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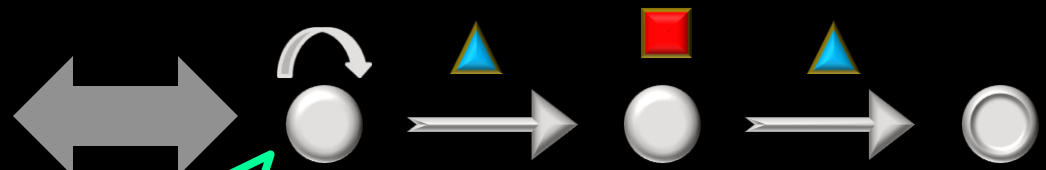
Finding Programming Errors Earlier by Evaluating Runtime Monitors Ahead-of-Time

```
boolean foo(Iterator i, Iterator j){
  while(i.hasNext() && i.hasNext()){
    if(i.next()!=j.next())
    return false;
  }
  return true;
}
```

property specification


```
boolean foo(Iterator i, Iterator j){
  while(i.hasNext() && i.hasNext()){
    if(i.next()!=j.next())
    return false;
  }
  return true;
}
```



No missed violations!

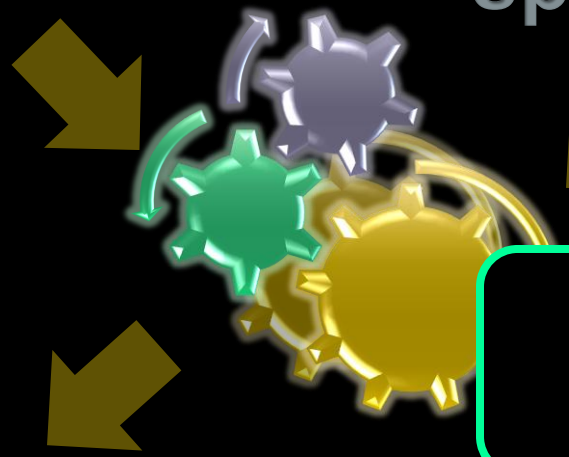
Problem 1:

Potentially large **runtime overhead**

Problem 2:
Dynamic, with no static guarantees

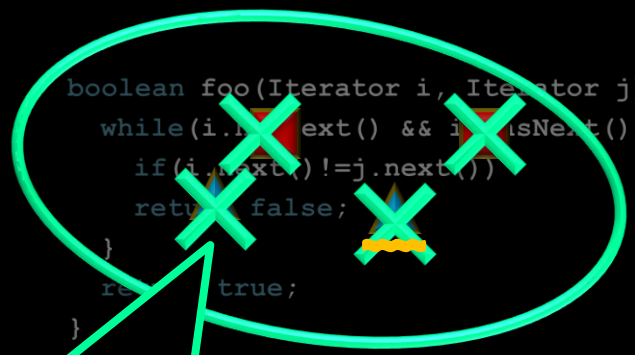
```
boolean foo(Iterator i, Iterator j){
  while(i.hasNext() && i.hasNext()){
    if(i.next()!=j.next())
    return false;
  }
  return true;
}
```

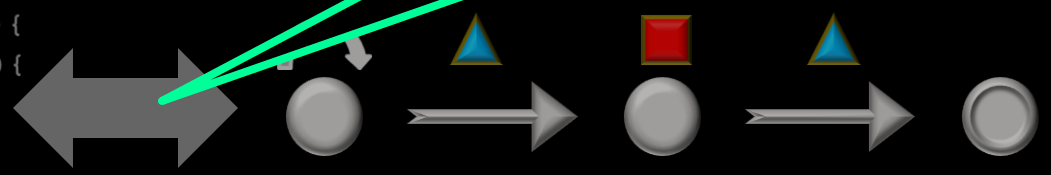
bug pattern specification



Novel static program analysis

Optimized Runtime





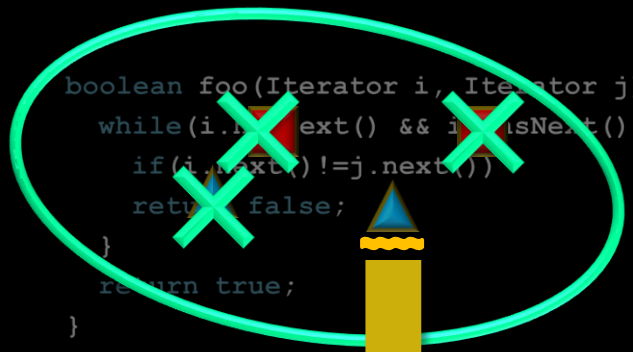
No missed violations!

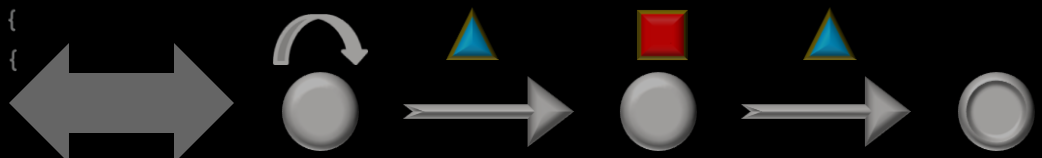
Problem 3:
Existing sound static approaches have many false positives

```
boolean foo(Iterator i, Iterator j){
  while(i.hasNext() && i.hasNext()){
    if(i.next()!=j.next())
    return false;
  }
  return true;
}
```

bug pattern specification

Novel static program analysis





Classification

Most simple example: HasNext

Don't call `next()` twice on an Iterator i without calling `hasNext()` in between!

Tracematch *HasNext*

```
tracematch(Iterator i) {

}
```

Allan *et al.*, OOPSLA 05

Tracematch *HasNext*

```
tracematch(Iterator i) {
   sym hasNext after returning:
      call(* Iterator.hasNext()) && target(i);
   sym next after returning:
      call(* Iterator.next()) && target(i);





}
```

Allan *et al.*, OOPSLA 05

Tracematch *HasNext*

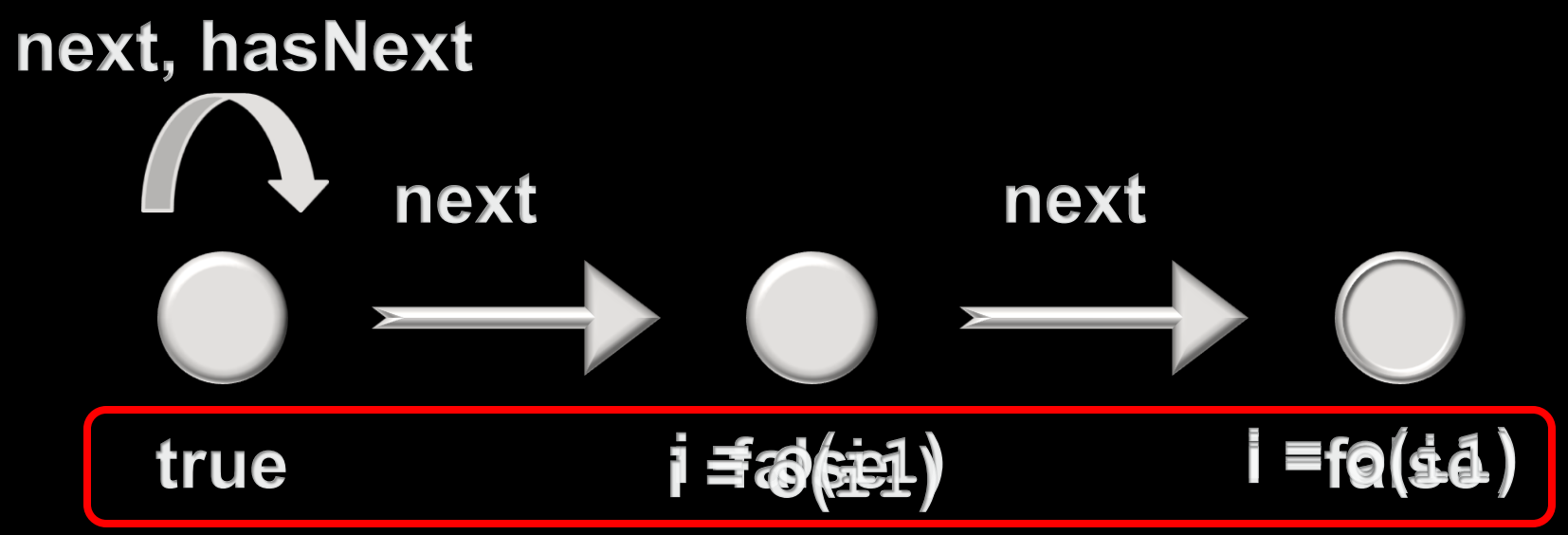
```
tracematch(Iterator i) {
   sym hasNext after returning:
      call(* Iterator.hasNext()) && target(i);
   sym next after returning:
      call(* Iterator.next()) && target(i);

   next next



}
```

Allan *et al.*, OOPSLA 05

Tracematch *HasNext*

```
tracematch(Iterator i) {
   sym hasNext after returning:
      call(* Iterator.hasNext()) && target(i);
   sym next after returning:
      call(* Iterator.next()) && target(i);

   next next
   {
      System.out.println(
            "Called 'next' twice on"+i+"!");
   }
}
```

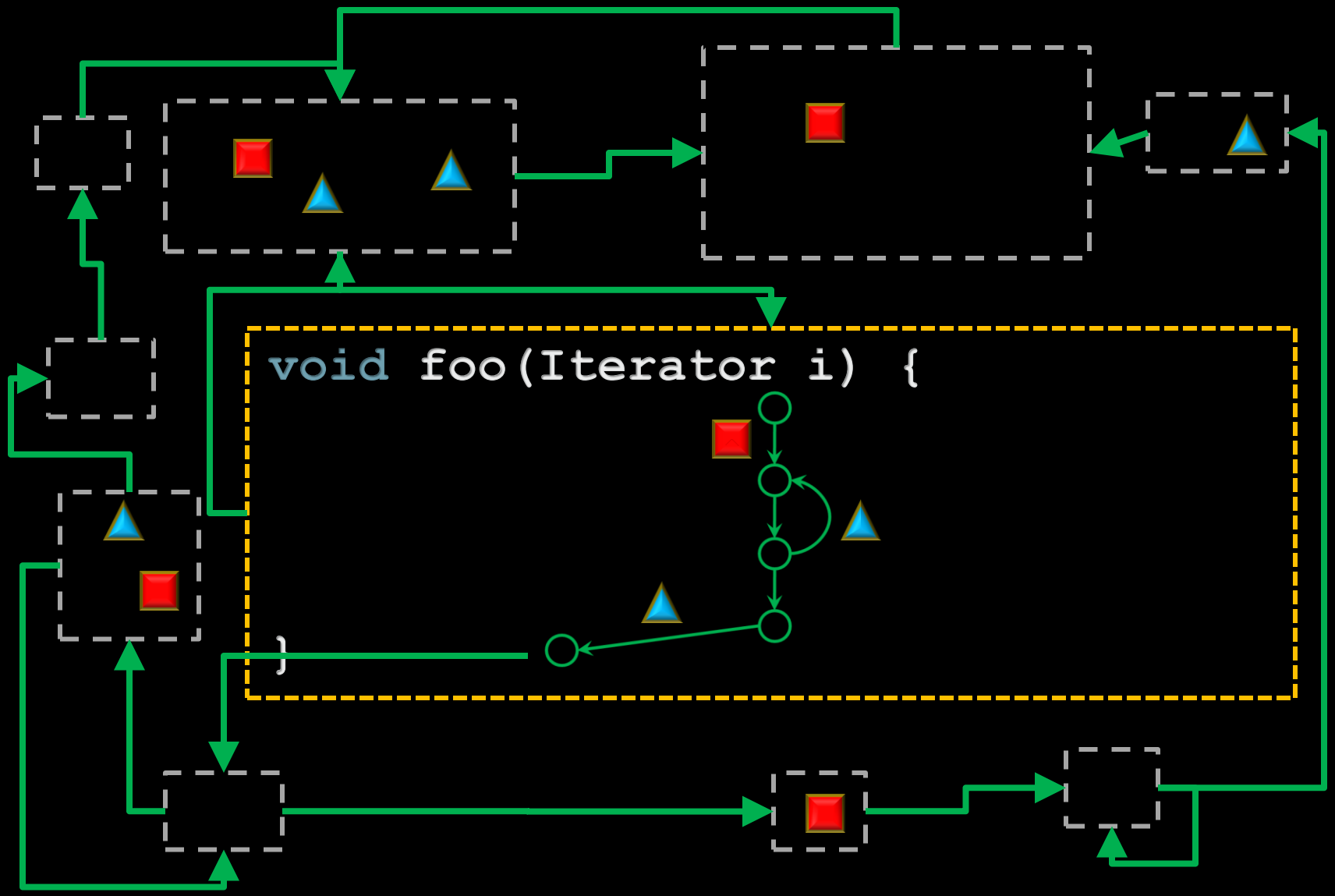
Allan *et al.*, OOPSLA 05



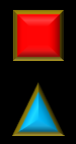

```
{
    System.out.println(
    "Called 'next' twice on"+i+"!");
}
```

Novel static program analyses

Trade-off: Speed vs. Precision



Summary Information

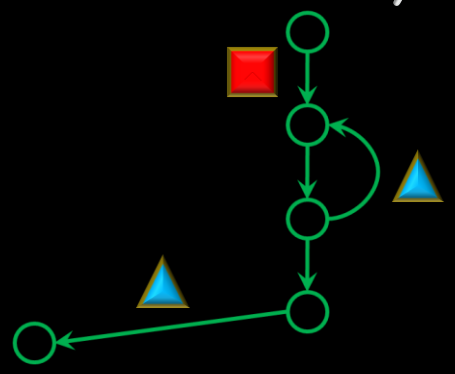


For every program variable `i`:

Can program variable `j` point to the same object as `i`?

"Only `hasNext()` and `next()`"

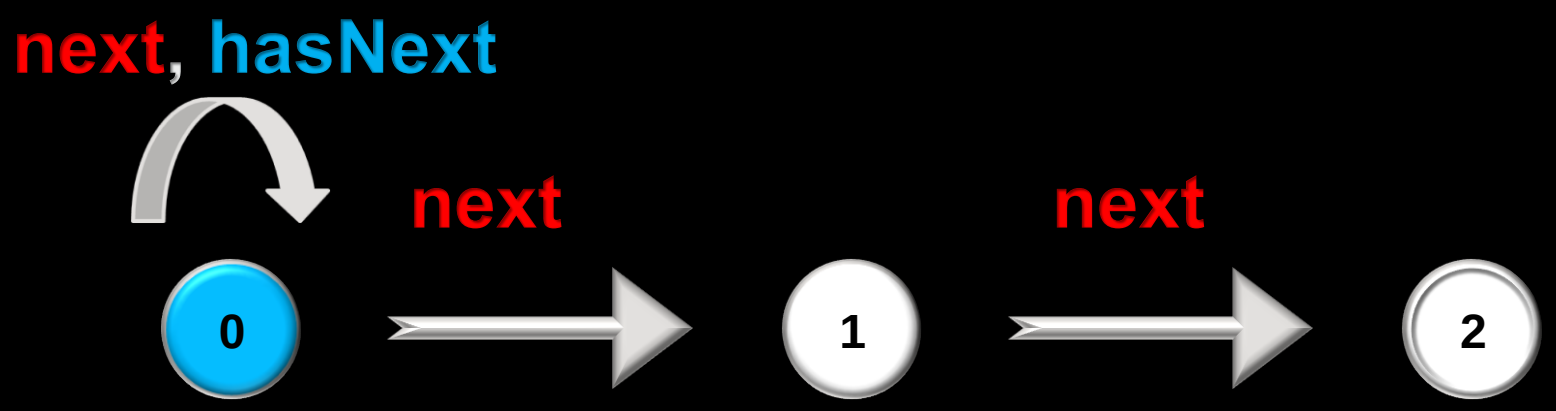
```
void foo(Iterator i) {
}
```



Problem 1:
Missing info at method entry

```
void foo(Iterator i) {

    i.next();

}
```

Key observation!

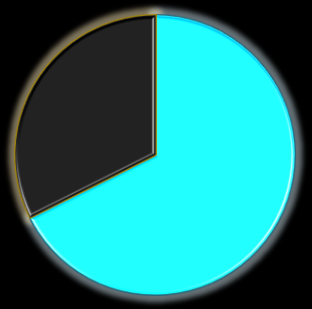


→ Possible targets of "hasNext"

→ *"hasNext" is a state-determining symbol!*

Key observation!

Benchmarks: ***68% of symbols*** are state-determining



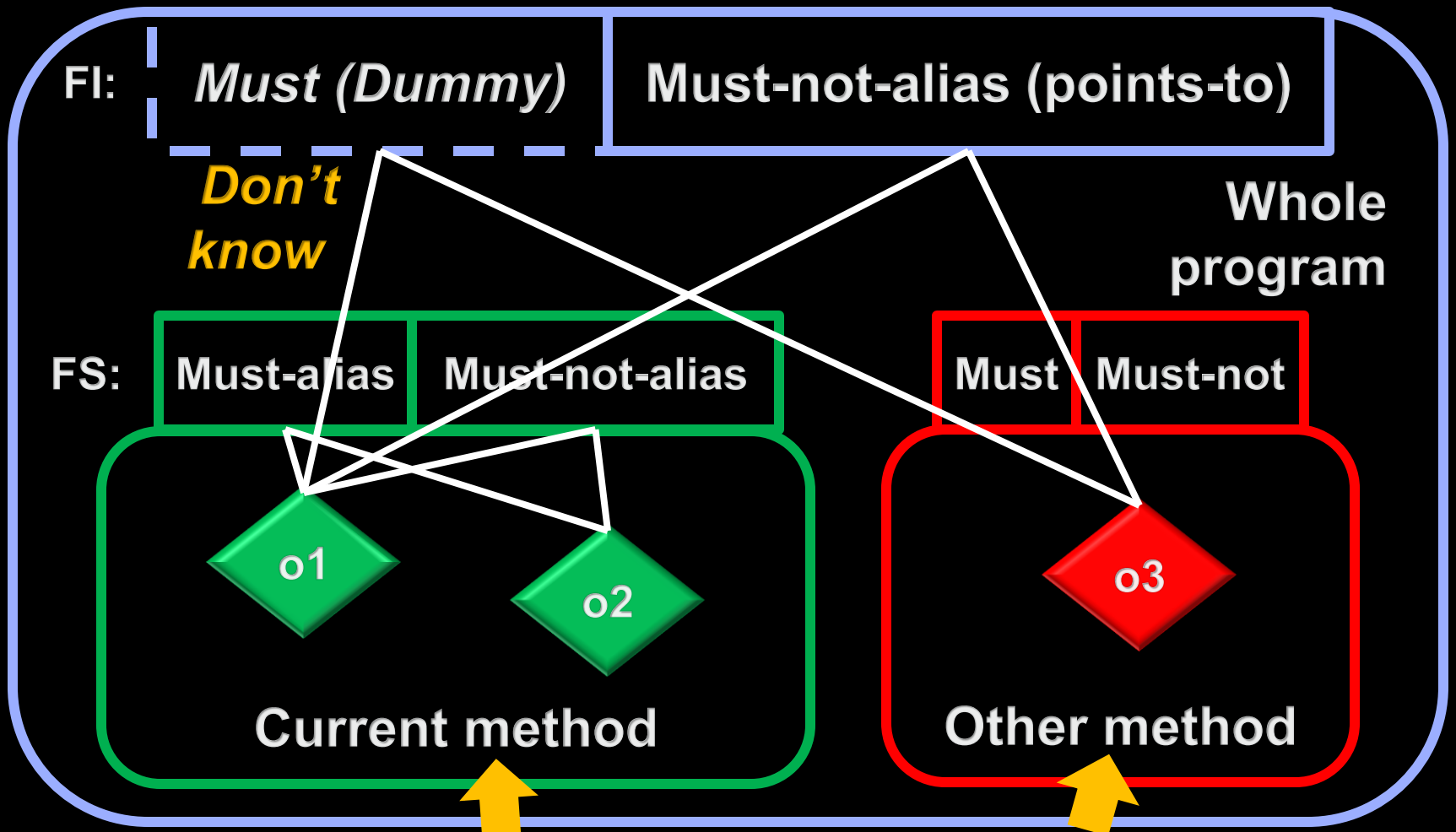
Problem 1:
Missing info at method entry

```
void foo(Iterator i) {
  if(i.hasNext()) {
    i.next();
  }
}
```

Problem 2: Aliasing

```
void foo(Iterator i) {
  if(i.hasNext()) {
    Iterator i2=i;
    i2.next();
  }
}
```

Object representatives



Precision where we need it

Speed where we need it

Problem 3:
Outgoing method calls?

```
void foo(Iterator i) {
  if(i.hasNext()) {
    bar(i);
    i.next();
  }
}
```

Summary Information

`bar(i)` may only call `hasNext()` on `i`!

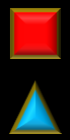
Problem 4: Continuati

NO! *Can we remove the instrumentation here?* NO!

```
void foo(Ite      or i) {
  if(i.hasNex    ()
    i.next();
  }
}
```

No missed violations at runtime!

Summary Information



Rest of program may call `next()` on `i`!

Let the fun begin…
binding multiple objects!

For every Collection `c` and Iterator `i`:

Don't modify `c` while `i` is used on `c`.

Let the fun begin…
binding multiple objects!

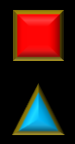
```
void whiz(Collection c1){

  Iterator i1 = c1.iterator();

  i1.next();

}
```

Solution: "Uniqueness Check"

Prove that:

$$i = o(i1) \rightarrow c = o(c1)$$

Summary Information



Requires clever combination of pointer analyses (using object representatives).

Benchmarks - Tracematches

ASyncIteration	HasNextElem
FailSafeEnum	LeakingSync
FailSafeIter	Reader
HashMap	Writer
HasNext	

Benchmark programs

DaCapo:

antlr	hsqldb
bloat	jython
chart	lucene
eclipse	pmd
fop	xalan

… and SciMark (with 4 extra tracematches)

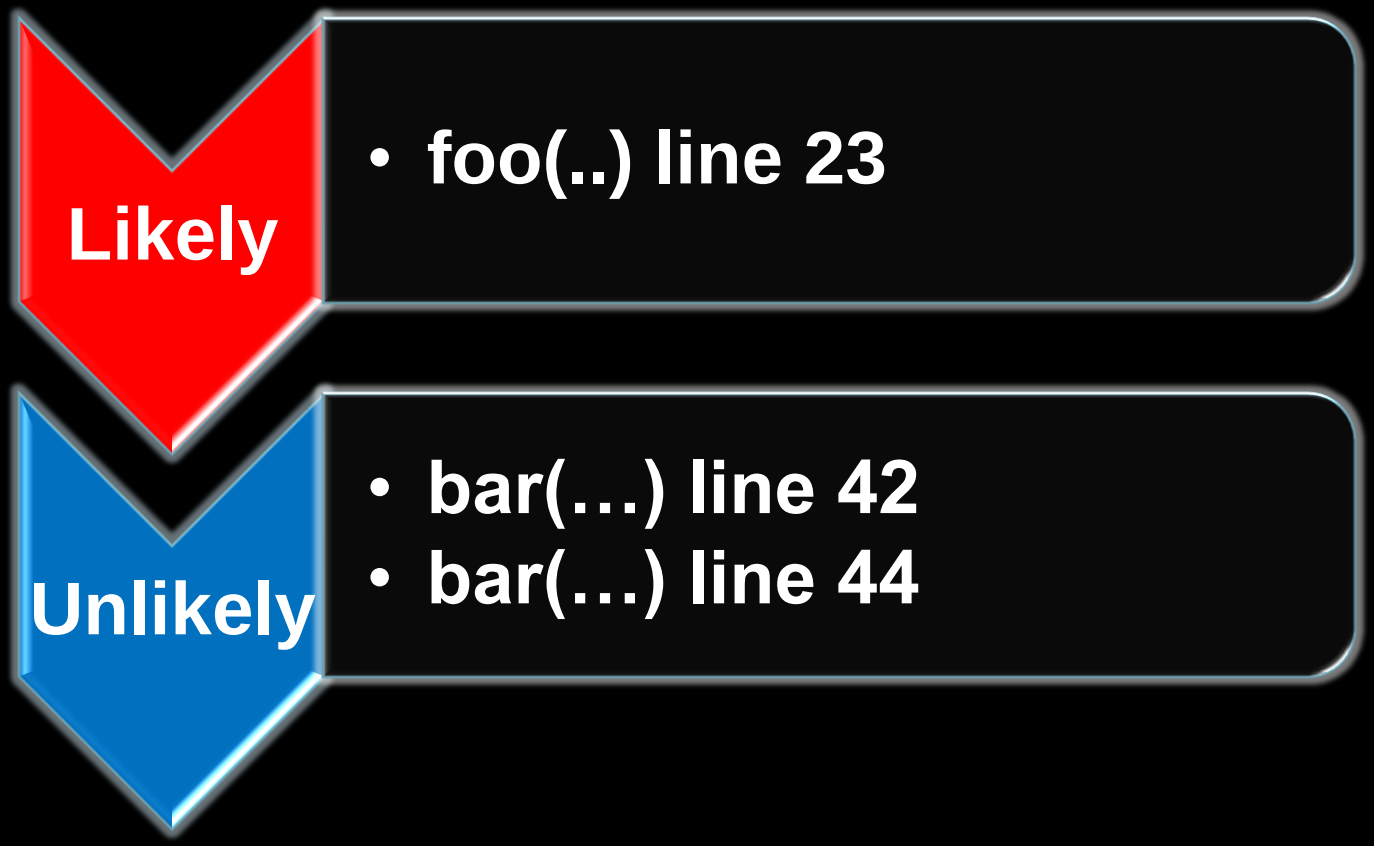
Results – Elimination of potential failure points

103 program/tracematch combinations

static guarantees in 84 cases

in 14 cases: less than 10 potential failure points

Classification of potential failure points



Analysis annotates *potential* failure points

```
HasNext:
next - <InductionVarAnalyzer.isMu(..)>
     @ line 217
next - <InductionVarAnalyzer.isMu(..)>
     @ line 218


HasNext:
next    - <CodeGenerator.removeEmptyBl(..)>
     @ line 587
hasNext - <CodeGenerator.removeEmptyBl(..)>
     @ line 586
```

Analysis annotates *potential* failure points

```
HasNext: features []
next - <InductionVarAnalyzer.isMu(..)>
     @ line 217
next - <InductionVarAnalyzer.isMu(..)>
     @ line 218


HasNext: features [CALL]
next    - <CodeGenerator.removeEmptyBl(..)>
     @ line 587
hasNext - <CodeGenerator.removeEmptyBl(..)>
     @ line 586
```

Features: Reasons for imprecision

- CALL
- ABORTED
- NO_CONTEXT
- DELEGATE

- CONTINUATION
- DYNAMIC_LOADING
- OVERLAPS

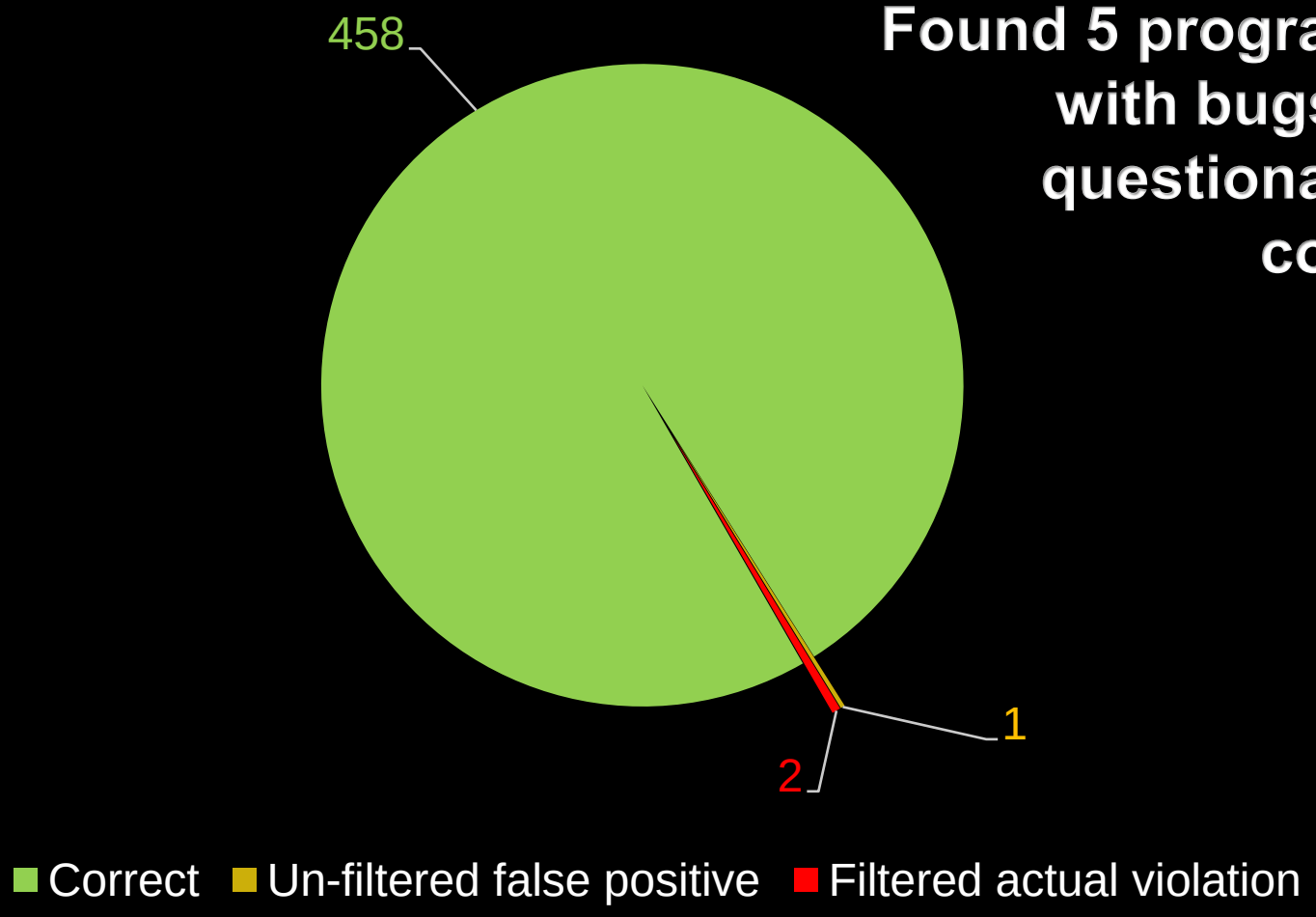
Manually annotated *actual* failure points

```
HasNext: features [], ACTUAL
next - <InductionVarAnalyzer.isMu(..)>
     @ line 217
next - <InductionVarAnalyzer.isMu(..)>
     @ line 218


HasNext: features [CALL]
next    - <CodeGenerator.removeEmptyBl(..)>
     @ line 587
hasNext - <CodeGenerator.removeEmptyBl(..)>
     @ line 586
```

Weka machine learning kit

```
CALL = 0
| ABORTED = 0
| | DELEGATE = 0
| | | NO_CONTEXT = 0: TRUE_POSITIVE (11.0/1.0)
| | | NO_CONTEXT = 1: FALSE_POSITIVE (4.0/1.0)
| | DELEGATE = 1: FALSE_POSITIVE (10.0)
| ABORTED = 1: FALSE_POSITIVE (30.0)
CALL = 1: FALSE_POSITIVE (406.0/1.0)
```

Results – Filtering



Found 5 programs with bugs or questionable code.

Related work: Typestate

Static and hybrid verification of typestate props.

- Typestate (Strom & Yemini, TSE Vol 12 No. 1, 86)
- Fugue for .NET (DeLine & Fähndrich, ECOOP 04)
- Typest. & Aliasing (Bierhoff & Aldrich, OOPSLA 07)
- Hybrid static/dynamic (Dwyer & Purandare, ASE 07)

Related work: Tracematch-like

Flow-sensitive analysis of Tracematches

- Naeem and Lhoták, OOPSLA 08

Other state-based runtime-verification tools for Java

- JavaMOP (Chen & Roşu, OOPSLA 08)
- PQL (Martin, Livshits & Lam, OOPSLA 05)
- PTQL (Goldsmith, O'Callahan & Aiken, OOPSLA 05)

Related work: Static checkers

Static checkers

- FindBugs (Hovemeyer & Pugh, OOPSLA 04)
- PMD (http://pmd.sf.net/)

Pre and postconditions, invariants

- ESC/Java (Flanagan *et al.*, PLDI 02)
- Java Modeling Language (JML)

Specialized interprocedural analyses

- Jlint (http://artho.com/jlint/)

Comparison: Rutar *et al.*, ISSRE 04

Related work: Invariant mining and checking

Dynamic invariant inference and checking

- Daikon (Ernst *et al.*, TSE Vol 27. No 2, 01)
- DIDUCE (Hangal & Lam, ICSE 02)
- JADET (Wasylkowski *et al.*, FSE 07)
- Spec. Mining (Ammons *et al.*, POPL 02)

Static rule mining and checking

- PR-Miner (Li & Zhou, FSE 05)
- Houdini (Flanagan & Leino, FME 01)

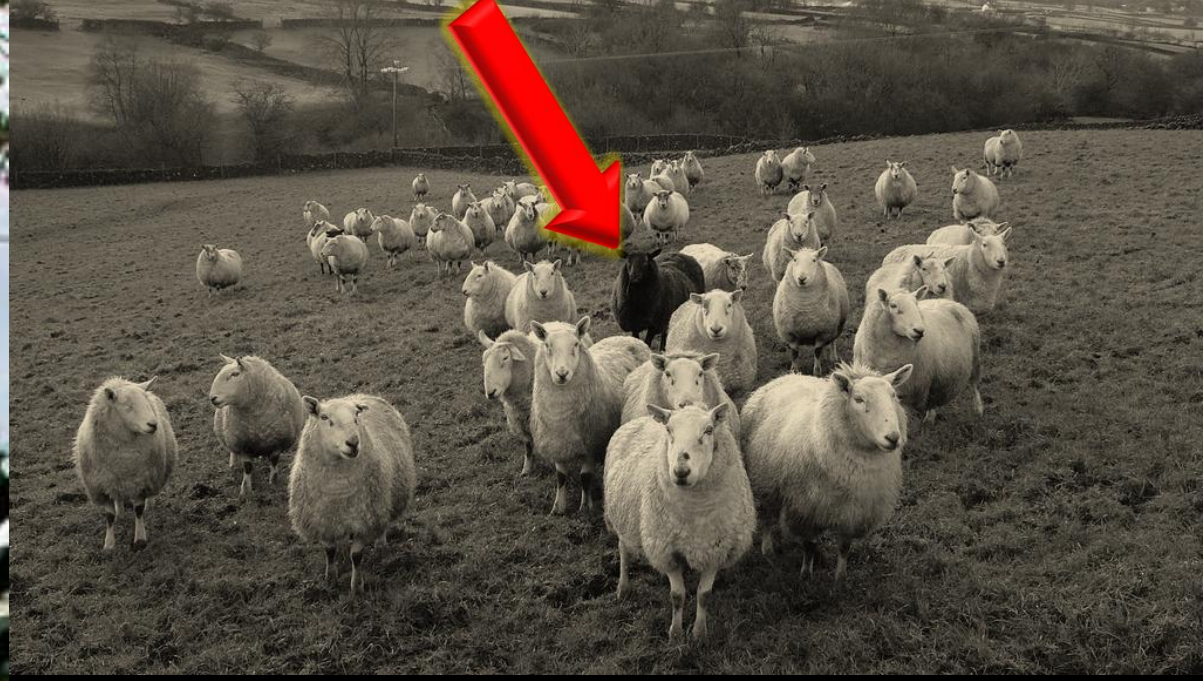
Special thanks to…

Co-workers

- Ondřej Lhoták
- Nomair Naeem

Maintainers of Tracematch implementation

- Pavel Avgustinov
- Julian Tibble



www.aspectbench.org
www.bodden.de

Jython / Reader (1/2)

```
private final void FillBuff() {
        ...
        try {
                if ((i = inputStream.read(...)) == -1) {
                        inputStream.close();
                        throw new java.io.IOException();
                }
                else
                        maxNextCharInd += i;
                return;
        }
        ...
}
```

Jython / Reader (2/2)

```
static String getLine(BufferedReader reader, int line)
{
    if (reader == null)
        return "";
    try {
        String text=null;
        for(int i=0; i < line; i++) {
            text = reader.readLine();
        }
        return text;
    } catch (IOException ioe) {
        return null;
    }
}
```

bloat-HasNext

```
public Block isMu(...) {
...
  final Iterator iter = cfg.preds(phi.block()).iterator();
  final Block pred1 = (Block) iter.next();
  final Block pred2 = (Block) iter.next();
```

pmd / HasNext (old version)

```
private List markUsages(IDataFlowNode inode) {
        ...
        for (Iterator k = ((List)entry.getValue())
                .iterator();k.hasNext();) {
                addAccess(k, inode);
        }
        ...
}

...

private void addAccess(Iterator k, IDataFlowNode inode)
{
        NameOccurrence occurrence =
                (NameOccurrence) k.next();
        ...
}
```

pmd / HasNext (fixed version)

```
private List markUsages(IDataFlowNode inode) {
        ...
        for (NameOccurrence occurrence: entry.getValue())
        {
                addAccess(occurrence, inode);
        }
        ...
}

...

private void addAccess(NameOccurrence occurrence,
                       IDataFlowNode inode) {
        ...
}
```

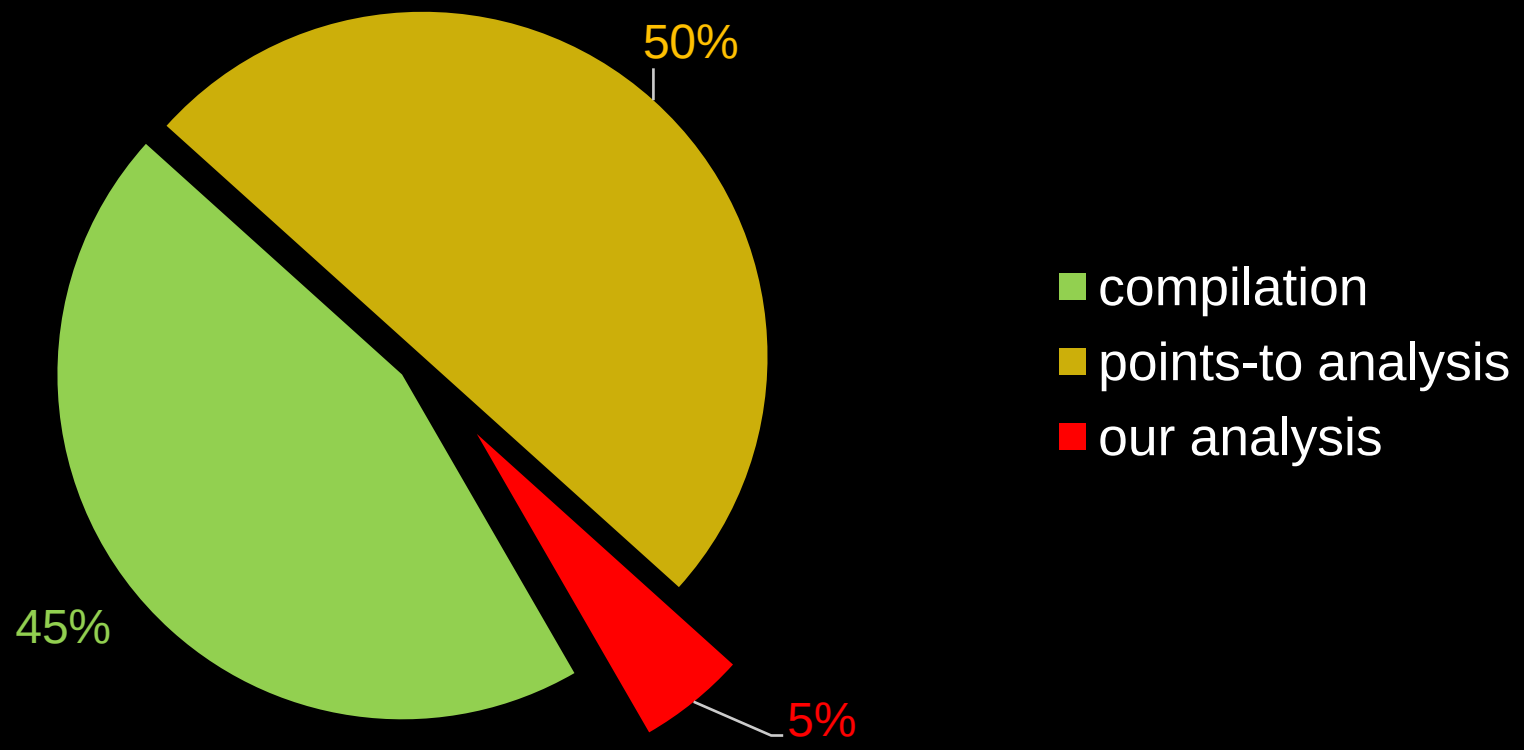
Eclipse, false positive

```
while (c == null && enumMap.hasMoreElements()) {
  ...
  if (!enumC.hasMoreElements())
  c = null;
}
// At this point, c == null if there are no more elements,
// and otherwise is the first collection with a free element
// (with enumC set up to return that element).
if (c == null) {
  // no more elements, so return null;
  return (null);
} else {
  Perm answer = (Perm) enumC.nextElement();
  ...
```

Jython / hasNext (delegate)

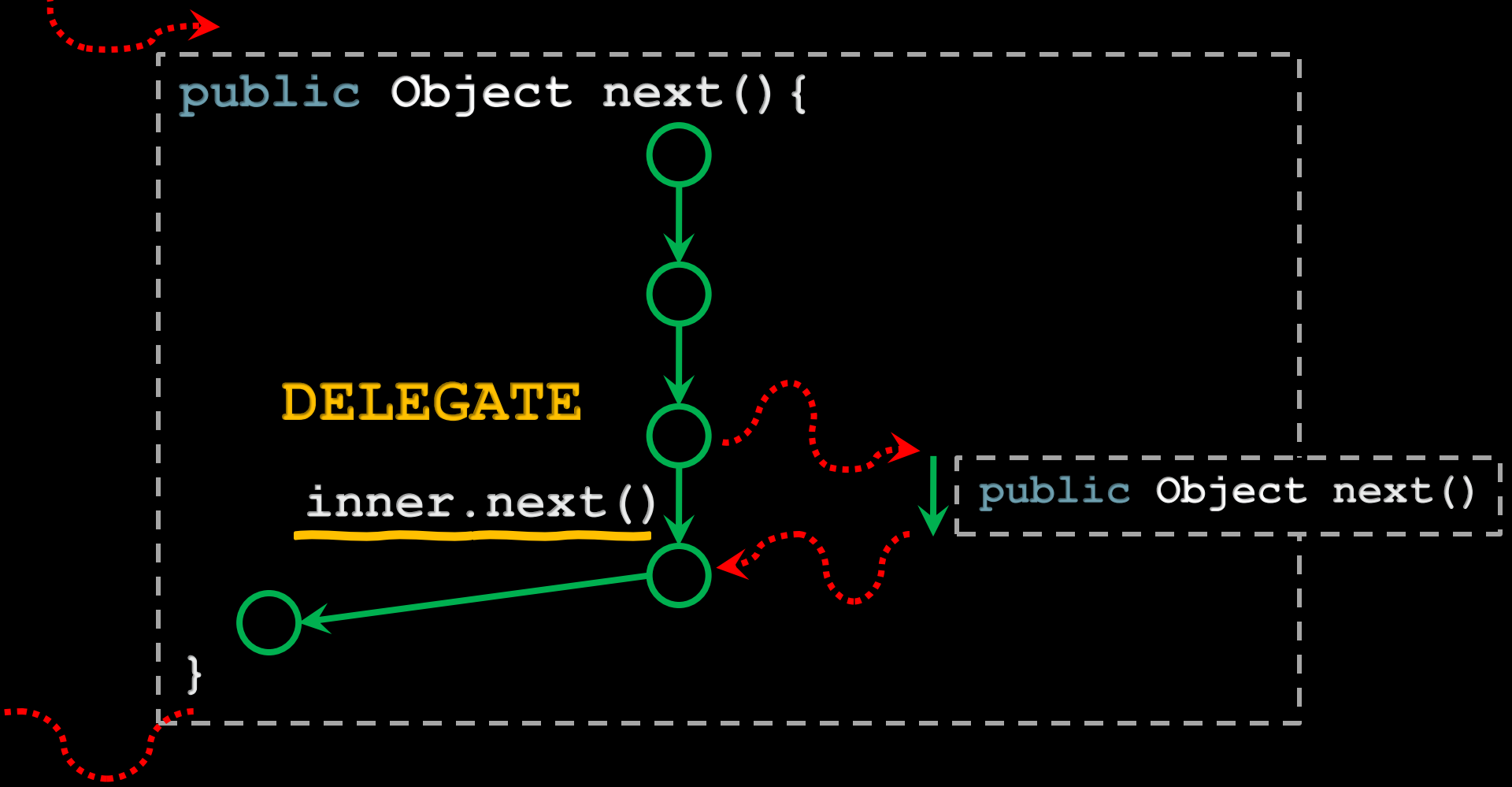
```
public Iterator iterator() {
    return new Iterator() {
        Iterator i = list.iterator();
        public void remove() {
            throw new UnsupportedOperationException();
        }
        public boolean hasNext() {
            return i.hasNext();
        }
        public Object next() {
            return i.next();
        }
    };
}
```

Results – Static analysis time

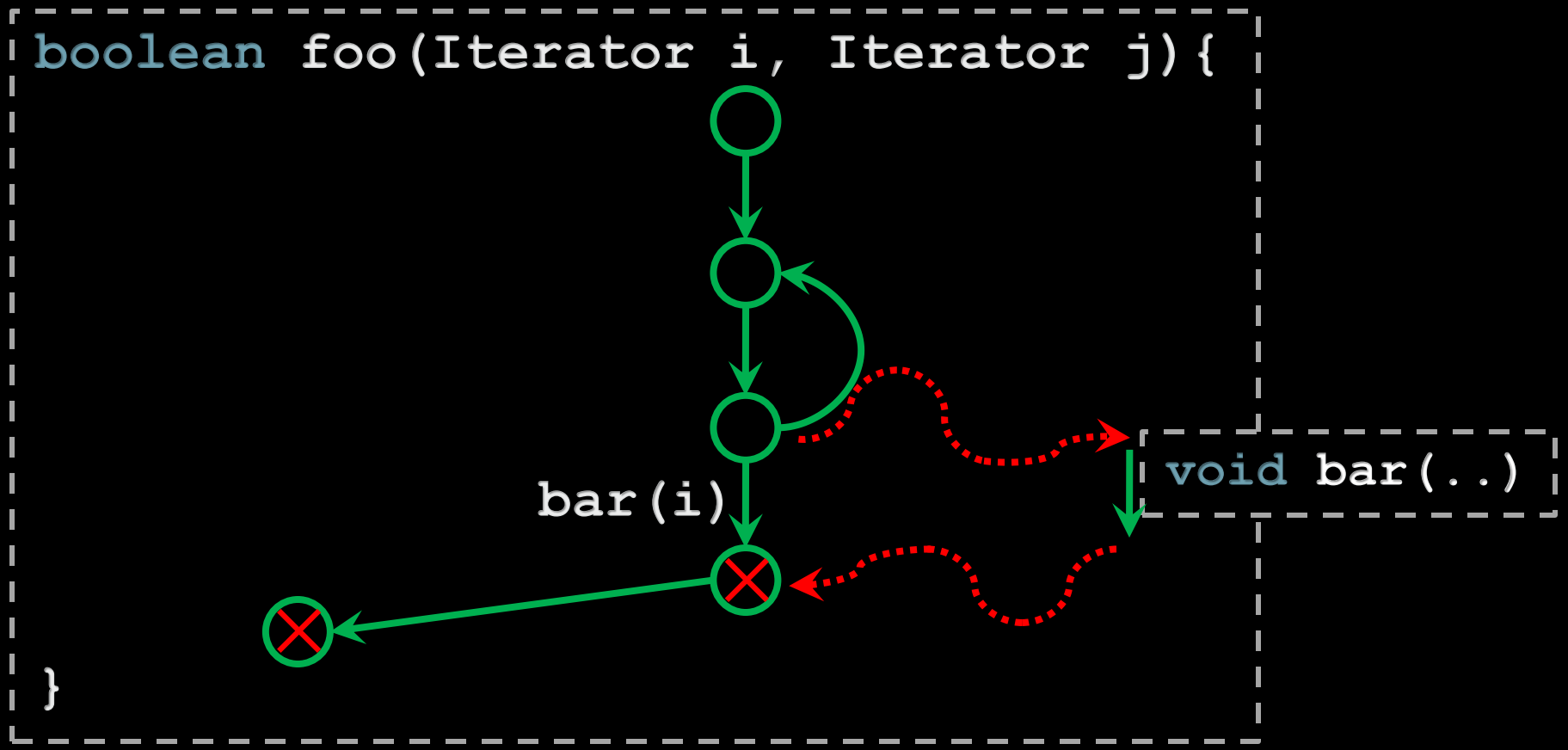


Average total: 6 minutes
Max total: 20 minutes

Delegating calls



Reasons for imprecision



CALL

Reasons for imprecision

```
boolean foz(Set c1, Set c2){

  i1 = c1.iterator();

  i2 = c2.iterator();

}
```

```
public Iterator iterator() {
   return new HashIterator();
}
```

NO_CONTEXT

Reasons for imprecision

3000

```
boolean baz(Iterator i, Iterator j){
}
```

ABORTED

Using alias queries to reduce false-positive rate

Assume we know r1 and r2 must-alias, r1 occurs in some constraint bound to x and we see an event that binds x to r2.

	$x = r1$	$x \neq r1$
$x = r2$	$x = r1 \equiv x = r2$	false
$x \neq r2$	false	$x \neq r1 \equiv x \neq r2$

Using alias queries to reduce false-positive rate

Assume we know r1 and r2 must-not-alias, r1 occurs in some constraint bound to x and we see an event that binds x to r2.

	x = r1	x ≠ r1
x = r2	false	x = r2
x ≠ r2	x = r1	x ≠ r1 ^ x ≠ r2