Declarative Static Program Analysis: An Intelligent System over Programs

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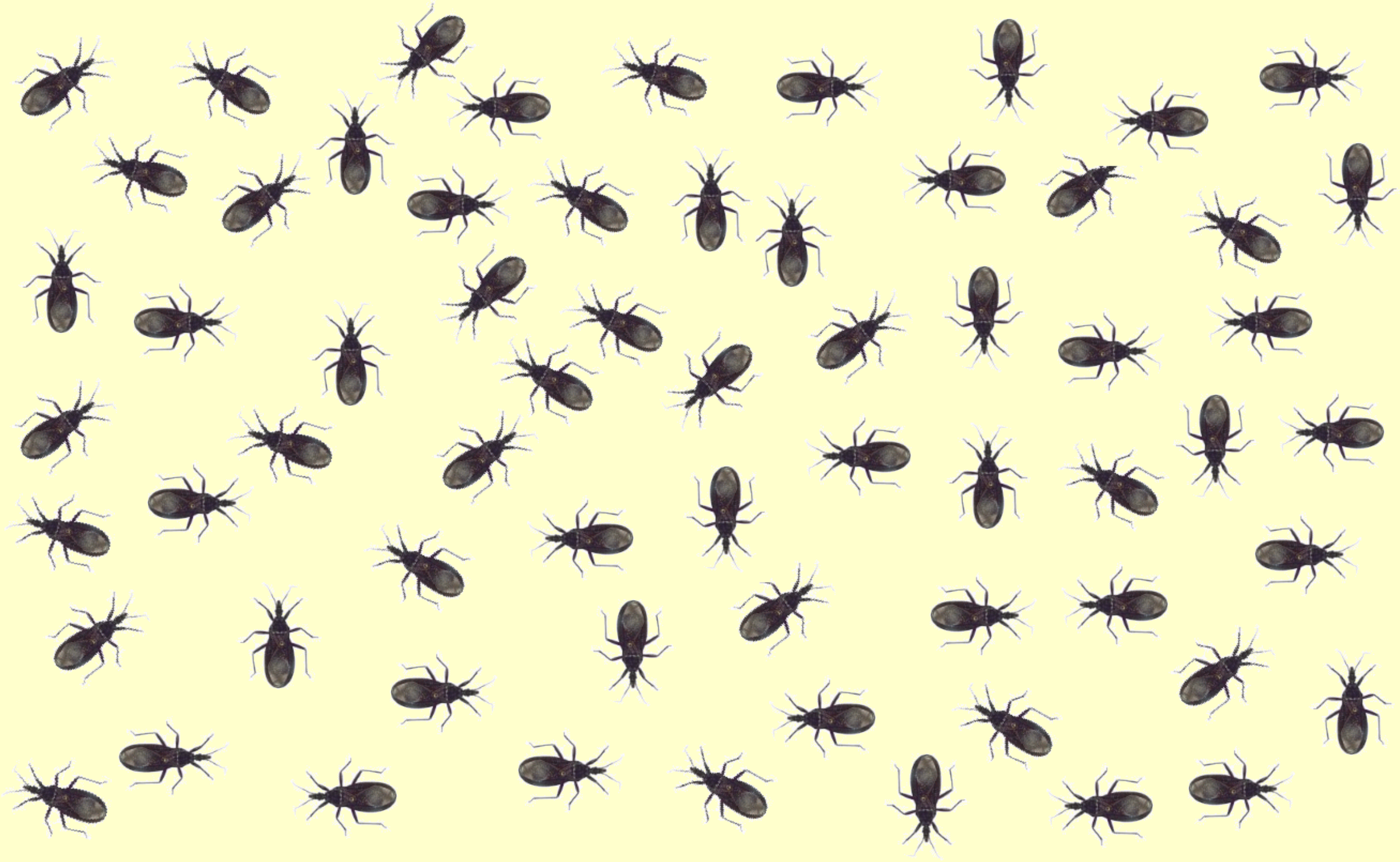
LOGICBLOX

Overview

- What do we do?
  - static program analysis
    - “discover program properties that hold for all executions”
- Vision: a system that knows more about your program than you do
- How do we do it?
  - declarative (logic-based specification)
    - fast, powerful, new insights

Program Analysis: Run Faster
(e.g., compiler optimization)

Program Analysis: Find Bugs



Program Analysis: Software Understanding

(e.g., slicing, refactoring, program queries)

My Research: Doop
and friends: CClyzer, MadMax

- Since 2008:
  - Doop: a powerful framework for analyzing Java bytecode
    - building on *pointer analysis*
      - now just a substrate for more analyses
  - declarative, using the Datalog language
- Lots of offshoots
  - Cclyzer, for LLVM bitcode
  - GigaHorse/MadMax for EVM bytecode

Pointer Analysis
(but really: value-flow analysis)

- What objects can a variable point to?

objects represented by allocation sites

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()

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	ne
id:a	n
foo:b	n
bar:b	n

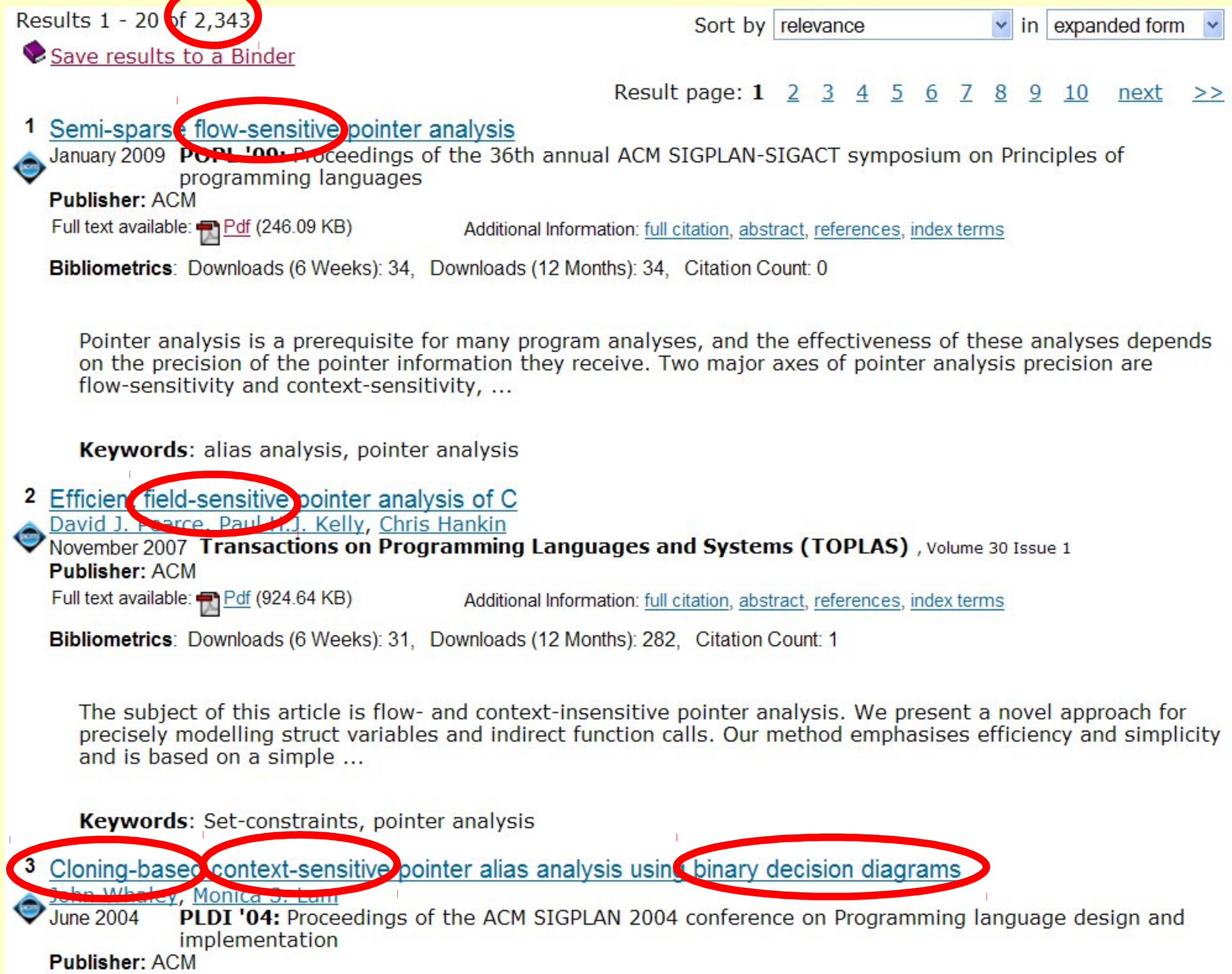
remember for later: context-sensitivity is what makes an analysis precise

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

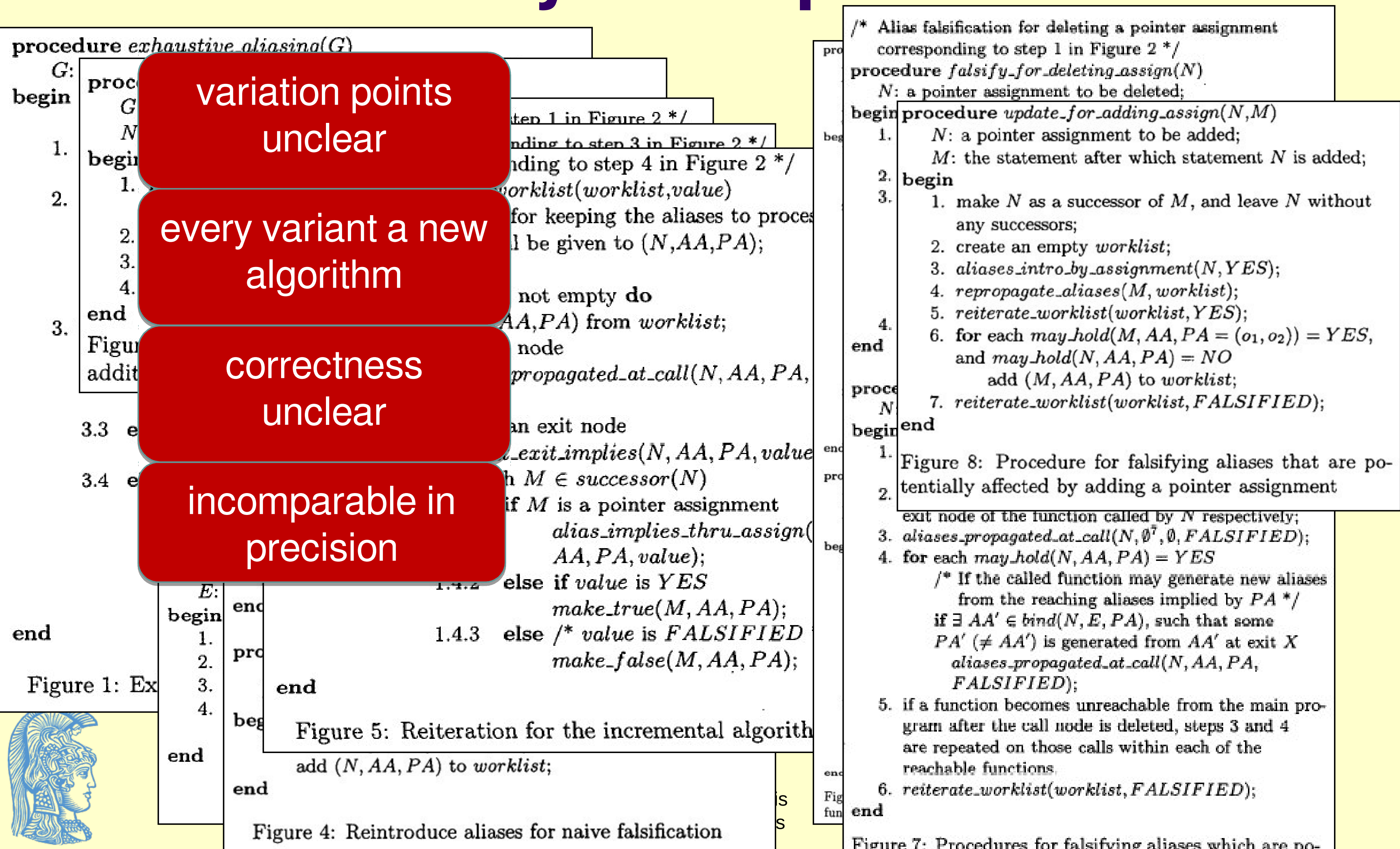
2 Efficient field-sensitive pointer analysis of C
David J. Pearce, Paul H.J. Kelly, Chris Hankin
November 2007 **Transactions on Programming Languages and Systems (TOPLAS)** , Volume 30 Issue 1
Publisher: ACM
Full text available: Pdf (924.64 KB) Additional Information: full citation, abstract, references,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

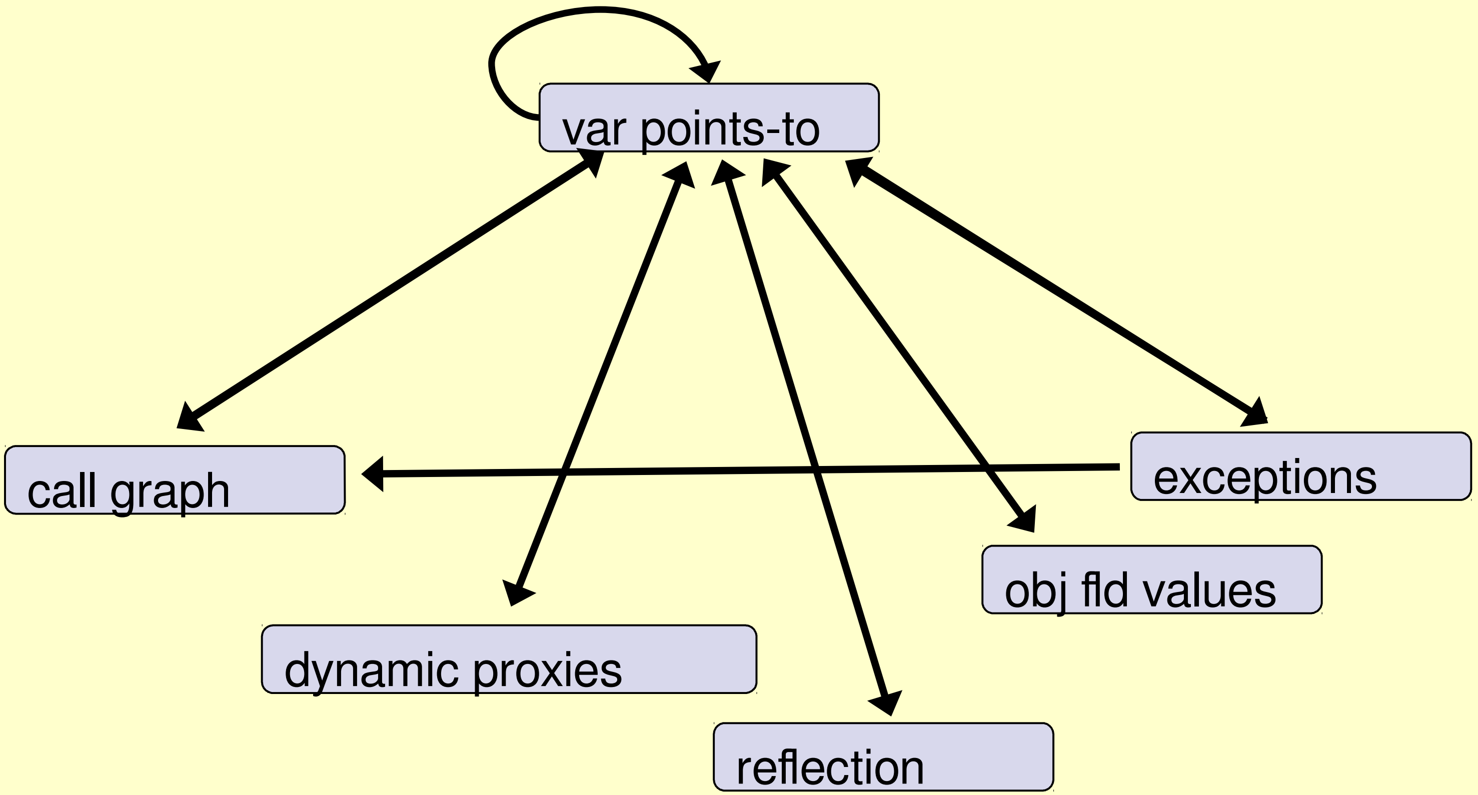
Keywords: Set-constraints, pointer analysis

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



***Holistic Program Analysis*:** "Everything Is Connected"

A Vision Within Reach

- *An intelligent system that knows more about your program than you do*
- “Everything is connected”
  - all analysis aspects encoded separately, all benefitting each other
- The Doop framework serves to illustrate
- Key: a declarative specification of all sorts of static analyses
- In Doop: use of Datalog

Datalog To The Rescue!

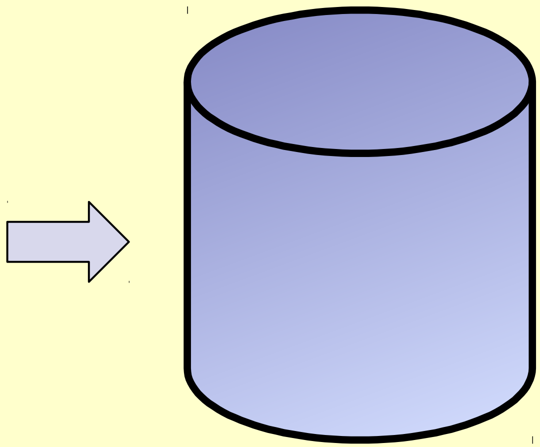
- Datalog is relations + recursion
- Limited logic programming
  - SQL with recursion
  - Prolog without complex terms (constructors)
- Captures PTIME complexity class
- Strictly declarative
  - e.g., as opposed to Prolog
    - conjunction commutative
    - rules commutative
  - monotonic

Less programming, more specification

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()

Move

a	b
b	a
c	b

VarPointsTo

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 variable

```
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()

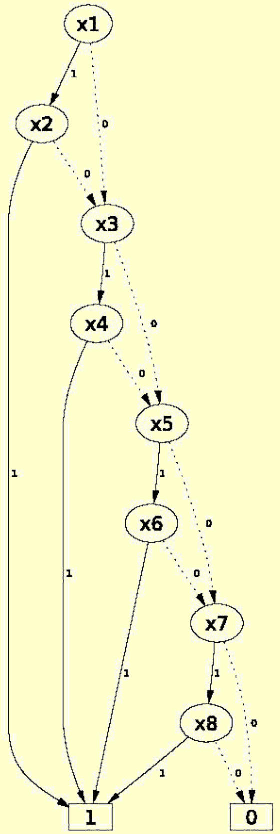
```
VarPointsTo(var, obj) <-
  Alloc(var, obj).

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

The Doop Framework

- Datalog-based static 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

Pointer Analysis: Previous Approaches



Context-sensitive pointer analysis for Java

- paddle
  - Java + relational algebra + binary decision diagrams (BDD)
- WALA
  - Java, conventional approach
- bddbddb (pioneered Datalog for realistic points to analysis)
  - Datalog + Java + BDD

Past Approaches and Declarative Analysis

- Past approaches have flirted with declarative analysis
- But no purely declarative approach
  - specification and algorithm confused
- Declarativeness considered unscalable in both complexity and performance
  - "*the first time I write an analysis it is typically in Datalog, but then, once I'm convinced it's precise, I throw it out and I write it in Java, when I want to focus on scalability.*" (*Naik, 2010*)

Doop Makes Declarative Analysis Real

- Complete, complex pointer analyses in Datalog
  - core specification: ~1500 logic rules
  - parameterized by a handful of rules per analysis flavor
- 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
  - no BDDs

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"

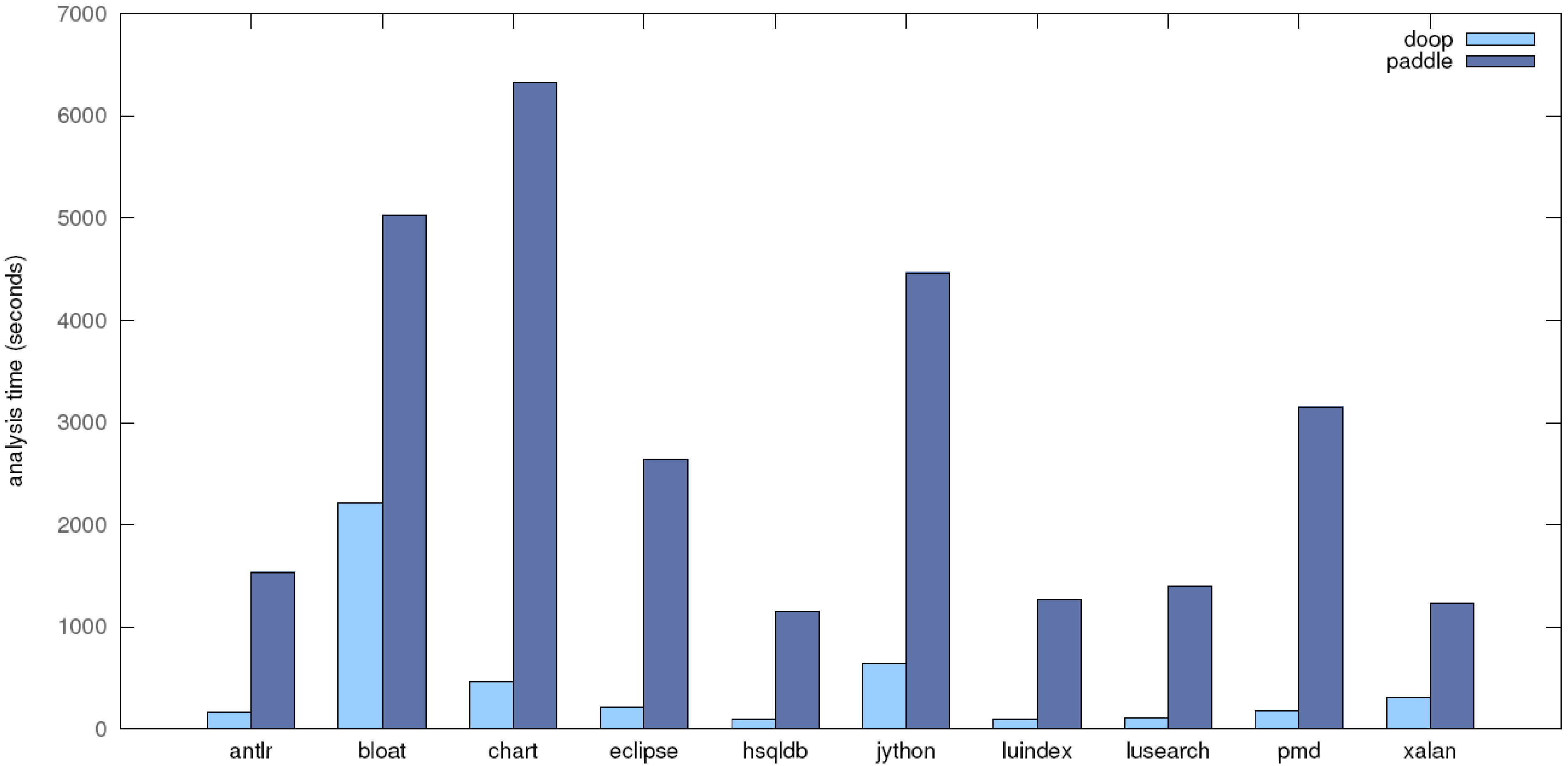
Flyover Tour of Interesting Results

What have we done with this?

Impressive Performance, Implementation Insights

[OOPSLA'09, ISSTA'09]

Large Speedup For Realistic Analyses



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

Better Understanding of Existing Algorithms, More Precise and Scalable New Algorithms

[PLDI’10, POPL’11, CC’13, PLDI’13, PLDI’14, FSE'18, OOPSLA'18]

Expressiveness and Insights

- Greatest benefit of the declarative approach: better algorithms
  - the same algorithms can be described non-declaratively
    - the algorithms are interesting regardless of *how* they are implemented
  - but the declarative formulation was helpful in finding them
    - and in conjecturing that they work well

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
(vs. call-site 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)

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

obj: var = new Something();

Rule 2: Variable Assignment

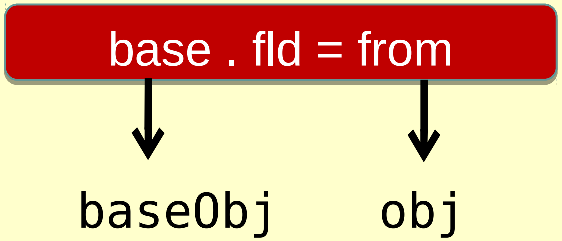
(Move)

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

to = from

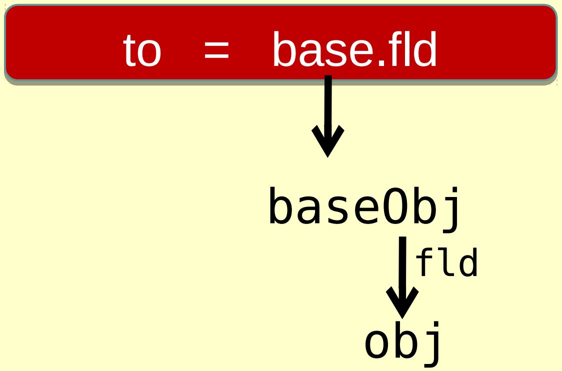
Rule 3: Object Field Write (Store)

```
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).
```



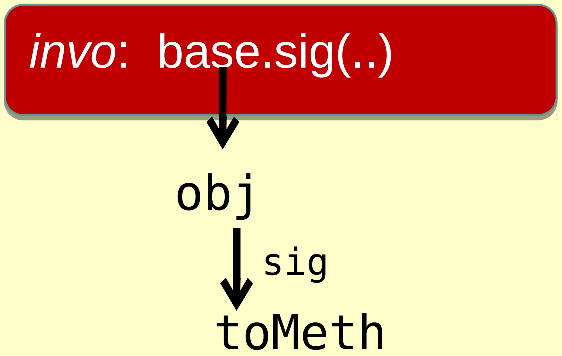
Rule 5: Static Method Calls
(SCall)

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

invo: toMeth(..)

Rule 6: Virtual Method Calls
(VCall)

```
Merge(obj, hctx, invo, callerCtx) = calleeCtx,
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).
```



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:
  - *Context* = *HContext* = 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* = 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* = Instr^2 , *HContext* = Instr
- Functions:
  - ***Record***`(obj, ctx) = first(ctx)`
  - ***Merge***`(obj, hctx, invo, callerCtx) = pair(obj, first(ctx))`
  - ***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*)

Many More Work Threads

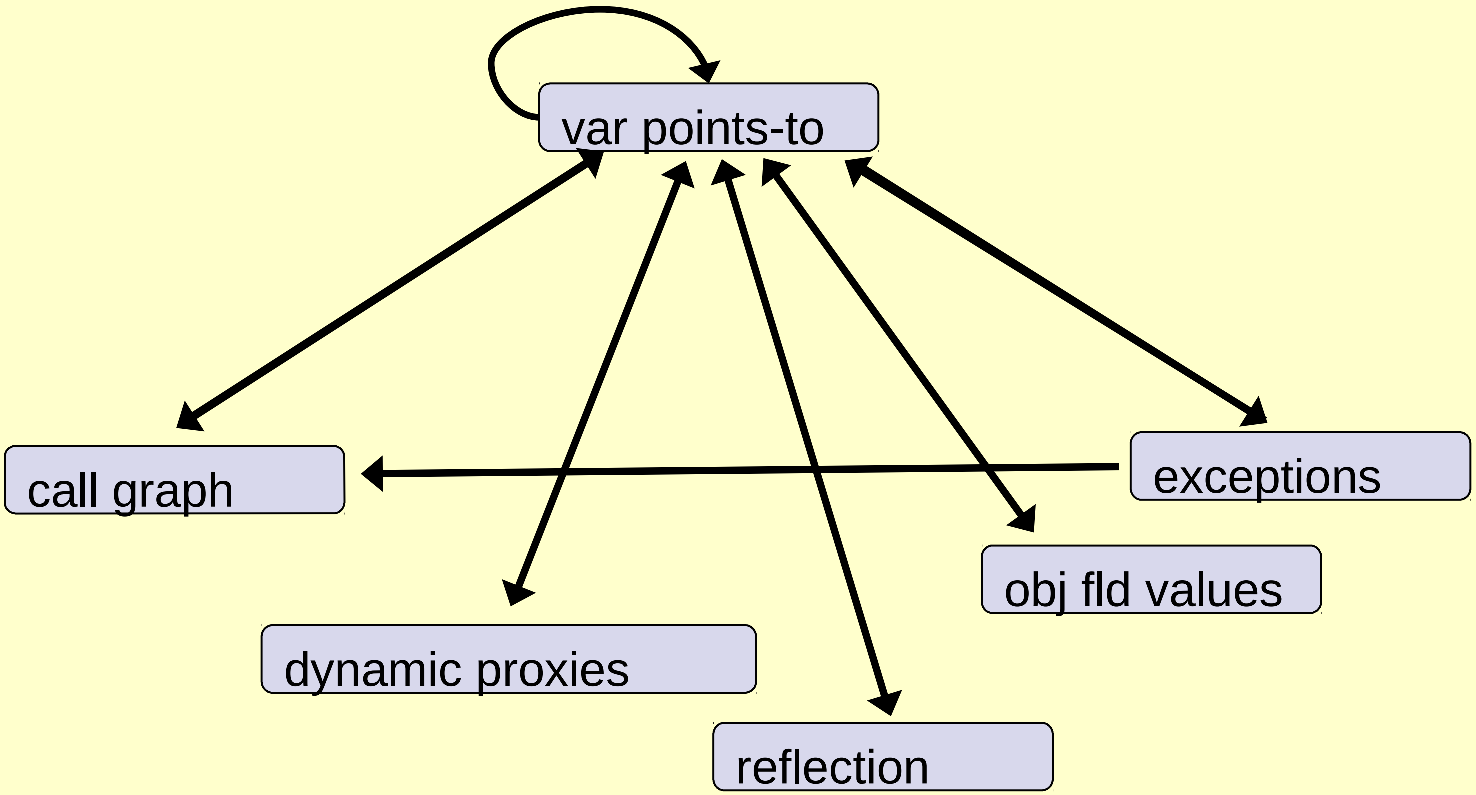
- Set-based pre-analysis [OOPSLA’13]
  - universal optimization technique
- Completing a partial program [OOPSLA’13]
  - making sense out of missing libraries
- Soundness [CACM 2/15, ECOOP'18 **(distinguished paper)**]
- Reflection and dynamic loading [APLAS'15, ECOOP'18, ISSTA'18]
- Port to Souffle: a parallel Datalog engine [SOAP’17]
- Must-alias analysis [SOAP’17, CC'18]
- Taint analysis using points-to algorithms! [OOPSLA’17]
- Integrating heap snapshots in static analysis [OOPSLA’17, ISSTA'18]

Summary and Vision

The Vision

- Doop: early instance of intelligent system that just *knows* things about your program
- The use of Datalog fits very well
  - knowledge-base
  - a database of inferences
  - rules that (if correct) apply independently of others
    - yet in mutual recursion
    - monotonically

Mutual Recursion: Cannot Emphasize Enough



Holistic Program Analysis: "Everything Is Connected"