Declarative Static Program Analysis with Doop

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17-355/17-665/17-819: Program Analysis

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Based on work with Martin Bravenboer,
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LOGICBLOX

Overview

- Declarative pointer analysis
  - Specified as logical rules in Datalog
  - Supports various forms of context-sensitivity
- Efficient implementation
  - Datalog execution model
  - Optimization of Datalog queries
- Why do we care?
  - Easy to understand, modify, and optimize
  - Best analysis performance available today

Pointer Analysis

- What objects can a variable point to?

program

```
void foo() {
  Object a = new A1();
  Object b = id(a);
}

void bar() {
  Object a = new A2();
  Object b = id(a);
}

Object id(Object a) {
  return a;
}
```

points-to

objects represented by allocation sites

foo:a	new A1()
bar:a	new A2()

Pointer Analysis

- What objects can a variable point to?

program

```
void foo() {
  Object a = new A1();
  Object b = id(a);
}

void bar() {
  Object a = new A2();
  Object b = id(a);
}

Object id(Object a) {
  return a;
}
```

points-to

foo:a	new A1()
bar:a	new A2()
id:a	new A1(), new A2()

Pointer Analysis

- What objects can a variable point to?

program

```
void foo() {
  Object a = new A1();
  Object b = id(a);
}

void bar() {
  Object a = new A2();
  Object b = id(a);
}

Object id(Object a) {
  return a;
}
```

points-to

foo:a	new A1()
bar:a	new A2()
id:a	
foo:b	
bar:b	

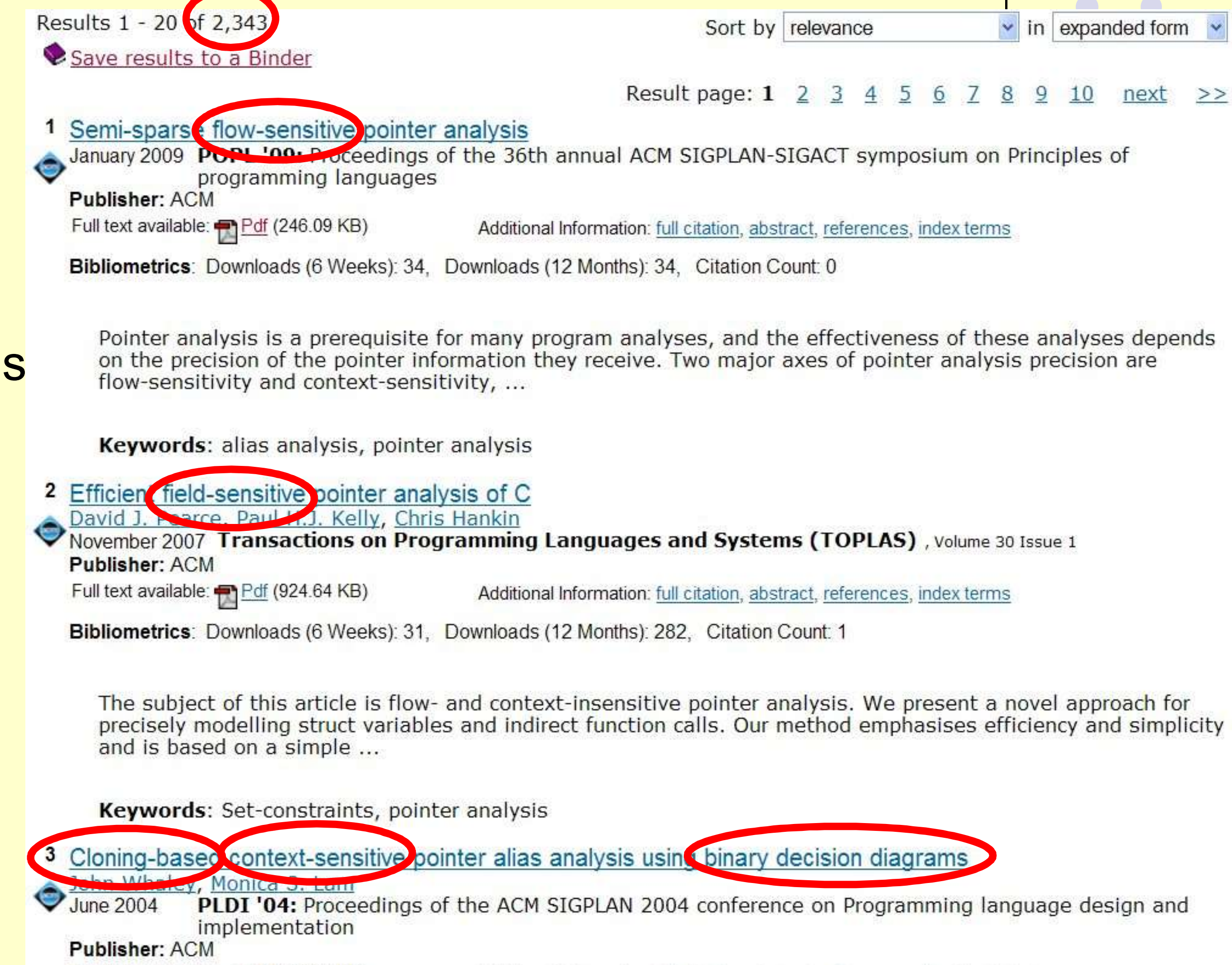
remember for later: context-sensitivity is what makes an analysis precise

context-sensitive points-to

foo:a	new A1()
bar:a	new A2()
id:a (foo)	new A1()
id:a (bar)	new A2()
foo:b	new A1()
bar:b	new A2()

Pointer Analysis: A Complex Domain

- flow-sensitive
- field-sensitive
- heap cloning
- context-sensitive
- binary decision diagrams
- inclusion-based
- unification-based
- on-the-fly call graph
- k-cfa
- object sensitive
- field-based
- demand-driven


Results 1 - 20 of 2,343 Sort by relevance in expanded form

Save results to a Binder

Result page: 1 2 3 4 5 6 7 8 9 10 next >>

1 Semi-sparse flow-sensitive pointer analysis
January 2009 POPL '09: Proceedings of the 36th annual ACM SIGPLAN-SIGACT symposium on Principles of programming languages
Publisher: ACM
Full text available: Pdf (246.09 KB) Additional Information: full citation, abstract, references, index terms
Bibliometrics: Downloads (6 Weeks): 34, Downloads (12 Months): 34, Citation Count: 0

Pointer analysis is a prerequisite for many program analyses, and the effectiveness of these analyses depends on the precision of the pointer information they receive. Two major axes of pointer analysis precision are flow-sensitivity and context-sensitivity, ...

Keywords: alias analysis, pointer analysis

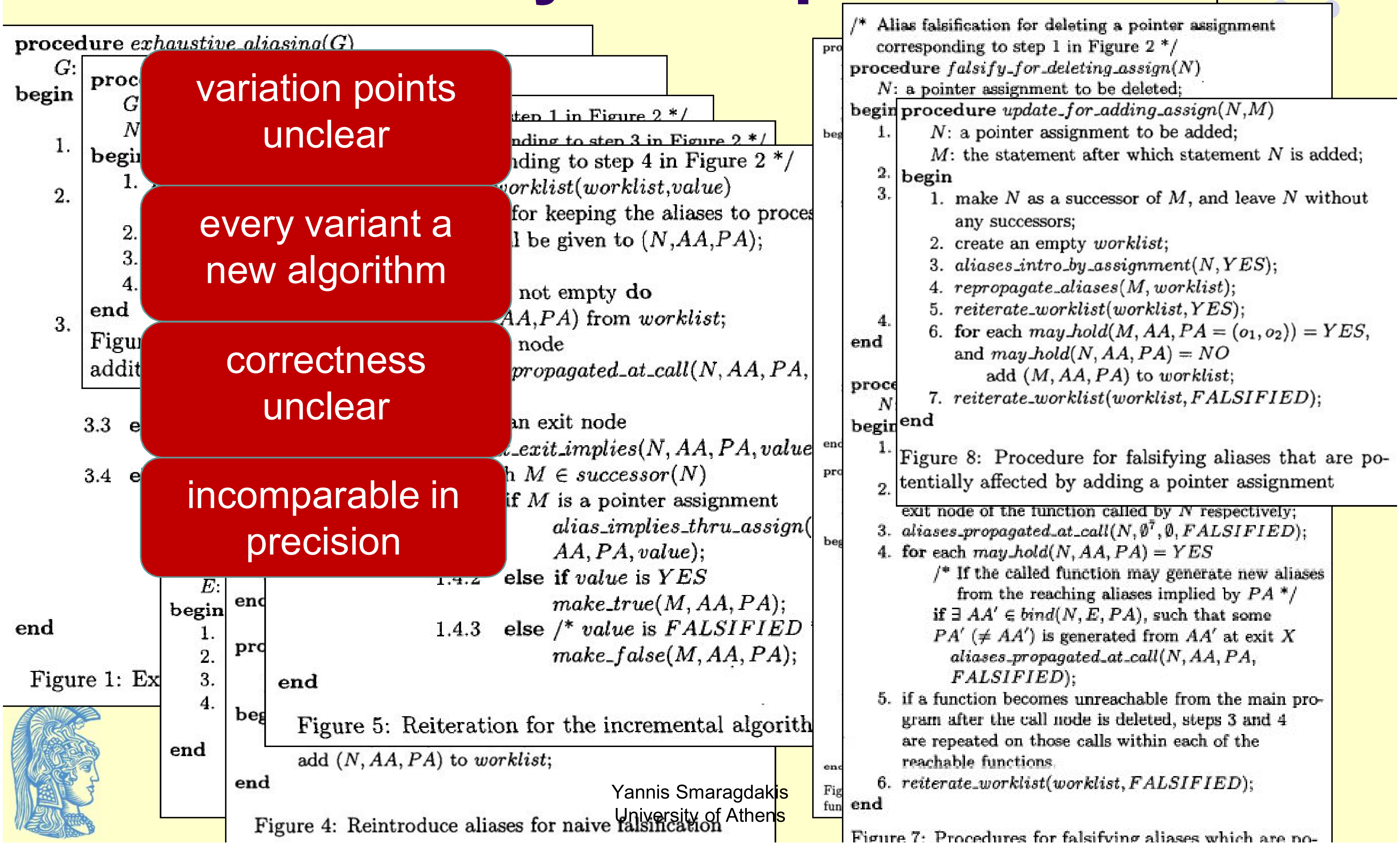
2 Efficient field-sensitive pointer analysis of C
David J. Pearce, Paul H.J. Kelly, Chris Hankin
November 2007 **Transactions on Programming Languages and Systems (TOPLAS)** , Volume 30 Issue 1
Publisher: ACM
Full text available: Pdf (924.64 KB) Additional Information: full citation, abstract, references, index terms
Bibliometrics: Downloads (6 Weeks): 31, Downloads (12 Months): 282, Citation Count: 1

The subject of this article is flow- and context-insensitive pointer analysis. We present a novel approach for precisely modelling struct variables and indirect function calls. Our method emphasises efficiency and simplicity and is based on a simple ...

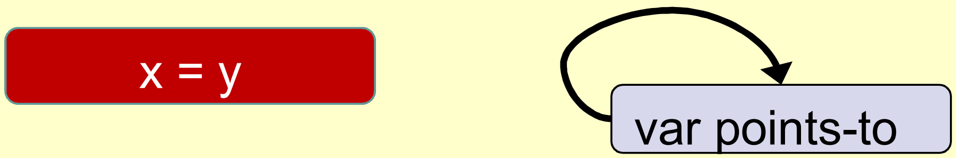
Keywords: Set-constraints, pointer analysis

3 Cloning-based context-sensitive pointer alias analysis using binary decision diagrams
John Whaley, Monica S. Lam
June 2004 **PLDI '04:** Proceedings of the ACM SIGPLAN 2004 conference on Programming language design and implementation
Publisher: ACM

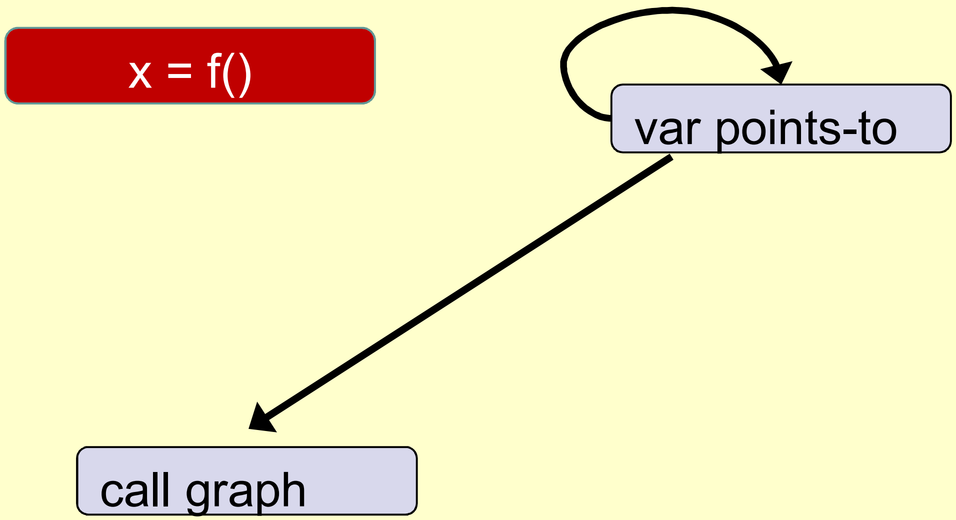
Algorithms Found In a 10-Page Pointer Analysis Paper



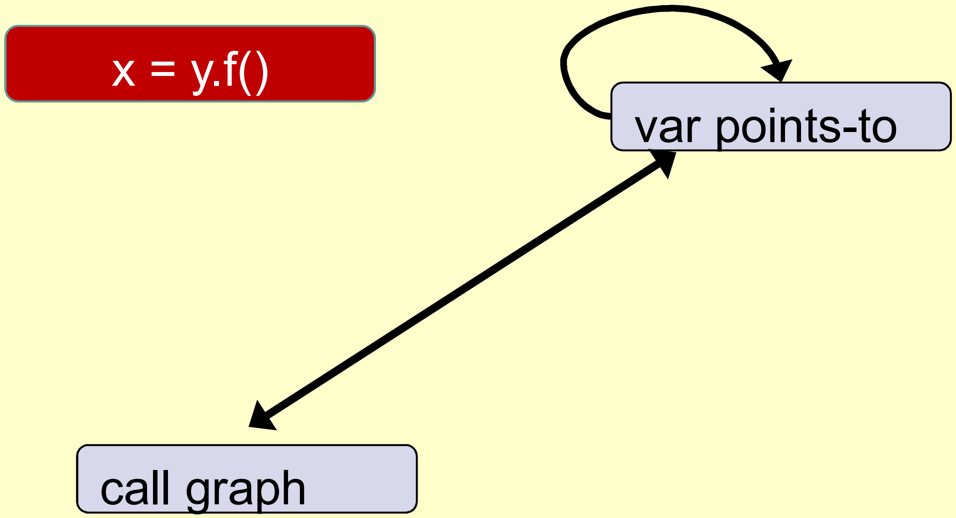
Program Analysis: a Domain of Mutual Recursion



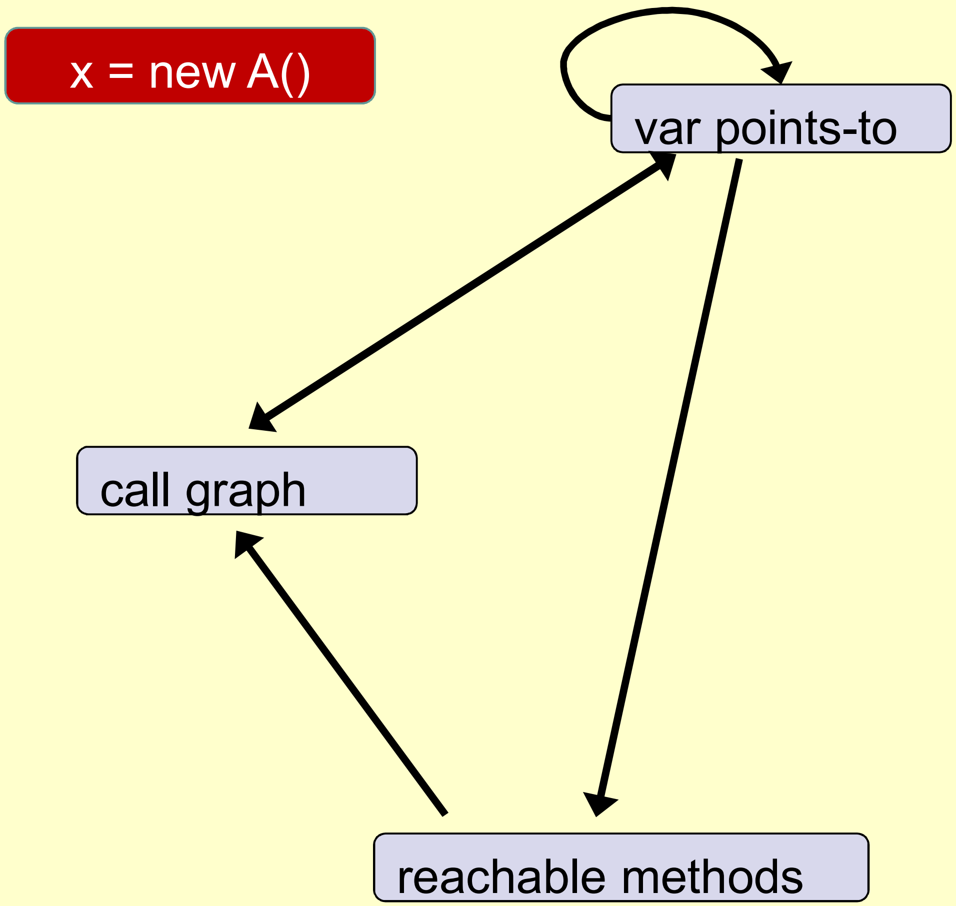
Program Analysis: a Domain of Mutual Recursion



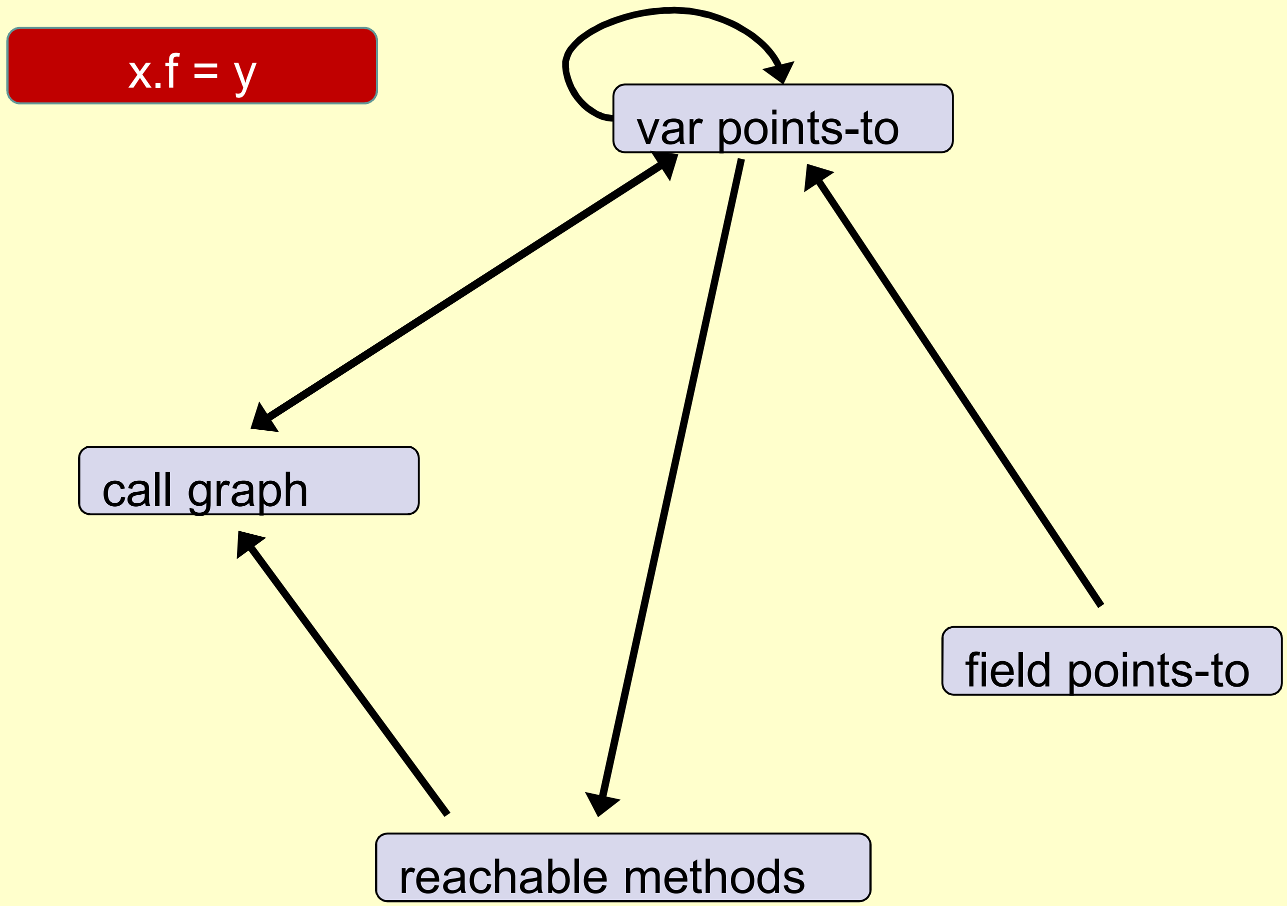
Program Analysis: a Domain of Mutual Recursion



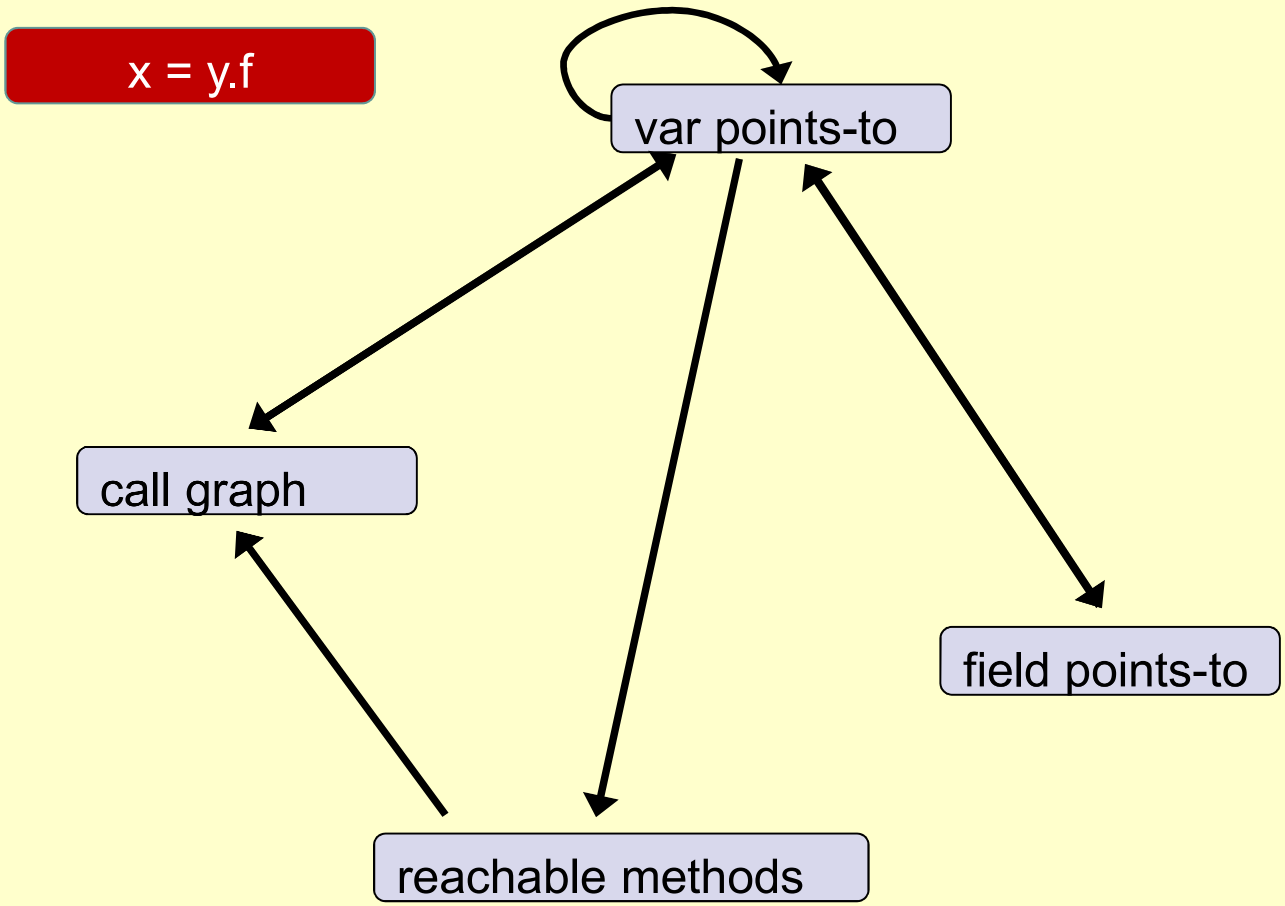
Program Analysis: a Domain of Mutual Recursion



Program Analysis: a Domain of Mutual Recursion



Program Analysis: a Domain of Mutual Recursion



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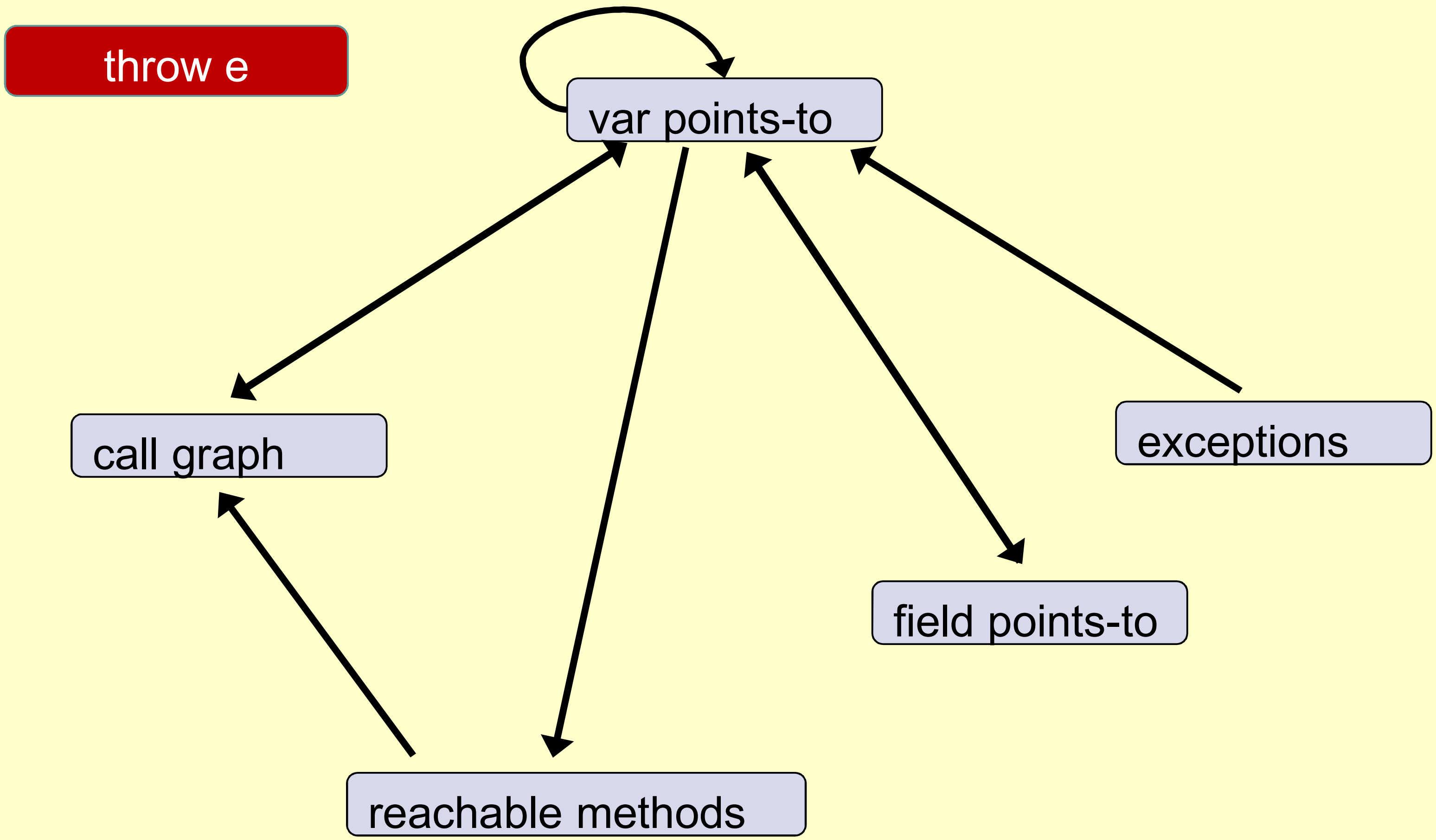

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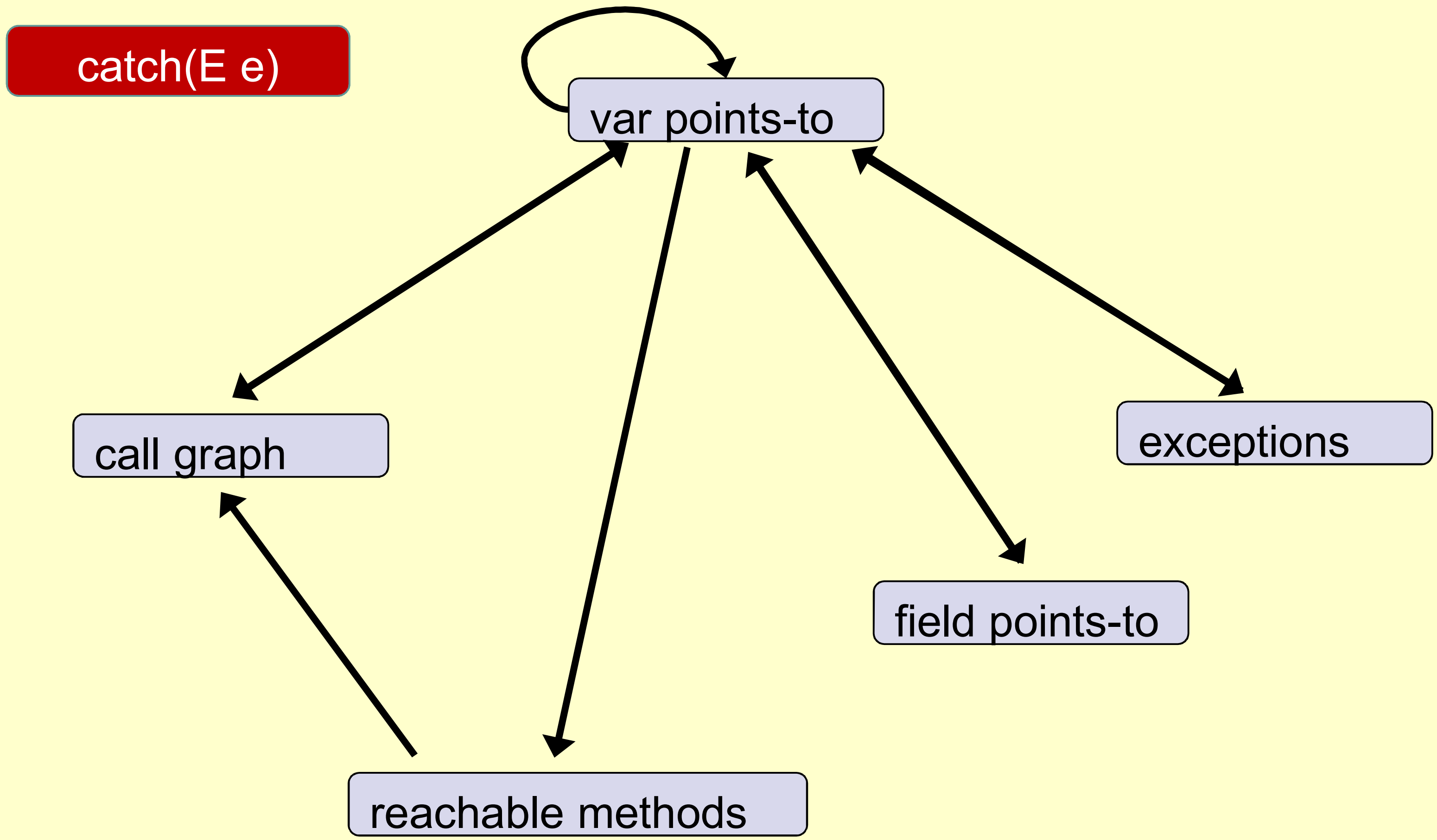
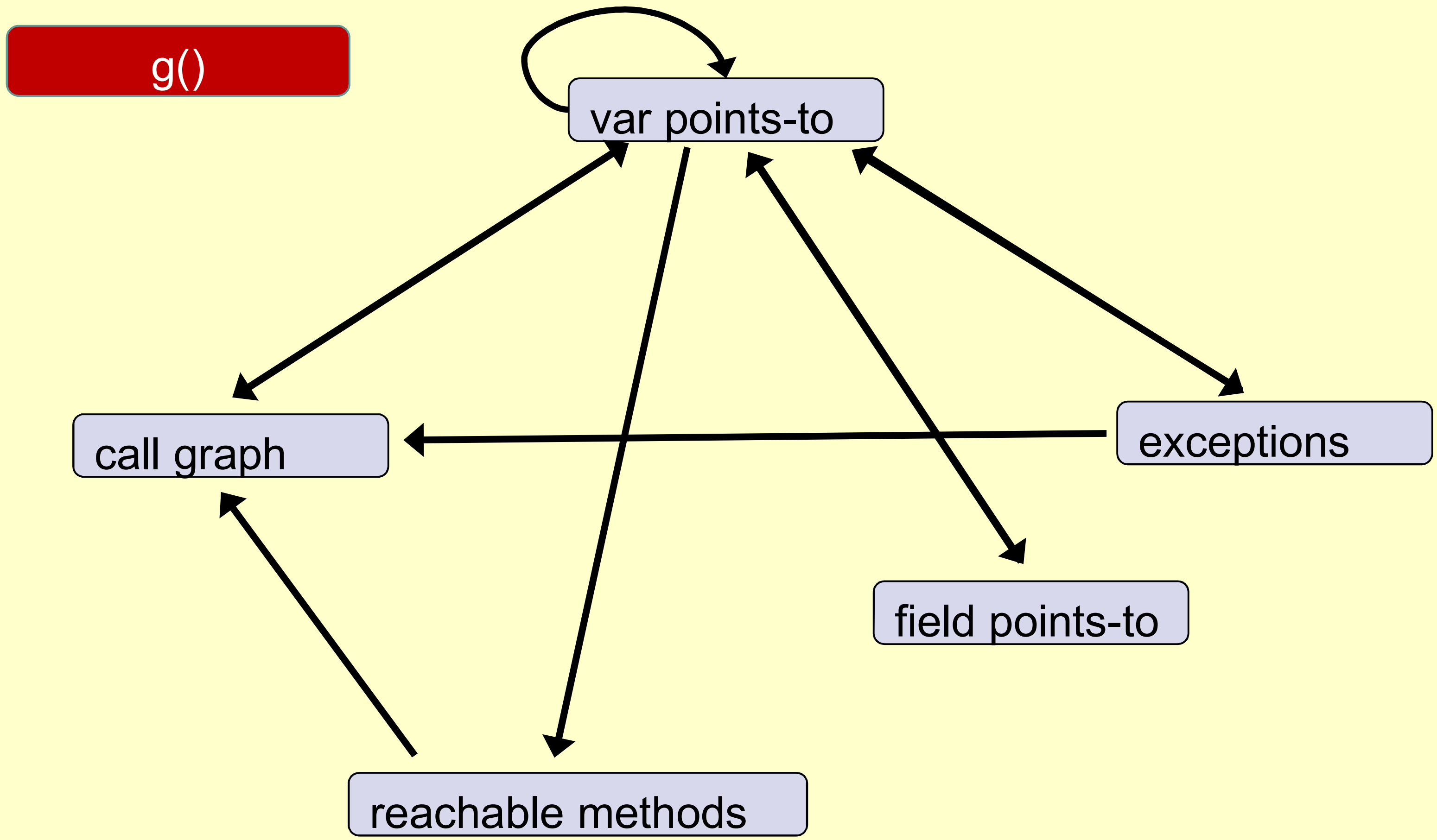
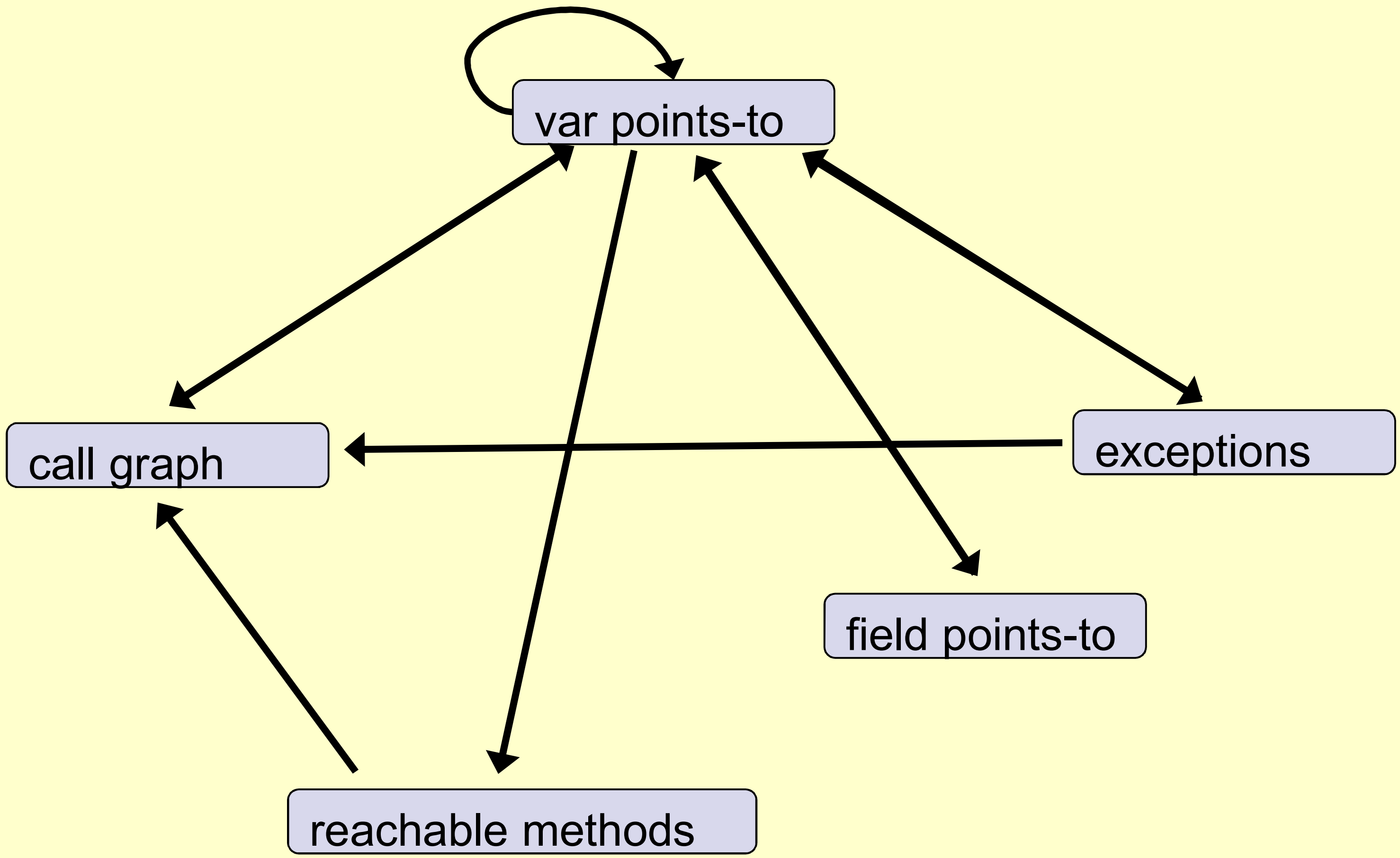


Program Analysis: a Domain of Mutual Recursion



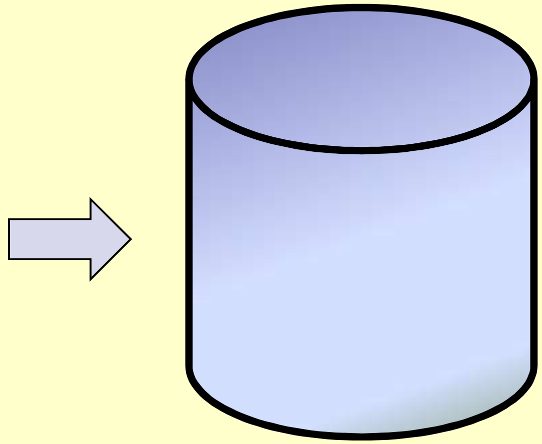
Program Analysis: a Domain of Mutual Recursion



Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```



Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

rules

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).
```

```
VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

head

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

head relation

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

bodies

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

VarPointsTo

Move

a	b
b	a
c	b

body relations

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

join variables

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

recursion

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

a	new A()
b	new B()
c	new C()

1st rule result

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;

Alloc	
a	new A()
b	new B()
c	new C()

Move	
a	b
b	a
c	b

VarPointsTo	
a	new A()
b	new B()
c	new C()

2nd rule evaluation

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

a	new A()
b	new B()
c	new C()
a	new B()

2nd rule result

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Declarative Mutual Recursion

source

```
a = new A();
b = new B();
c = new C();
a = b;
b = a;
c = b;
```

Alloc

a	new A()
b	new B()
c	new C()

Move

a	b
b	a
c	b

VarPointsTo

a	new A()
b	new B()
c	new C()
a	new B()
b	new A()
c	new B()
c	new A()

```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

Datalog: Properties

- Limited logic programming
  - SQL with recursion
  - Prolog without complex terms (constructors)
- Captures PTIME complexity class
- Strictly declarative
  - as opposed to Prolog
    - conjunction commutative
    - rules commutative
  - increases algorithm space
    - enables different execution strategies, aggressive optimization

Less programming, more specification

The DOOP Framework

- Datalog-based pointer analysis framework for Java
- Declarative: what, not how
- Sophisticated, very rich set of analyses
  - subset-based analysis, fully on-the-fly call graph discovery, field-sensitivity, context-sensitivity, call-site sensitive, object sensitive, thread sensitive, context-sensitive heap, abstraction, type filtering, precise exception analysis
- Support for full semantic complexity of Java
  - jvm initialization, reflection analysis, threads, reference queues, native methods, class initialization, finalization, cast checking, assignment compatibility

http://doop.program-analysis.org

Some Doop Contributions

- Expressed complete, complex pointer analyses in Datalog
  - core specification: ~1500 logic rules
  - parameterized by a handful of rules per analysis flavor
- Synthesized efficient algorithms from specification
  - order of magnitude performance improvement
  - allowed to explore more analyses than past literature
- Approach: heuristics for searching algorithm space
  - targeted at recursive problem domains
- Demonstrated scalability with explicit representation
  - Contrast: previous work used BDDs (bddbddb, Paddle)

Not Expected

- Expressed complete, complex pointer analyses in Datalog

  “*[E]ncoding all the details of a complicated program analysis problem [on-the-fly call graph construction, handling of Java features] purely in terms of subset constraints may be difficult or impossible.” (Lhotak)*

- Scalability and Efficiency

  “Efficiently implementing a 1H-object-sensitive analysis without BDDs will require new improvements in data structures and algorithms”

How Datalog Executes*

***Note: we will focus on bottom-up execution, as used in Doop. A top-down execution strategy is possible, and is useful for other applications of Datalog**

Naïve Datalog Execution

- Execute each rule against all facts in the current database
- Add the resulting facts to the database
- Repeat until no more facts are added

- Efficiency problem
  - Facts inferred in the first iteration are re-inferred in all subsequent iterations
  - In second iteration, need only consider rule instantiations based on at least one new fact

Semi-Naïve Datalog Execution

- Execute program incrementally
  - For each rule r, for each fact f produced in relation R in the previous round, generate all facts inferable via rule r, fact f, and all current facts for relations other than R
- Example
  - Original program

```
VarPointsTo(to, obj) <-
  Move(to, from),
  VarPointsTo(from, obj).
```

  - Semi-Naïve rewriting

```
Δ VarPointsTo(to, obj) <-
  Move(to, from),
  ΔVarPointsTo(from, obj).
```

  - Note that we don't have a similar Δ rule for Move, because Move represents program text and we never get more facts there

Semi-Naïve Datalog Execution

- Rewritten program

```
VarPointsTo(var, obj) <-
  AssignHeapAllocation(var, obj).
ΔVarPointsTo(to, obj) <-
  Move(to, from),
  ΔVarPointsTo(from, obj).
```

- Initial facts

```
AssignHeapAllocation(“y”, “o1”).
AssignHeapAllocation(“z”, “o2”).

Move(“x”, “y”).
Move(“y”, “z”).
```

Practice: Semi-Naïve Execution

```
VarPointsTo(var, obj) <-
  AssignHeapAllocation(var, obj).

VarPointsTo(to, obj) <-
  LoadField(base, field, to),
  VarPointsTo(base, baseobj),
  FieldPointsTo(baseobj, field, obj).

FieldPointsTo(baseobj, field, obj) <-
  StoreField(base, field, from),
  VarPointsTo(base, baseobj),
  VarPointsTo(from, obj).
```

```
AssignHeapAllocation("x", "o1").
AssignHeapAllocation("y", "o2").

LoadField("x", "f", "x").  % x.f = x
StoreField("x", "f", "y"). % y = x.f
```

Practice: Writing Reachability Analysis

- Reachable(meth) % method implementation meth is reachable
- VarPointsTo(var, obj) % var may point to an object allocated at obj
- Alloc(var, obj, meth) % obj: var = new ...(...) in meth
- VCall(base, sig, inMeth)% virtual call: base.sig(...) in "inMeth"
- Lookup(obj, sig, meth) % looks up the method implementation for allocation
% site obj and method signature sig

- var, base - variable
- obj - object allocation site
- meth, inMeth - method implementation
- sig - method name and signature

- Give rules for Reachable and VarPointsTo, assuming Alloc, VCall, and Lookup are given

Encoding Context-Sensitive Pointer Analysis in Datalog

[PLDI’10, POPL’11, CC’13, PLDI’13, PLDI’14]

Recall: Context-Sensitivity (call-site sensitivity)

- What objects can a variable point to?

program

```
void foo() {
  Object a = new A1();
  Object b = id(a);
}

void bar() {
  Object a = new A2();
  Object b = id(a);
}

Object id(Object a) {
  return a;
}
```

points-to

foo:a	new A1()
bar:a	new A2()
id:a	new A1(), new A2()
foo:b	new A1(), new A2()
bar:b	new A1(), new A2()

call-site-sensitive points-to

foo:a	new A1()
bar:a	new A2()
id:a (foo)	new A1()
id:a (bar)	new A2()
foo:b	new A1()
bar:b	new A2()

Object-Sensitivity

program

```
class S {
  Object id(Object a) { return a; }
  Object id2(Object a) { return id(a); }
}
class C extends S {
  void fun1() {
    Object a1 = new A1();
    Object b1 = id2(a1);
  }
}
class D extends S {
  void fun2() {
    Object a2 = new A2();
    Object b2 = id2(a2);
  }
}
```

1-call-site-sensitive points-to

`fun1:a1`	`new A1()`
`fun2:a2`	`new A2()`
`id2:a (fun1)`	`new A1()`
`id2:a (fun2)`	`new A2()`
`id:a (id2)`	`new A1(),new A2()`
`id2:ret (*)`	`new A1(),new A2()`
`fun1:b1`	`new A1(),new A2()`
`fun2:b2`	`new A1(),new A2()`

Object-Sensitivity

program

```
class S {
  Object id(Object a) { return a; }
  Object id2(Object a) { return id(a); }
}
class C extends S {
  void fun1() {
    Object a1 = new A1();
    Object b1 = id2(a1);
  }
}
class D extends S {
  void fun2() {
    Object a2 = new A2();
    Object b2 = id2(a2);
  }
}
```

1-object-sensitive points-to

fun1:a1	new A1()
fun2:a2	new A2()
id2:a (C*1*)	new A1()
id2:a (D*1*)	new A2()
id:a (C*1*)	new A1()
id:a (D*1*)	new A2()
id2:ret (C*1*)	new A1()
fun1:b1	new A1()
fun2:b2	new A2()

A General Formulation of Context-Sensitive Analyses

- *Every context-sensitive flow-insensitive analysis there is* (ECSFIATI)
  - ok, almost every
    - most not handled are strictly less sophisticated
  - and also many more than people ever thought
- Also with on-the-fly call-graph construction
- In 9 easy rules!

Simple Intermediate Language

- We consider Java-bytecode-like language
  - allocation instructions (`Alloc`)
  - local assignments (`Move`)
  - virtual and static calls (`VCall`, `SCall`)
  - field access, assignments (`Load`, `Store`)
  - standard type system and symbol table info (`Type`, `Subtype`, `FormalArg`, `ActualArg`, etc.)

Rule 1: Allocating Objects (Alloc)

```
VarPointsTo(var, ctx, obj, hctx)
<-
  Alloc(var, obj, meth),
  Reachable(meth, ctx).
where hctx = Record(obj, ctx)
```

obj: var = new Something();

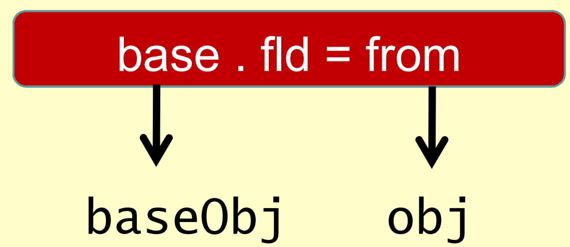
Rule 2: Variable Assignment
(Move)

```
VarPointsTo(to, ctx, obj, hctx)
<-
  Move(to, from),
  VarPointsTo(from, ctx, obj, hctx).
```

to = from

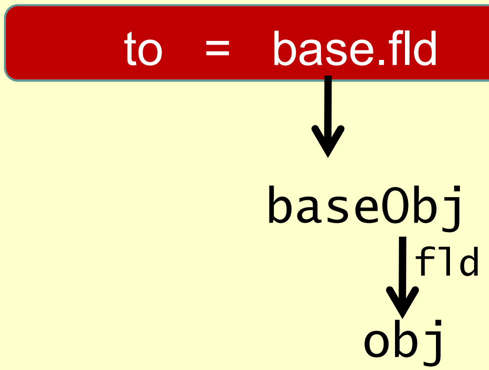
Rule 3: Object Field Write
(Store)

```
FldPointsTo(baseObj, baseHCtx, fld, obj, hctx)
<-
  Store(base, fld, from),
  VarPointsTo(from, ctx, obj, hctx),
  VarPointsTo(base, ctx, baseObj, baseHCtx).
```



Rule 4: Object Field Read (Load)

```
VarPointsTo(to, ctx, obj, hctx)
<-
  Load(to, base, fld),
  FldPointsTo(baseObj, baseHCtx, fld, obj, hctx),
  VarPointsTo(base, ctx, baseObj, baseHCtx).
```



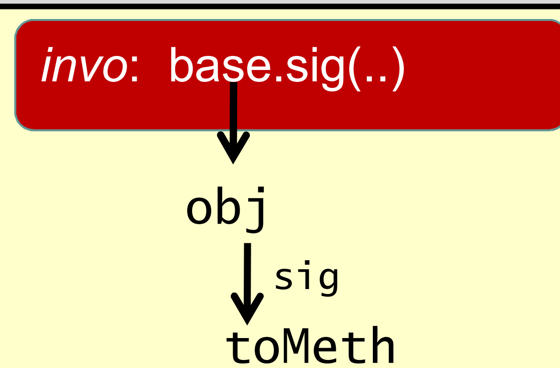
Rule 5: Static Method Calls (`SCall`)

```
Reachable(toMeth, calleeCtx),
CallGraph(invo, callerCtx, toMeth, calleeCtx)
<-
  SCall(toMeth, invo, inMeth),
  Reachable(inMeth, callerCtx).
where calleeCtx = MergeStatic(invo, callerCtx)
```

invo: toMeth(..)

Rule 6: Virtual Method Calls
(VCall)

```
Reachable(toMeth, calleeCtx),
VarPointsTo(this, calleeCtx, obj, hctx),
CallGraph(invo, callerCtx, toMeth, calleeCtx)
<-
  VCall(base, sig, invo, inMeth),
  Reachable(inMeth, callerCtx),
  VarPointsTo(base, callerCtx, obj, hctx),
  LookUp(obj, sig, toMeth),
  ThisVar(toMeth, this).
where calleeCtx = Merge(obj, hctx, invo, callerCtx)
```



Rule 7: Parameter Passing

```
InterProcAssign(to, calleeCtx, from, callerCtx)
<-
  CallGraph(invo, callerCtx, meth, calleeCtx),
  ActualArg(invo, i, from),
  FormalArg(meth, i, to).
```

invo: meth(.., from, ..) → meth(.., to, ..)

Rule 8: Return Value Passing

```
InterProcAssign(to, callerCtx, from, calleeCtx)
<-
  CallGraph(invo, callerCtx, meth, calleeCtx),
  ActualReturn(invo, to),
  FormalReturn(meth, from).
```

invo: to = meth(..) → meth(..) { .. return from; }

Rule 9: Parameter/Result Passing as Assignment

```
VarPointsTo(to, toCtx, obj, hctx)
<-
  InterProcAssign(to, toCtx, from, fromCtx),
  VarPointsTo(from, fromCtx, obj, hctx).
```

Can Now Express Past Analyses Nicely

- 1-call-site-sensitive with context-sensitive heap:
  - $\mathit{Context} = \mathit{HContext} = \mathrm{Instr}$
- Functions:
  - ***Record***`(obj, ctx) = ctx`
  - ***Merge***`(obj, hctx, invo, callerCtx) = invo`
  - ***MergeStatic***`(invo, callerCtx) = invo`

Can Now Express Past Analyses Nicely

- 1-object-sensitive+heap:
  - $Context = HContext = \mathrm{Instr}$
- Functions:
  - ***Record***`(obj, ctx) = ctx`
  - ***Merge***`(obj, hctx, invo, callerCtx) = obj`
  - ***MergeStatic***`(invo, callerCtx) = callerCtx`

Can Now Express Past Analyses Nicely

- PADDLE-style 2-object-sensitive+heap:
  - $Context = \mathrm{Instr}^2$, $HContext = \mathrm{Instr}$
- Functions:
  - ***Record***`(obj, ctx) = first(ctx)`
  - ***Merge***`(obj, hctx, invo, callerCtx) =`
    `pair(obj, first(callerCtx))`
  - ***MergeStatic***`(invo, callerCtx) = callerCtx`

Lots of Insights and New Algorithms (all with major benefits)

- Discovered that the same name was used for two past algorithms with very different behavior
- Proposed a new kind of context (*type-sensitivity*), easily implemented by uniformly tweaking **`Record`**/**`Merge`** functions
- Found connections between analyses in functional/OO languages
- Showed that merging different kinds of contexts works great (*hybrid context-sensitivity*)

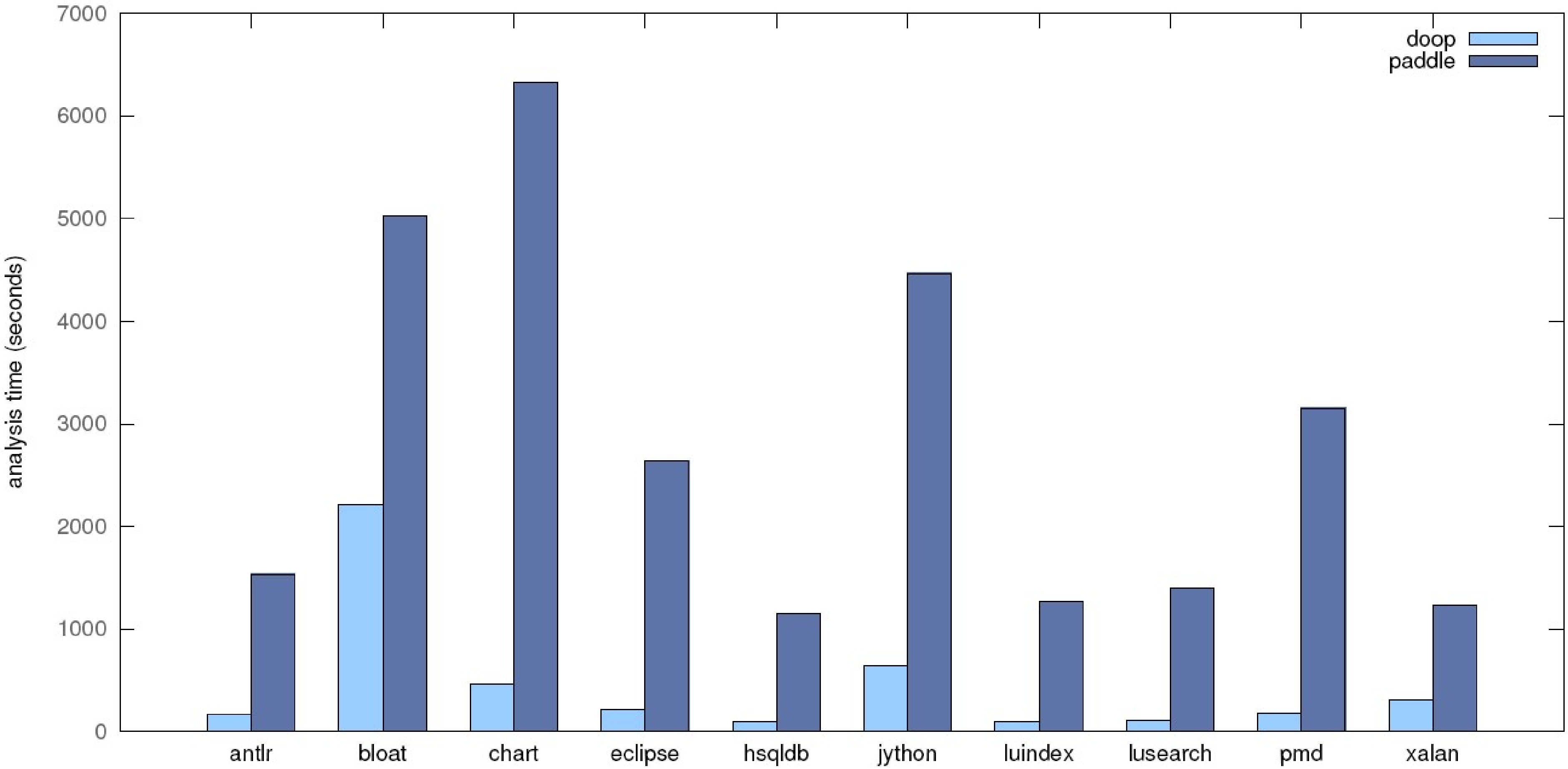
Impressive Performance, Implementation Insights

[OOPSLA’09, ISSTA’09]

Impressive Performance

- Compared to Paddle
  - most complete, scalable past framework
    - includes analyses with a context sensitive heap
- Large speedup for fully equivalent results
  - 15.2x faster for 1-obj, 16.3x faster for 1-call, 7.3x faster for 1-call+heap, 6.6x faster for 1-obj+heap
- Large speedup for more precise results!
  - 9.7x for 1-call, 12.3x for 1-call+heap, 3x for 1-obj+heap
- Scaling to analyses Paddle cannot handle
  - 2-call+1-heap, 2-object+1-heap, 2-call+2-heap

1-call-site-sensitive+heap



Where Is The Magic?

- Surprisingly, in very few places
  - 4 orders of magnitude via optimization methodology for highly recursive Datalog!
    - straightforward data processing optimization (indexes), but with an understanding of how Datalog does recursive evaluation
  - no BDDs
    - are they needed for pointer analysis?
  - simple domain-specific enhancements that increase both precision and performance in a direct (non-BDD) implementation

Identifying Performance Problems

- Inefficient Datalog:

```
VarPointsTo(?var, ?obj) <-
  AssignObjectAllocation(?var, ?obj).

VarPointsTo(?to, ?obj) <-
  Assign(?from, ?to), VarPointsTo(?from, ?obj).
```

  - LogicBlox Datalog indexes on the *last* variable in a relation
  - This code joins on the *first* variables of Assign, VarPointsTo

- After re-ordering variables:

```
VarPointsTo(?obj, ?var) <-
  AssignObjectAllocation(?obj, ?var).

VarPointsTo(?obj, ?to) <-
  Assign(?to, ?from), VarPointsTo(?obj, ?from).
```

More Challenging

- Specification

```
FieldPointsTo(?obj, ?field, ?baseobj) <-
  StoreField(?from, ?field, ?base),
  VarPointsTo(?baseobj, ?base),
  VarPointsTo(?obj, ?from).
```

- Semi-naïve executions

```
ΔFieldPointsTo(?obj, ?field, ?baseobj) <-
  StoreField(?from, ?field, ?base),
  ΔVarPointsTo(?baseobj, ?base),
  VarPointsTo(?obj, ?from).

ΔFieldPointsTo(?obj, ?field, ?baseobj) <-
  StoreField(?from, ?field, ?base),
  VarPointsTo(?baseobj, ?base),
  ΔVarPointsTo(?obj, ?from).
```

Folding

- Original

```
FieldPointsTo(?obj, ?field, ?baseobj) <-
  StoreField(?from, ?field, ?base),
  VarPointsTo(?baseobj, ?base),
  VarPointsTo(?obj, ?from).
```

- Implemented with an extra relation
  - and an extra index

```
FieldPointsTo(?obj, ?field, ?baseobj) <-
  StoreObjectField(?baseobj, ?field, ?from)
  VarPointsTo(?obj, ?from).

StoreObjectField(?baseobj, ?field, ?from)
  StoreField(?from, ?field, ?base),
  VarPointsTo(?baseobj, ?base),
```

Optimization Practice

- Original

```
VarPointsTo(?obj, ?to) <-
  LoadField(?to, ?base, ?field),
  VarPointsTo(?baseobj, ?base),
  FieldPointsTo(?obj, ?field, ?baseobj).
```

- Optimize the variable order of LoadField and add folds
  - You may not change variable order in other relations

Optimization Insight

- For highly recursive Datalog programs, ***relation deltas produced by semi-naive evaluation should bind all the variables needed to index into other relations***
- Can require complex reasoning
  - whole program optimization
  - human needs to be in the loop in the search of algorithm space!

Algorithmic Enhancements

- BDDs are necessary if one is not careful about precision
- We introduced simple algorithmic enhancements to avoid redundancy
  - static initializers handled context-insensitively
  - on-the-fly exception handling
- Better analyses, as well as faster!

Conclusions, Future Work

Declarative Program Analysis

- Doop is probably the most complete points-to analysis framework for Java
  - aids exploration
  - competitive performance
- Already yielded new algorithms, implementation techniques
- Latest: flow-sensitive, LLVM, client analyses
- Future: commercialization as program comprehension service