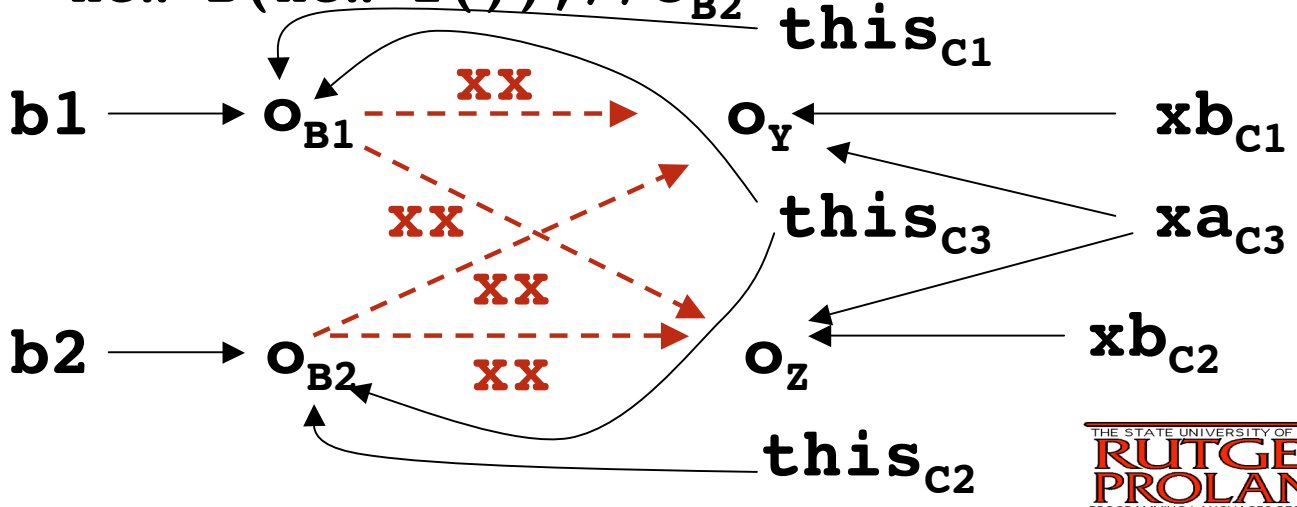

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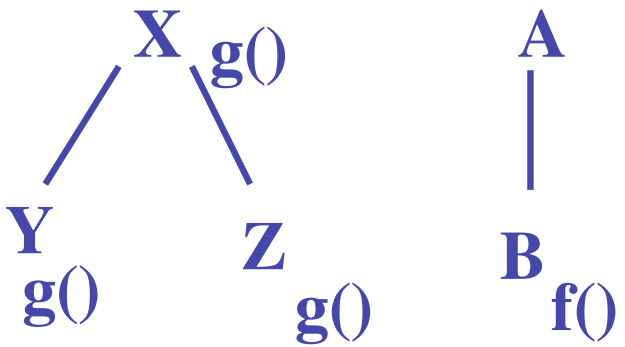

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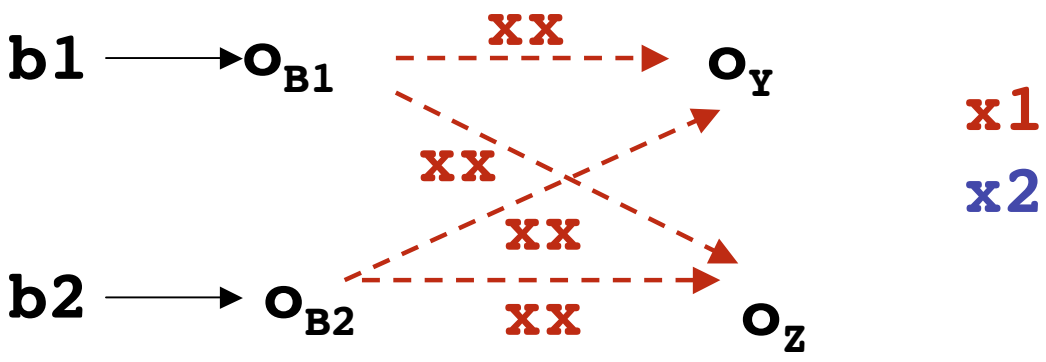

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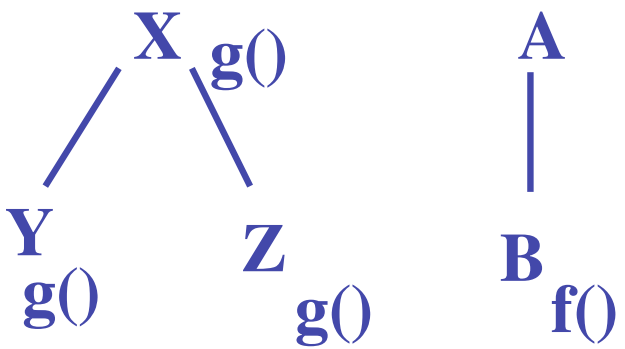

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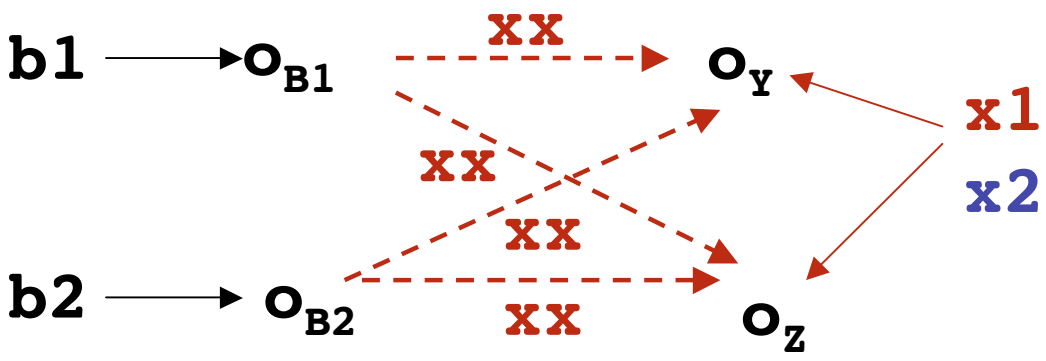

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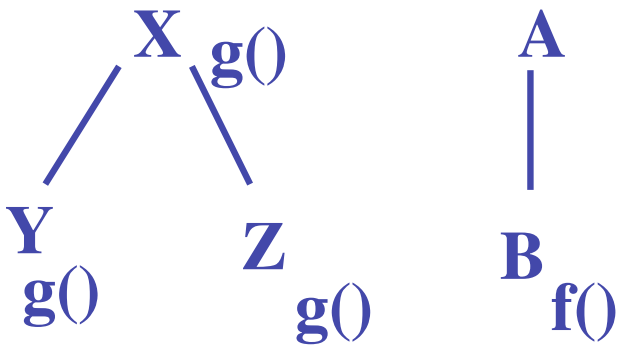

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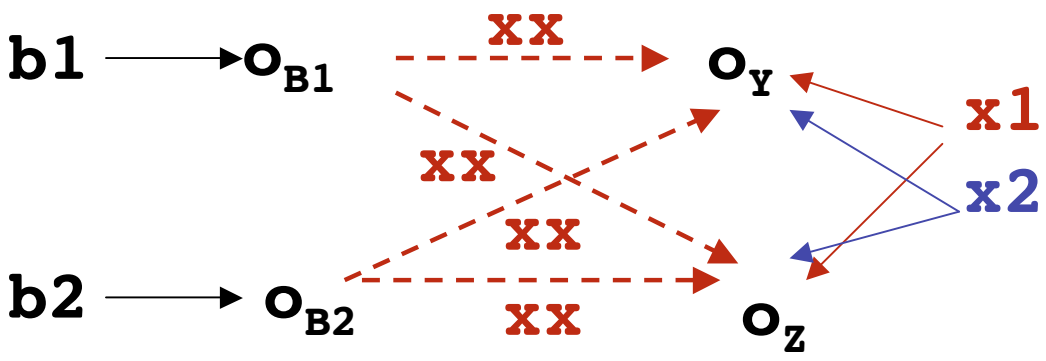

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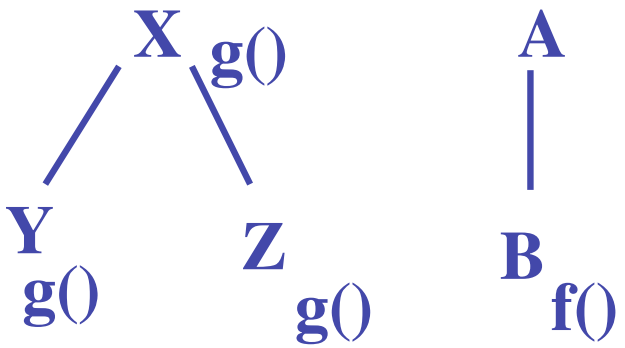

1-CFA finds
C4 calls Y.g(), Z.g() and
C5 calls Y.g(), Z.g()

Comparison Conclusion

- The call string and functional approaches to context sensitivity are incomparable!
- Neither is more powerful than the other

Open Issues

- Reflection
- Java native methods
- Exceptions
- Dynamic class loading
- Incomplete programs
- Benchmarks

Summary

- Challenge in reference analysis of OOPLs is to match the right analysis to a specific client
  - Experimentation with analysis clients is necessary to validate good analysis
- Good analyses for call graph construction exist
- Analyses capable of finding data dependences are being developed now
  - Context sensitivity may give significant precision improvement for acceptable cost

Summary

- Dimensions of precision define the design space of new reference analyses
  - Program, object (w/wo fields) and reference representations
  - Directionality
  - Flow and context sensitivity
- Given the use of method calls as a primitive in OOPLs, context sensitivity should be exploited to add analysis precision

Thank You

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