Reflection Analysis for Java

Benjamin Livshits,
John Whaley,
Monica S. Lam

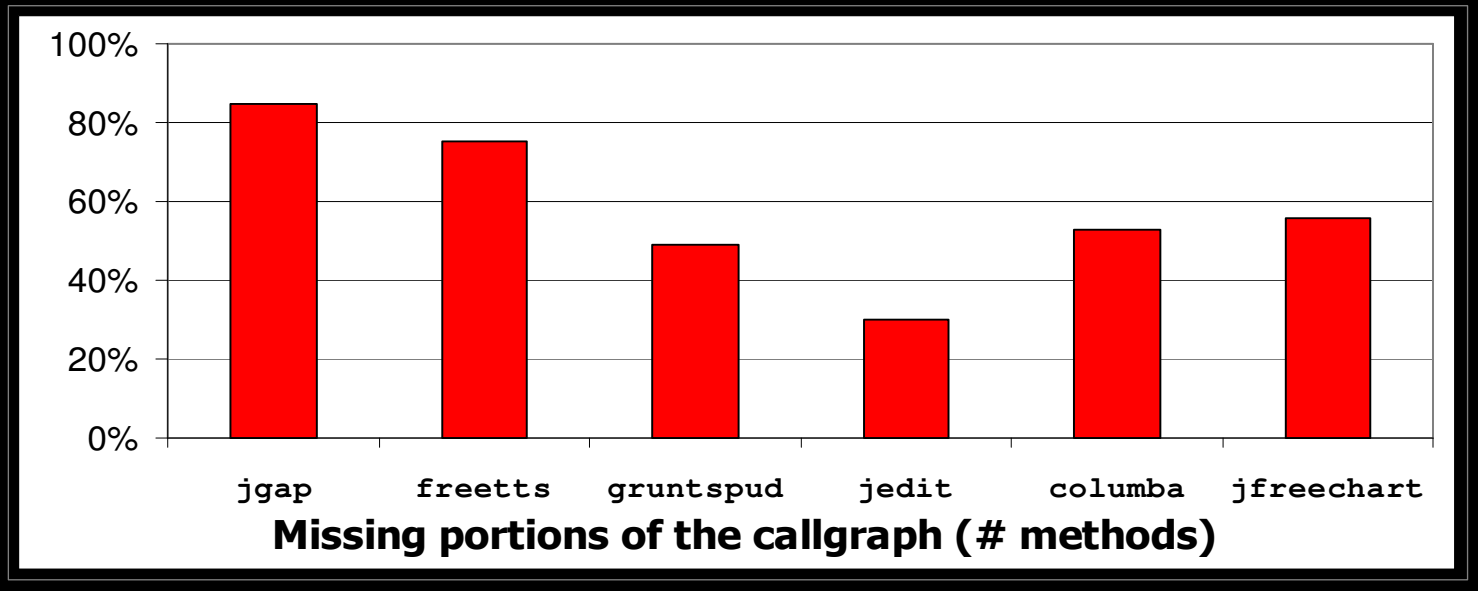
Stanford University

Background: Bug Detection

- Our focus: bug detection tools
- Troubling observation: large portions of the program are not analyzed

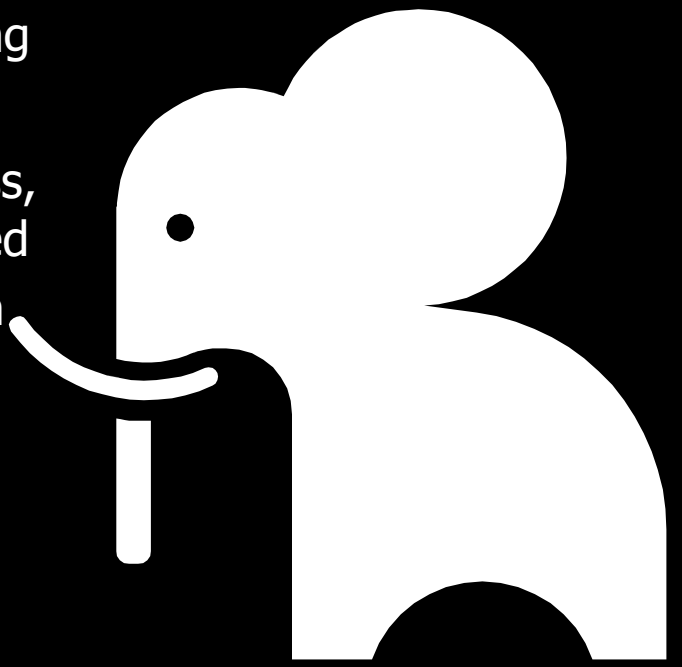
Race conditions | Memory leaks | SQL injections

null dereferences | Resource usage errors | Cross-site scripting



Reflection is to Blame

- Reflection is at the core of the problem
- Most analyses for Java ignore reflection
  - Fine approach for a while
  - SpecJVM hardly uses reflection at all
- Call graph is **incomplete**
  - **Code** not analyzed => **bugs** are missing
- Can no longer get away with this
  - Reflection is very common in Java: JBoss, Tomcat, Eclipse, etc. are reflection-based
  - Ignoring reflection misses ½ application & more
- Reflection is the proverbial **white elephant**: neglected issues nobody is talking about



Introduction to Reflection

- Reflection is a dynamic language feature
- Used to query object and class information
  - `static Class Class.forName(String className)`
    - Obtain a `java.lang.Class` object
    - I.e. `Class.forName("java.lang.String")` gets an object corresponding to class `String`
  - `Object Class.newInstance()`
    - Object constructor in disguise
    - Create a new object of a given class

```
Class  c = Class.forName("java.lang.String");
Object o = c.newInstance();
```

    - This makes a new empty string `o`

Running Example

- Most typical use of reflection:
  - Take a class name, make a `Class` object
  - Create object of that class, cast and use it

```
1. String className = ...;
2. Class  c = Class.forName(className);
3. Object o = c.newIns  new T1();
4. T t      = (T) o;    new T2();
                        ...
```

- Statically convert

  `Class.newInstance => new T()`

Other Reflective Constructs

- Object creation – most common idiom
- But there is more:
  - Access methods
  - Access fields
  - Constructor objects
- Please refer to the paper for more…

Loading Application Plugins

```
public void addHandlers(String path) {
    ...
    while (it.hasNext()) {
        XmlElement child = (XmlElement) it.next();
        String id = child.getAttribute("id");
        String clazz = child.getAttribute("class");

        AbstractPluginHandler handler = null;
        try {
            Class c = Class.forName(clazz);
            handler = (AbstractPluginHandler)
                                    c.newInstance();
            registerHandler(handler);
        } catch (ClassNotFoundException e) {
            ...
        }
    }
}
```

1

2

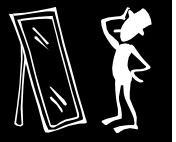
3,4

Real-life Reflection Scenarios

- Real-life scenarios:
  - Specifying application extensions
    - Read names of extension classes from a file
  - Custom object serialization
    - Serialized objects are converted into runtime data structures using reflection
  - Code may be unavailable on a given platform
    - Check before calling a method or creating an object
    - Can be used to get around JDK incompatibilities
- Our 60-page TR has detailed case studies

Talk Outline

- Introduction to Reflection
- Reflection analysis framework
  - Possible analysis approaches to constructing a call graph in the presence of reflection
  - Pointer analysis-based approximation
  - Deciding when to ask for user input
  - Cast-based approximation
  - Overall analysis framework architecture
- Experimental results
- Conclusions



What to Do About Reflection?

```
1. String className = ...;
2. Class  c = Class.forName(className);
3. Object o = c.newInstance();
4. T t      = (T) o;
```

1. Anything goes

+ Obviously conservative
- Call graph extremely big and imprecise

2. Ask the user

+ Good results
- A lot of work for user, difficult to find answers

3. Subtypes of `T`

+ More precise
- `T` may have many subtypes

4. Analyze `className`

+ Better still
- Need to know where **`className`** comes from

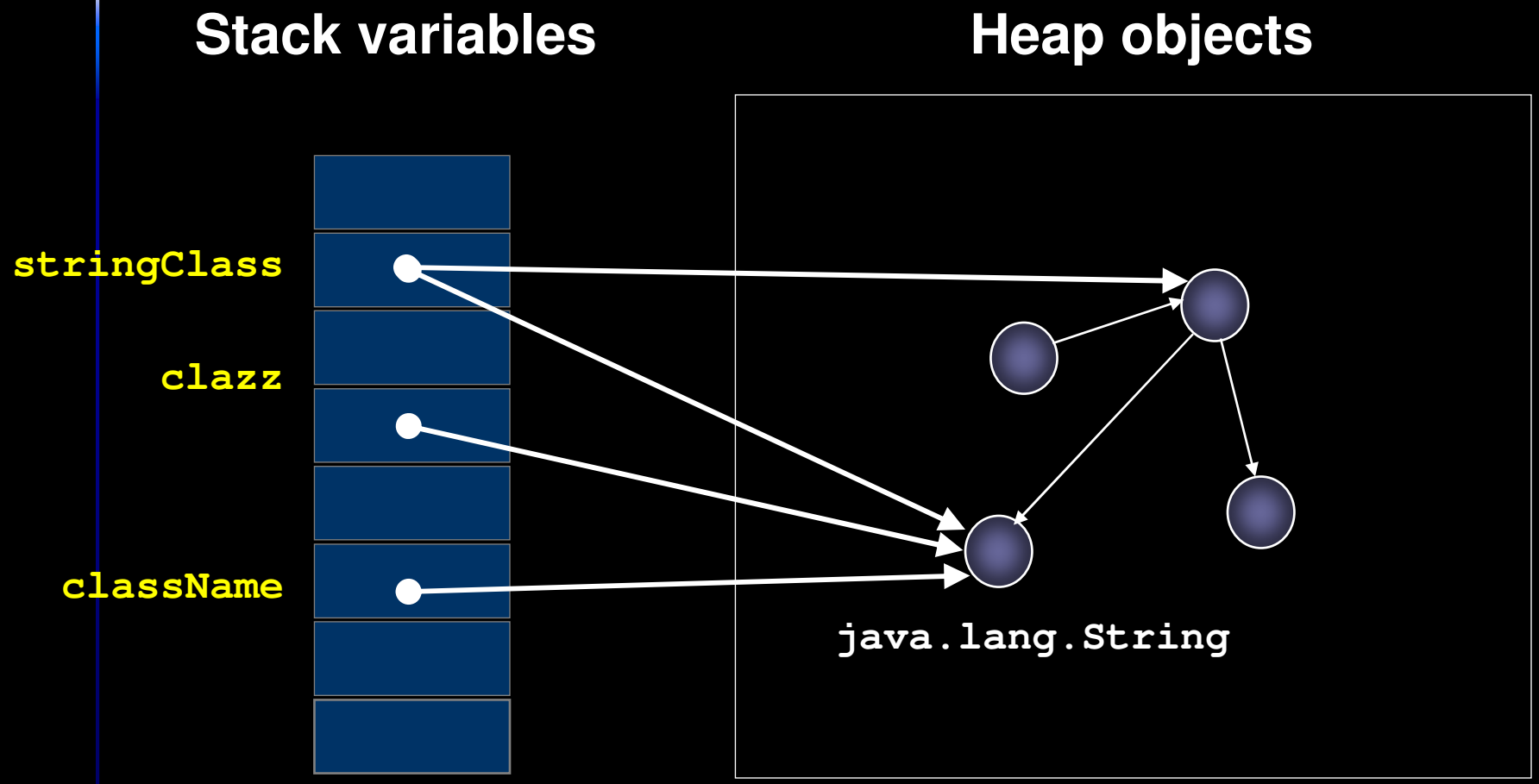
Analyzing Class Names

- Looking at **`className`** seems promising

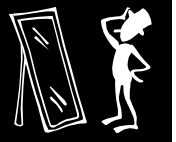
```
String stringClass = "java.lang.String";
foo(stringClass);
...
void foo(String clazz){
        bar(clazz);
}
void bar(String className){
        Class c = Class.forName(className);
}
```

- This is interprocedural const+copy prop on strings

Pointer Analysis Can Help



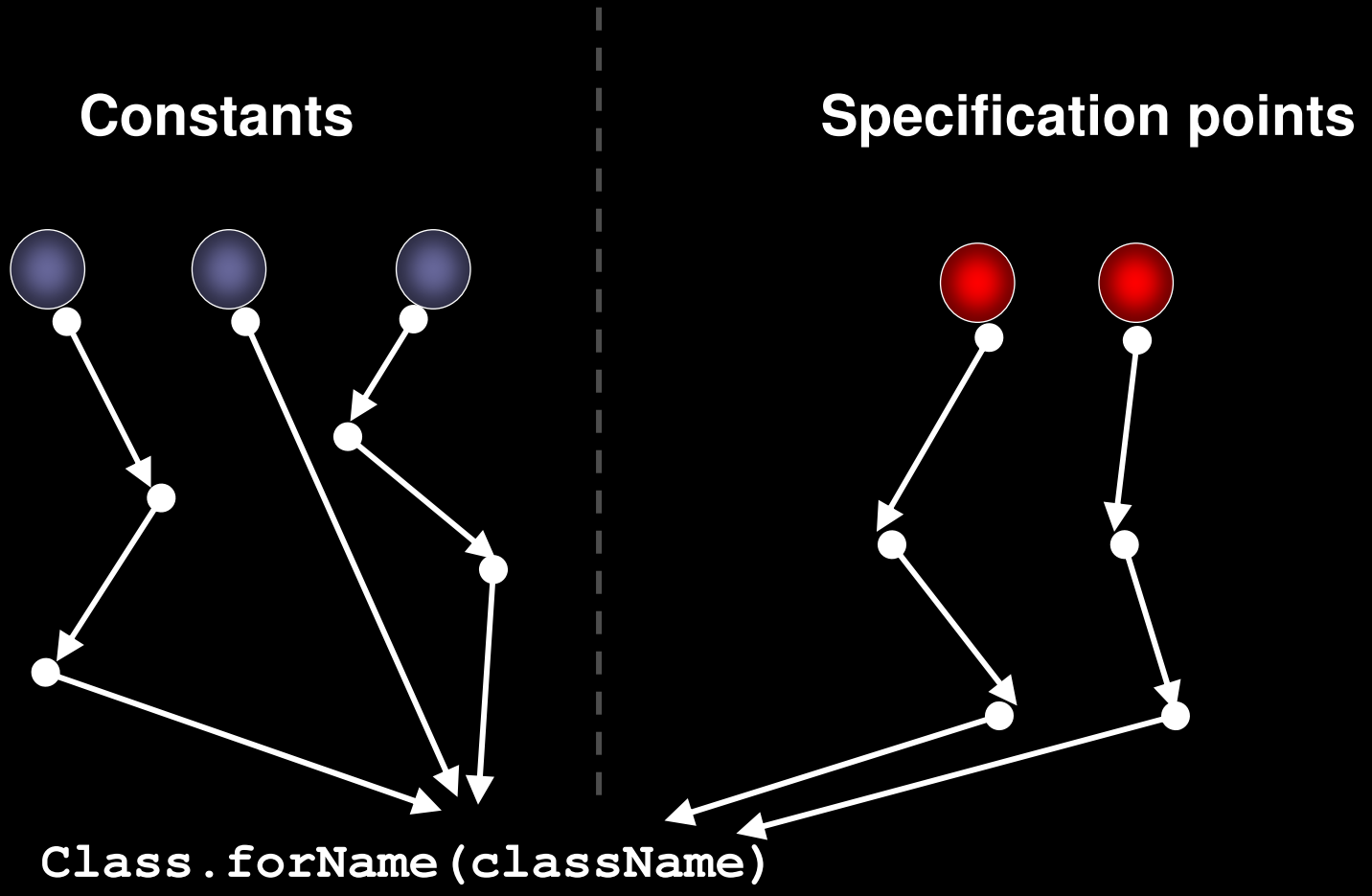
Reflection Resolution Using Points-to



```
1. String className = ...;
2. Class  c = Class.forName(className);
3. Object o = c.newInstance();
4. T t      = (T) o;
```

- Need to know what **`className`** is
  - Could be a local string constant like **`java.lang.String`**
  - But could be a variable passed through many layers of calls
- Points-to analysis says what **`className`** refers to
  - className --> concrete heap object

Reflection Resolution



Resolution May Fail!

```
1. String className = r.readLine();
2. Class  c = Class.forName(className);
3. Object o = c.newInstance();
4. T t      = (T) o;
```

- Need help figuring out what **`className`** is
- Two options
  1. Can ask user for help
     - Call to **`r.readLine`** on line 1 is a specification point
     - User needs to specify what can be read from a file
     - Analysis helps the user by listing all specification points
  2. Can use cast information
     - Constrain possible types instantiated on line 3 to subclasses of **`T`**
     - Need additional assumptions

1. Specification Files

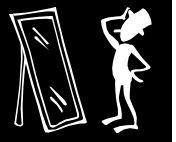
- Format: **invocation site => class**

```
loadImpl() @ 43 InetAddress.java:1231 =>
   java.net.Inet4AddressImpl

loadImpl() @ 43 InetAddress.java:1231 =>
   java.net.Inet6AddressImpl

lookup() @ 86 AbstractCharsetProvider.java:126 =>
   sun.nio.cs.ISO_8859_15

lookup() @ 86 AbstractCharsetProvider.java:126 =>
   sun.nio.cs.MS1251

tryToLoadClass() @ 29 DataFlavor.java:64 =>
   java.io.InputStream
```

2. Using Cast Information

```
1. String className = ...;
2. Class  c = Class.forName(className);
3. Object o = c.newInstance();
4. T t      = (T) o;
```

- Providing specification files is tedious, time-consuming, error-prone
- Leverage cast data instead
  - `o instanceof T`
  - Can constrain type of `o` if
    1. Cast succeeds
    2. We know **all** subclasses of `T`



Analysis Assumptions

1. **Assumption: Correct casts.**

   Type cast operations that always operate on the result of a call to `Class.newInstance` are correct; they will always succeed without throwing a `ClassCastException`.

2. **Assumption: Closed world.**

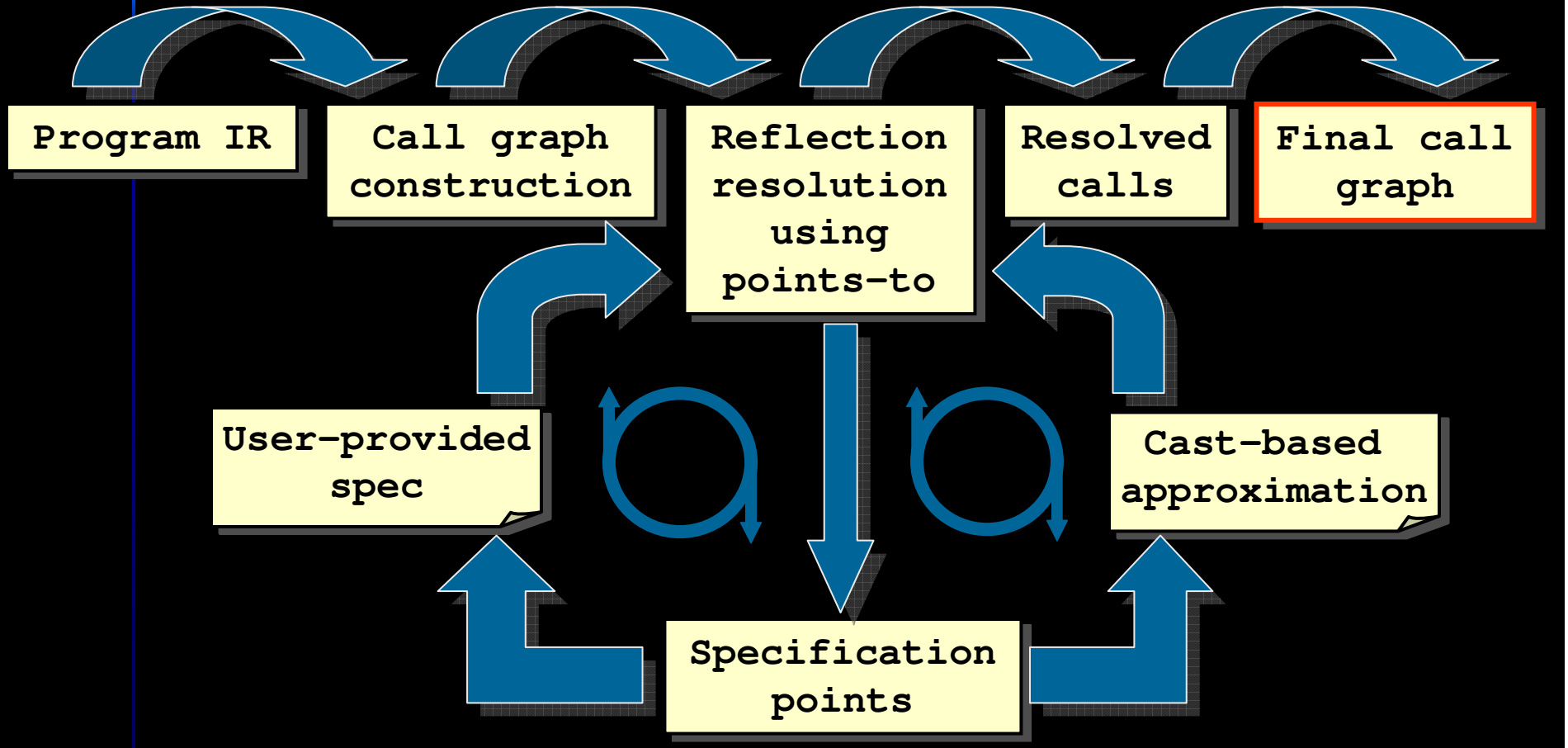
   We assume that only classes reachable from the class path at analysis time can be used by the application at runtime.

Casts Aren't Always Present

- Can't do anything if no cast **post-dominating** a `Class.newInstance` call

```
Object factory(String className){
        Class c = Class.forName(className);
        return c.newInstance();
}
...
SunEncoder t     = (SunEncoder)
                factory("sun.io.encoder." + enc);
SomethingElse e = (SomethingElse)
                factory("SomethingElse");
```

Call Graph Discovery Process



Juicy Implementation Details

- Call graph construction algorithm in the presence of reflection is integrated with pointer analysis
  - Pointer analysis already has to deal with virtual calls: new methods are discovered, points-to relations for them are created
  - Reflection analysis is another level of complexity
- Uses **bddbddb**, an efficient program analysis tool
  - Come to talk tomorrow
  - Rules are expressed in Datalog, see the paper
  - Rules that have to do with resolving method calls, etc. can get quite involved
  - Datalog makes experimentation easy

Talk Outline

- Introduction to Reflection
- Reflection analysis framework
- Experimental results
  - Benchmark information
  - Setup: 5 flavors of reflection analysis
  - Comparing…
    - Effectiveness of `Class.forName` resolution
    - Specification effort involved
    - Call graph sizes
- Conclusions

Experimental Summary

- Ran experiments on 6 very large applications in common use
- Compare the following analysis strategies:

1. None -- no reflection resolution at all
2. Local -- intraprocedural analysis
3. Points-to -- relies on pointer analysis
4. Casts -- points-to + casts
5. Sound -- points-to + user spec

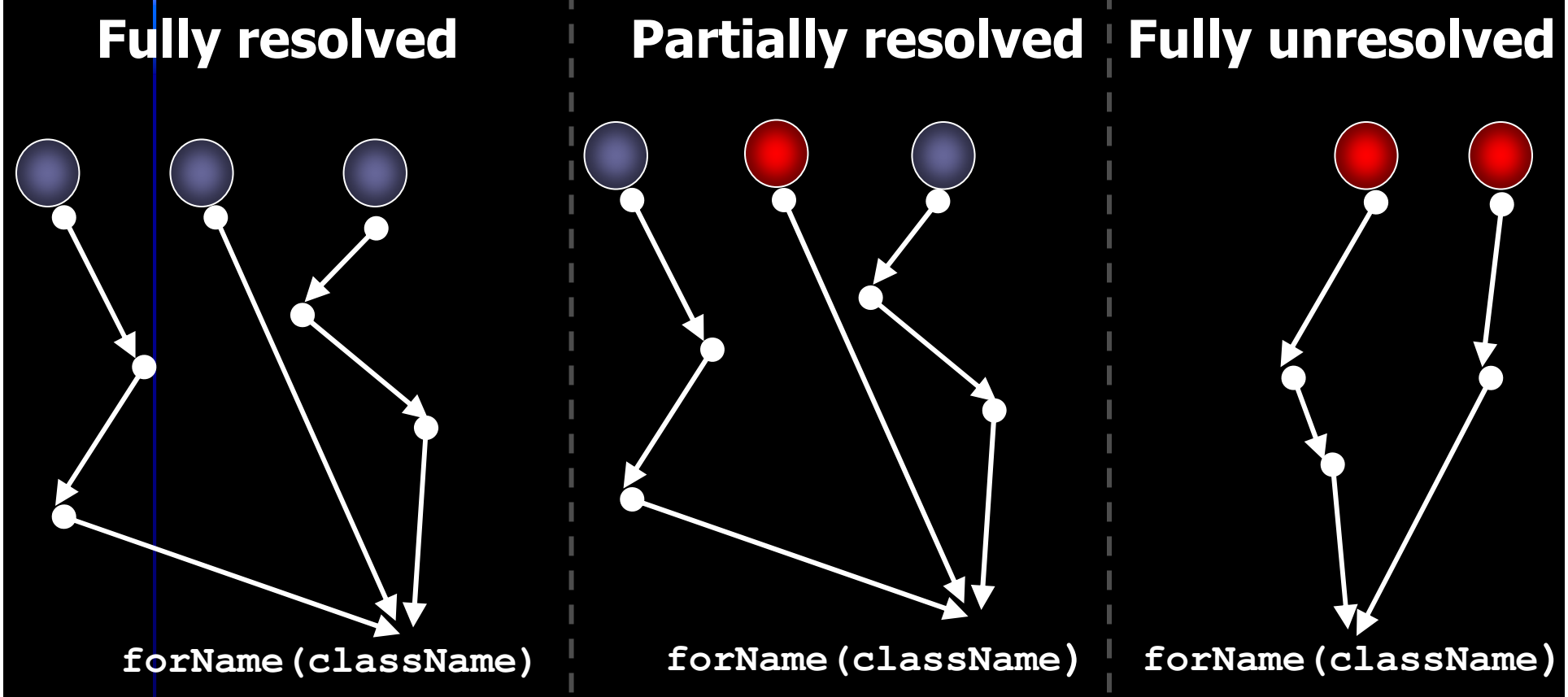
- Only version "Sound" is conservative

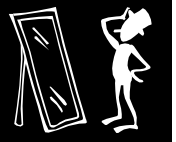
Benchmark Information

- Among top Java apps on SourceForge
- Large, modern apps, not Spec JVM

Benchmark	Description	Line count	File count	App Jars	Available classes
`jgap`	genetic algorithms package	32,961	172	9	62,727
`freetts`	speech synthesis system	42,993	167	19	62,821
`gruntspud`	graphical CVS client	80,138	378	10	63,847
`jedit`	graphical text editor	144,496	427	1	62,910
`columba`	graphical email client	149,044	1,170	35	53,689
`jfreechart`	chart drawing library	193,396	707	6	62,885
Total		643,028	3,021	80	368,879

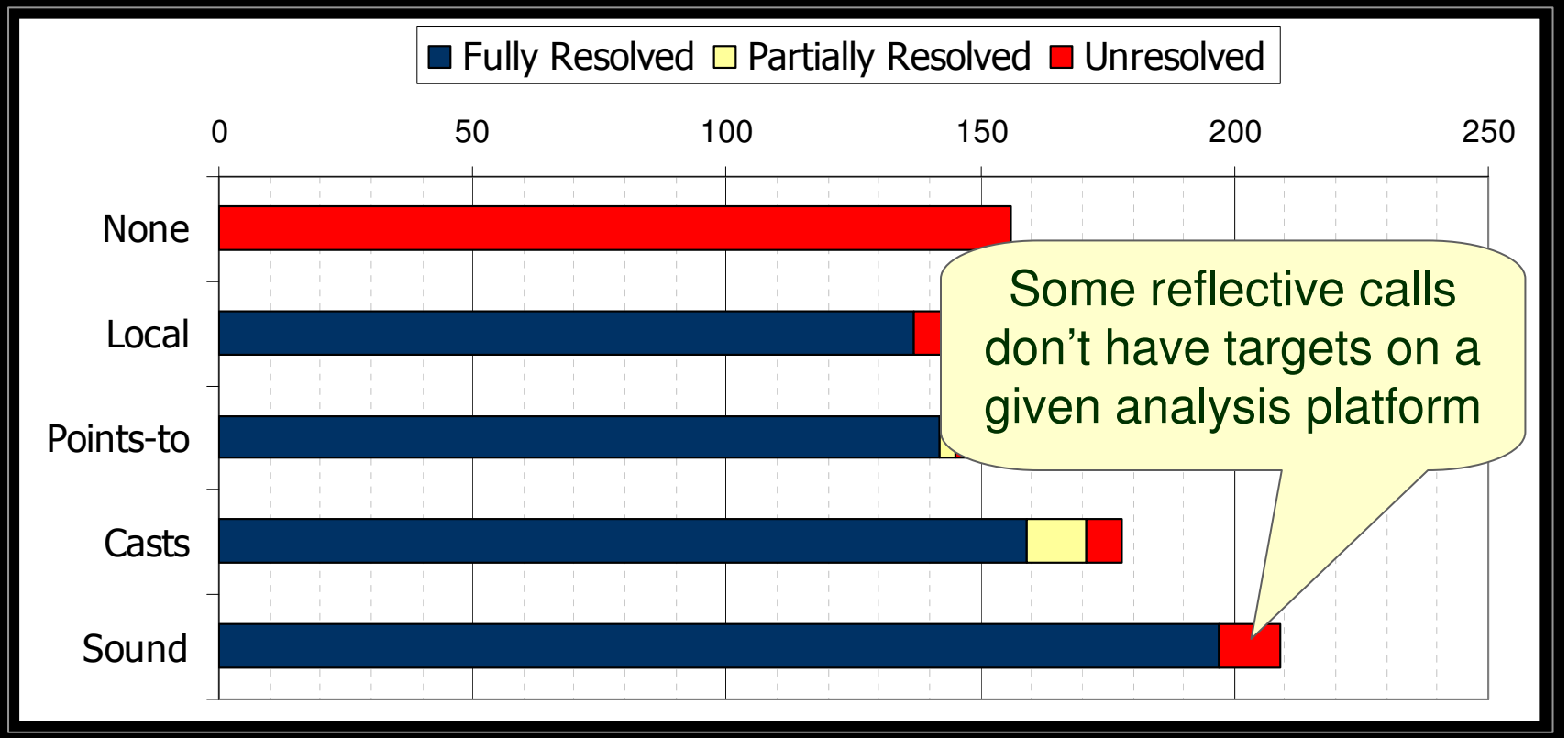
Classification of Calls





`Class.forName` Resolution Stats

- Consider `Class.forName` resolution in `jedit`

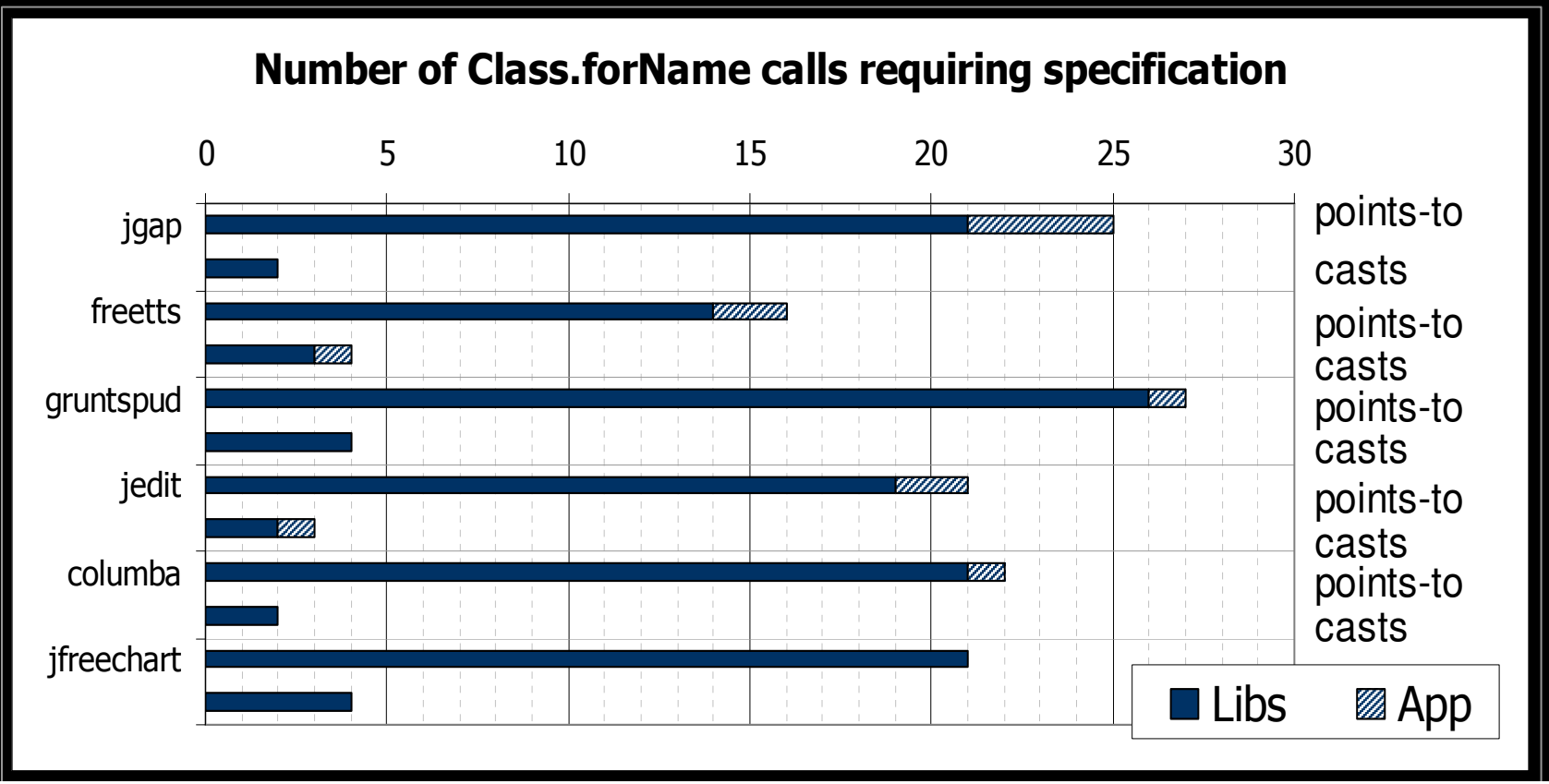


Reflective Calls with No Targets

```
// Class javax.sound.sampled.AudioSystem

private static final String defaultServicesClassName =
        "com.sun.media.sound.DefaultServices";

Vector getDefaultServices(String serviceName ) {
   Vector v = null;
   try {
        Class defaultServices =
            Class.forName( defaultServicesClassName );
        Method m = defaultServices.getMethod(
                servicesMethodName,  servicesParamTypes);
        Object[] arguments = new Object[] { serviceName };
        v = (Vector) m.invoke(defaultServices,arguments);
   } catch(InvocationTargetException e1) {
   ...
   }
   return v;
}
```

Specification Effort

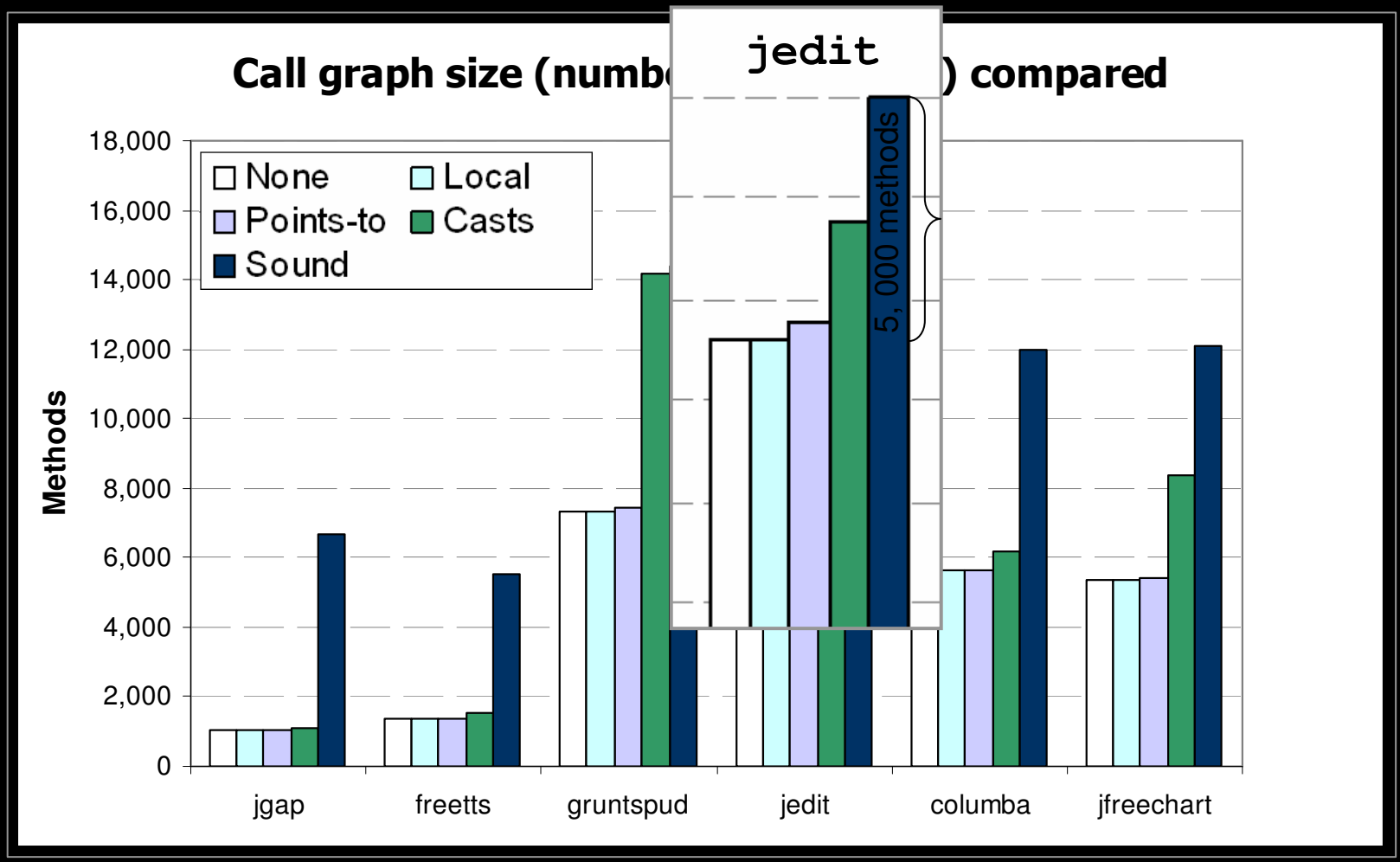
- Significantly less specification effort when starting from **Casts** compared to starting with **Points-to**



Specification is Hard

- Took us about 15 hours to provide specification for all benchmarks
- In many cases 2-3 iterations are necessary
  - More reflective calls are gradually discovered
  - More specification may be needed
- Fortunately, most unresolved calls are in library code
  - JDK, Apache, Swing, etc. have unresolved calls
  - Specifications can be shared among libraries

Call Graph Sizes



Callgraph Sizes Compared: Sound vs None

Benchmark	Classes	Methods
jgap	(6X) 5.94	(7X) 6.58
freetts	4.58	4.05
gruntspud	2.21	1.96
jedit	(50% more) 1.66	(50% more) 1.43
columba	2.43	2.13
jfreechart	2.65	2.25

Related Work

- Call graph construction algorithms:
  - Function pointers in C [EGH94,Zha98,MRR01,MRR04]
  - Virtual functions in C++ [BS96,Bac98,AH96]
  - Methods in Java [GC01,GDDC97,TP00,SHR+00,ALS02,RRHK00]

- Reflection is a relatively unexplored research area
  - Partial evaluation [BN99,Ruf93,MY98]
    - "Compile reflection away"
    - Type constrains are provided by hand
  - Compiler frameworks accepting specification [TLSS99,LH03]
    - Can add user-provided edges to the call graph
  - Dynamic analysis [HDH2004]
    - Dynamic online pointer analysis that addresses dynamic class loading

Conclusions

- First call graph construction algorithm to explicitly deal with the issue of reflection
  - Uses points-to analysis for call graph discovery
  - Finds specification points
  - Casts are used to reduce specification effort
- Applied to 6 large apps, 190,000 LOC combined
  - About 95% of calls to `Class.forName` are resolved at least partially without any specs
  - There are some "stubborn" calls that require user-provided specification or cast-based approximation
  - Cast-based approach reduces the specification burden
  - Reflection resolution significantly increases call graph size: as much as 7X more methods, 7,000+ new methods