Points-to Analysis for Java Using Annotated Constraints*

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*Joint research with Atanas Rountev and Ana Milanova, supported by NSF-CCR 9900988.

Outline

- PROLANGS research projects
- Points-to analysis for Java
- Initial constraint-based implementation, OOPSLA'01
  - Empirical results
- Object-sensitive analysis, ISSTA'02
  - Empirical results
- Related work
- Summary

PROLANGS

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- Research projects at boundary of Programming Languages/Compilers and Software Engineering
  - Algorithm design and prototyping
- Mature research projects
  - Pointer analysis of C programs
  - Side-effect analysis of C systems
  - Semantic software change analysis
  - Studies of Java exception usages
  - PROLANGS Analysis Framework (PAF), version 1.1 released June 1999

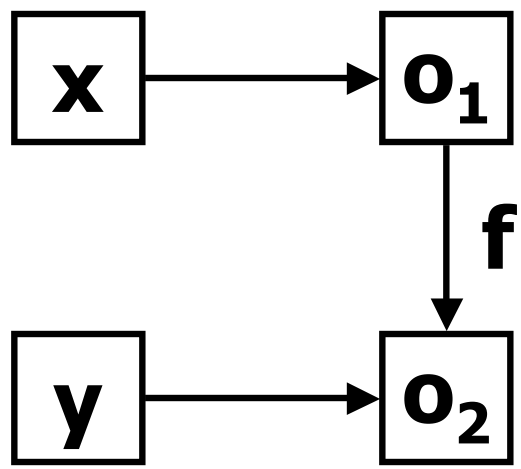
Ongoing Research

- **Object-oriented systems** (C++/Java)
  - Analysis
    - Points-to, side-effect analyses POPL'99, OOPSLA'01, ISSTA'02, ICSM'02
    - Change impact analysis (with Frank Tip, IBM) PASTE'01
  - Optimization
    - Profiling framework for feedback-directed optimization PLDI'01
    - Experience with feedback-directed optimization OOPSLA'02
- **Static/dynamic analyses of application resource usage** (with Rich Martin and Thu Nguyen, Rutgers)
- **Analysis of program fragments** FSE'99, CC'01, ICSE'03

Points-to Analysis for Java

- Which objects may reference variable x point to?
- Builds a points-to graph

```
x = new A();
y = new B();
x.f = y;
```



Uses of Points-to Information in Compilers

- Object read-write information
  - Side-effect analysis, dependence analysis
- Call graph construction
  - Devirtualization & inlining
- Synchronization removal
- Stack-based object allocation

Uses of Points-to Information in Software Engineering Tools

- Object read-write information
  - Semantic browers
  - Program slicers
  - Debuggers
- Change impact analysis tools
- Testing
  - Object relationships (Object relation diagrams)
  - Program-based coverage metrics

Contributions

Points-to Analyses for Java using annotated constraints

- Initial analysis based on Andersen's analysis for C, OOPSLA'01
  - Annotations embody OO notions needed
  - Maintained efficient constraint-based implementation
  - Empirical evaluation of cost and precision

Contributions

- Object-sensitive analysis, ISSTA'02
  - Adding context sensitivity
    - Parameterization framework
  - Empirical evaluation demonstrates more precision for same cost

Points-to Analysis, OOPSLA'01

- Handles virtual calls
  - Simulates the run-time method lookup
- Models the fields of objects
- Analyzes executable code
  - Ignores unreachable code from libraries

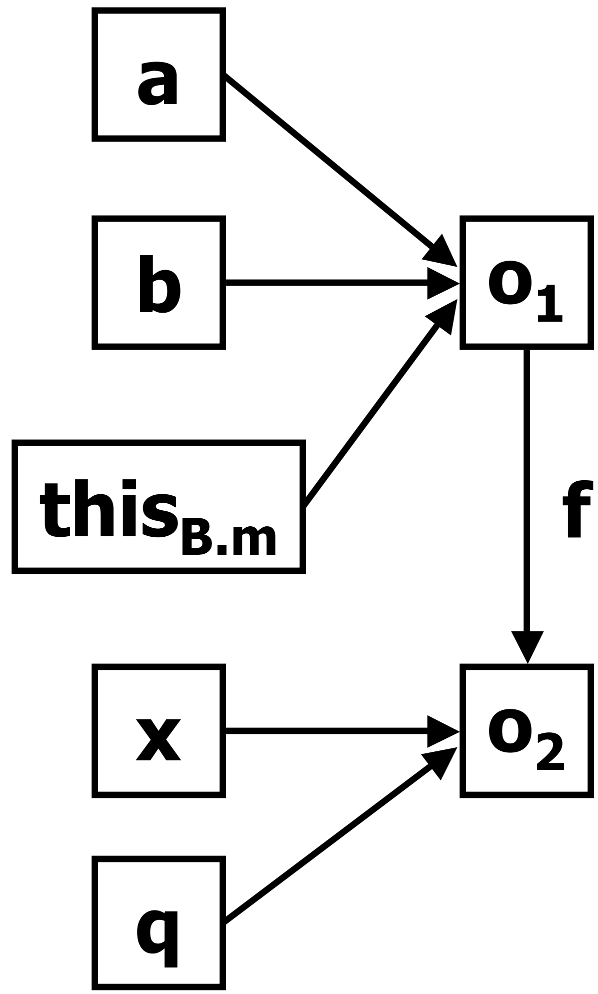
Points-to Analysis in Action

A.m() not analyzed because
it's unreachable.

```
class A { void m(X p) {..} }

class B extends A {
    X f;
    void m(X q) {  this.f=q; }
}

B b = new B();
X x = new X();
A a = b;
a.m(x);
```



Efficient Implementation

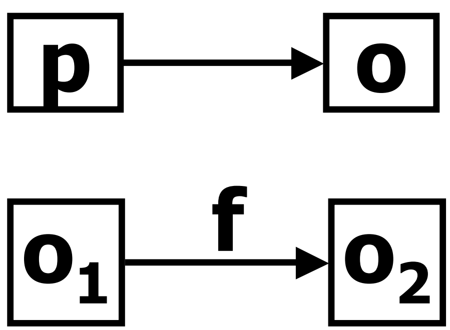
- Constraint-based approach
  - Extends previous work for C pointer analysis using BANE (UC Berkeley)
    - Extended constraint system and resolution rules
- Define and solve a system of annotated set-inclusion constraints to obtain points-to sets

Annotated Constraints

- Form: $L \subseteq_a R$
  - L and R denote set expressions
  - Annotation a: additional information (e.g., object fields)
- Kinds of set expressions L and R
  - Set variables: represent points-to sets
  - *ref* terms: represent objects
  - Other kinds of expressions

Set variables and *ref* terms

- Set variables represent points-to sets
  - For each reference variable p: V_p
  - For each object o: V_o
- Object o is denoted by term $\mathit{ref}(o, V_o)$

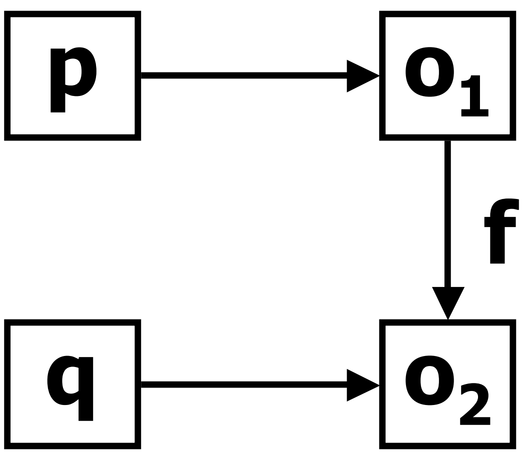


$$ref(o,V_o) \subseteq V_p$$

$$ref(o_2,V_{o_2}) \subseteq_f V_{o_1}$$

Example: Accessing Fields

Statement	Constraint
p = new A();	$ref(o_1, V_{o_1}) \subseteq V_p$
q = new B();	$ref(o_2, V_{o_2}) \subseteq V_q$
p.f = q;	$V_p \subseteq proj(ref, W)$ $V_q \subseteq_f W$



Constraint generation

Example: Solving Constraints

$ref(o_1, V_{o_1}) \subseteq V_p$

$ref(o_2, V_{o_2}) \subseteq V_q$

$V_p \subseteq proj(ref, W)$

$V_q \subseteq_f W$

$W \subseteq V_{o_1}$

$V_q \subseteq_f V_{o_1}$

$ref(o_2, V_{o_2}) \subseteq_f V_{o_1}$

Constraint resolution

o_1.f points to o_2

Example: Virtual Calls

p.m(x); ⇨ $V_P \subseteq_{m} lam(V_x)$

---

receiver object **o** ⇨ $ref(o,V_O) \subseteq V_P$

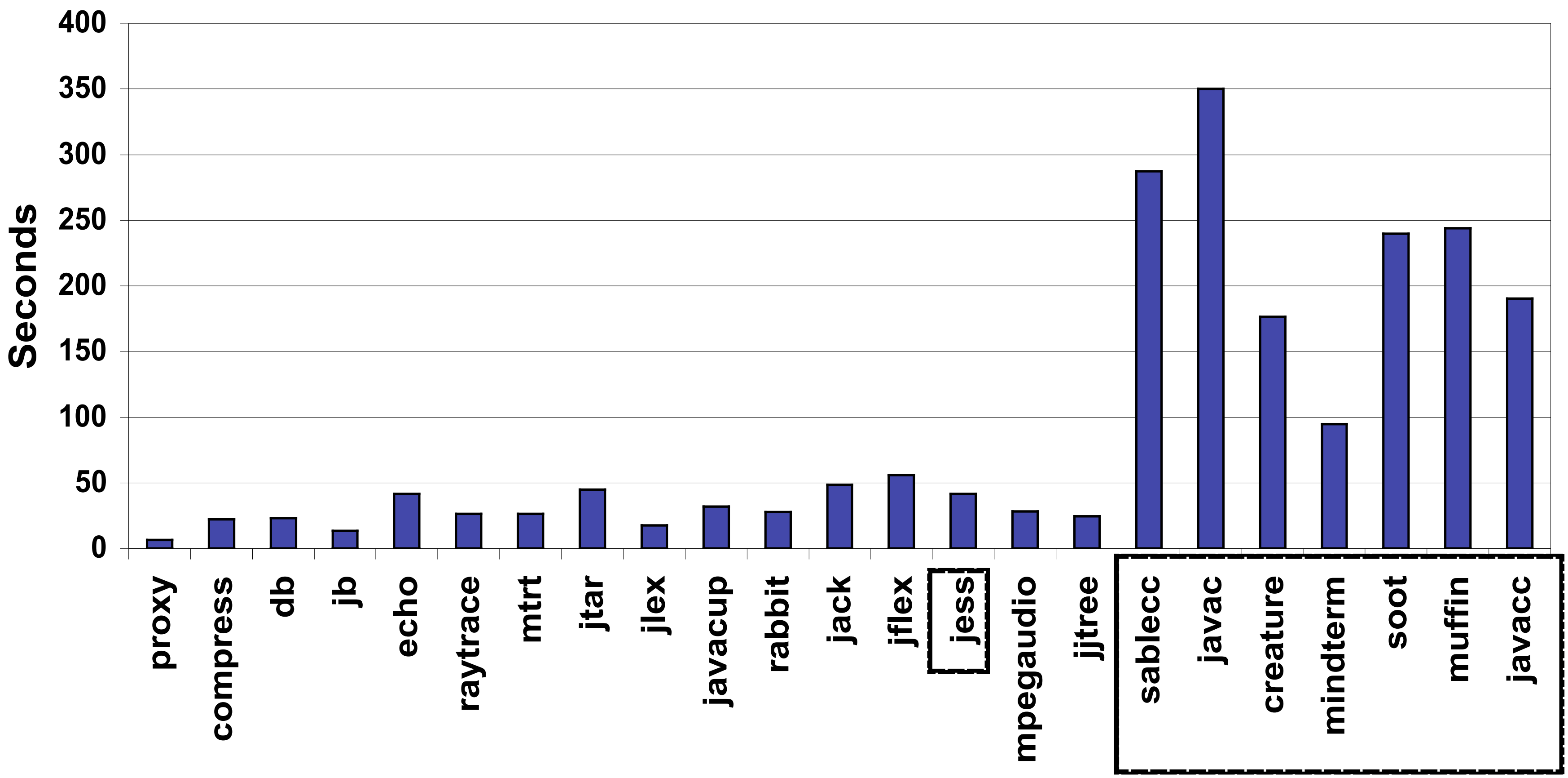
Actual method called, **A.m** ⇨ $V_x \subseteq V_z$

$ref(o,V_O) \subseteq V_{this(A.m)}$

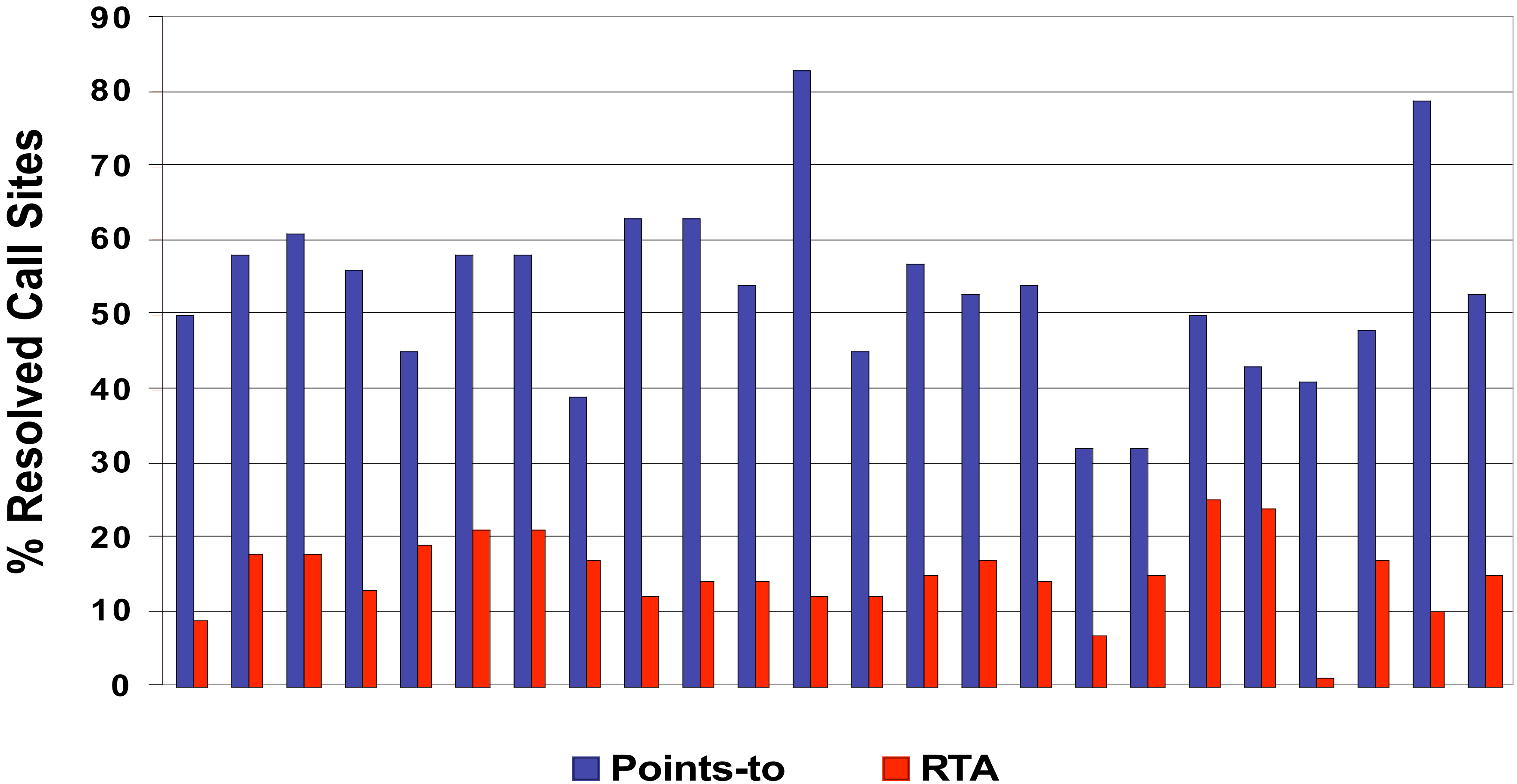
Experiments

- 23 Java programs: 14 – 677 user classes
  - Added the necessary library classes
  - Machine: 360 MHz, 512Mb SUN Ultra-60
- Cost measured in time and memory
- Precision (wrt usage in client analyses and tranformations)
  - Object read-write information
  - Call graph construction
  - Synchronization removal and stack allocation

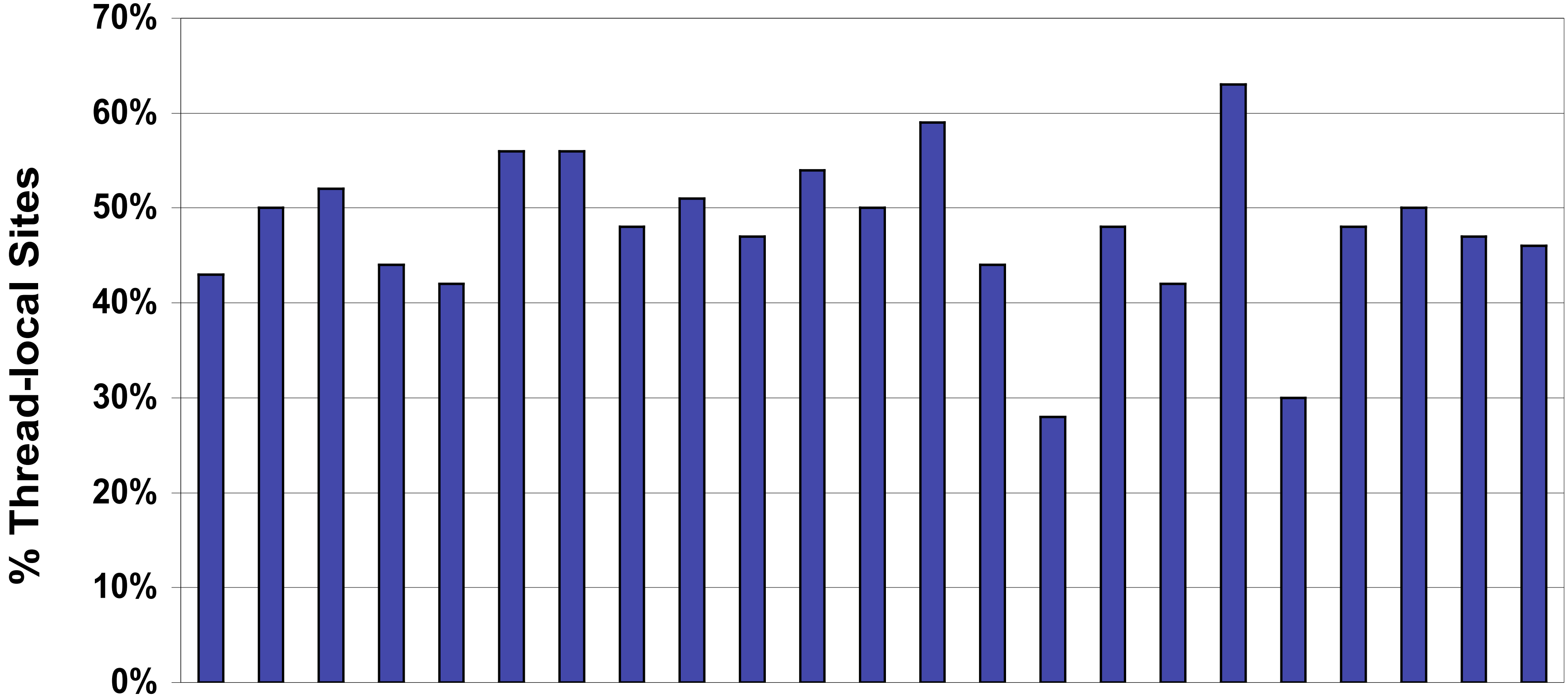
Analysis Time



Resolution of Virtual Call Sites



Thread-local new sites



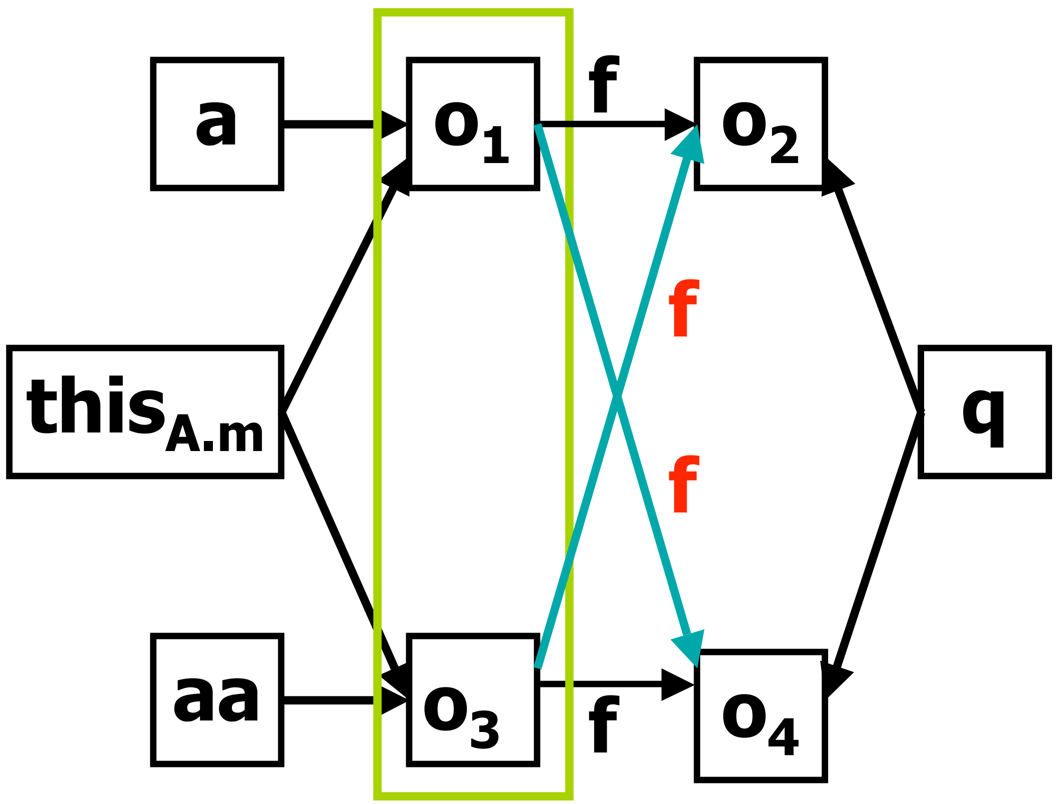
Practical Points-to Analyses for Java, ISSTA'02

- Existing analyses were flow- and context-insensitive extensions of C analyses
- Context insensitivity inherently compromises precision for object-oriented languages
- Goal: Introduce context sensitivity and remain practical

Example: Imprecision

```
class Y extends X { … }

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



Imprecision of Context-insensitive Analysis

- Does not distinguish contexts for instance methods and constructors
  - States of distinct objects are merged
- Common OO features and idioms
  - Encapsulation
  - Inheritance
  - Containers, maps and iterators

Object-sensitive Points-to Analysis

- Object sensitivity
  - Form of context sensitivity for flow-insensitive points-to analysis of OO languages
- Object-sensitive Andersen's analysis
  - Object sensitivity applicable to other analyses
- Parameterization framework
  - Cost vs. precision tradeoff
- Empirical evaluation
  - Vs. context-insensitive OOPSLA'01 analysis

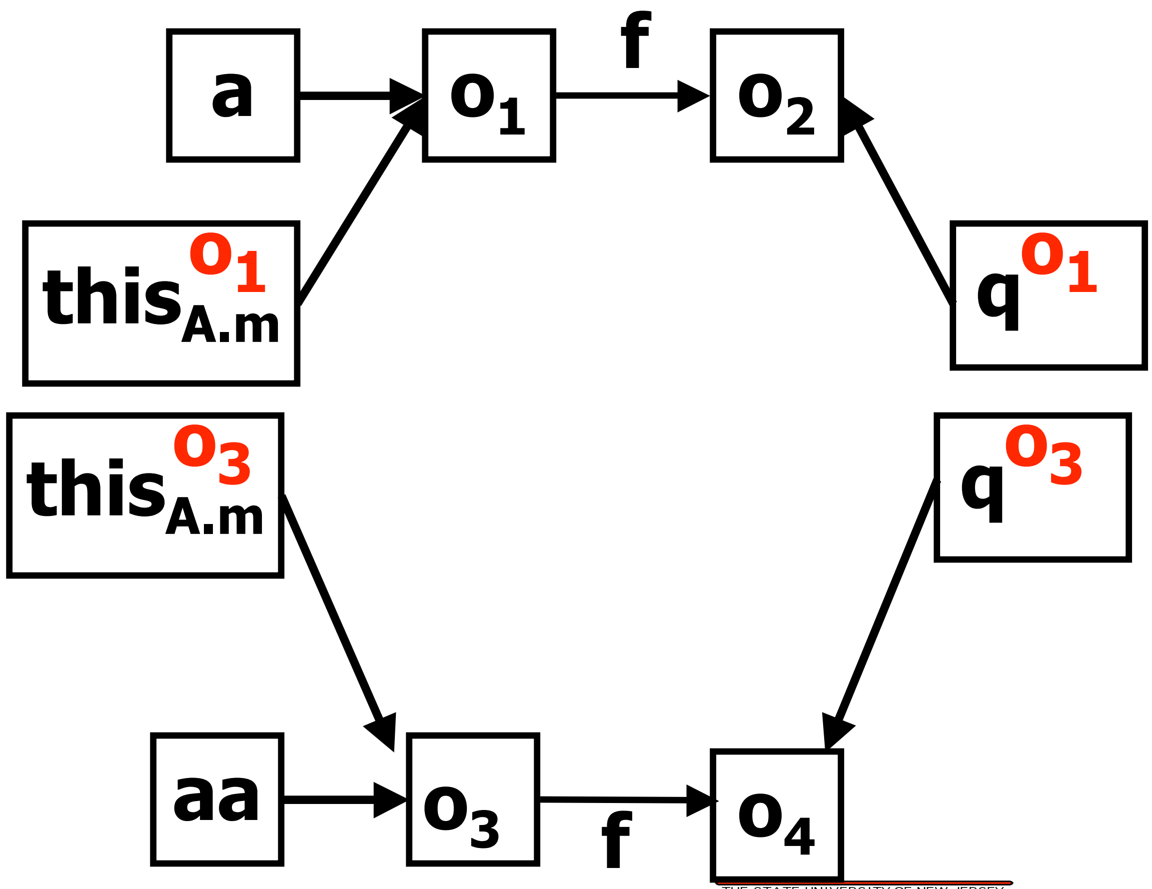
Details

- Instance methods and constructors analyzed for different contexts
- Receiver objects used as contexts
- Multiple copies of reference variables

$$\text{this.f=q} \xrightarrow{o_1} \text{this}^{o_1}_{A.m}\text{.f=q}^{o_1}$$

Example: Object-sensitive Analysis

```
class A {
  X f;
  void m(X q) {
this_A.m^o3.f=q^o3; }
  }
A a = new A() ;
a.m(new X()) ;
A aa = new A() ;
aa.m(new Y()) ;
```



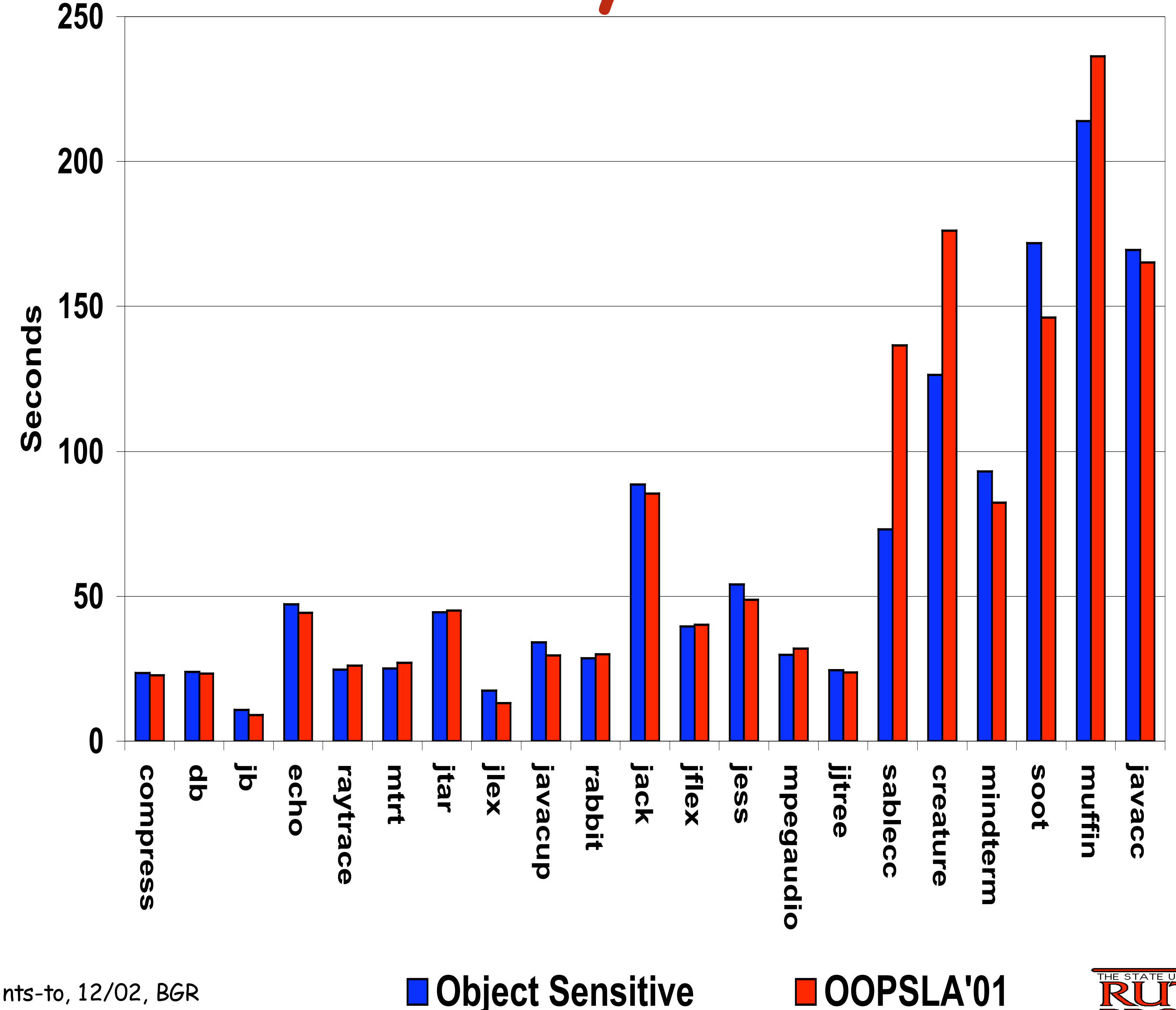
Implementation

- Implemented one instance of parameterization framework
  - `this`, formals and return variables (effectively) replicated
  - Optimized constraint-based analysis using previous technique
  - Comparison with OOPSLA'01 analysis

Empirical Results

- 23 Java programs: 14 – 677 user classes
  - Added the necessary library classes
  - Machine: 360 MHz, 512Mb, SUN Ultra-60
- Object Sensitive vs. OOPSLA'01 points-to
- Found comparable cost with better precision
    - Modification side-effect analysis
    - Virtual call resolution

Analysis Time



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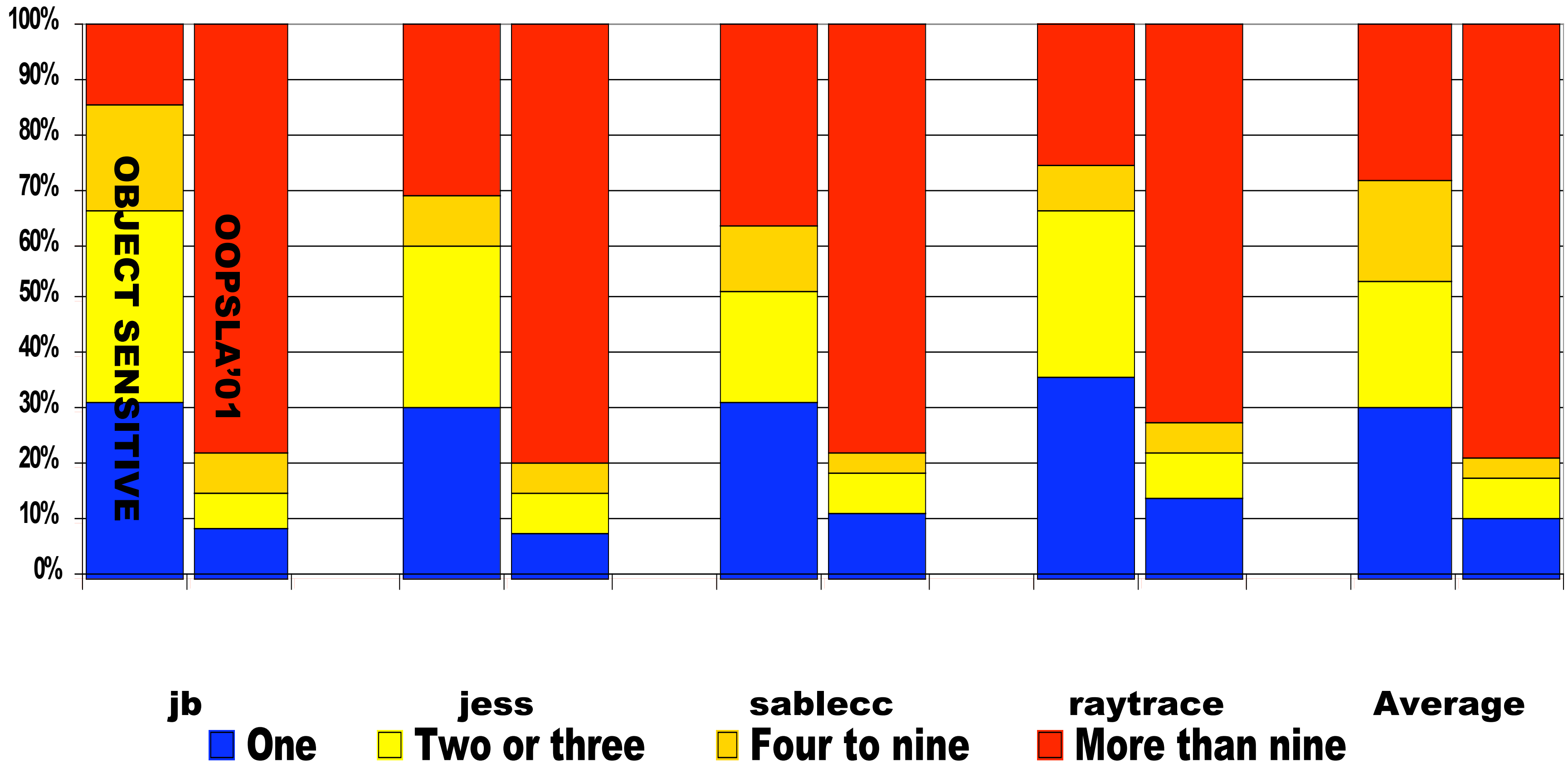
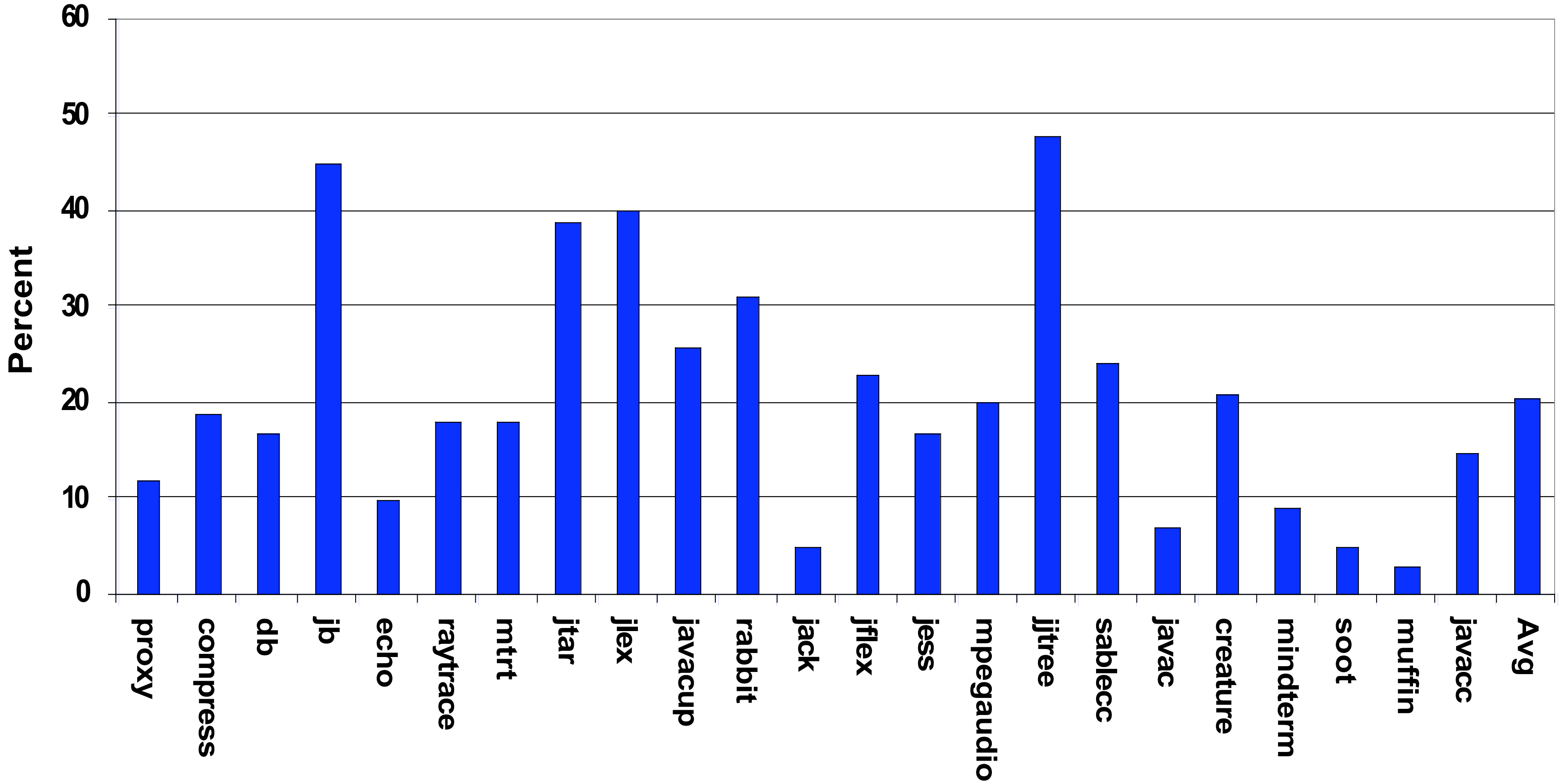
Side-effect Analysis: Modified Objects Per Statement



Improvement in Resolved Calls



Related Work

- **Context-sensitive points-to analysis for OO languages**
  - **Grove et al. OOPSLA'97, Chatterjee et al. POPL'99, Ruf PLDI'00, Grove-Chambers TOPLAS'01**
- **Context-insensitive points-to analysis for OO languages**
  - **Liang et al. PASTE'01**
- **0Context-sensitive class analysis**
  - **Oxhoj et al. ECOOP'92, Agesen SAS'94, Plevyak-Chien OOPSLA'94, Agesen ECOOP'95, Grove et al. OOPSLA'97, Grove-Chambers TOPLAS'01**

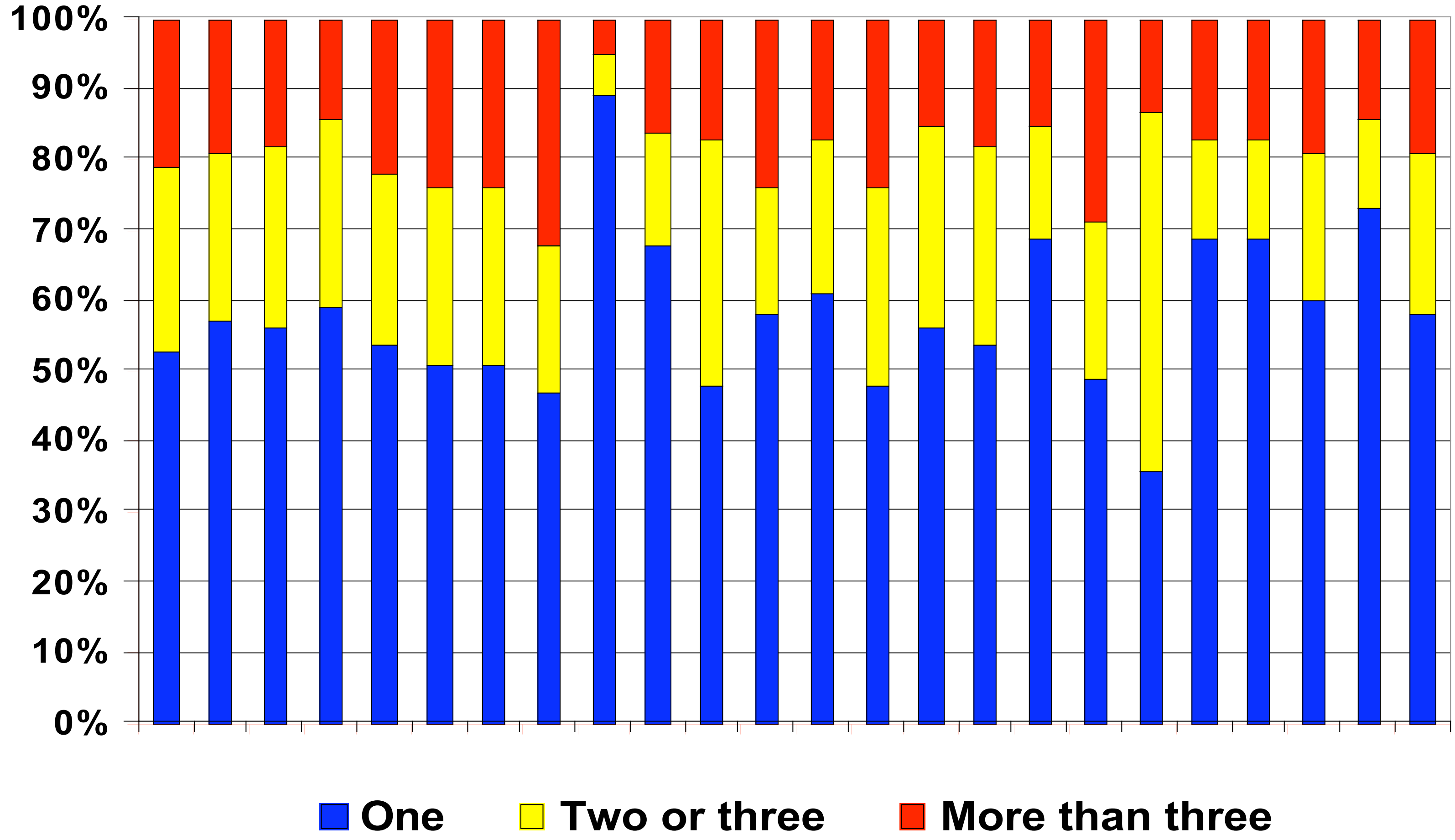
Summary

- Defined two new points-to analyses for references in OOPLs using annotated constraints
- Context-insensitive analysis (OOPSLA'01)
  - Based on Andersen's points-to for C
  - Practical cost and good precision wrt client analyses and transformations

Summary

- Object-sensitive (context-sensitive) points-to analysis -
  - New kind of context sensitivity for flow-insensitive analysis
  - Parameterization framework allows tunable algorithm choice
  - Practical cost, comparable to OOPSLA'01 analysis
  - Better precision than OOPSLA'01 analysis

Number of new X() whose objects are accessed by p.f



Parameterization

- Goal: tunable analysis
- Multiple copies for a subset of variables
  - For the other variables a single copy
- Result: reduces points-to graph size and analysis cost
  - At the expense of precision loss