

A Tour of Pointer Analysis

Ondřej Lhoták



Pointer analysis

[PASTE 2001]

Pointer Analysis: Haven't We Solved This Problem Yet?

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ABSTRACT

During the past twenty-one years, over seventy-five papers and two Ph.D. theses have been published on pointer analysis. Given the tonnes of work on this topic one may wonder, "Haven't we solved this problem yet?" With input from ongoing researches in the field, this paper describes issues related to pointer analysis and remaining open problems.

1. INTRODUCTION

Analysing programs written in languages with pointers requires knowledge of pointer behavior. Without such knowledge, conservative assumptions regarding pointer accesses must be made, which can adversely affect the precision and efficiency of any analysis that requires this information, such as an optimizing compiler or a program understanding tool. A pointer analysis attempts to statically determine the possible runtime values of a pointer. As such an analysis is, in general, undecidable [51, 43, 70, 42], a large collection of approximation algorithms have been published that provide a trade-off between the efficiency of the analysis and the precision of the computed solution. The worst case time complexity of these analyses range from almost linear [34] to doubly exponential [88]. To complicate matters, most of these analyses are often not indicative of typical performance. Given the long history of pointer analysis research, it is appropriate to take stock of the current field and to outline those problems that remain open. This paper, with varied input from many pointer analysis researchers, attempts to review this role, as well as categorizing existing work.

2. BACKGROUND

A pointer when analysed attempts to determine when two pointer expressions refer to the same storage location. A pointer in analysis [27, 42, 2], or similarly, an analysis based on a "compact representation" [18, 4, 38] attempts to determine what storage locations a pointer can point to. This information can then be used to determine the alias in the

program.¹ Alias information is central to determining what memory locations are modified or referenced. There are several dimensions that affect the cost/precision trade-off of intraprocedural pointer analysis. How a pointer analysis addresses each of these dimensions helps to categorize the analysis. An empirical comparison with a different one is more than one dimension can limit the usefulness of the comparison. Some of the dimensions are:

- Flow-sensitivity:** Is control flow information of a procedure used during the analysis? If not considering control flow information, and therefore computing a conservative summary, flow-insensitive analysis can limit the usefulness of the whole program analysis. If not considering control flow information, and therefore computing a conservative summary, flow-insensitive analysis can limit the usefulness of the whole program analysis. If not considering control flow information, and therefore computing a conservative summary, flow-insensitive analysis can limit the usefulness of the whole program analysis.
- Context-sensitivity:** Is calling context considered when analysing a function or can values flow from one call through the function and return to another call?
- Heap modelling:** Are objects named by allocation *etc.*, or is a more sophisticated shape analysis performed?
- Aggregate modelling:** Are elements of aggregate distinguished or collapsed into one object?
- Whole program:** Does an analysis require the whole program or can a sound solution be obtained by analysing only components of a program?
- Alias representation:** Is an explicit alias representation [51, 64] or a pointer-to-compact representation used?

3. GENERAL ISSUES

Before discussing open problems, we first address some more general issues that plague the field of pointer analysis.

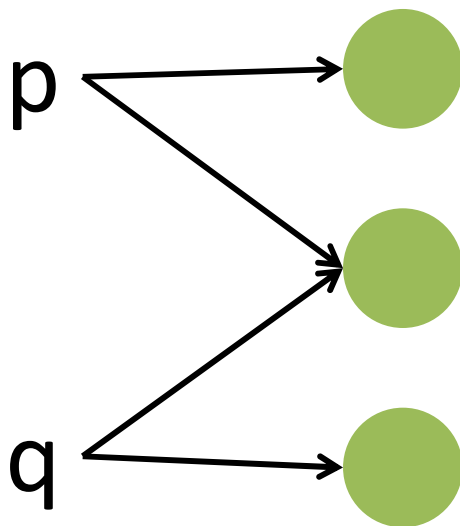
3.1 Terminology

The pointer analysis community has sometimes done a disservice to its audience by using different terminology to refer to the same concepts. For example, context-sensitive/flow-sensitive analysis are also known as polymorphic/abstract analysis. Disjunction-based flow-insensitive analysis are also known as Shoenberg-style analysis and similarly, inclusion-based flow-insensitive analysis are also known as Andersen-style analysis. The point at which such information is referred can affect the precision and efficiency of the analysis [61, 6, 38, 86].

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What does pointer analysis do?

For each pointer (reference) in the program, what memory locations (objects) does it point to?



Why pointer analysis?

a = 1

b = 2

c = ~~a + b~~ 3

Why pointer analysis?

a = 1

b = 2

*x = 4

c = a + b ?

Why pointer analysis?

a = 1

b = 2

*x = 4

c = a + b ?

If $x == \&a$, then $c = 6$.

If $x == \&b$, then $c = 5$.

If $x \neq \&a \ \&\& \ x \neq \&b$, then $c = 3$.

Why pointer analysis?

```
a = 1
```

```
b = 2
```

```
foo()
```

```
c = a + b
```

```
void foo() { ... }
```



Why pointer analysis?

```
a = 1
```

```
b = 2
```

```
x.foo()
```

```
c = a + b
```

```
class X {
```

```
  void foo() { ... }
```

```
}
```

```
class Y extends X {
```

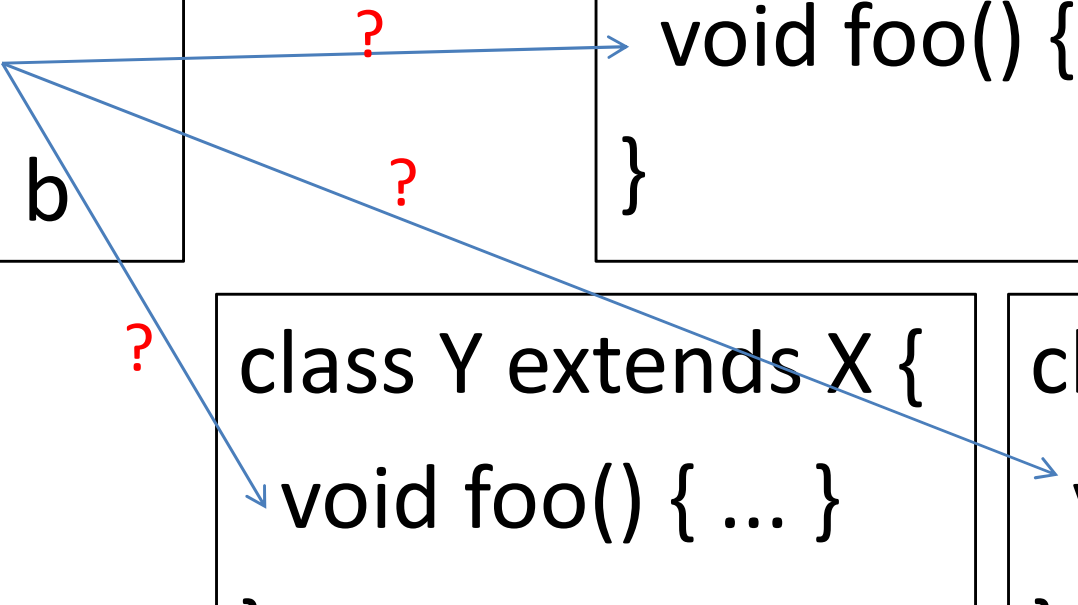
```
  void foo() { ... }
```

```
}
```

```
class Z extends X {
```

```
  void foo() { ... }
```

```
}
```

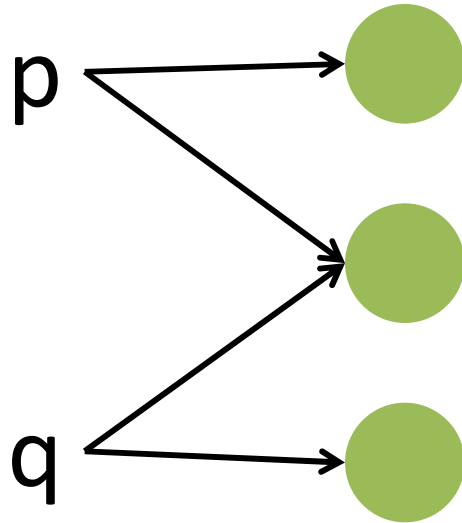


Applications of pointer analysis

- Call graph construction
- Dependence analysis and optimization
- Cast check elimination
- Side effect analysis
- Escape analysis
- Slicing
- Parallelization
- ...

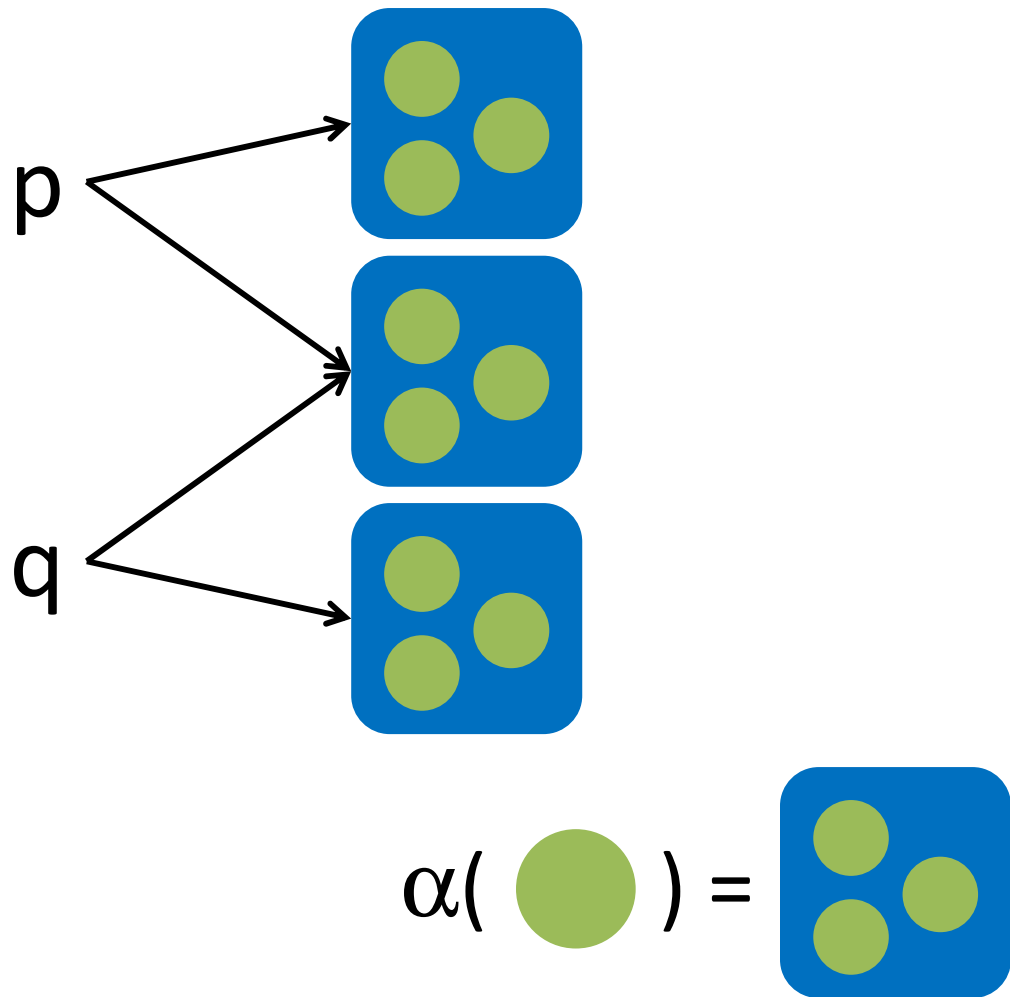
Pointer analysis as an abstraction

For each pointer (reference) in the program, what memory locations (objects) does it point to?



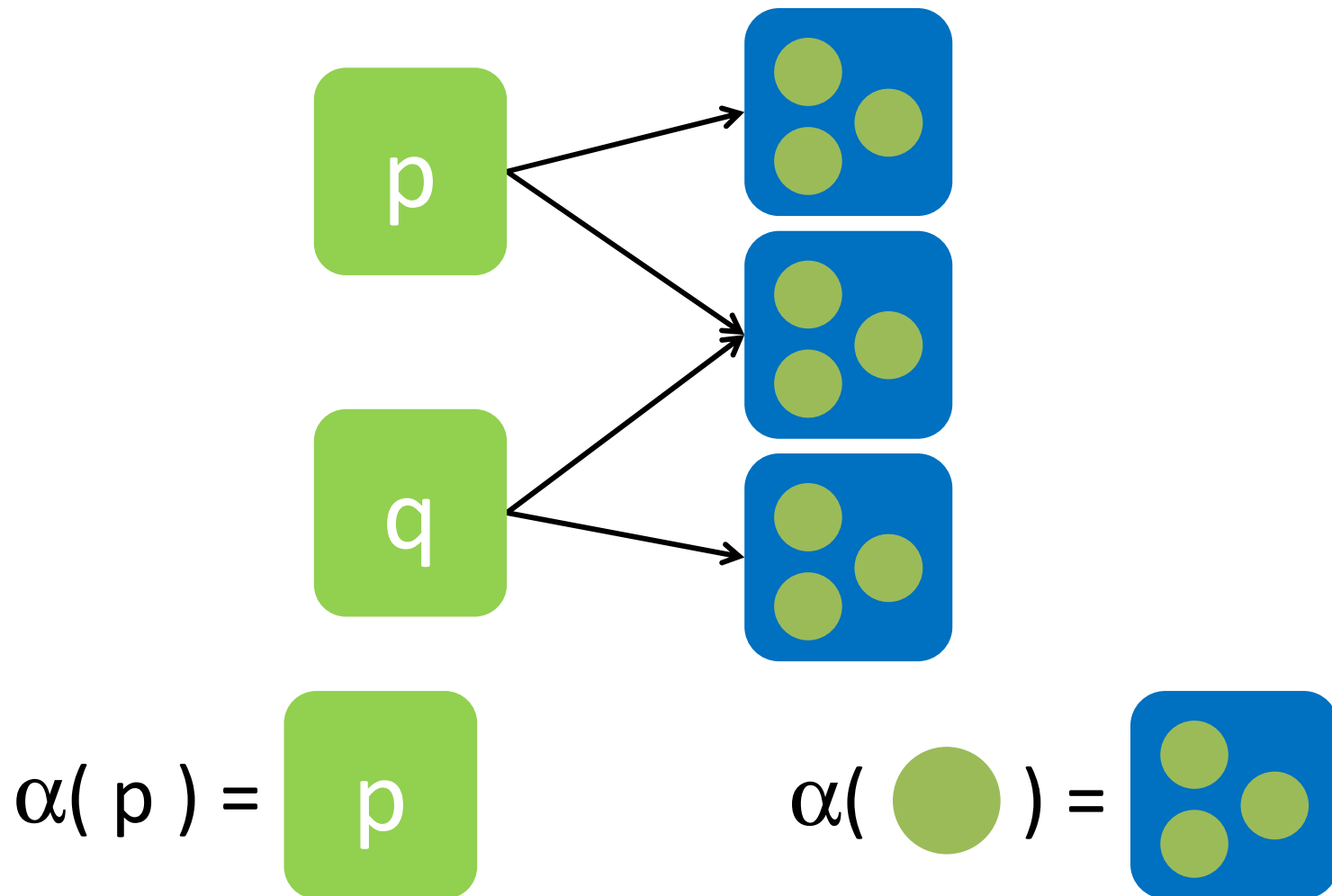
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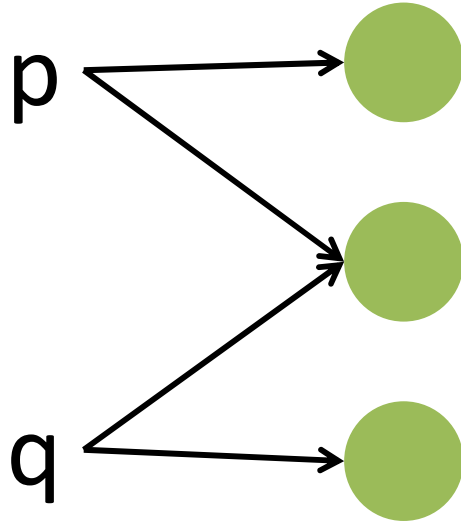
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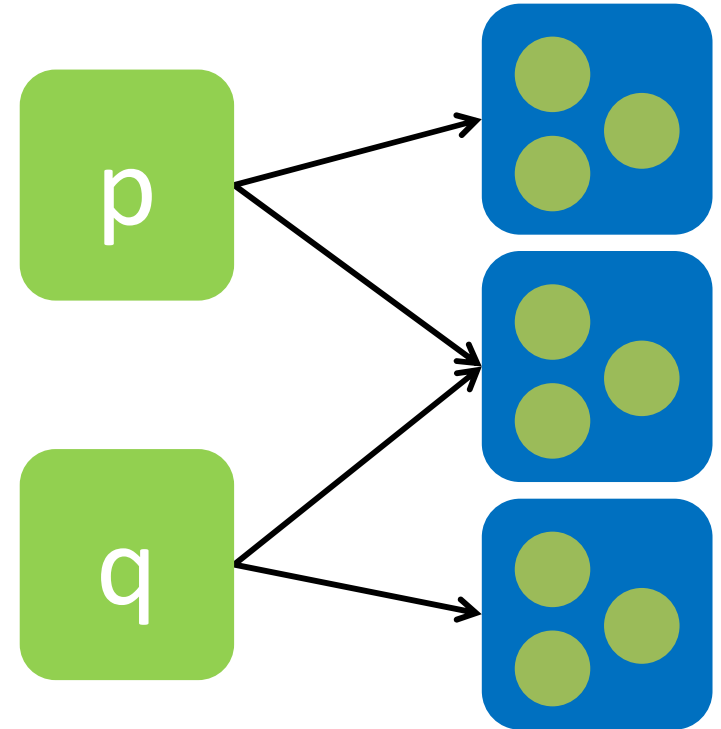


Pointer analysis as an abstraction

Concrete program execution



Abstract analysis



$$\alpha(p) = \text{[green rounded square with 'p']}$$

$$\alpha(\text{green circle}) = \text{[blue rounded square with 3 green circles]}$$

Precision of points-to sets

← more precise

less precise →

unsound

uncomputable

conservative

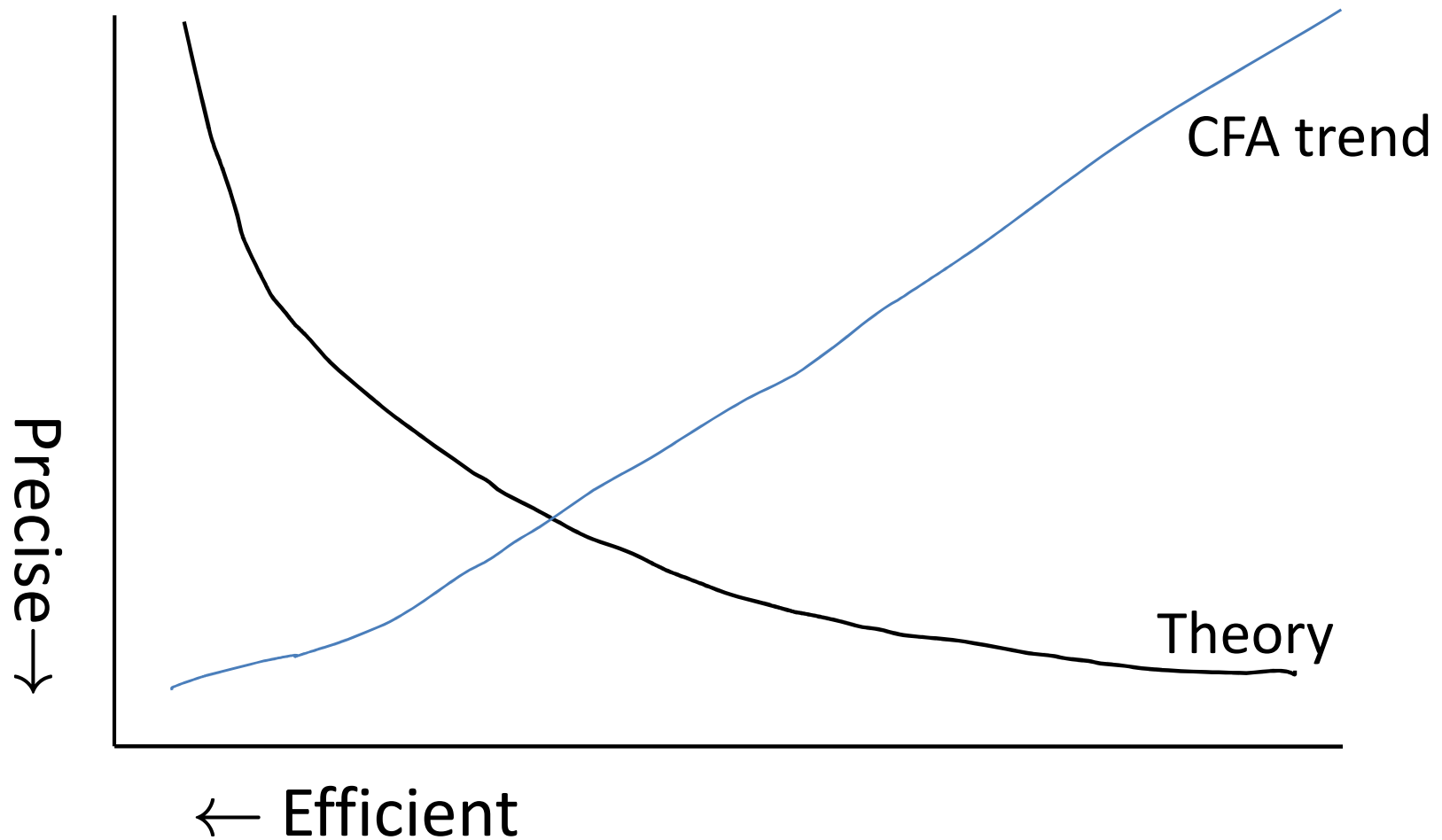
$\{\text{L1}\} \subset \{\text{L1}, \text{L2}\} \subset \{\text{L1}, \text{L2}, \text{L3}\} \subset \{\text{L1}, \text{L2}, \text{L3}, \text{L4}\}$

actual
behaviour
on **some**
executions

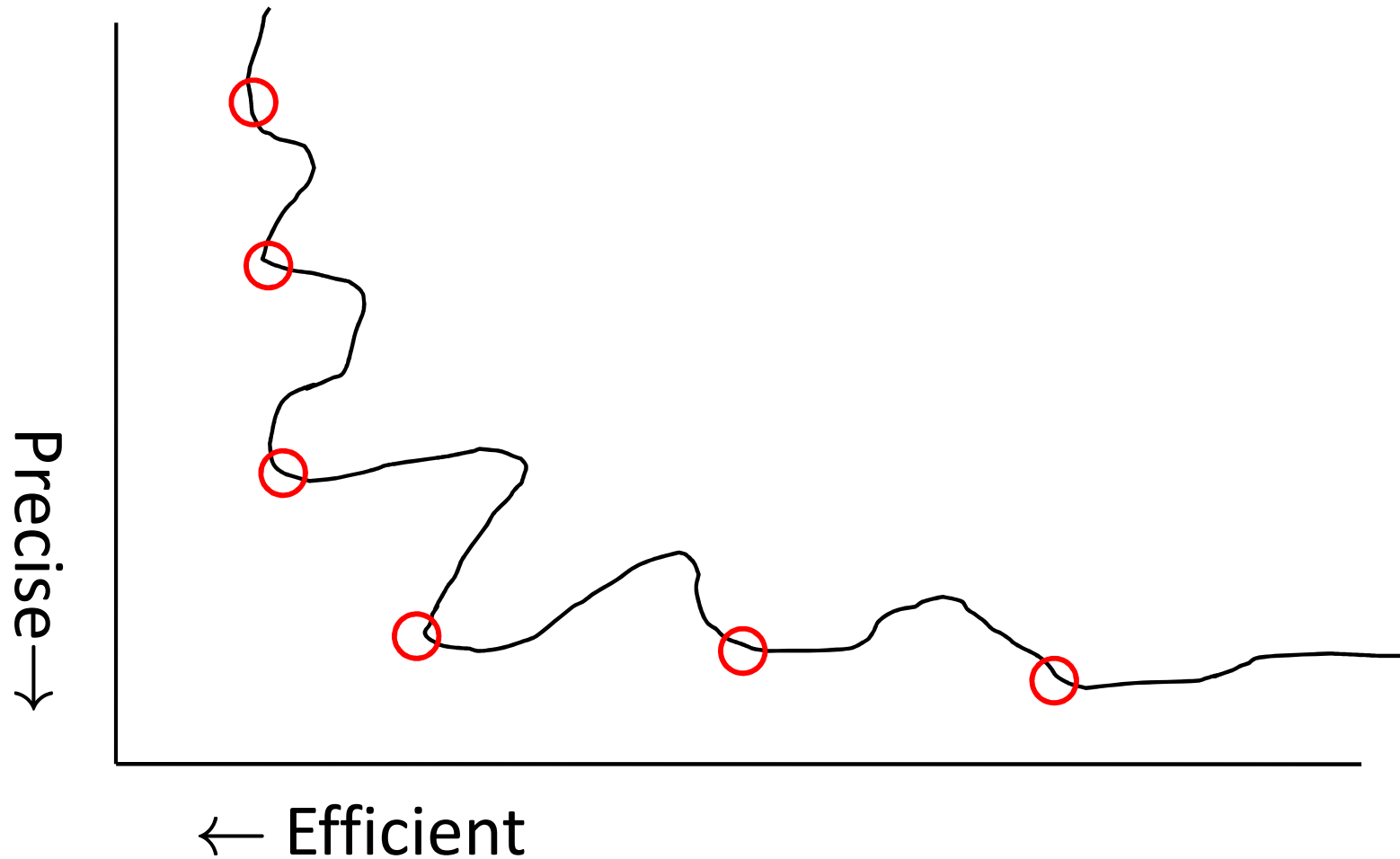
actual
behaviour
on **all**
executions

possible analysis results

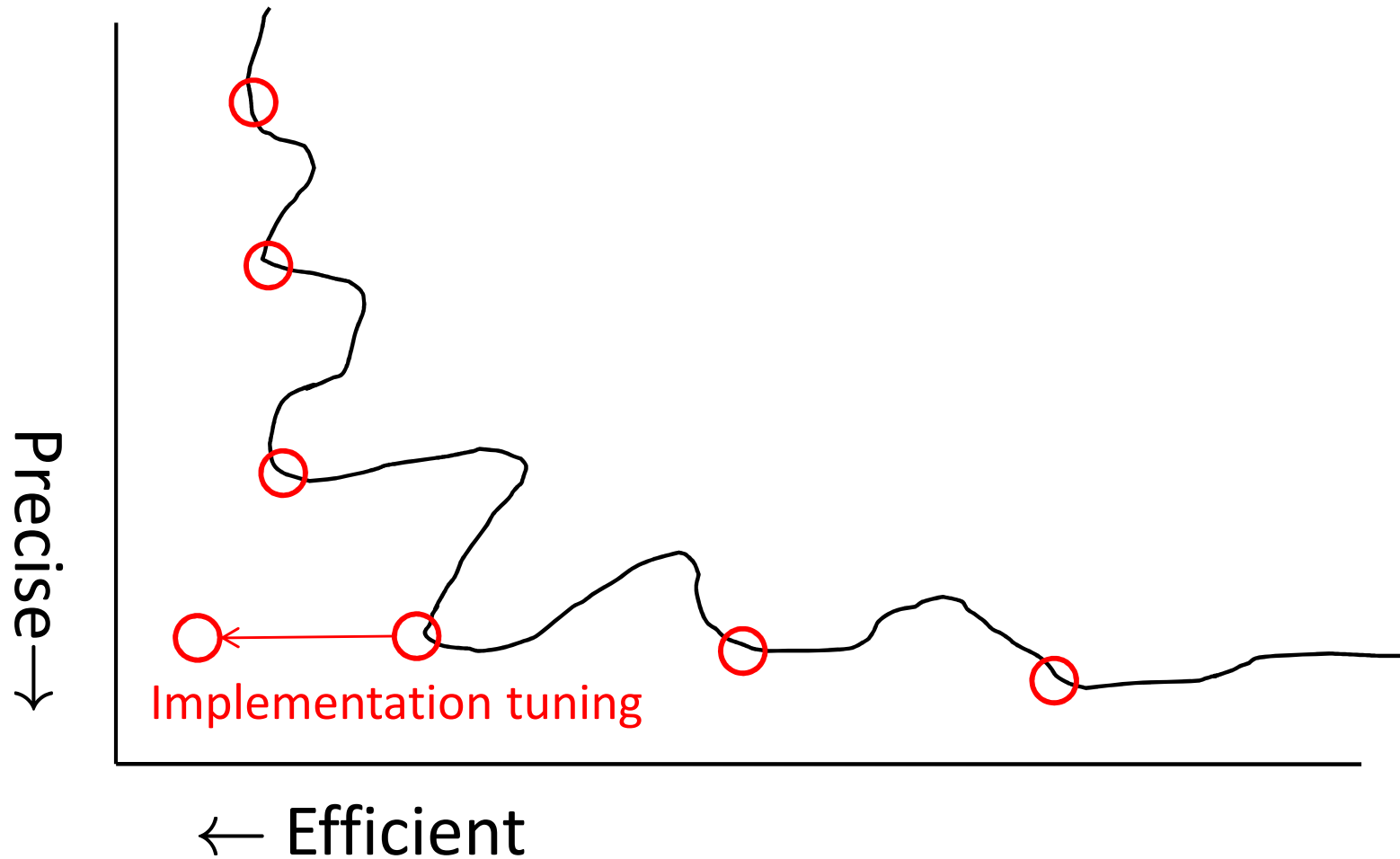
Precision vs. efficiency



Precision vs. efficiency



Precision vs. efficiency



Precision for a specific application

$$\{\text{L1}, \text{L2}\} \subset \{\text{L1}, \text{L2}, \text{L3}, \text{L4}\}$$


This points-to set is more precise because it is smaller.

But suppose a particular application only cares whether **L1** is in the set. Then for that application, both sets are equally precise.

Thus, precision/efficiency tradeoff must consider the application.

Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

An example abstraction and analysis

- The abstraction:

- Type filtering
- Field sensitivity
- Directionality
- Call graph construction
- Context sensitivity
- Flow sensitivity

First example:

- without type filtering
- field-sensitive
- subset-based
- ahead-of-time call graph
- context-insensitive
- flow-insensitive

Pointer Assignment Graph abstraction

Abstract object node:



Java:

L1: `x = new Object()`

C:

L1: `x = malloc(42)`

Represents some set of run-time objects (targets of pointers).
e.g. all objects allocated at a given allocation site
e.g. all objects of a given dynamic type

Pointer Assignment Graph abstraction

Address-of abstract object node:

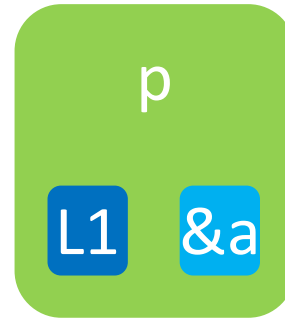


```
C:  
x = &a
```

Represents some set of run-time objects (targets of pointers).
e.g. the object whose address is `&a`.

Pointer Assignment Graph abstraction

Pointer variable node:



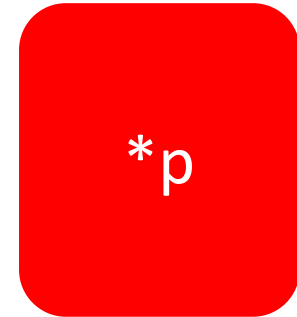
$pt(p) = \{L1, \&a\}$

Points-to set
↑

Represents some pointer-typed variable(s).
e.g. all instances of the local variable *p* in method *m*.

Pointer Assignment Graph abstraction

Pointer dereference node:



Java:
`y = p.f`

C:
`y = *p`

Represents a dereference of some pointer
(where the pointer is a pointer variable node).

Pointer Assignment Graph abstraction

Heap pointer node:



$\text{pt}(\text{L1.f}) = \{\text{L2}, \text{L3}\}$



Represents a pointer stored in some object in the heap.

State space (the analysis result)

$$\text{pt}(\text{p}) = \{ \text{L1}, \text{L2}, \&\text{q} \}$$

$$\text{pt}(\text{L1.f}) = \{ \text{L1}, \text{L2}, \&\text{q} \}$$

$$\text{pt} : (\text{Var} \cup (\text{Obj} \times \text{Field})) \rightarrow \wp(\text{Obj})$$

$$\text{pt} : (\text{Var} \times \text{Obj}) \cup (\text{Obj} \times \text{Field} \times \text{Obj})$$

where $\text{Obj} = \text{Alloc} \cup \text{AddrOf}$

State space (the analysis result)

pt() = {, , }

pt() = {, , }

Pointer Assignment Graph edges

allocation L1: x = new Object()



$$\frac{L1 \rightarrow x}{\{L1\} \subseteq pt(x)}$$

assignment

x = y



$$\frac{y \rightarrow x}{pt(y) \subseteq pt(x)}$$

store

y.f = x



$$\frac{x \rightarrow y.f \quad o \in pt(y)}{pt(x) \subseteq pt(o.f)}$$

load

x = y.f



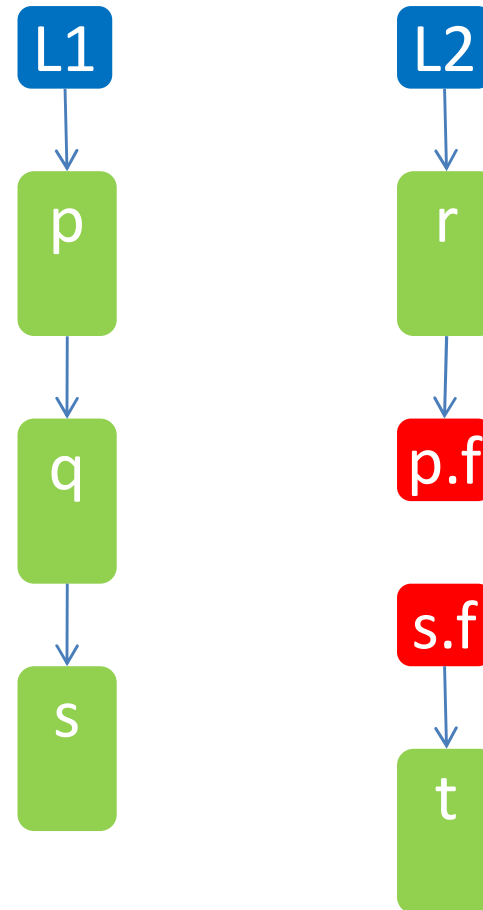
$$\frac{y.f \rightarrow x \quad o \in pt(y)}{pt(o.f) \subseteq pt(x)}$$

Example

```
static void foo() {  
L1:  p = new O();  
      q = p;  
L2:  r = new O();  
      p.f = r;  
      t = bar( q );  
}  
  
static O bar( O s ) {  
      return s.f;  
}
```

Example

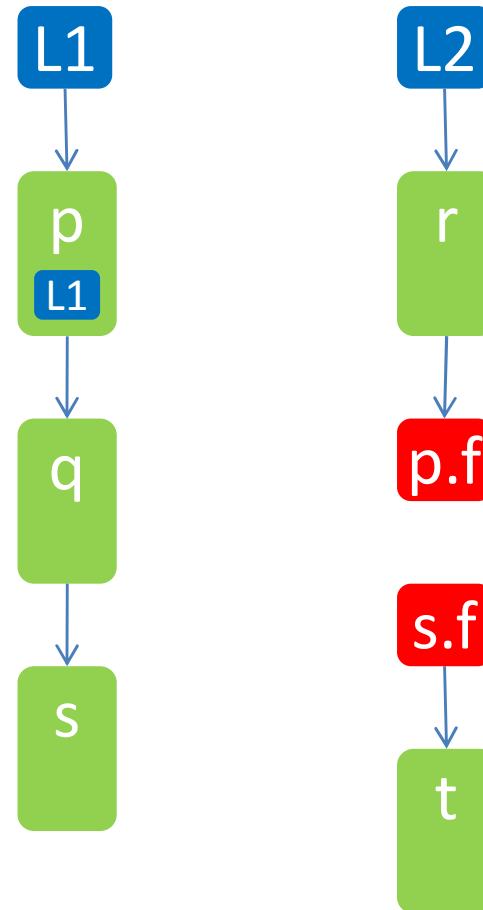
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}  
  
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}
```



Generate points-to assignment graph.

Example

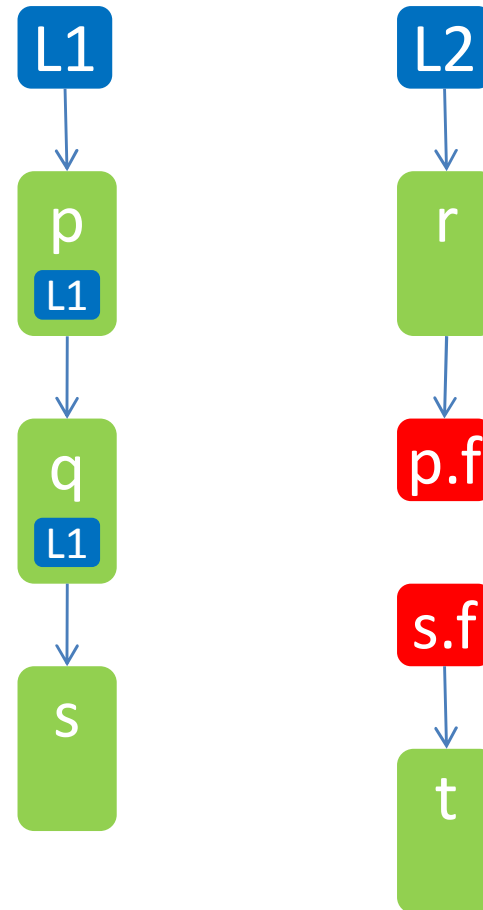
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}
```



Propagate points-to sets.

Example

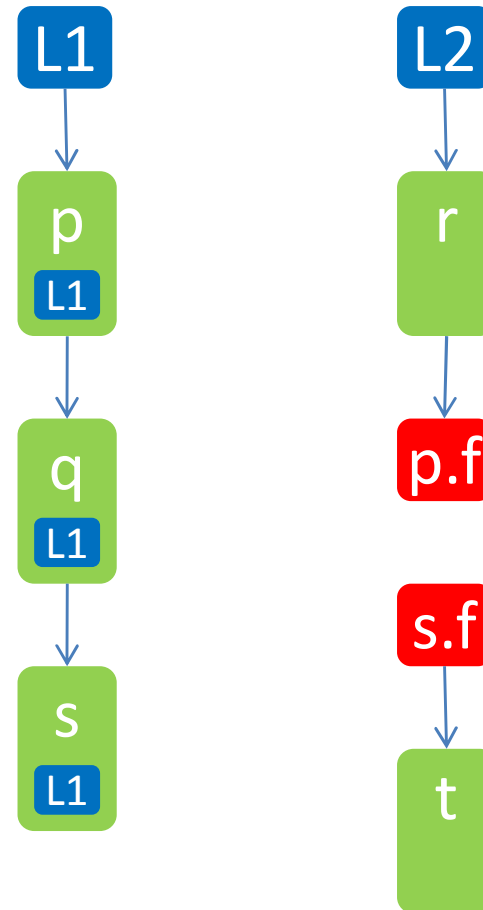
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Propagate points-to sets.

Example

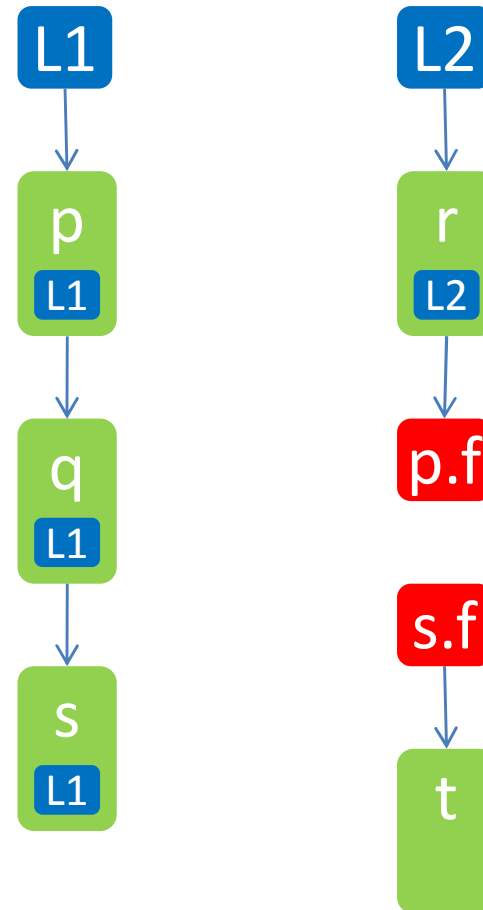
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```



Propagate points-to sets.

Example

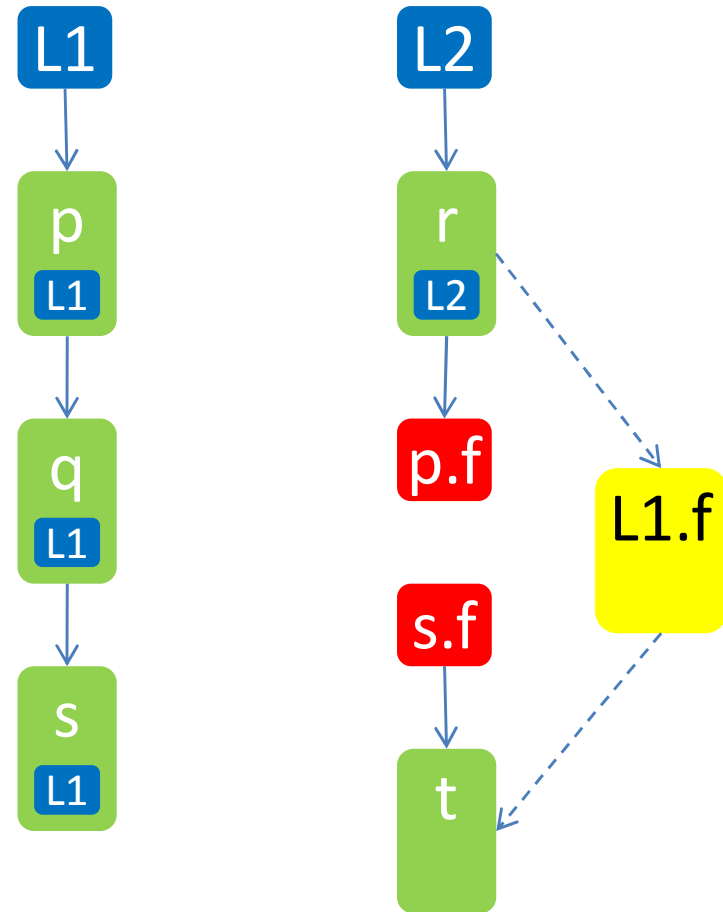
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```



Propagate points-to sets.

Example

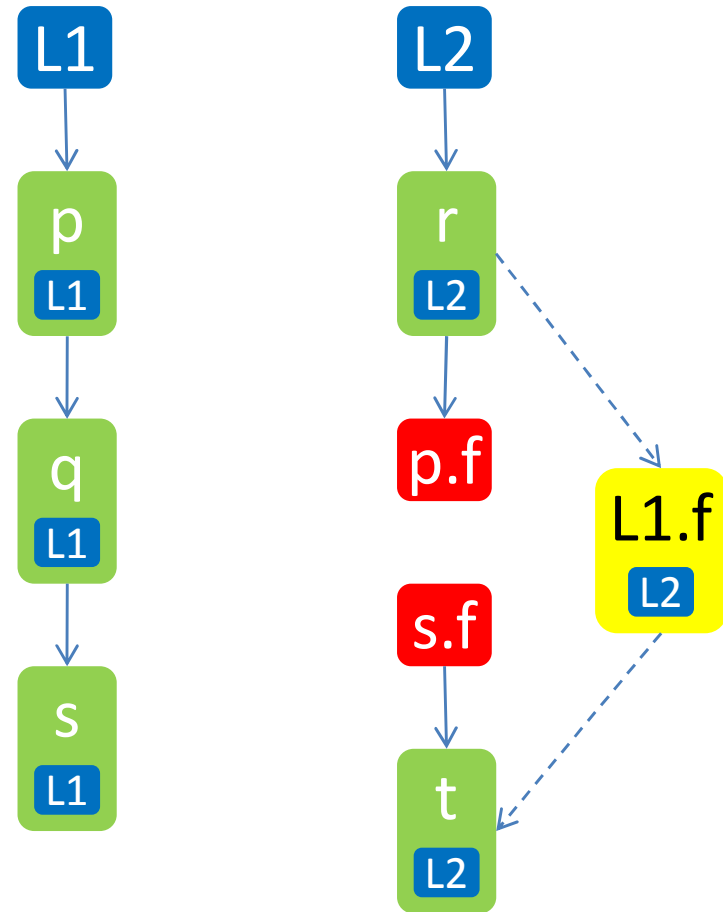
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static void foo() {  
  L1: p = new O();  
      q = p;  
  L2: r = new O();  
      p.f = r;  
      t = bar( q );  
}  
  
static O bar( O s ) {  
  return s.f;  
}
```



Add load/store edges.

Example

```
static void foo() {  
  L1: p = new O();  
      q = p;  
  L2: r = new O();  
      p.f = r;  
      t = bar( q );  
}  
  
static O bar( O s ) {  
  return s.f;  
}
```



Re-propagate points-to sets.

Overall algorithm

Simple:

```
repeat until no change {  
    propagate abstract objects along edges  
    for each load/store, add indirect edges to heap ptr nodes  
}
```

Detailed:

```
add all allocation nodes to worklist  
while worklist not empty {  
    remove node v1 from worklist  
    for each edge v1 -> v2, propagate pt(v1) into pt(v2)  
        if v2 changed, add v2 to worklist  
    for each load v1.f -> v3 {  
        for each a in pt(v1) {  
            add edge a.f -> v3 to assignment graph  
            add node a.f to worklist  
        }  
    }  
    for each store v3 -> v1.f {  
        ... (as above)  
    }  
}
```

Comparison with OCFA

Field-sensitive subset-based points-to analysis:

$$\text{pt} : (\text{Var} \cup (\text{Obj} \times \text{Field})) \rightarrow \wp(\text{Obj})$$

OCFA:

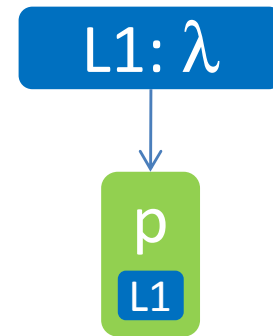
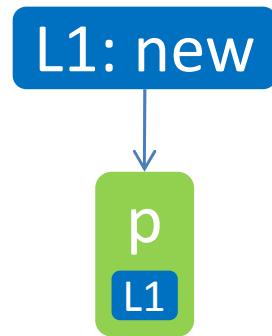
$$\hat{\varsigma} \in \hat{\Sigma} = \text{Call} \times \widehat{Env}$$

$$\hat{\rho} \in \widehat{Env} = \text{Var} \rightarrow \mathcal{P}(\widehat{Clo})$$

$$\widehat{clo} \in \widehat{Clo} = \text{Lam}$$

$$\Rightarrow \Sigma = \text{Call} \times (\text{Var} \rightarrow \wp(\text{Lam}))$$

Comparison with OCFA



Set implementation

- **hash:** Using java.util.HashSet
- **array:** Sorted array, binary search

a	b	d	g
---	---	---	---

- **bit vector:**

a	b	c	d	e	f	g	h	i	j
1	1	0	1	0	0	1	0	0	0

- **hybrid:**
 - array for small sets
 - bit vector for large sets

- **sparse bit vector:**

0 (ab)	1	1
1 (cd)	0	1
3 (gh)	1	0

- **binary decision diagram:**

Set implementation

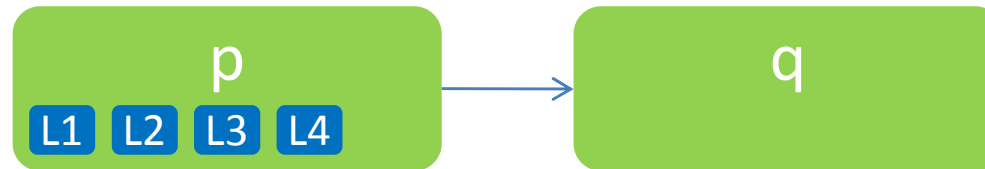
hash	slow	large
array	slow	small
bit vector	fast	large
hybrid	fast	small
sparse bit vector	fast	small
binary decision diagram	depends	depends

Slow vs. fast: up to 100x difference

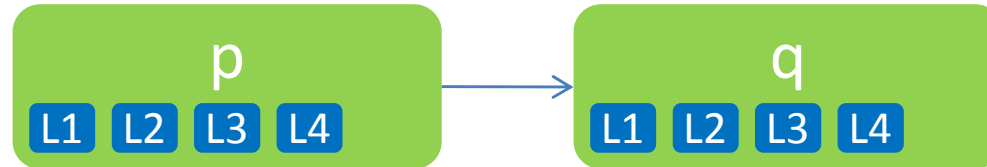
Large vs. small: up to 3x difference

Set implementation is very important.

Incremental propagation

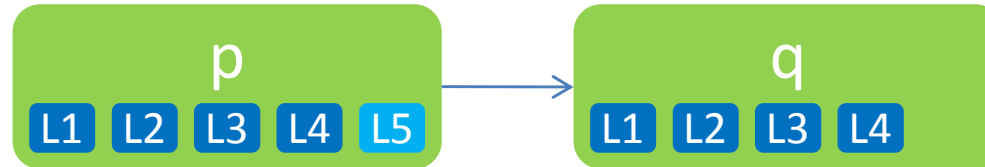


Incremental propagation



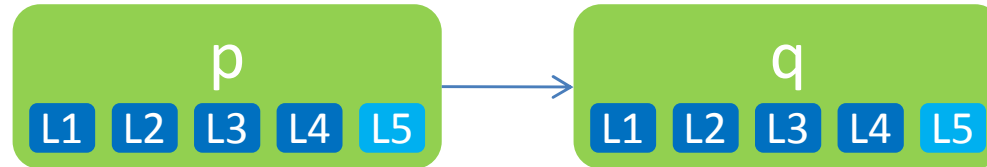
- 1st iteration: propagate {L1, L2, L3, L4}

Incremental propagation



- 1st iteration: propagate {L1, L2, L3, L4}
- add L5 to pt(p)

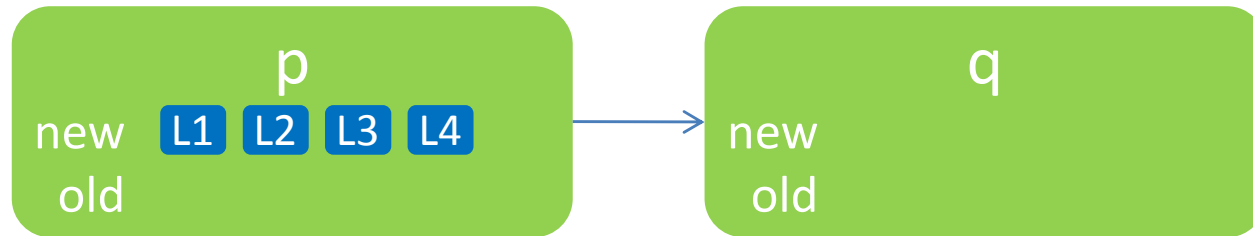
Incremental propagation



- 1st iteration: propagate {L1, L2, L3, L4}
- add L5 to pt(p)
- 2nd iteration: propagate {L1, L2, L3, L4, L5}

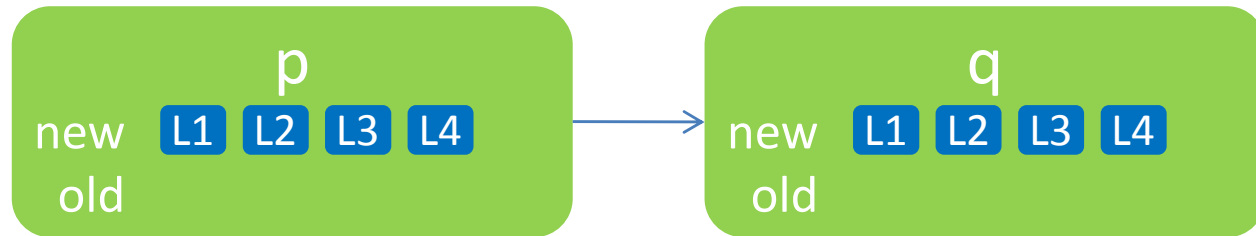
Incremental propagation

Idea: Split sets into old part and new part.



Incremental propagation

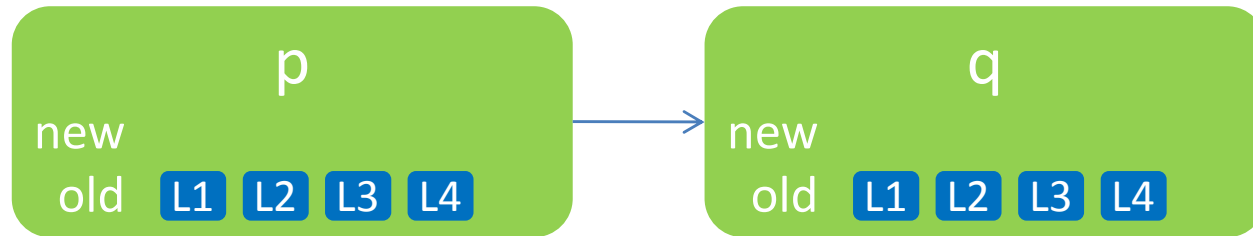
Idea: Split sets into old part and new part.



- 1st iteration: propagate {L1, L2, L3, L4}

Incremental propagation

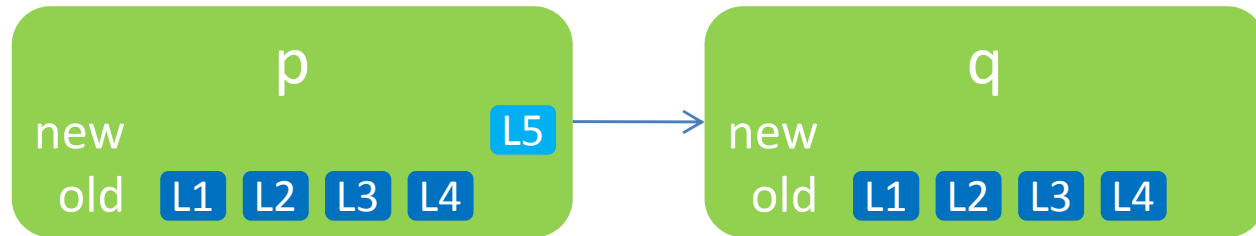
Idea: Split sets into old part and new part.



- 1st iteration: propagate {L1, L2, L3, L4}
- flush new to old

Incremental propagation

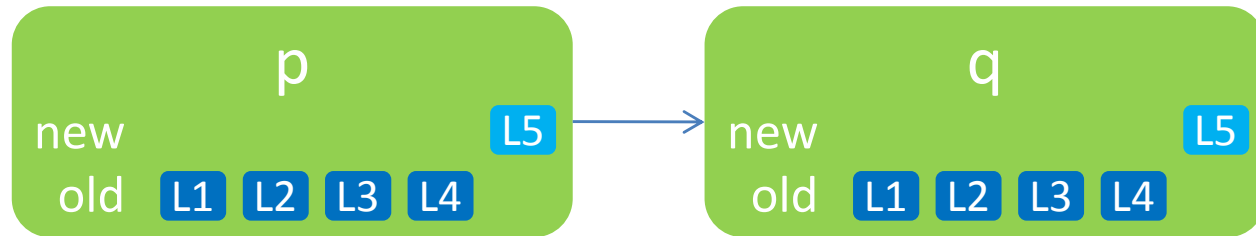
Idea: Split sets into old part and new part.



- 1st iteration: propagate $\{L1, L2, L3, L4\}$
- flush new to old
- add L5 to new part of $pt(p)$

Incremental propagation

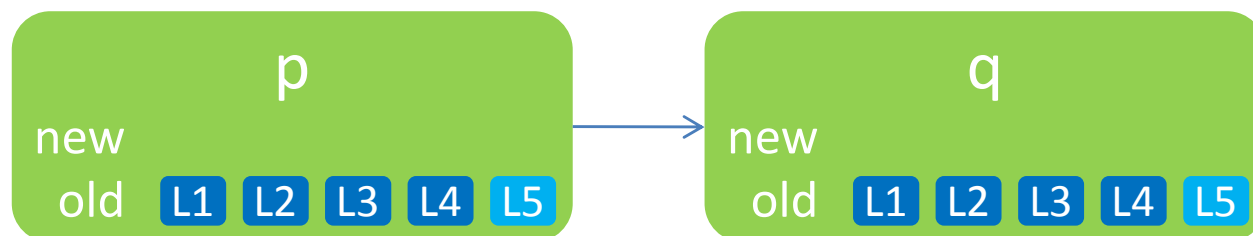
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- 1st iteration: propagate {L1, L2, L3, L4}
- flush new to old
- add L5 to new part of $pt(p)$
- 2nd iteration: propagate {L5}

Incremental propagation

Idea: Split sets into old part and new part.



- 1st iteration: propagate $\{L1, L2, L3, L4\}$
- flush new to old
- add $L5$ to new part of $pt(p)$
- 2nd iteration: propagate $\{L5\}$
- flush new to old

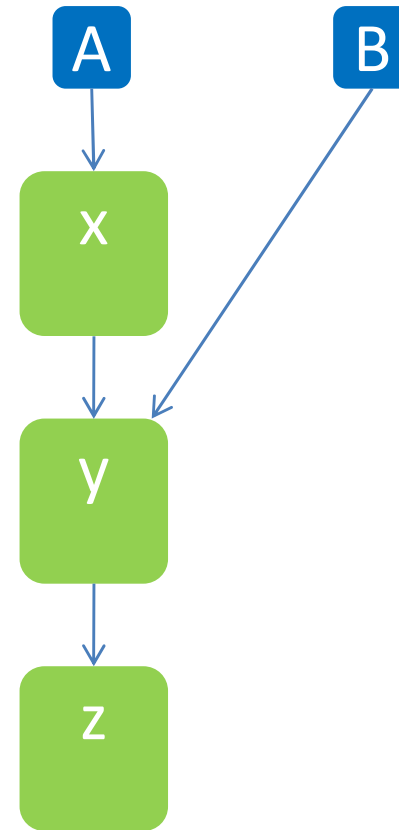
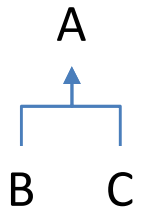
Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

Type filtering

```
A x, z;  
B y;  
A: x = new A();  
B: y = new B();  
  y = (B) x;  
  z = y;
```

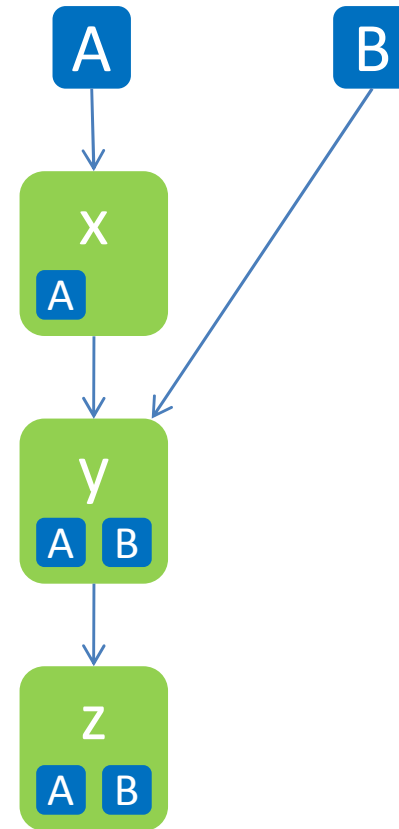
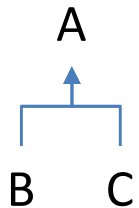
Inheritance hierarchy:



Type filtering: none

```
A x, z;  
B y;  
A: x = new A();  
B: y = new B();  
  y = (B) x;  
  z = y;
```

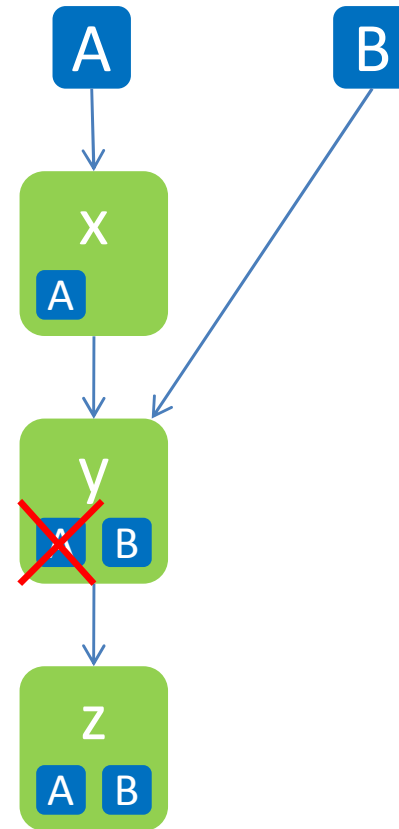
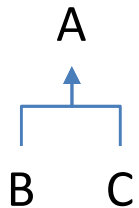
Inheritance hierarchy:



Type filtering: after analysis

```
A x, z;  
B y;  
A: x = new A();  
B: y = new B();  
  y = (B) x;  
  z = y;
```

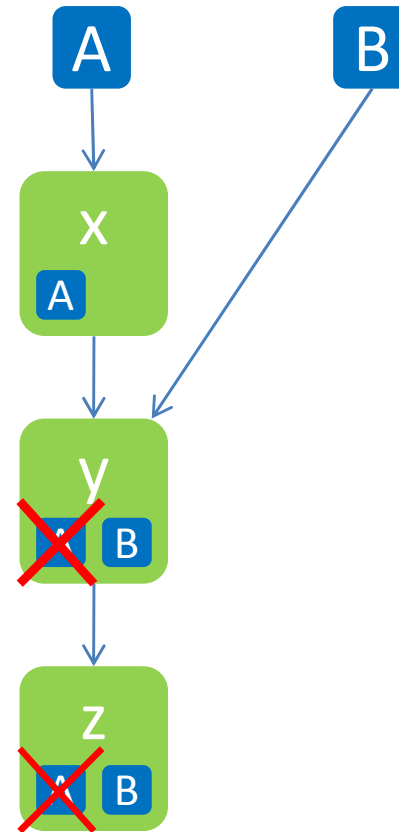
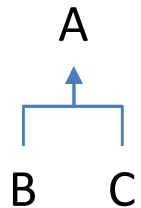
Inheritance hierarchy:



Type filtering: during analysis

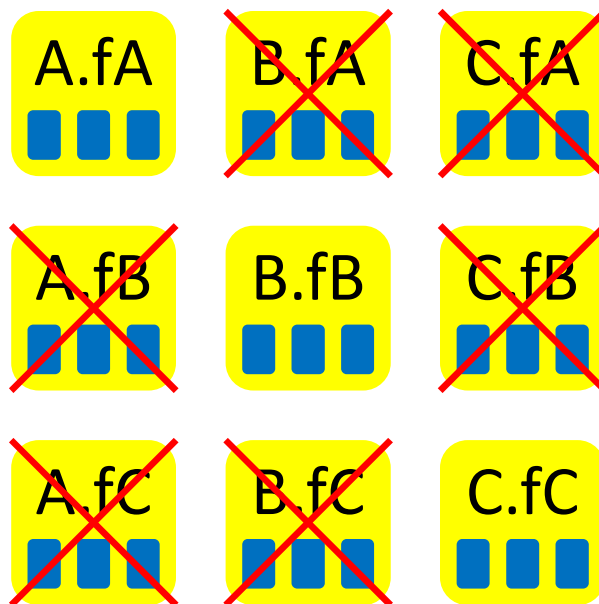
```
A x, z;  
B y;  
A: x = new A();  
B: y = new B();  
  y = (B) x;  
  z = y;
```

Inheritance hierarchy:



Type filtering: effect on heap nodes

```
class A {  
    Object fA;  
}  
class B {  
    Object fB;  
}  
class C {  
    Object fC;  
}  
A: a = new A();  
B: b = new B();  
C: c = new C();
```



Type filtering

- Ignoring types yields many large points-to sets.
- Filtering after propagation is almost as precise as during propagation.
- Filtering during propagation is both most precise and most efficient.

ignore	slow	imprecise
after propagation	slow	precise
during propagation	fast	precise

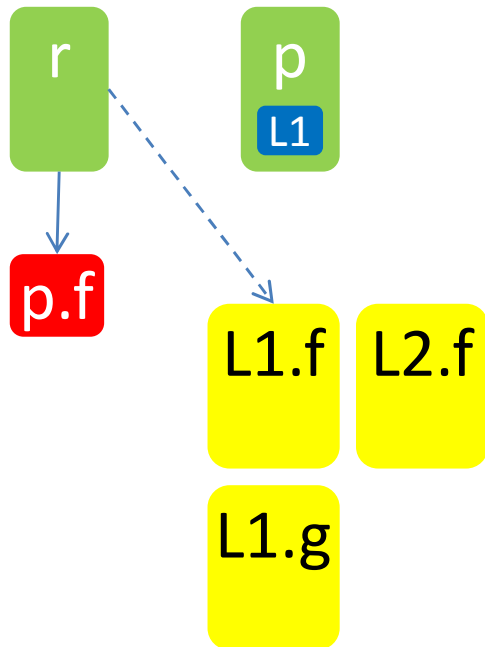
Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - **Field sensitivity**
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

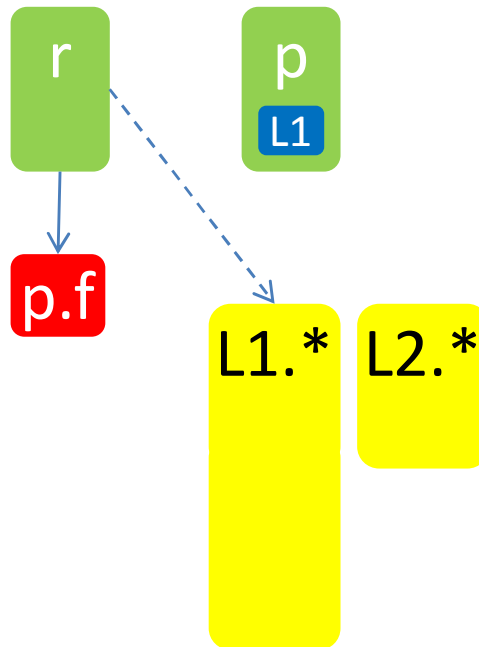
Field reference representation

Idea: merge yellow nodes with same abstract object (resp. same field).

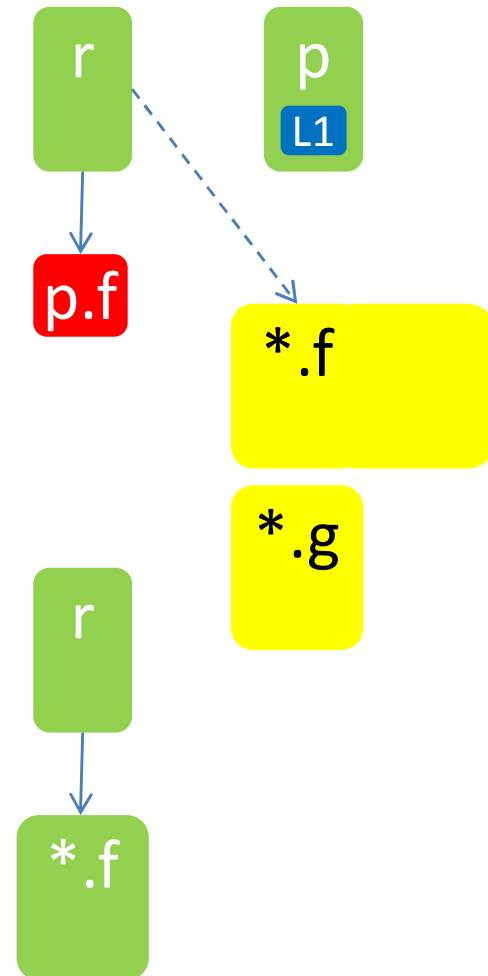
Field-sensitive



Field-insensitive

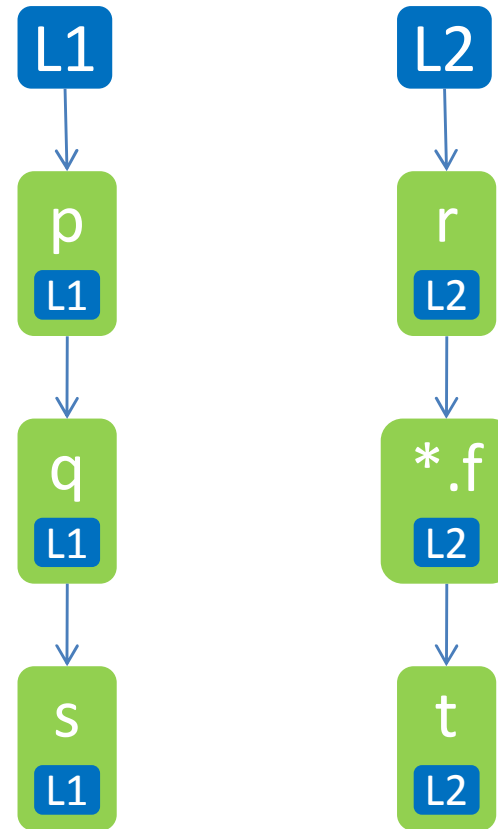


Field-based



Example (field-based)

```
static void foo() {  
  L1: p = new O();  
      q = p;  
  L2: r = new O();  
      p.f = r;  
      t = bar( q );  
}  
  
static O bar( O s ) {  
  return s.f;  
}
```



Overall (field-based) algorithm

```
merge each SCC in assignment graph into a single node
topologically sort resulting DAG
for each node v1 in topological order {
    for each edge v1 -> v2 {
        propagate pt(v1) into pt(v2)
    }
}
```

Each edge is processed only once.

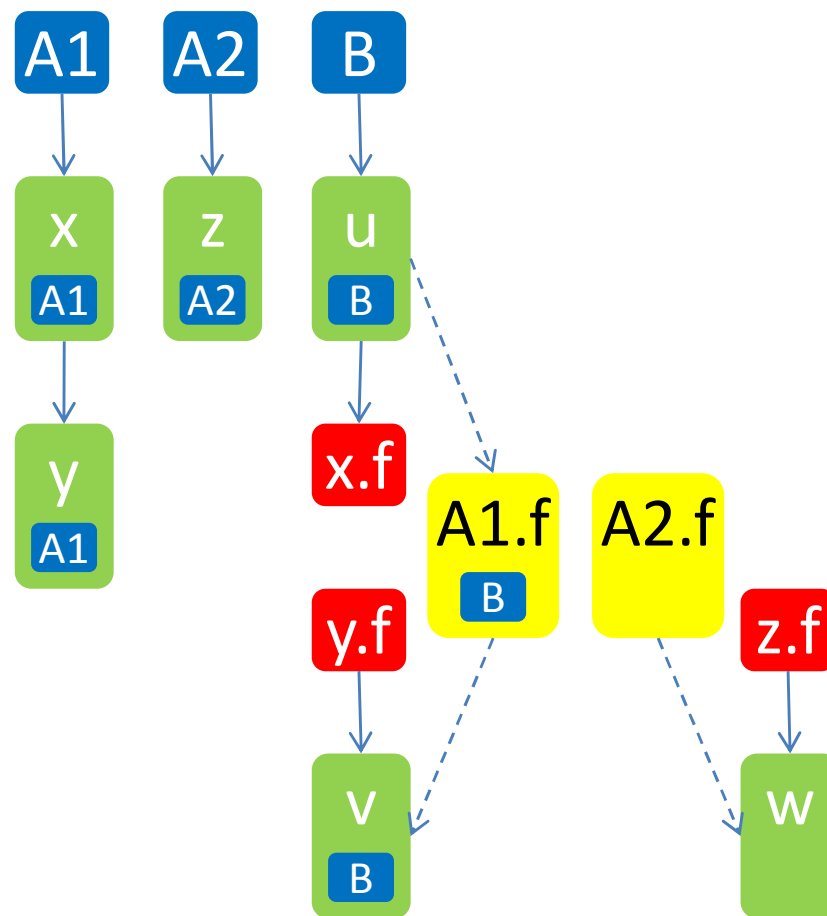
Worst-case $O(n^2)$.

Also, worst-case is linear in size of output.

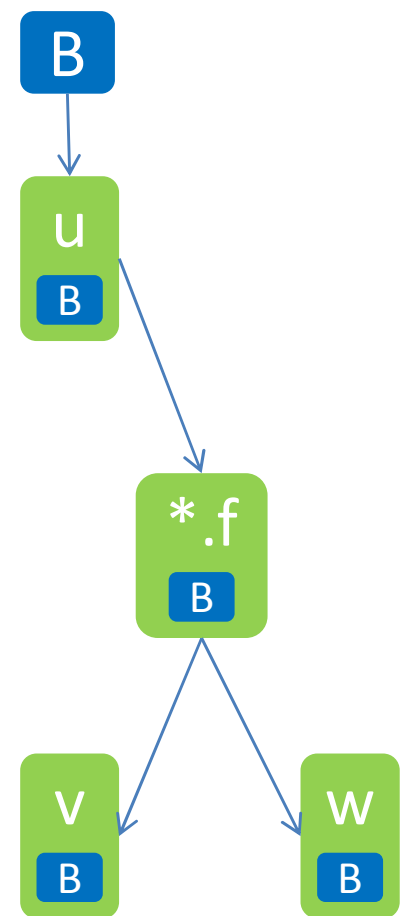
In contrast, field-sensitive algorithm is $O(n^3)$.

Example of precision loss

```
A x, y, z;  
B u, v, w;  
A1: x = new A();  
    y = x;  
A2: z = new A();  
B:  u = new B();  
    x.f = u;  
    v = y.f;  
    w = z.f;
```



Field-sensitive



Field-based

Field sensitivity summary

	Java	C
field-insensitive	sound slow imprecise	sound slow imprecise 
field-based	sound fast imprecise 	unsound
field-sensitive	sound slowest precise 	sound slowest precise 

Comparison: field-based PTA vs. OCFA

Field-based subset-based points-to analysis:

$$\text{pt} : \text{Var} \rightarrow \wp(\text{Obj})$$

OCFA:

$$\hat{\varsigma} \in \hat{\Sigma} = \text{Call} \times \widehat{Env}$$

$$\hat{\rho} \in \widehat{Env} = \text{Var} \rightarrow \mathcal{P}(\widehat{Clo})$$

$$\widehat{clo} \in \widehat{Clo} = \text{Lam}$$

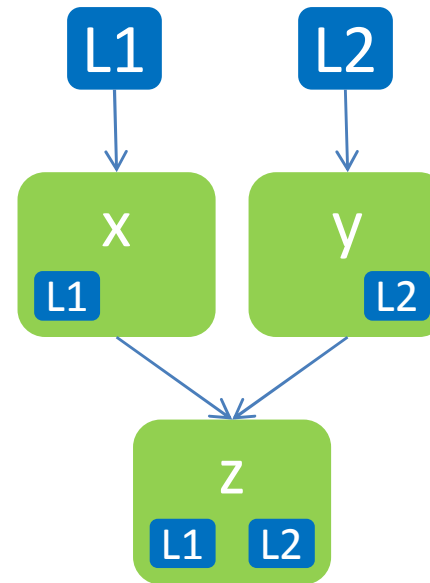
$$\Rightarrow \Sigma = \text{Call} \times (\text{Var} \rightarrow \wp(\text{Lam}))$$

Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - **Directionality**
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

Directionality

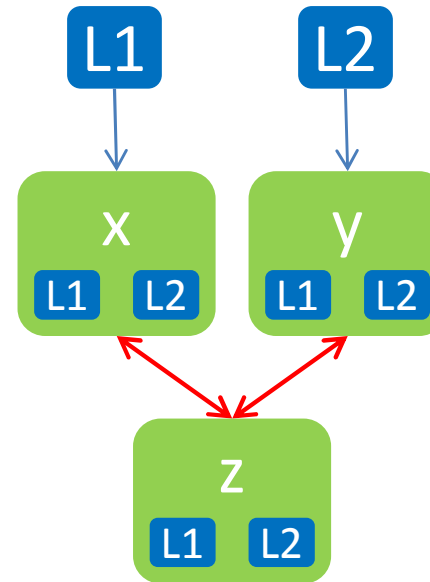
```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
    if(*) {  
        z = x;  
    } else {  
        z = y;  
    }
```



Subset-based analysis
aka Inclusion-based analysis
aka Andersen's analysis

Directionality

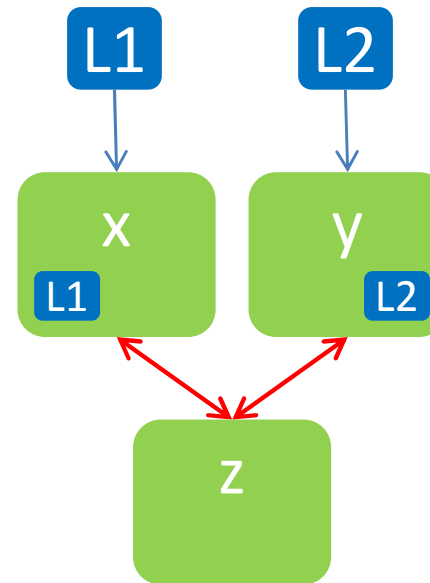
```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
    if(*) {  
        z = x;  
    } else {  
        z = y;  
    }
```



Equality-based analysis
aka Unification-based analysis
aka Steensgaard's analysis

Implementation of unification

```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
    if(*) {  
        z = x;  
    } else {  
        z = y;  
    }  
}
```

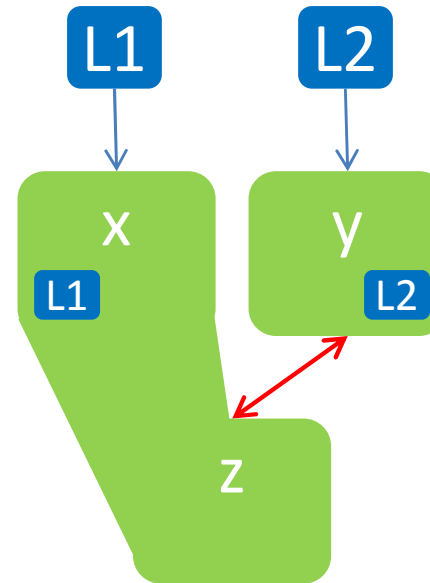


Step 1: Process allocation edges

Equality-based analysis
aka Unification-based analysis
aka Steensgaard's analysis

Implementation of unification

```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
  if(*) {  
    z = x;  
  } else {  
    z = y;  
  }
```



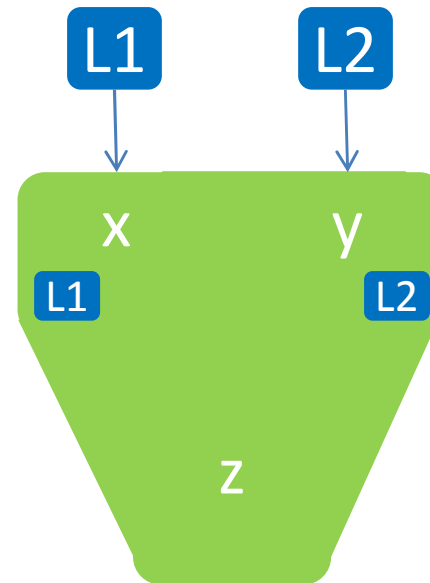
Equality-based analysis
aka Unification-based analysis
aka Steensgaard's analysis

Step 1: Process allocation edges
Step 2: Repeatedly unify nodes
connected by assignments

Running time: almost linear

Implementation of unification

```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
  if(*) {  
    z = x;  
  } else {  
    z = y;  
  }
```

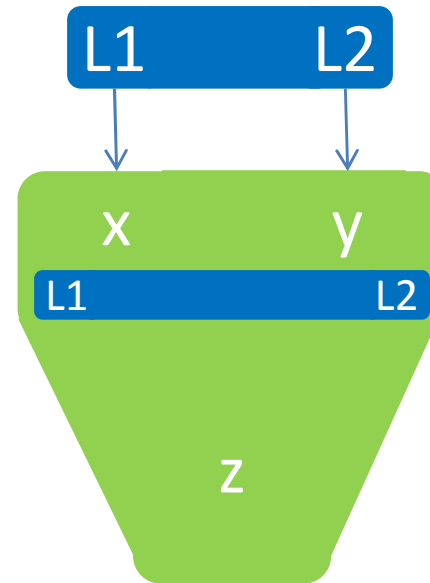


Equality-based analysis
aka Unification-based analysis
aka Steensgaard's analysis

Step 1: Process allocation edges
Step 2: Repeatedly unify nodes
connected by assignments.

Implementation of unification

```
Object x, y, z;  
L1: x = new Object();  
L2: y = new Object();  
  if(*) {  
    z = x;  
  } else {  
    z = y;  
  }
```



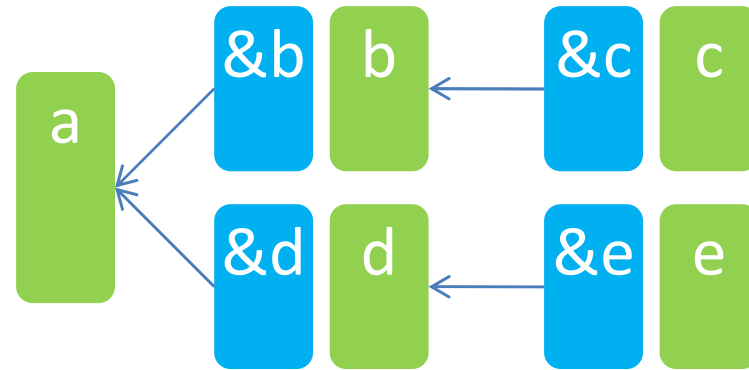
Equality-based analysis
aka Unification-based analysis
aka Steensgaard's analysis

Step 1: Process allocation edges
Step 2: Repeatedly unify nodes
connected by assignments.
Also unify nodes pointed-to by
same node.

Running time: almost linear

A C example

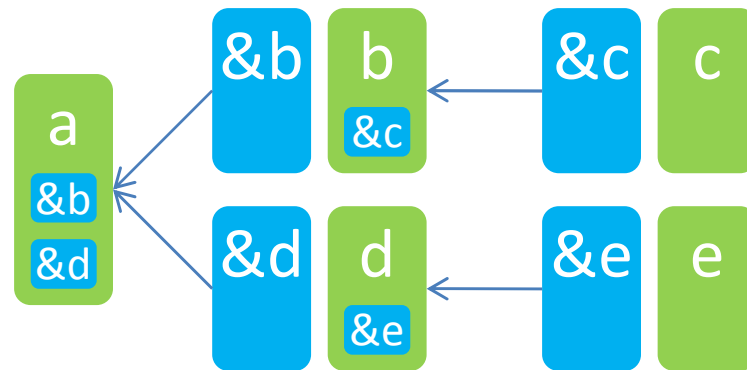
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Subset-based analysis

A C example

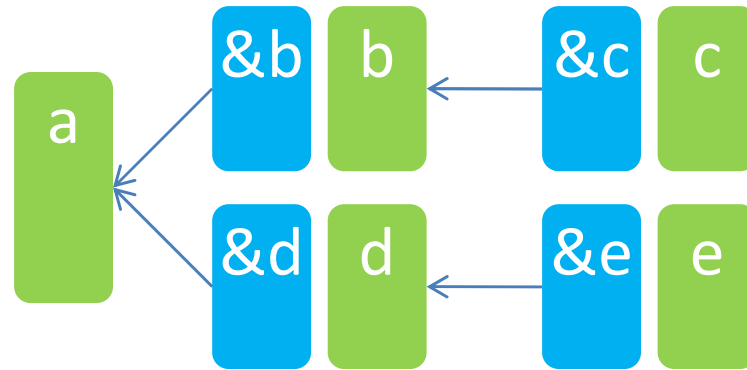
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Subset-based analysis

A C example

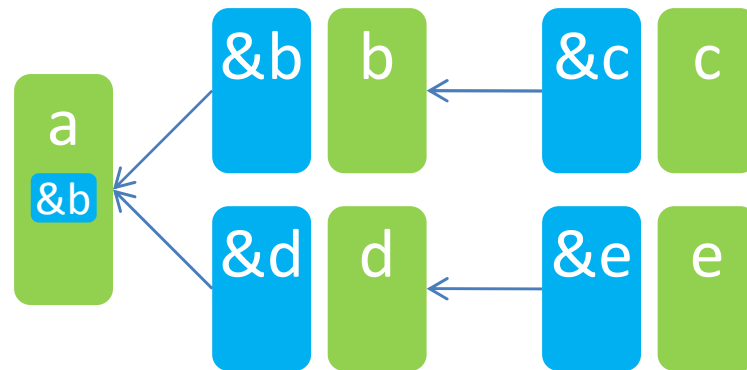
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Equality-based analysis

A C example

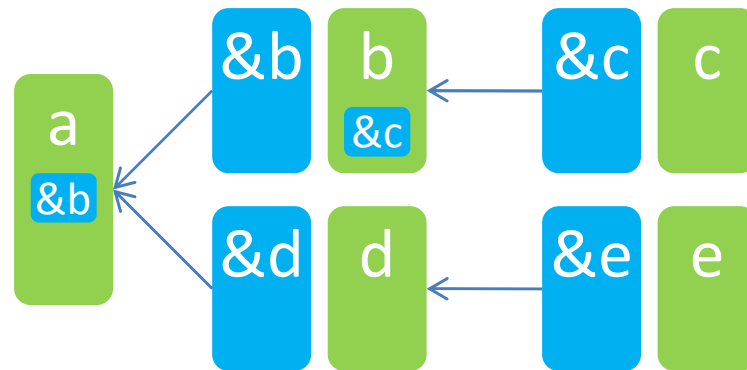
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Equality-based analysis

A C example

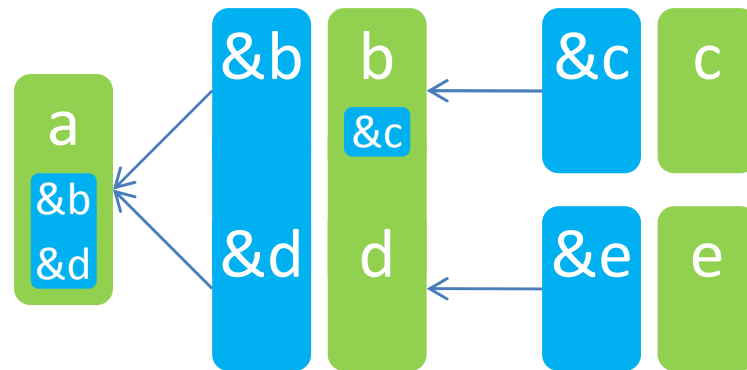
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Equality-based analysis

A C example

```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```

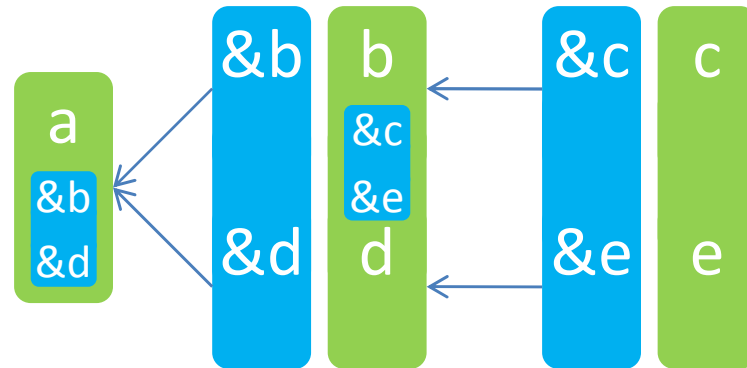


Equality-based analysis

Invariant: each node points to at most one other node.

A C example

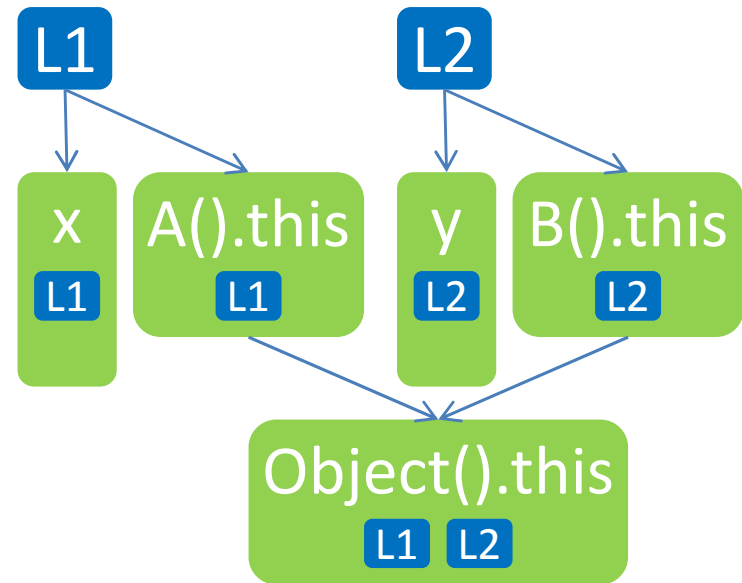
```
a = &b;  
b = &c;  
a = &d;  
d = &e;
```



Equality-based analysis

A problem with unification and OOP

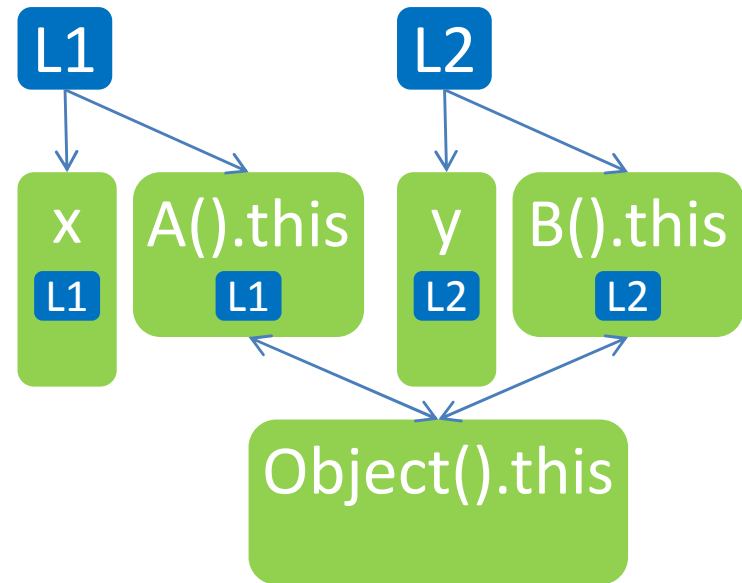
```
class A extends Object {  
  public A() {  
    super();  
  }  
}  
class B extends Object {  
  ...  
}  
L1: x = new A();  
L2: y = new B();
```



Subset-based analysis

A problem with unification and OOP

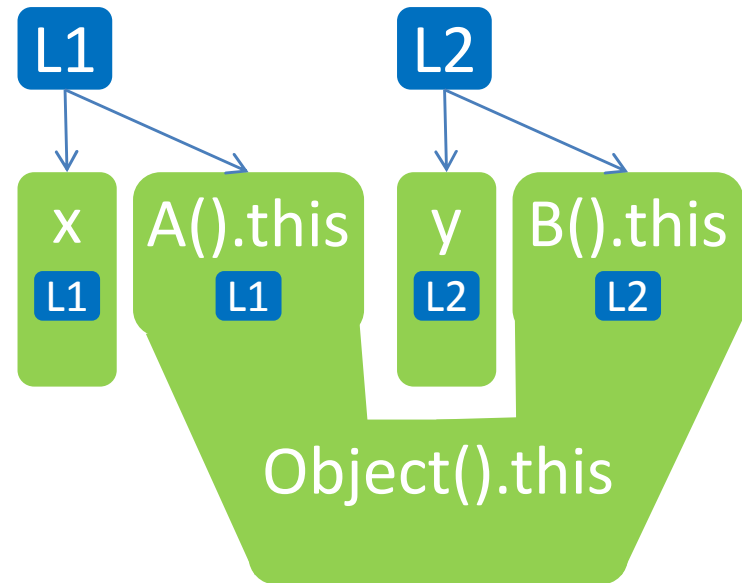
```
class A extends Object {  
    public A() {  
        super();  
    }  
}  
class B extends Object {  
    ...  
}  
L1: x = new A();  
L2: y = new B();
```



Equality-based analysis

A problem with unification and OOP

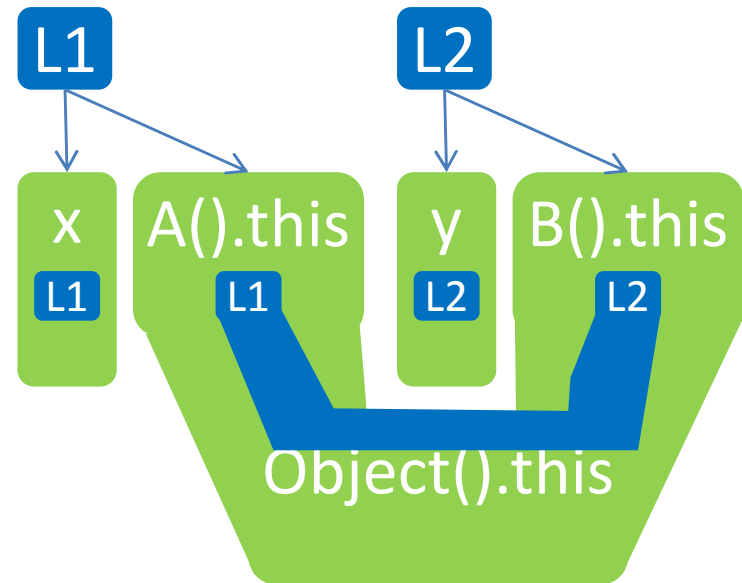
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  public A() {  
    super();  
  }  
}  
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```



Equality-based analysis

A problem with unification and OOP

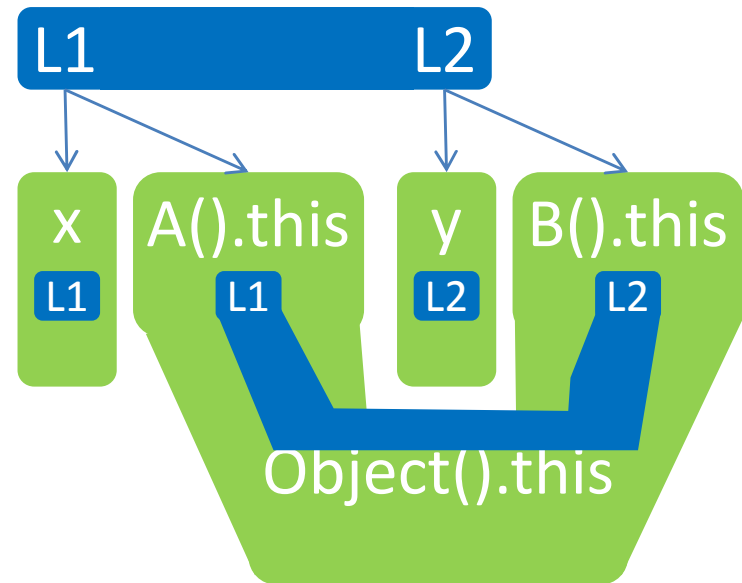
```
class A extends Object {  
  public A() {  
    super();  
  }  
}  
class B extends Object {  
  ...  
}  
L1: x = new A();  
L2: y = new B();
```



Equality-based analysis

A problem with unification and OOP

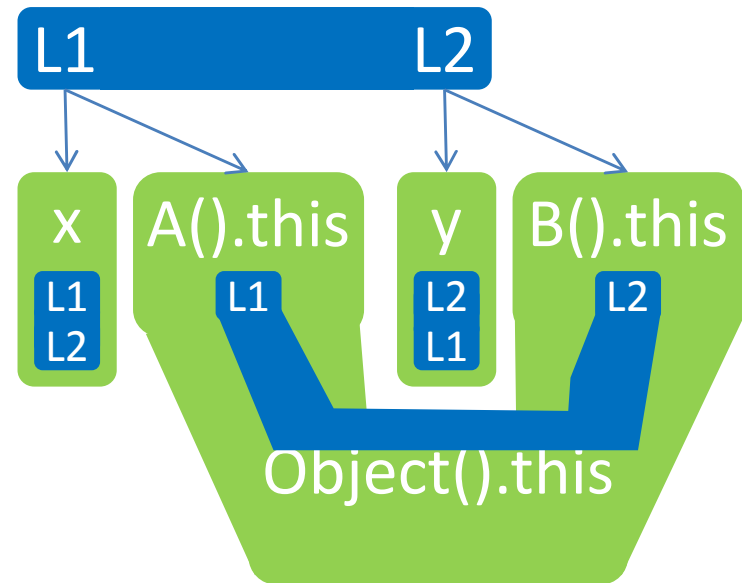
```
class A extends Object {  
  public A() {  
    super();  
  }  
}  
class B extends Object {  
  ...  
}  
L1: x = new A();  
L2: y = new B();
```



Equality-based analysis

A problem with unification and OOP

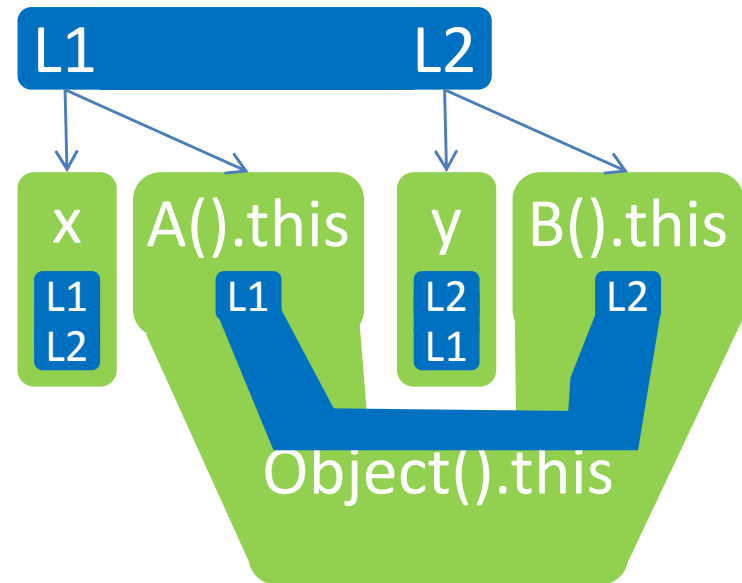
```
class A extends Object {  
  public A() {  
    super();  
  }  
}  
class B extends Object {  
  ...  
}  
L1: x = new A();  
L2: y = new B();
```



Equality-based analysis

A problem with unification and OOP

```
class A extends Object {  
    public A() {  
        super();  
    }  
}  
class B extends Object {  
    ...  
}  
L1: x = new A();  
L2: y = new B();
```



Equality-based analysis

Every pointer points to every object!
... but context sensitivity will fix this.

Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

How big is the call graph?

```
public class Hello {  
    public static final void main(String[] args) {  
        System.out.println("Hello");  
    }  
}
```

- Number of methods actually executed: ??
- Number of methods in static call graph: ??

How big is the call graph?

```
public class Hello {  
    public static final void main(String[] args) {  
        System.out.println("Hello");  
    }  
}
```

- Number of methods actually executed: 498
- Number of methods in static call graph: ??

How big is the call graph?

```
public class Hello {  
    public static final void main(String[] args) {  
        System.out.println("Hello");  
    }  
}
```

- Number of methods actually executed: 498
- Number of methods in static call graph: 3204

Call graph construction

To determine ...	... we need to know
points-to sets	
pointer assignment edges	
reachable methods	
call graph edges	

Call graph construction

To determine ...	... we need to know
points-to sets	pointer assignment edges
pointer assignment edges	
reachable methods	
call graph edges	

Call graph construction

To determine ...	... we need to know
points-to sets	pointer assignment edges
pointer assignment edges	reachable methods call graph edges
reachable methods	
call graph edges	

Call graph construction

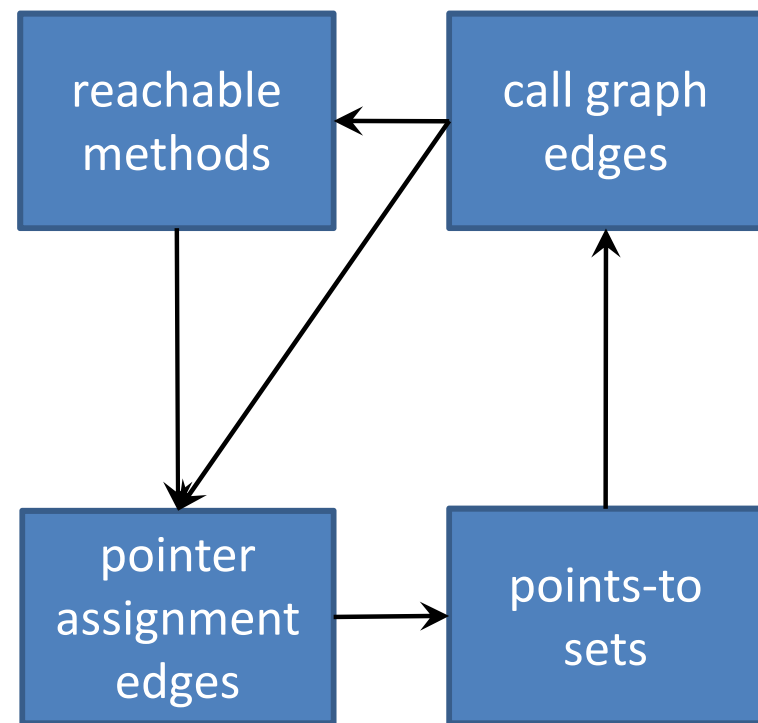
To determine ...	... we need to know
points-to sets	pointer assignment edges
pointer assignment edges	reachable methods call graph edges
reachable methods	call graph edges
call graph edges	

Call graph construction

To determine ...	... we need to know
points-to sets	pointer assignment edges
pointer assignment edges	reachable methods call graph edges
reachable methods	call graph edges
call graph edges	points-to sets

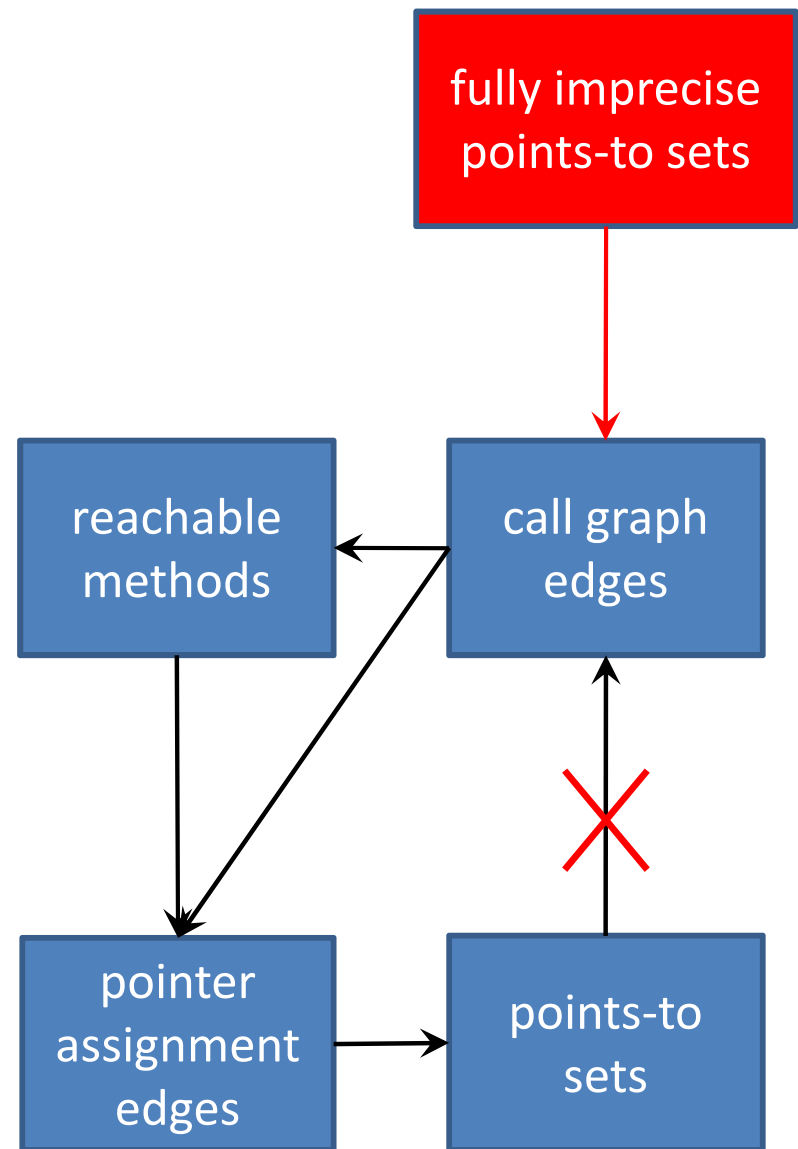
Call graph construction

To determine ...	... we need to know
points-to sets	pointer assignment edges
pointer assignment edges	reachable methods call graph edges
reachable methods	call graph edges
call graph edges	points-to sets



Ahead of time call graph construction

1. Assume every pointer can point to any object compatible with its declared type.
2. Explore call graph using this assumption, listing reachable methods (Class Hierarchy Analysis).
3. Generate pointer assignment graph using resulting call edges and reachable methods.
4. Propagate points-to sets along pointer assignment graph.



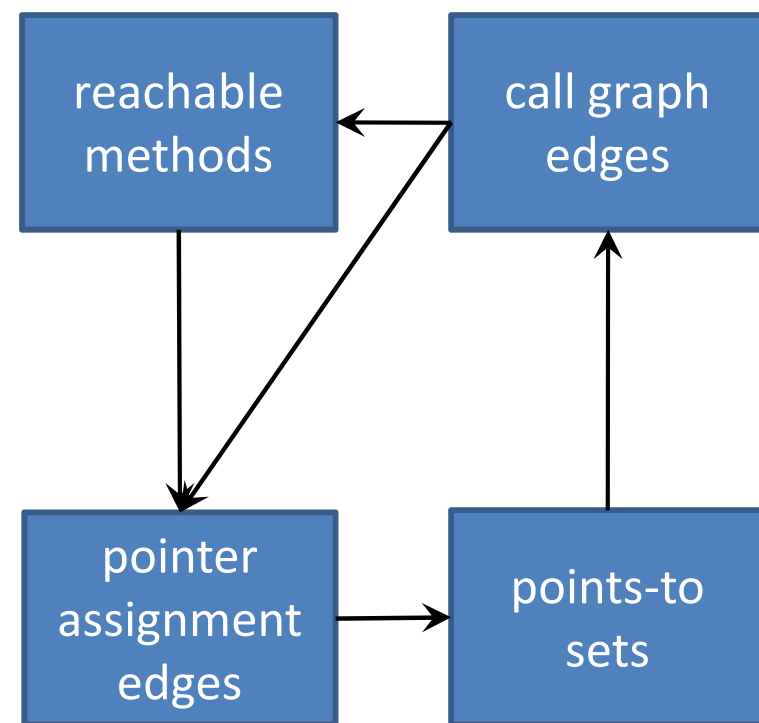
Ahead of time call graph construction

1. Assume every pointer can point to any object compatible with its declared type.
2. Explore call graph using this assumption, listing reachable methods (Class Hierarchy Analysis).
3. Generate pointer assignment graph using resulting call edges and reachable methods.
4. Propagate points-to sets along pointer assignment graph.

- no iteration
- very imprecise due to many reachable methods

On-the-fly call graph construction

1. Start with only initial reachable methods, no call edges, no pointer assignment edges, and no points-to sets.
2. Iteratively generate pointer assignment edges, points-to sets, call edges, and reachable methods implied by current information.
3. Stop when overall fixed point is reached.



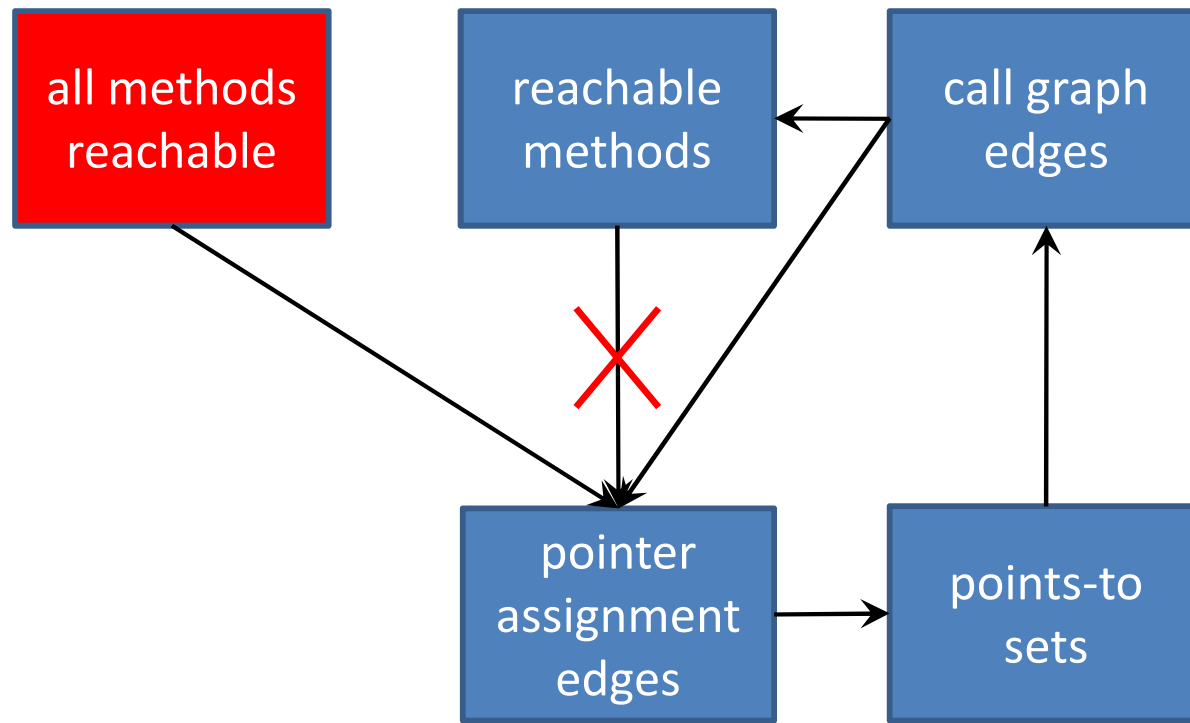
On-the-fly call graph construction

1. Start with only initial reachable methods, no call edges, no pointer assignment edges, and no points-to sets.
2. Iteratively generate pointer assignment edges, points-to sets, call edges, and reachable methods implied by current information.
3. Stop when overall fixed point is reached.

- requires iteration
 - slower
 - more complicated
 - much more precise
- due to fewer reachable methods

Partly on-the-fly call graph construction

1. Assume all methods are reachable.
2. Generate pointer assignment edges for all methods.
3. Iteratively propagate points-to sets, add call edges, and generate pointer assignment edges for new call edges.



Partly on-the-fly call graph construction

1. Assume all methods are reachable.
2. Generate pointer assignment edges for all methods.
3. Iteratively propagate points-to sets, add call edges, and generate pointer assignment edges for new call edges.

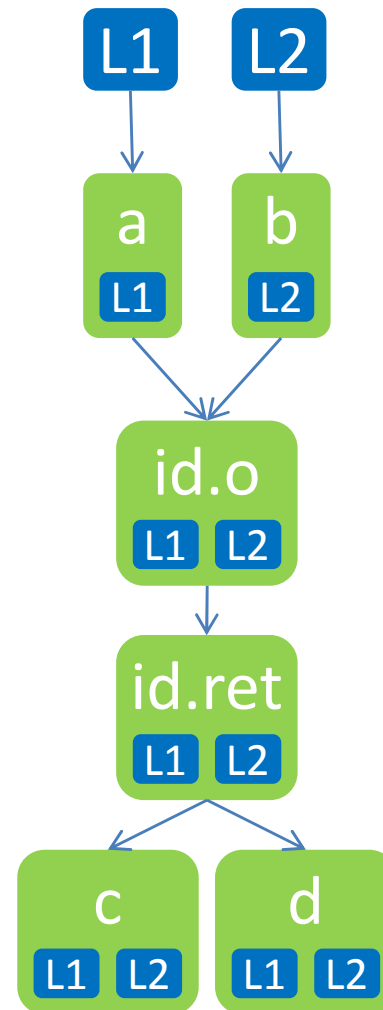
- requires iteration
- speed is in between ahead-of-time and on-the-fly
- complexity is in between...
- still imprecise due to many reachable methods

Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

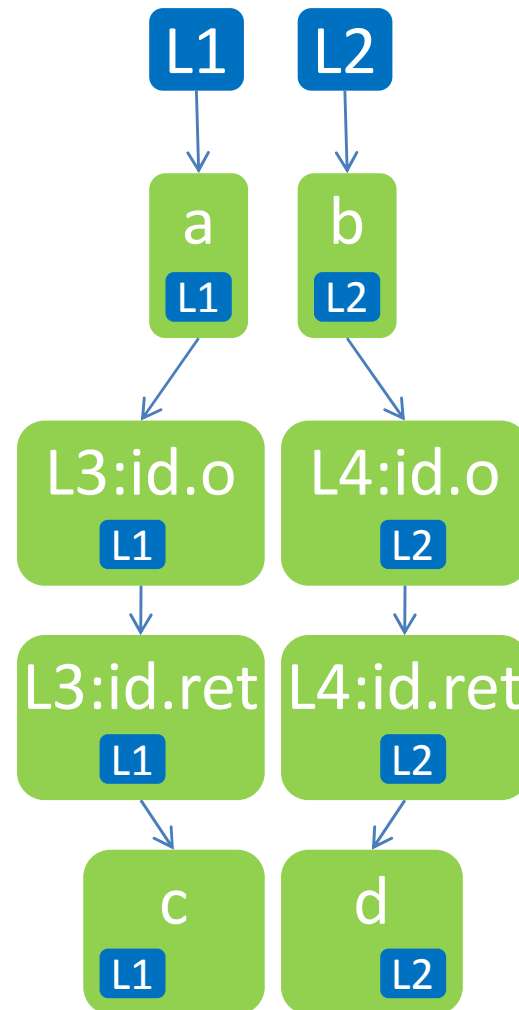
Context sensitivity motivation

```
Object id(Object o) {  
    return o;  
}  
  
void f() {  
    L1: Object a = new Object();  
    L2: Object b = new Object();  
    Object c = id(a);  
    Object d = id(b);  
}
```



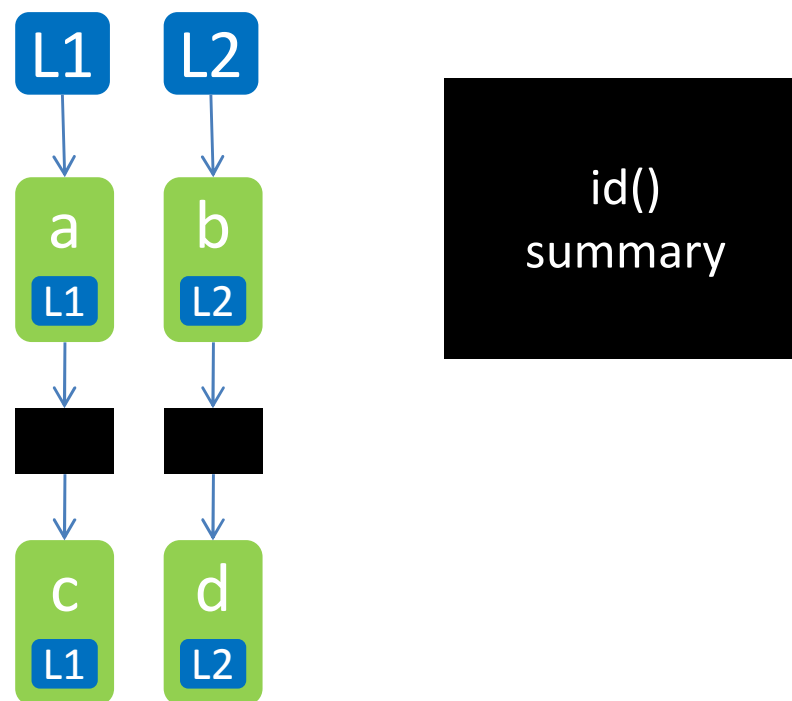
Call strings approach (aka cloning)

```
Object id(Object o) {  
    return o;  
}  
  
void f() {  
    L1: Object a = new Object();  
    L2: Object b = new Object();  
    L3: Object c = id(a);  
    L4: Object d = id(b);  
}
```



Summary-based approach

```
Object id(Object o) {  
    return o;  
}  
  
void f() {  
    L1: Object a = new Object();  
    L2: Object b = new Object();  
    Object c = id(a);  
    Object d = id(b);  
}
```



Challenge: how to design a summary that

- precisely models all effects of `id()` (and its transitive callees)
- is cheap to compute and represent
- is cheap to instantiate

Comparison with 1CFA

Field-sensitive subset-based 1-call-site-sensitive points-to analysis:

$$\text{pt} : (\text{Call} \times \text{Var} \cup (\text{Obj} \times \text{Field})) \rightarrow \wp(\text{Obj})$$

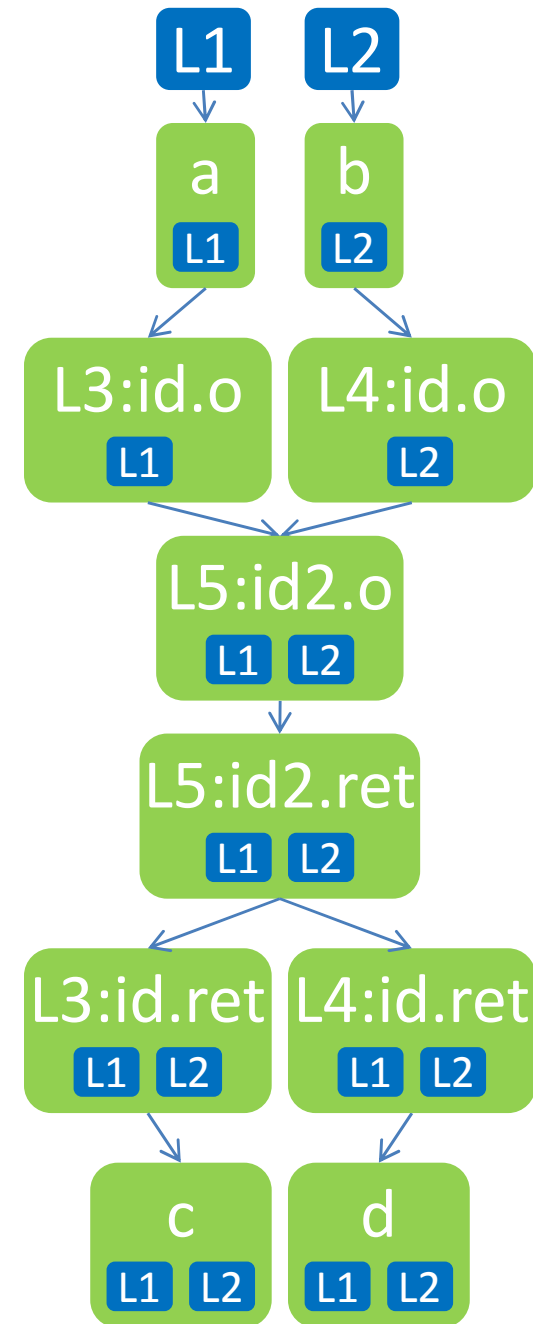
1CFA:

$\Sigma =$

$$\text{Call} \times (\text{Var} \rightarrow \text{Addr}) \times (\text{Addr} \rightarrow \wp(\text{Lam} \times \text{Var} \rightarrow \text{Addr})) \times \text{Call}$$

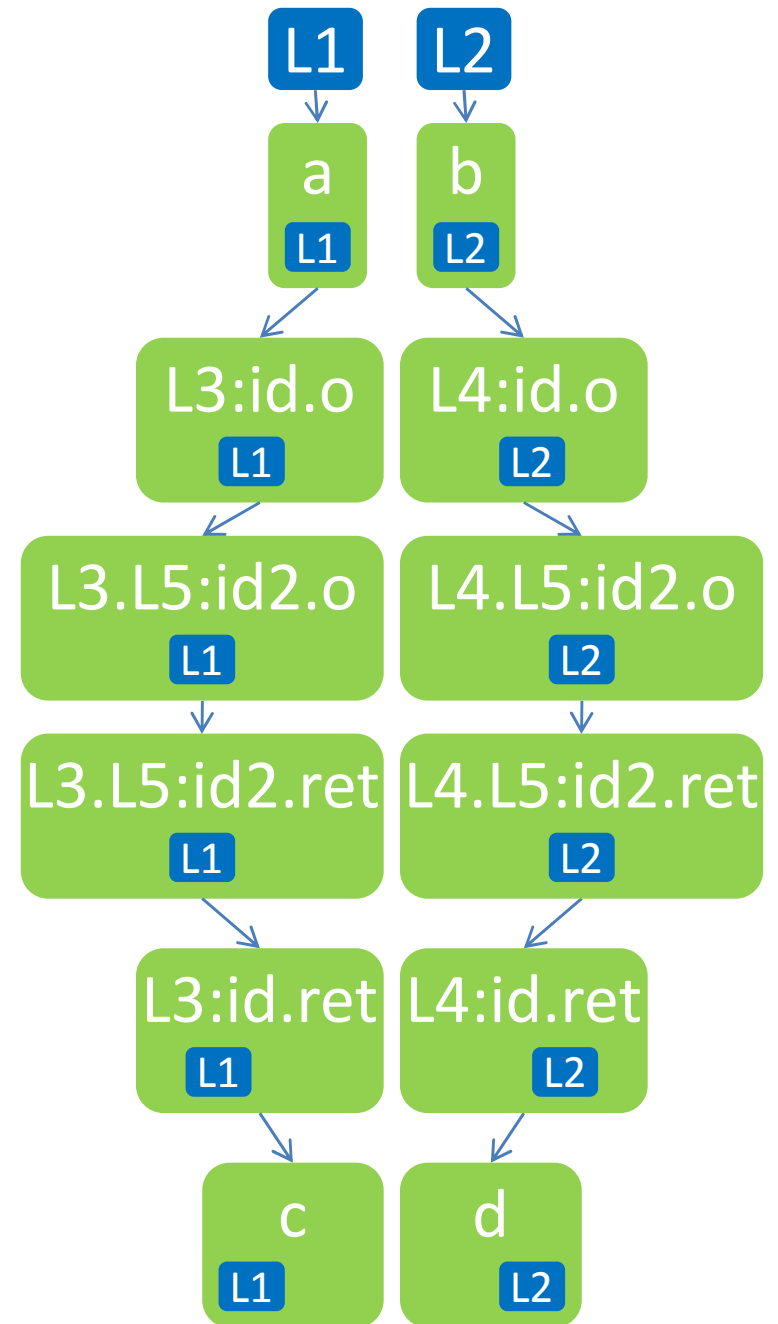
Limitation of single call site context

```
Object id(Object o) {  
  L5: return id2(o);  
}  
  
Object id2(Object o) {  
  return o;  
}  
  
void f() {  
  L1: Object a = new Object();  
  L2: Object b = new Object();  
  L3: Object c = id(a);  
  L4: Object d = id(b);  
}
```



2-call-site context sensitivity

```
Object id(Object o) {  
  L5: return id2(o);  
}  
  
Object id2(Object o) {  
  return o;  
}  
  
void f() {  
  L1: Object a = new Object();  
  L2: Object b = new Object();  
  L3: Object c = id(a);  
  L4: Object d = id(b);  
}
```

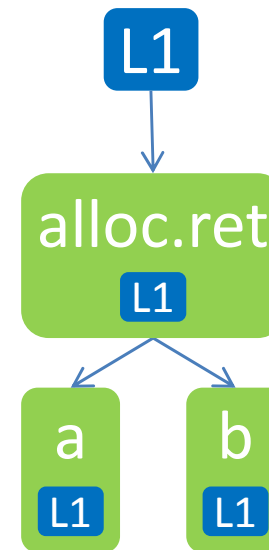


k-call-site context sensitivity

- k-Call-Site: keep last k call sites
 - space/time complexity exponential in k
- Full Call String: keep full string of call sites
 - exponential number of call strings
 - recursion: infinite number of call strings
 - exclude any call site that is in a recursive cycle from string
 - still exponential
 - what if many call sites are in recursive cycle ?
 - C: call graph is almost DAG => works well
 - Java: half of call graph is one big SCC => no precision

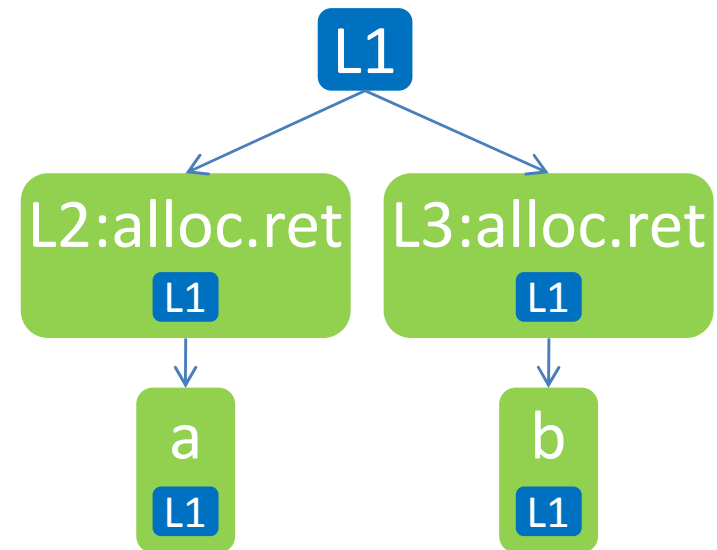
Context-sensitive heap abstraction

```
Object alloc() {  
  L1: return new Object();  
}  
  
void f() {  
  Object a = alloc();  
  Object b = alloc();  
}
```



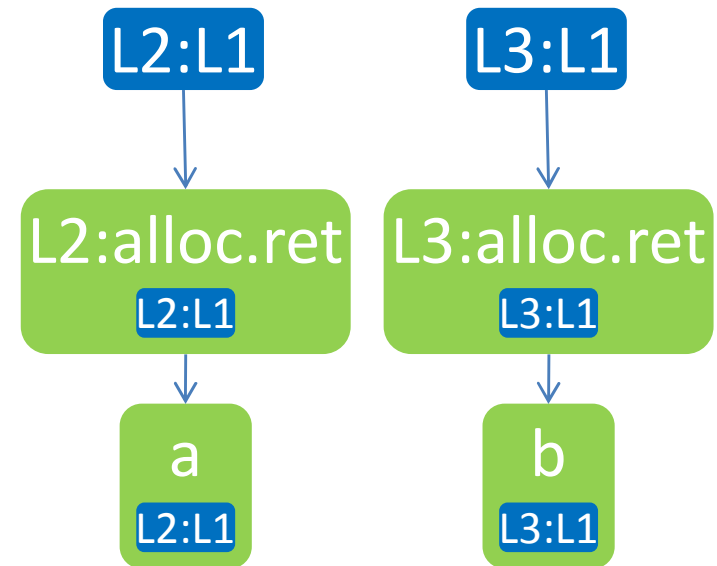
Context-sensitive heap abstraction

```
Object alloc() {  
  L1: return new Object();  
}  
  
void f() {  
  L2: Object a = alloc();  
  L3: Object b = alloc();  
}
```



Context-sensitive heap abstraction

```
Object alloc() {  
  L1: return new Object();  
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void f() {  
  L2: Object a = alloc();  
  L3: Object b = alloc();  
}
```



Comparison with 1CFA

Field-sensitive subset-based 1-call-site-sensitive points-to analysis with context-sensitive heap abstraction:

pt :

$$(\text{Call} \times \text{Var} \cup (\text{Call} \times \text{Obj} \times \text{Field})) \rightarrow \wp(\text{Call} \times \text{Obj})$$

1CFA:

$\Sigma =$

$$\text{Call} \times (\text{Var} \rightarrow \text{Addr}) \times (\text{Addr} \rightarrow \wp(\text{Lam} \times \text{Var} \rightarrow \text{Addr})) \times \text{Call}$$

Object-sensitive analysis

```
class Container {  
    private Item item;  
    public void set(Item i) {  
        this.item = i;  
    }  
}
```

L1: Container c1 = new Container();

L2: Item i1 = new Item();

L3: c1.set(i1);

L4: Container c2 = new Container();

L5: Item i2 = new Item();

L6: c2.set(i2);

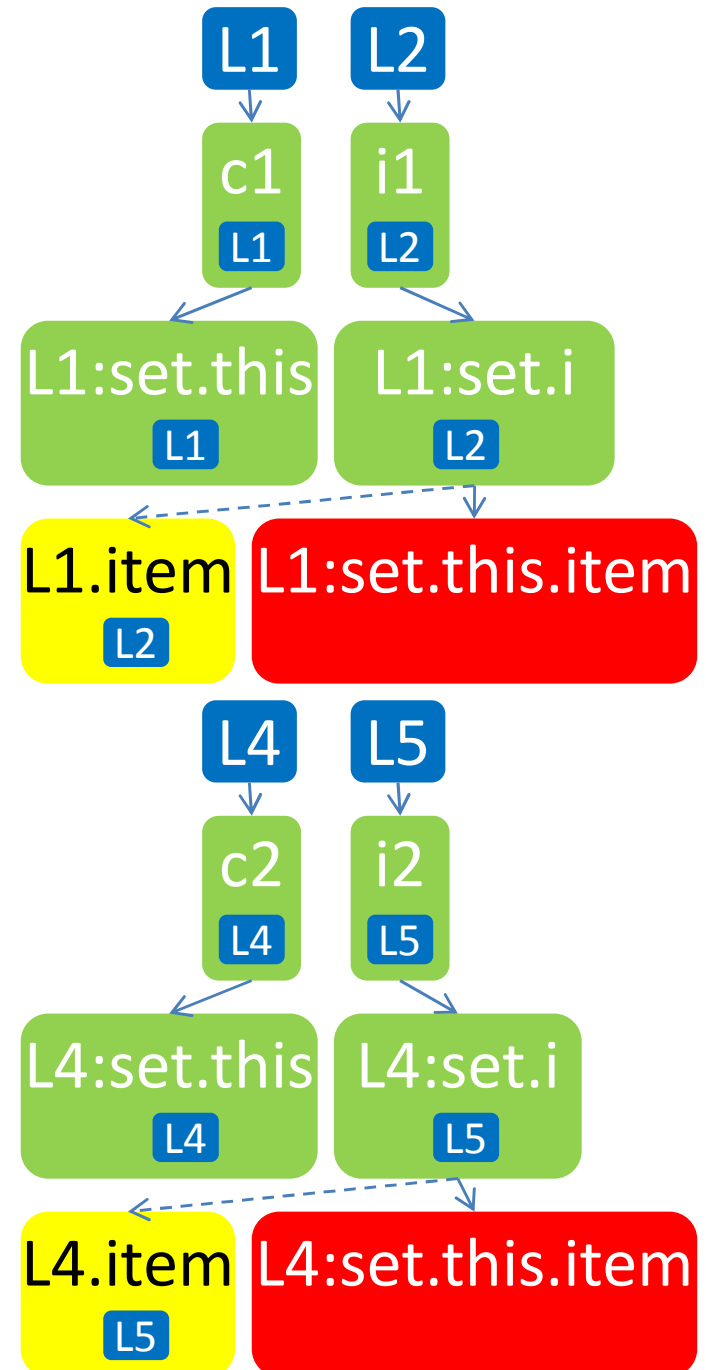


Object-sensitive analysis

```
class Container {  
    private Item item;  
    public void set(Item i) {  
        this.item = i;  
    }  
}
```

```
L1: Container c1 = new Container();  
L2: Item i1 = new Item();  
L3: c1.set(i1);
```

```
L4: Container c2 = new Container();  
L5: Item i2 = new Item();  
L6: c2.set(i2);
```



Object-sensitive analysis

- Like call-site context-sensitive analysis:
 - can use strings of abstract objects
 - can make heap abstraction (object-)context-sensitive
- Call-site CS and object-sensitive CS have incomparable precision (neither is theoretically more precise)
- In practice, for OO programs, object sensitivity more precise than call-site sensitivity for the same context string length

Effect of context-sensitivity in Java

- For call graph construction:
 - context sensitivity has some effect
- For cast safety analysis:
 - context sensitivity substantially improves precision
 - object sensitivity more precise than call sites
 - context sensitive heap abstraction further improves precision
 - context strings longer than 1 add little precision
 - ∞ -call-site ignoring cycles less precise than 1-call-site

Context-sensitive equality-based analysis

```
f(a, b, c) {  
  d = a;  
  d = b;  
  e = c;  
  e = a.f;  
  return e;  
}
```

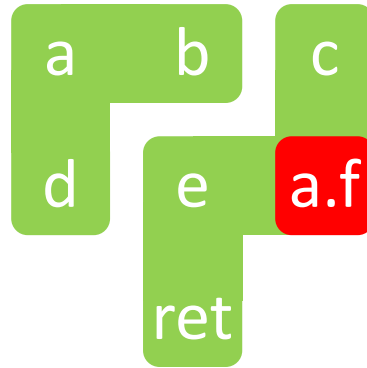
```
L1: x = new A();  
L2: y = new A();  
L3: z = new A();  
L4: w = new A();  
    x.f = w;  
    v = f(x, y, z);
```



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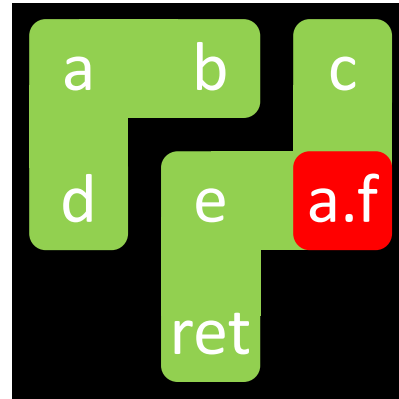
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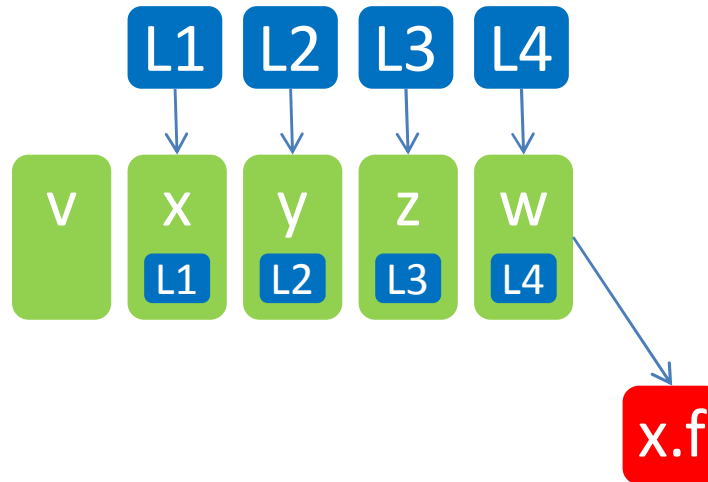
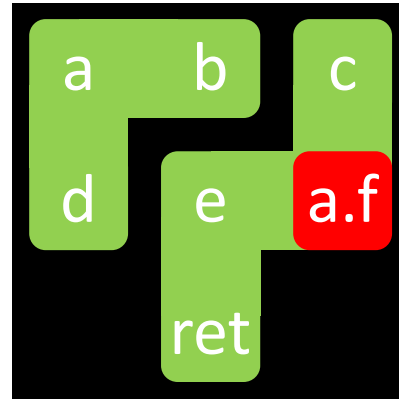
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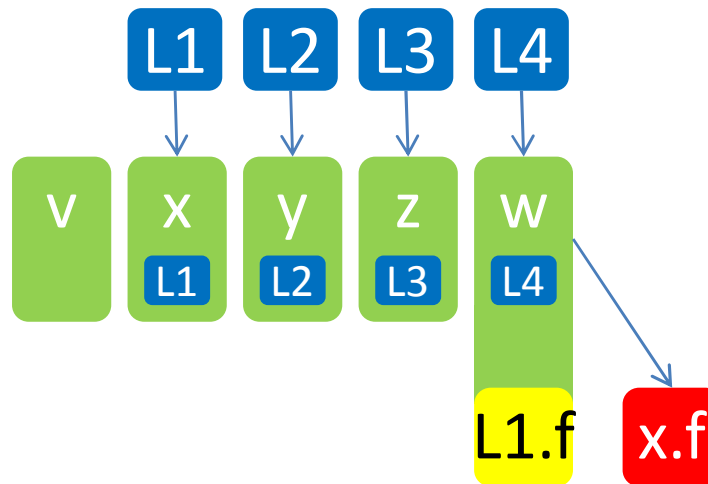
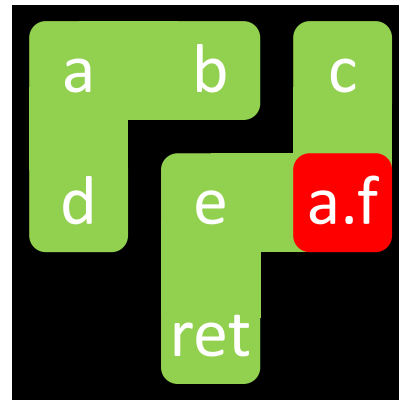
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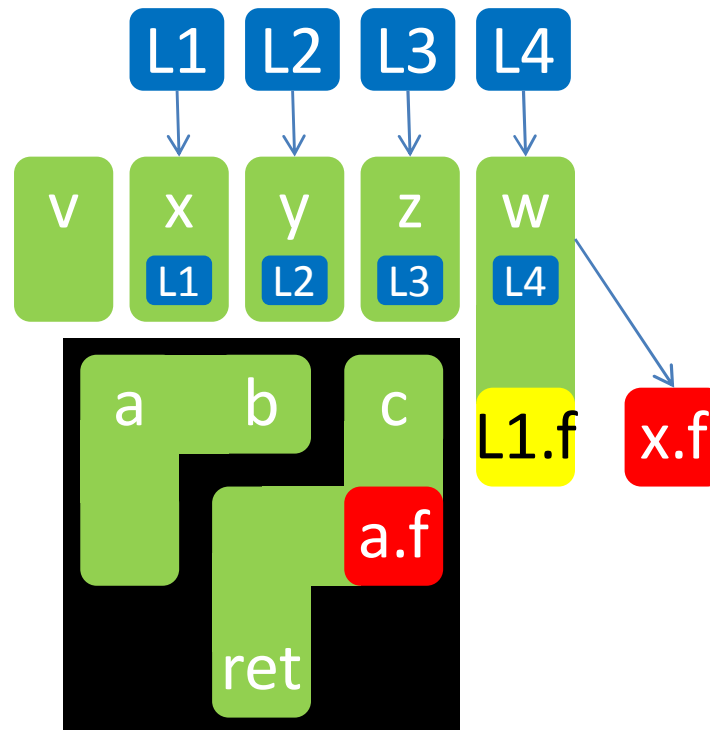
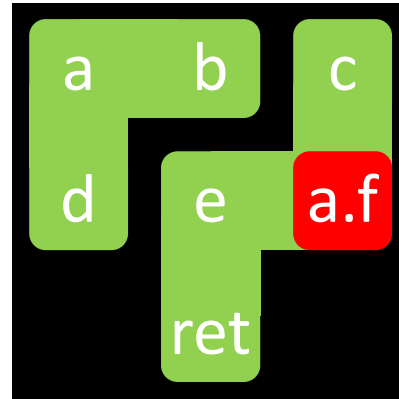
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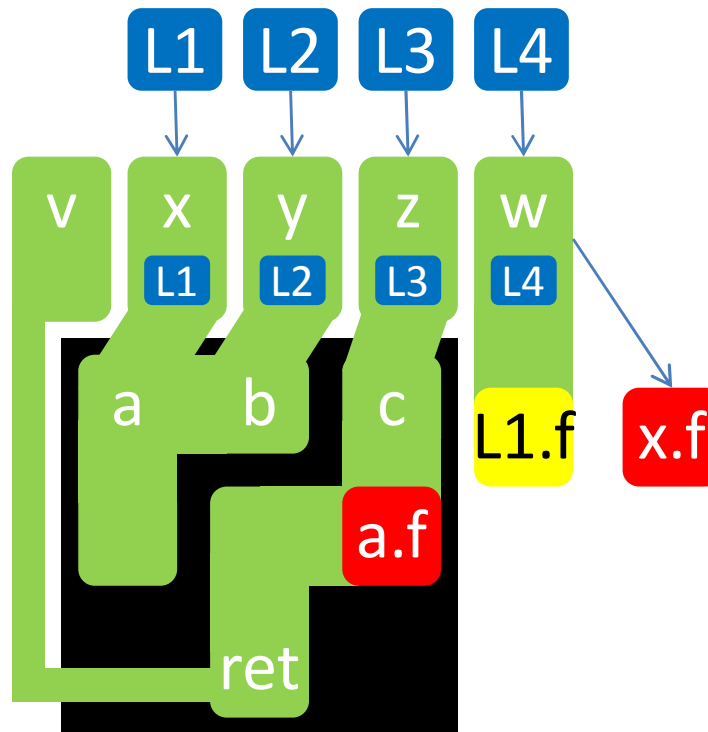
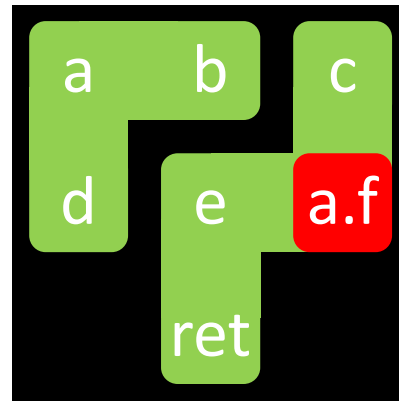


[Lattner&Adve]

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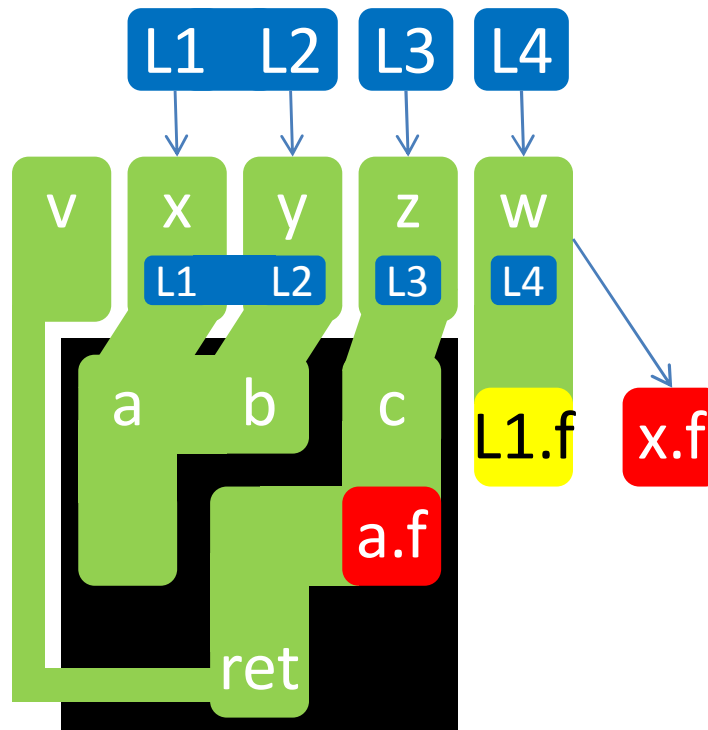
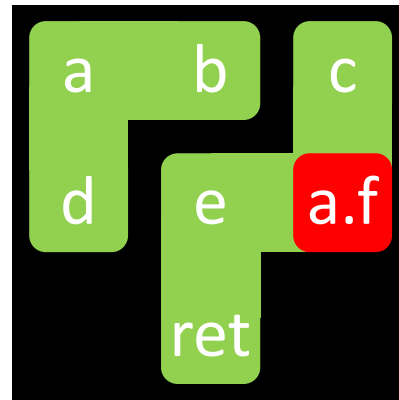


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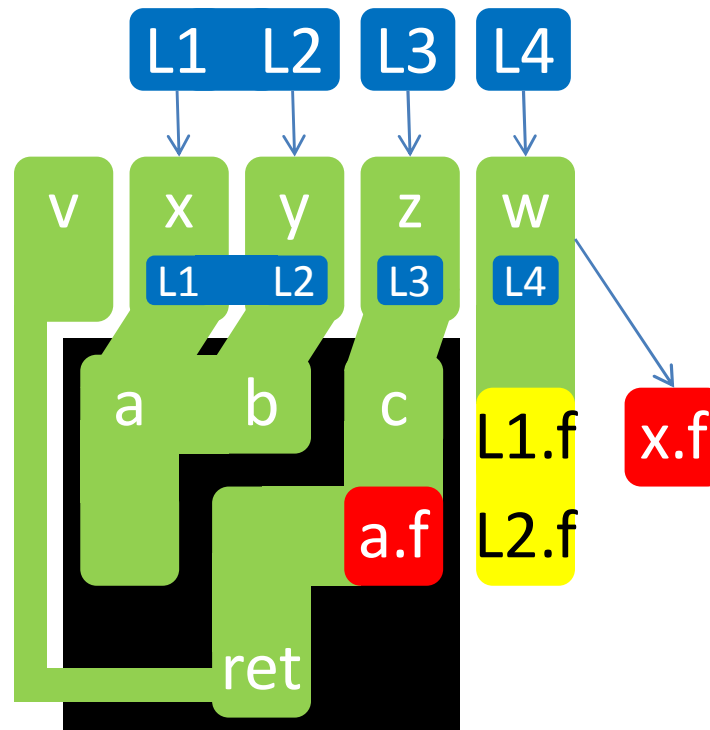
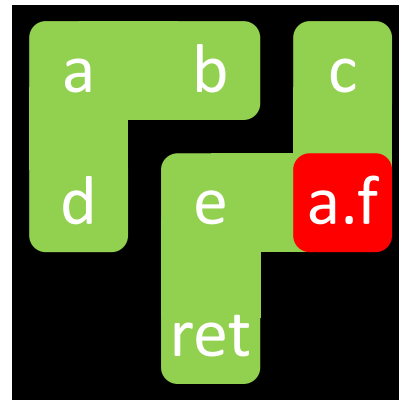


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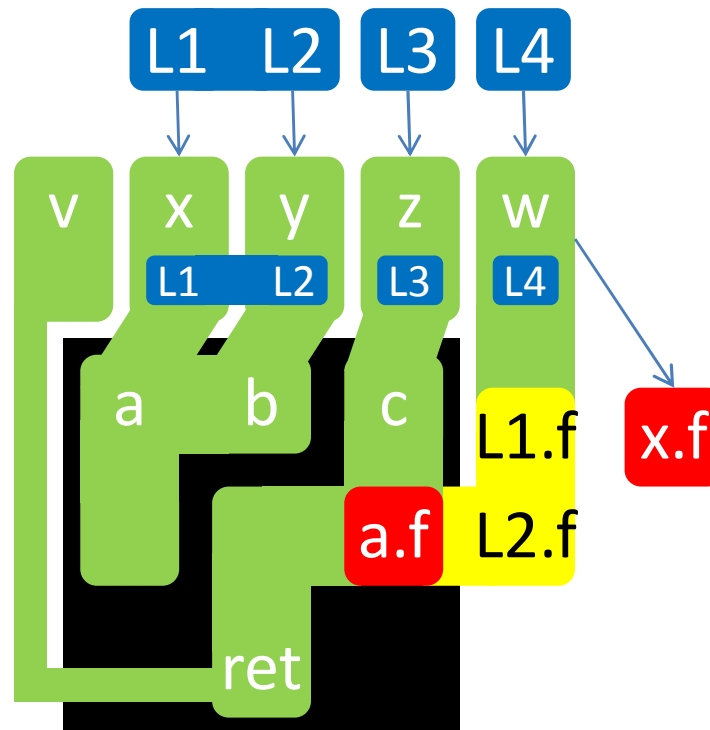
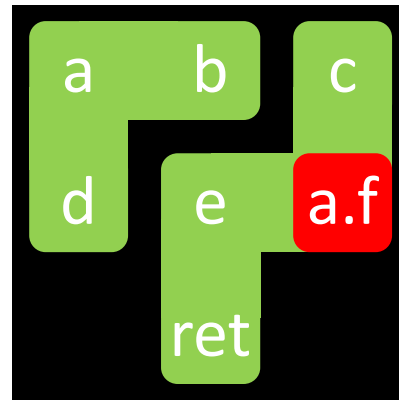
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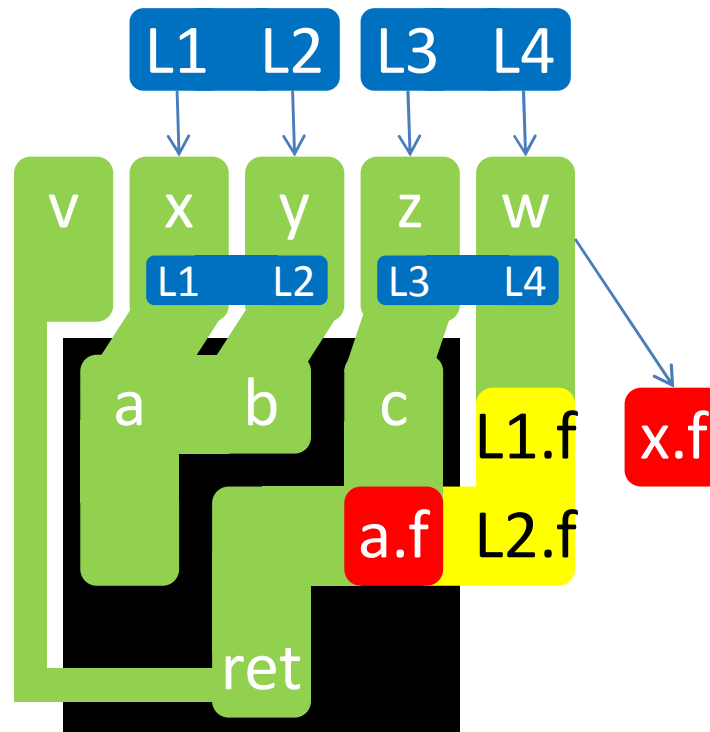
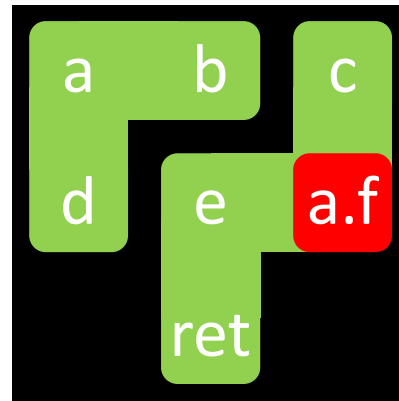


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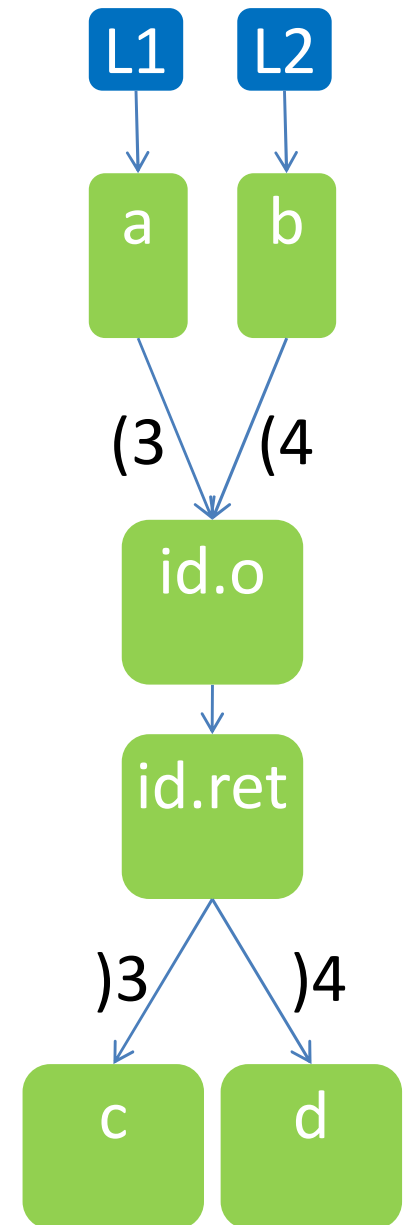
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[Lattner&Adve]

Refinement demand-driven analysis

```
Object id(Object o) {  
    return o;  
}  
  
void f() {  
    L1: Object a = new Object();  
    L2: Object b = new Object();  
    L3: Object c = id(a);  
    L4: Object d = id(b);  
}
```

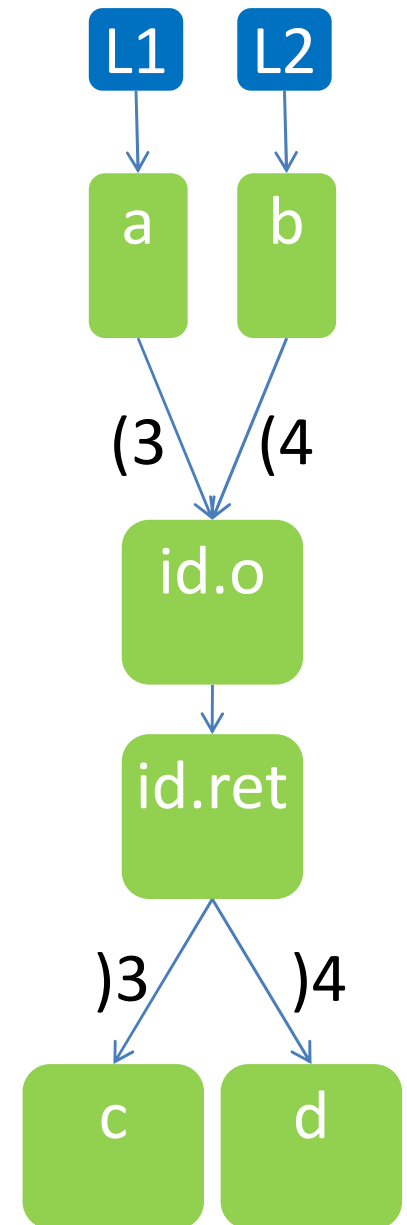


[Sridharan&Bodík]

Refinement demand-driven analysis

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    L3: Object c = id(a);  
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}
```

$L1 \in \text{pt}(d) \Leftrightarrow \exists \text{ balanced-parens path from } L1 \text{ to } d$

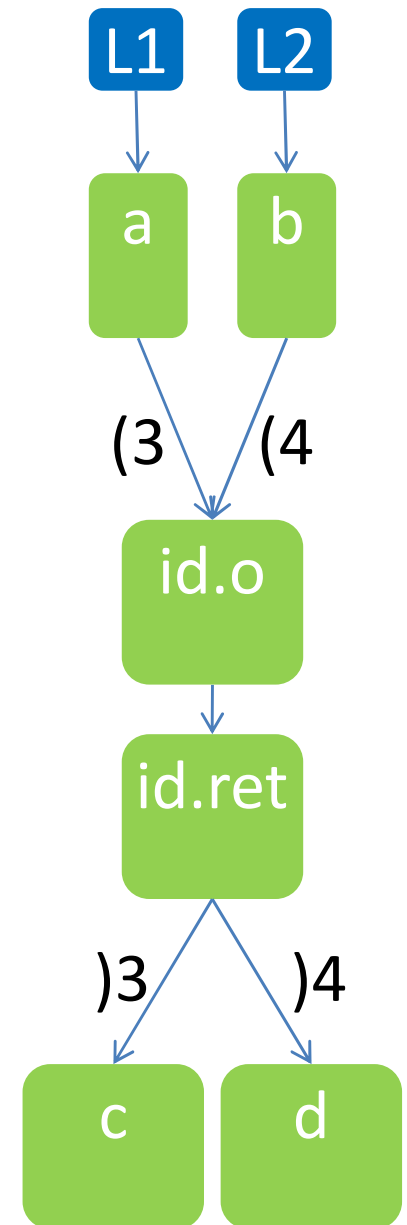


[Sridharan&Bodík]

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}
```

$L1 \in \text{pt}(d) \Leftrightarrow \exists$ balanced-parens path from L1 to d
But there are lots of paths to search.



[Sridharan&Bodík]

Refinement demand-driven analysis

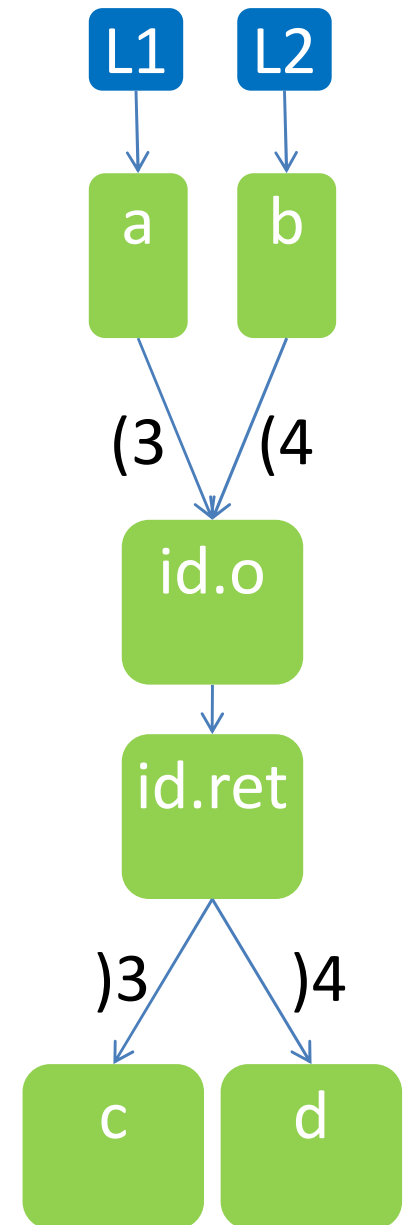
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```

$L1 \in \text{pt}(d) \Leftrightarrow \exists$ balanced-parens path from L1 to d

But there are lots of paths to search.

Add shortcut edges to graph.

No path even with shortcuts $\Rightarrow$ no path at all.



[Sridharan&Bodík]

Refinement demand-driven analysis

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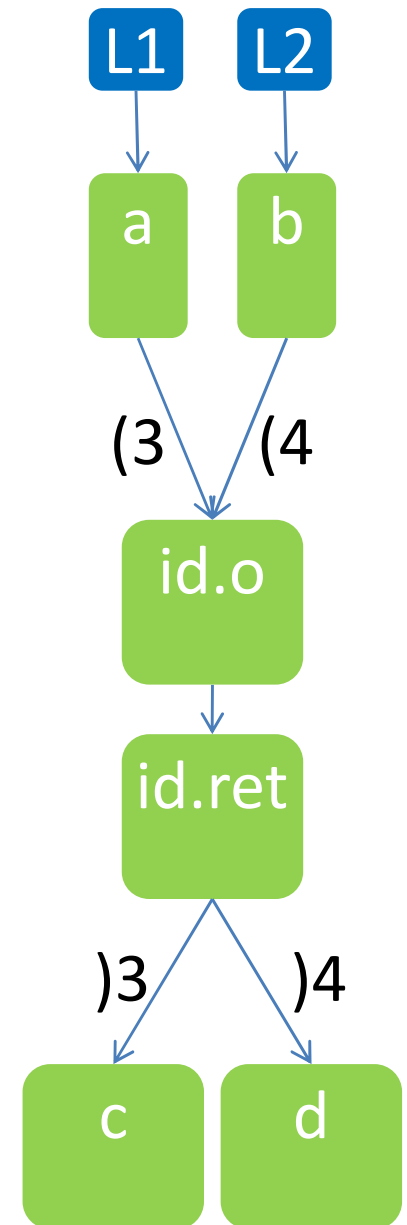
$L1 \in \text{pt}(d) \Leftrightarrow \exists$ balanced-parens path from L1 to d

But there are lots of paths to search.

Add shortcut edges to graph.

No path even with shortcuts $\Rightarrow$ no path at all.

On balanced paths found, gradually remove shortcuts.



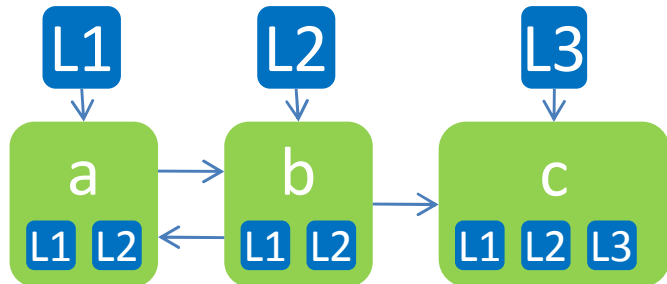
[Sridharan&Bodík]

Design decisions for precision/efficiency

- The abstraction (affects precision and efficiency):
 - Type filtering
 - Field sensitivity
 - Directionality
 - Call graph construction
 - Context sensitivity
 - Flow sensitivity
- Algorithm and implementation (affects efficiency)
 - Propagation algorithm
 - Set implementation

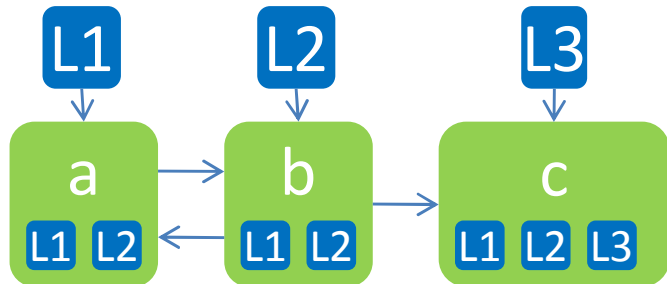
Flow sensitivity

```
L1: a = new Object();  
L2: b = new Object();  
L3: c = new Object();  
L4: a = b;  
L5: b = a;  
L6: c = b;
```



Flow sensitivity

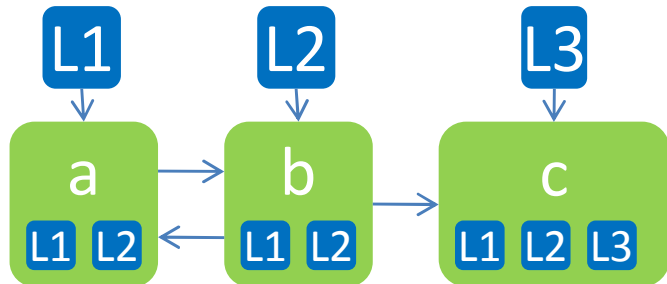
L1: a = new Object();	a -> {L1}
L2: b = new Object();	a -> {L1}, b -> {L2}
L3: c = new Object();	a -> {L1}, b -> {L2}, c -> {L3}
L4: a = b;	a -> {L2}, b -> {L2}, c -> {L3}
L5: b = a;	a -> {L2}, b -> {L2}, c -> {L3}
L6: c = b;	a -> {L2}, b -> {L2}, c -> {L2}



Strong updates: overwrite existing pt-set contents

Flow sensitivity using SSA form

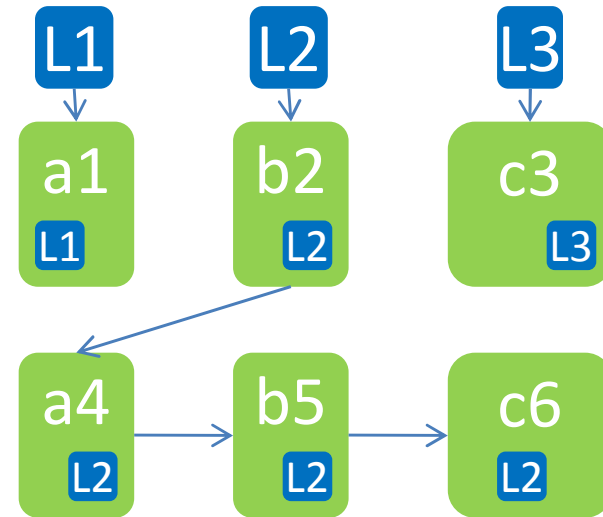
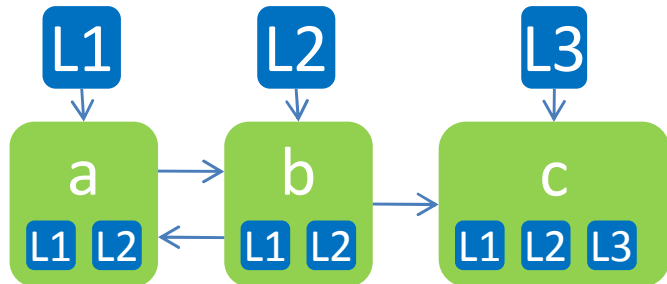
				a	b	c
L1: a = new Object();	a -> {L1}			1		
L2: b = new Object();	a -> {L1}, b -> {L2}			1	2	
L3: c = new Object();	a -> {L1}, b -> {L2}, c -> {L3}			1	2	3
L4: a = b;	a -> {L2}, b -> {L2}, c -> {L3}			4	2	3
L5: b = a;	a -> {L2}, b -> {L2}, c -> {L3}			4	5	3
L6: c = b;	a -> {L2}, b -> {L2}, c -> {L2}			4	5	6



Currently live reaching definition of each variable.

Flow sensitivity using SSA form

				a	b	c
L1: a1= new Object();	a1-> {L1}			1		
L2: b2= new Object();	a1-> {L1}, b2-> {L2}			1	2	
L3: c3= new Object();	a1-> {L1}, b2-> {L2}, c3-> {L3}			1	2	3
L4: a4= b2;	a4-> {L2}, b2-> {L2}, c3-> {L3}			4	2	3
L5: b5= a4;	a4-> {L2}, b5-> {L2}, c3-> {L3}			4	5	3
L6: c6= b5;	a4-> {L2}, b5-> {L2}, c6-> {L2}			4	5	6



For local variables, FI analysis on SSA form gives same result as FS analysis on original program.

Flow sensitivity using SSA form

	a
L1: if(*) {	
L2: a = b;	2
L3: } else {	
L4: a = c;	4
L5: }	?
L6:	?
L7: d = a;	?

Which definition of a is current at L7?

Flow sensitivity using SSA form

	a
L1: if(*) {	
L2: a = b;	2
L3: } else {	
L4: a = c;	4
L5: }	?
L6: a = $\phi(a2, a4)$	6
L7: d = a;	6

Which definition of a is current at L7?

Use ϕ to create new definition of a.

$pt(a6) = pt(a2) \cup pt(a4)$

When does flow sensitivity matter?

	Java	C/C++
local variables	no, use SSA form	
address-taken local variables	no, don't exist	possibly
global variables	unlikely, values usually long-lived	
fields of heap objects	no strong updates on heap objects unless analysis extended with single-concrete-object abstraction	

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