

Exception Analysis and Points-to Analysis

Better Together

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ISSTA 2009

International Symposium on Software Testing and Analysis

what do we do?

precise analysis of exception handling

improve precision and speed of points-to analyses

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- precise analysis of exception handling
- improve precision and speed of points-to analyses

how do we do it?

- fully declarative specification
- modular extension



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- precise analysis of exception handling
- improve precision and speed of points-to analyses

how do we do it?

- fully declarative specification
- modular extension

why do you care?

- fast, sophisticated, simple
- different



what do we do?

precise analysis of exception handling
improve precision and speed of points-to analyses

how do we do it?

fully declarative specification
modular extension

why do you care?

fast, sophisticated, simple
different

why is it relevant?

major new experimental findings
state-of-the-art points-to analyses



computation of control-flow induced by exceptions

```
void foo() {  
    if(...)  
        throw new FooException();  
}  
  
void mid() {  
    foo();  
}  
  
void bar() {  
    try {  
        foo();  
    }  
    catch(Exception exc) {...}  
}
```

computation of control-flow induced by exceptions

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void foo() {  
    if(...)  
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void mid() {  
    foo();  
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void bar() {  
    try {  
        foo();  
    }  
    catch(Exception exc) {...}  
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```

- exception-flow induces interprocedural assignments
- exceptions are normal objects
- arbitrary expressions can be thrown

computation of control-flow induced by exceptions

```
void foo() {  
    if(...)  
        throw new FooException();  
}  
  
void mid() {  
    foo();  
}  
  
void bar() {  
    try {  
        foo();  
    }  
    catch(Exception exc) {...}  
}
```

- exception-flow induces interprocedural assignments
- exceptions are normal objects
- arbitrary expressions can be thrown

```
catch(SomeException e) {  
    throw e.getCause();  
}
```

```
throw  
    createSomeException();
```

computation of control-flow induced by exceptions

```
void foo() {  
    if(...)  
        throw new FooException();  
}  
  
void mid() {  
    foo();  
}  
  
void bar() {  
    try {  
        foo();  
    }  
    catch(Exception exc) {...}  
}
```

questions answered:

- what exceptions may foo throw?
- where may the FooException thrown in foo get caught?
- what exceptions may get caught by the handler in bar?

application: program understanding

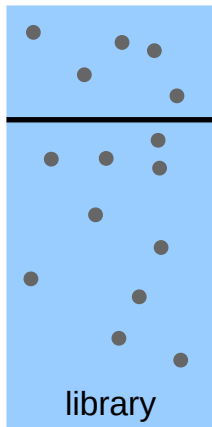
- understand exception-flow in codebases
- coding assistance tool
- also for languages with declared checked exceptions
 - unchecked exceptions
 - `throws`-clause specifies superset
 - e.g. `IOException`

⇒ exception types do not explain where exceptions originate

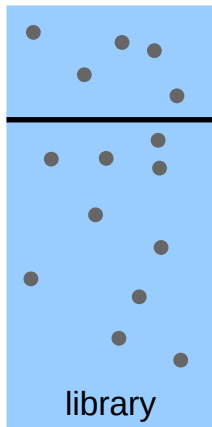
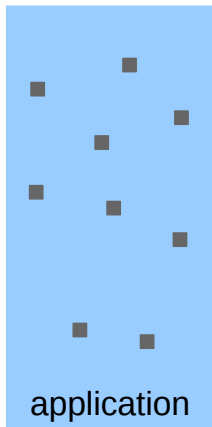
application: test coverage of exceptional situations [Fu et al.]



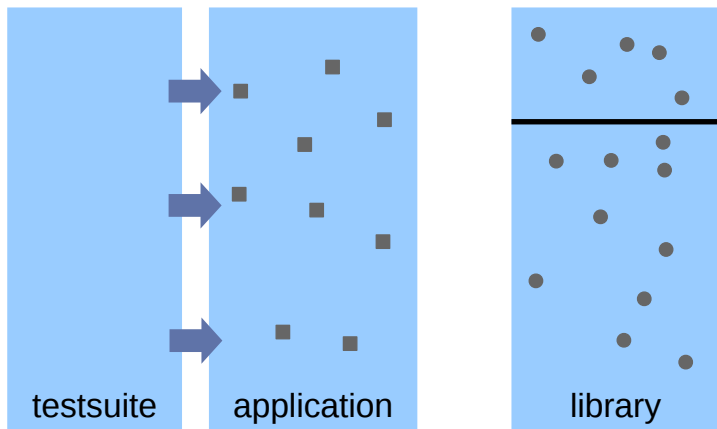
application: test coverage of exceptional situations [Fu et al.]



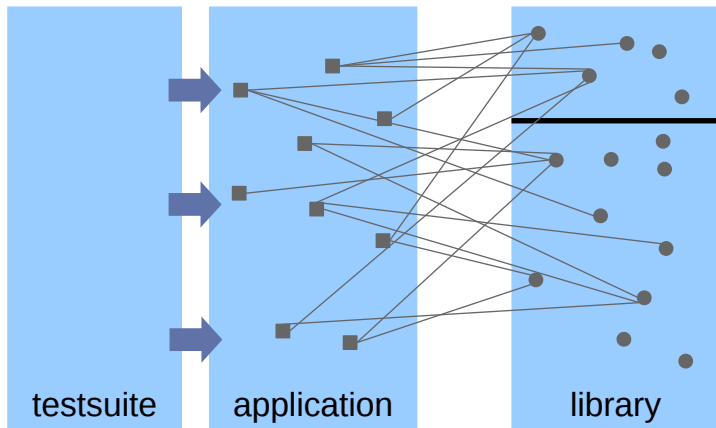
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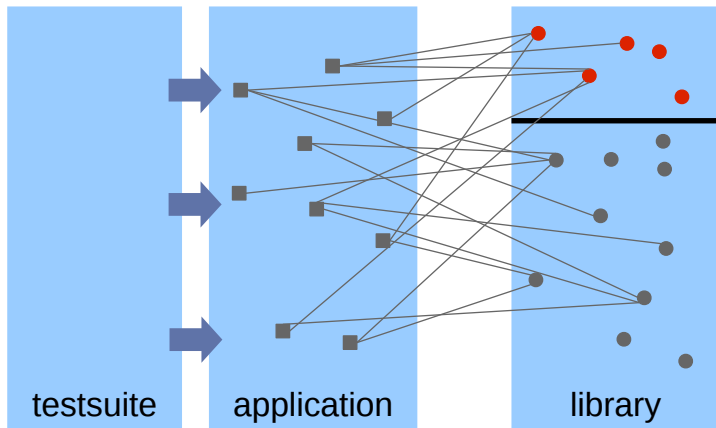
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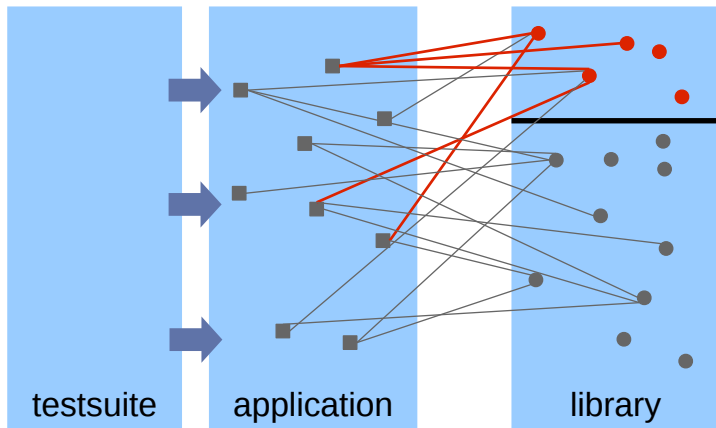
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application: test coverage of exceptional situations [Fu et al.]



points-to analysis (facilitate other applications)

what objects can a variable point to?

program

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

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

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

what objects can a variable point to?

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```
void foo() {  
  a = new A1();  
  b = id(a);  
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void bar() {  
  a = new A2();  
  b = id(a);  
}
```

```
A id(A a) {  
  return a;  
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```

points-to

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

objects represented
by allocation sites

what objects can a variable point to?

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  a = new A2();  
  b = id(a);  
}
```

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

points-to

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

objects represented
by allocation sites

what objects can a variable point to?

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void foo() {  
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void bar() {  
  a = new A2();  
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A id(A a) {  
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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()

objects represented
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what objects can a variable point to?

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```
A id(A 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()

objects represented
by allocation sites

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()

points-to analysis

- necessity: sound points-to analyses need to handle all language constructs
- exception analysis is different, and complicates points-to algorithms

workaround: imprecise exception analysis

```
throw e;           ⇒  THROWN_EXCEPTIONS = e;  
catch(Exception e); ⇒  e = THROWN_EXCEPTIONS;
```

sneak preview: our finding

imprecise exception handling dominates the output of precise context-sensitive points-to analysis

points-to analysis

call graph analysis

exception analysis

points-to analysis

call graph analysis

exception analysis

$x = y$



call graph analysis

exception analysis

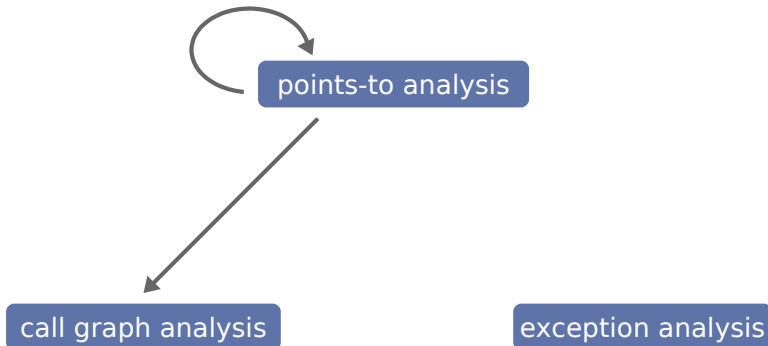
$x = y$



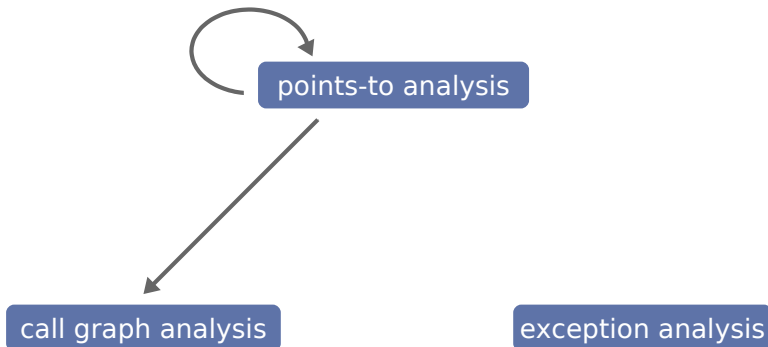
call graph analysis

exception analysis

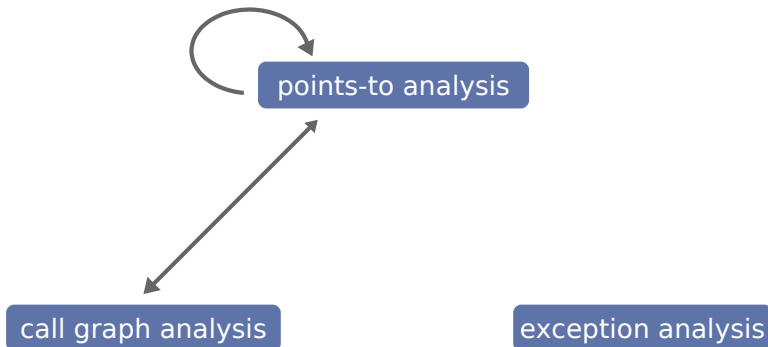
`x = f()`



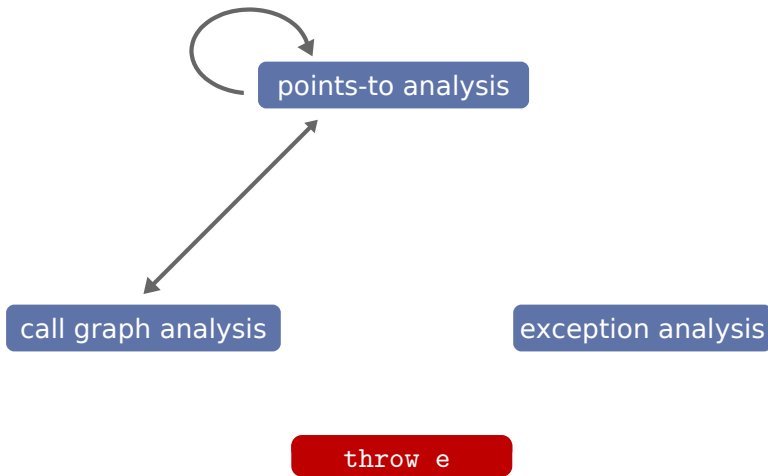
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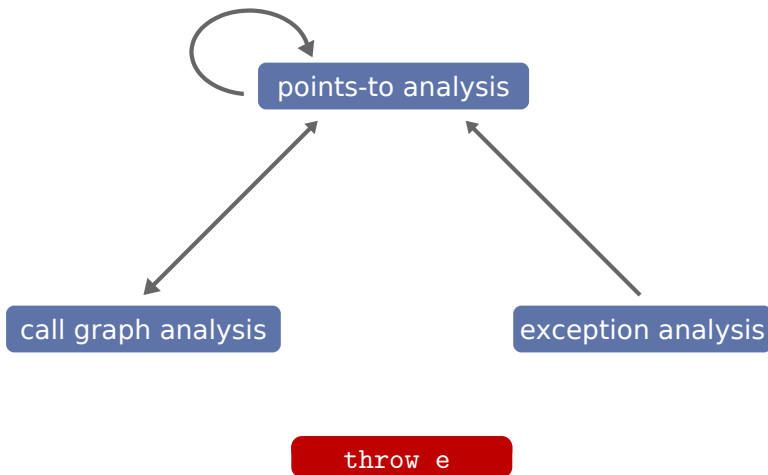


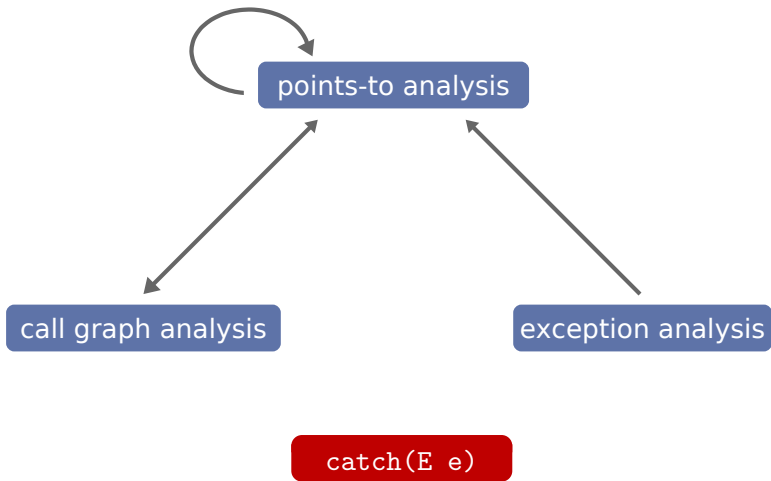
`x = y.f()`

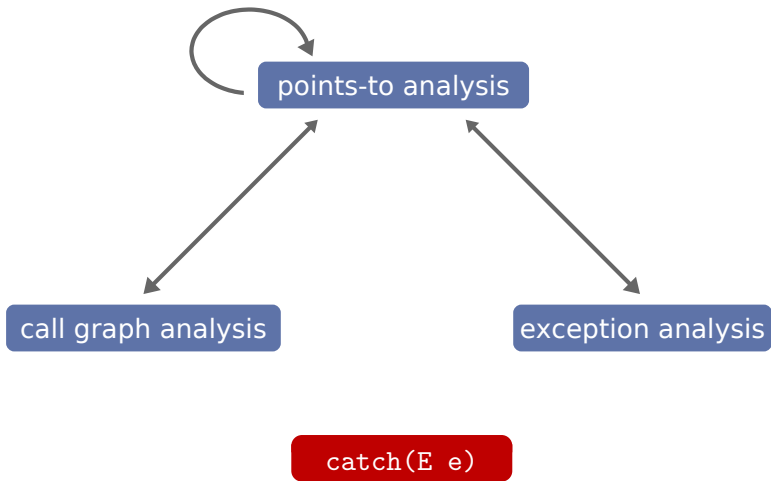


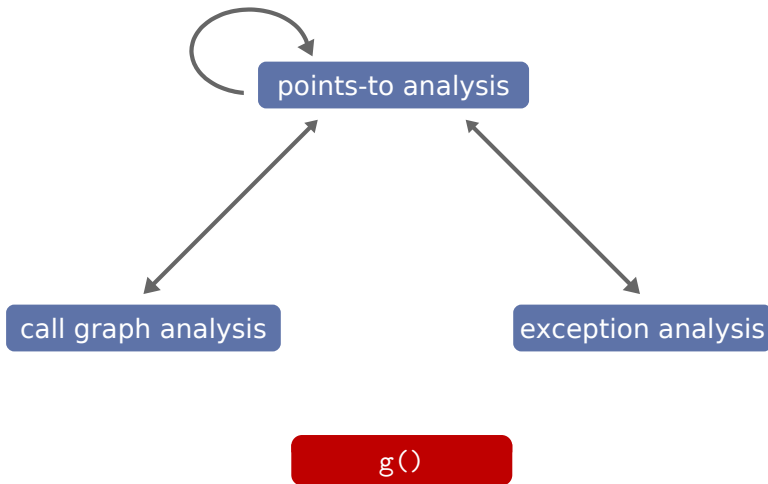
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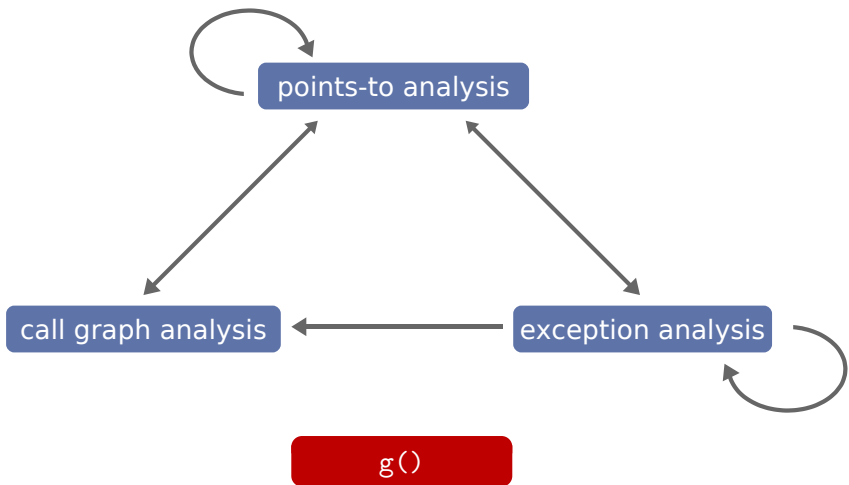


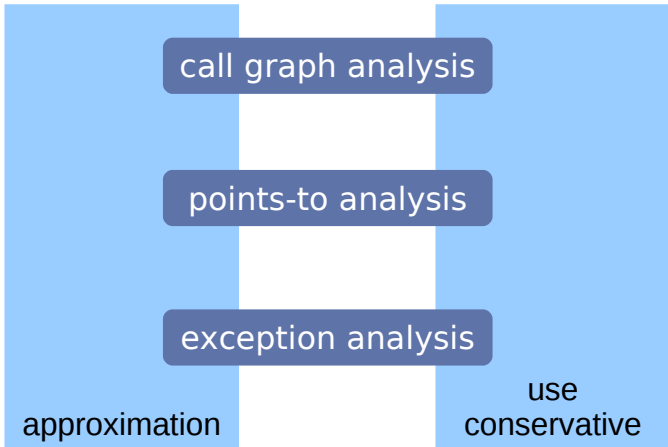


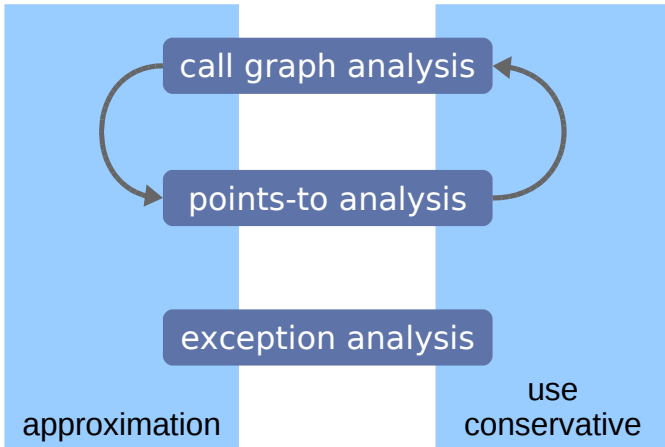


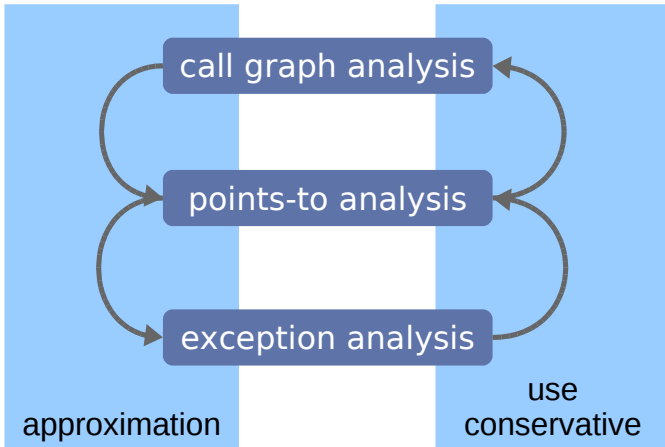


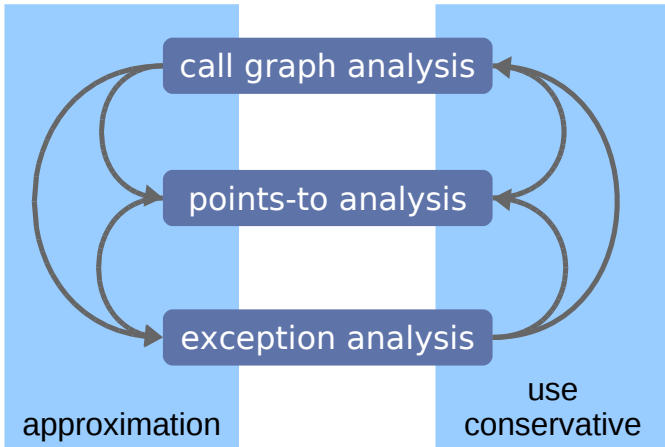


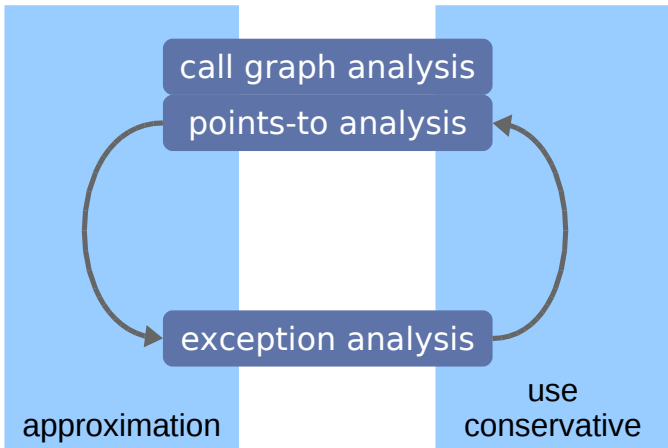


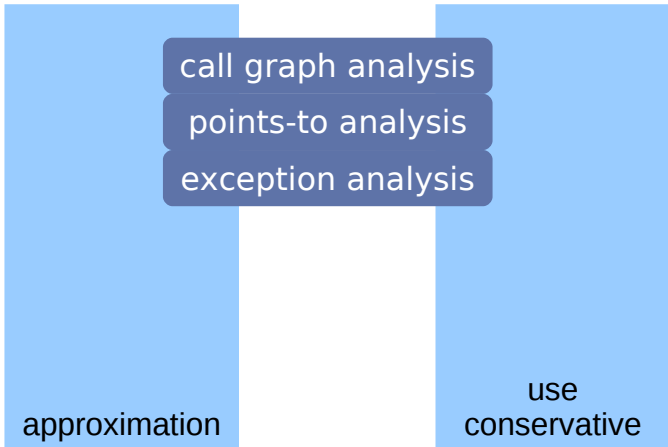












joint exception analysis and points-to analysis

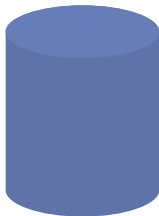
- major improvement in overall precision
- major performance improvement

where is the magic?

- our approach: no imperative algorithm, only declarative specification
- simple declarative specification of highly complex mutually recursive dependencies in datalog

source

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



source

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

AssignObjectAllocation

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

Assign

b		a
a		b
b		c

source

```
a = new A();  
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a = b;  
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```

AssignObjectAllocation

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

Assign

b		a
a		b
b		c

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

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

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VarPointsTo

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AssignObjectAllocation

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VarPointsTo

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AssignObjectAllocation

a	new A()
b	new B()
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Assign

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a	b
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VarPointsTo

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```

AssignObjectAllocation

a	new A()
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Assign

b	a
a	b
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VarPointsTo

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c	new C()

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  Assign(?from, ?to),
  VarPointsTo(?from, ?obj).

```

source

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b = new B();
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a = b;
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```

AssignObjectAllocation

a	new A()
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Assign

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b	c

VarPointsTo

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```

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a = b;
b = a;
c = b;

```

AssignObjectAllocation

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

Assign

b	a
a	b
b	c

VarPointsTo

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

```

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

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

source

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

AssignObjectAllocation

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

Assign

```
b | a
a | b
b | c
```

VarPointsTo

```
a | new A()
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a | new B()
b | new A()
c | new B()
c | new A()
```

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

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 optimization opportunities
 - enables different execution strategies
 - enables more aggressive optimization

writing datalog is less programming, more specification

Strictly Declarative Specification of Sophisticated Points-to Analyses

- performance
- scalability
- declarative specification
- no BDDs



<http://doop.program-analysis.org>

method invocations: propagated exceptions

```
void f() {  
    ...  
}
```

method invocations: propagated exceptions

```
void f() {  
    g();  
}
```

method invocations: propagated exceptions

- `ThrowPointsTo(?caller, ?obj) <-`

```
void f() {  
    g();  
}
```

Method declaration `?caller`
may throw exception object
`?obj`

method invocations: propagated exceptions

- `ThrowPointsTo(?caller, ?obj) <-
 CallGraphEdge(?invocation, ?tomethod),`

```
void f() {  
    g();  
}
```

Method invocation
`?invocation` may invoke
method `?tomethod`

method invocations: propagated exceptions

- `ThrowPointsTo(?caller, ?obj) <-
 CallGraphEdge(?invocation, ?tomethod),
 ThrowPointsTo(?tomethod, ?obj),`

```
void f() {  
    g();  
}
```

Method declaration `?tomethod`
may throw exception object
`?obj`

method invocations: propagated exceptions

- ```
ThrowPointsTo(?caller, ?obj) <-
 CallGraphEdge(?invocation, ?tomethod),
 ThrowPointsTo(?tomethod, ?obj),
 Object:Type[?obj] = ?objtype,
```

```
void f() {
 g();
}
```

The type of the object allocated  
at ?obj is ?objtype

**method invocations: propagated exceptions**

ThrowPointsTo(?caller, ?obj) <-  
 CallGraphEdge(?invocation, ?tomethod),  
 ThrowPointsTo(?tomethod, ?obj),  
 Object:Type[?obj] = ?objtype,  
 not exists ExceptionHandler[?objtype, ?invocation],

```
void f() {
 g();
}
```

Exceptions of specific type  
?objtype, thrown at instruction  
?invocation, are handled by  
exception handler ?handler

**method invocations: propagated exceptions**

- ```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Object:Type[?obj] = ?objtype,  
  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
  g();  
}
```

Instruction ?invocation is
in method ?caller

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Object:Type[?obj] = ?objtype,  
  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
  g();  
}
```

method invocations: caught exceptions

```
void f() {  
  try {...}  
  catch(E e) {...}  
}
```

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Object:Type[?obj] = ?objtype,  
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  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
    g();  
}
```

method invocations: caught exceptions

```
void f() {  
    try { g(); }  
    catch(E e) {...}  
}
```

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
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  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
  g();  
}
```

method invocations: caught exceptions

```
VarPointsTo(?param, ?obj) <-
```

```
void f() {  
  try { g(); }  
  catch(E e) {...}  
}
```

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
● CallGraphEdge(?invocation, ?tomethod),  
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● Object:Type[?obj] = ?objtype,  
  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
    g();  
}
```

method invocations: caught exceptions

```
VarPointsTo(?param, ?obj) <-  
● CallGraphEdge(?invocation, ?tomethod),  
● ThrowPointsTo(?tomethod, ?obj),  
● Type[?obj] = ?objtype,
```

```
void f() {  
    try { g(); }  
    catch(E e) {...}  
}
```

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Object:Type[?obj] = ?objtype,  
  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
  g();  
}
```

method invocations: caught exceptions

```
VarPointsTo(?param, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Type[?obj] = ?objtype,  
  ExceptionHandler[?objtype, ?invocation] = ?handler,
```

```
void f() {  
  try { g(); }  
  catch(E e) {...}  
}
```

method invocations: propagated exceptions

```
ThrowPointsTo(?caller, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Object:Type[?obj] = ?objtype,  
  not exists ExceptionHandler[?objtype, ?invocation],  
  Instruction:Method[?invocation] = ?caller.
```

```
void f() {  
  g();  
}
```

method invocations: caught exceptions

```
VarPointsTo(?param, ?obj) <-  
  CallGraphEdge(?invocation, ?tomethod),  
  ThrowPointsTo(?tomethod, ?obj),  
  Type[?obj] = ?objtype,  
  ExceptionHandler[?objtype, ?invocation] = ?handler,  
  ExceptionHandler:FormalParam[?handler] = ?param.
```

```
void f() {  
  try { g(); }  
  catch(E e) {...}  
}
```

what did you just see here?

- modular extension of variety of base points-to analyses
- approximation only comes from points-to abstraction – exception logic as precise as possible!
- complex mutually recursive dependencies
- specified elegantly in a few lines of logic

you might wonder ... does that work?!

experimental findings

statistics highlights for **object sensitive** analysis:

- precision of points-to results

context-insensitive: imprecise $>$ precise $\times 1.9$

context-sensitive: imprecise $>$ precise $\times 3$

- size of call graph

context-insensitive: no significant difference

context-sensitive: $1.9\times$ to $6.1\times$ more edges

- performance

imprecise $14\times$, $12\times$, $5-10\times$, $1.8\times$ slower

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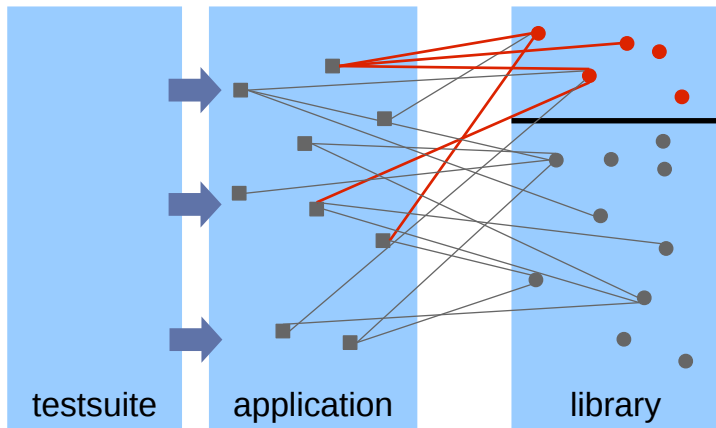
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our finding

Precise exception handling has a major impact on the precision and performance of context-sensitive points-to analyses. With imprecise exception handling, the size of the problem is largely determined by exceptions.

application: test coverage of exceptional situations [Fu et al.]



test coverage: possible exception-catch links [Fu et al.]

			I/O_{sel}	time
imprecise	ftpd	insens	104	12s
		1 obj	91	23s
	muffin	insens	490	22s
		1 obj	420	86s
precise	ftpd	insens		
		1 obj		
	muffin	insens		
		1 obj		

test coverage: possible exception-catch links [Fu et al.]

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our finding

Our **general** joint points-to and exception analysis achieves precision comparable to a **custom** exception-flow analysis, but runs much faster.

selectively remove features from fully precise analysis

- order of exception handlers not considered (o)

```
catch(FileNotFoundException e) {...}  
catch(IOException e) {...}
```

- no filtering of caught exceptions (f)

```
void foo() {  
    try {...}  
    catch(IOException e) {...}  
}
```

- context-insensitive throw points-to (cs)
 - methods throw same exceptions in all contexts

cs o f	call graph edges	var points-to	throw points-to
x x x	1.0M	598K	579K

cs	o	f	call graph edges	var points-to	throw points-to
x	x	x	1.0M	598K	579K
x		x	×1.5	×1.0	×1.1

cs	o	f	call graph edges	var points-to	throw points-to
×	×	×	1.0M	598K	579K
×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9

cs	o	f	call graph edges	var points-to	throw points-to
×	×	×	1.0M	598K	579K
×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9
×			×2.6	×1.3	×1.9

cs	o	f	call graph edges	var points-to	throw points-to
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×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9
×			×2.6	×1.3	×1.9
	×	×	×1.1	×1.1	×1.9

cs	o	f	call graph edges	var points-to	throw points-to
×	×	×	1.0M	598K	579K
×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9
×			×2.6	×1.3	×1.9
	×	×	×1.1	×1.1	×1.9
		×	×1.6	×1.2	×2.1
	×		×2.7	×1.4	×3.4
			×2.7	×1.5	×3.4

cs	o	f	call graph edges	var points-to	throw points-to
×	×	×	1.0M	598K	579K
×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9
×			×2.6	×1.3	×1.9
	×	×	×1.1	×1.1	×1.9
		×	×1.6	×1.2	×2.1
	×		×2.7	×1.4	×3.4
			×2.7	×1.5	×3.4
imprecise			×6.1	×2.0	-

cs	o	f	call graph edges	var points-to	throw points-to
×	×	×	1.0M	598K	579K
×		×	×1.5	×1.0	×1.1
×	×		×2.6	×1.2	×1.9
×			×2.6	×1.3	×1.9
	×	×	×1.1	×1.1	×1.9
		×	×1.6	×1.2	×2.1
	×		×2.7	×1.4	×3.4
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our finding

Every approximation of exception handling significantly increases var points-to, throw points-to, or call graph edges.

points-to analysis

Precise exception handling has a major impact on the precision and performance of context-sensitive points-to analyses.

exception-flow analysis

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approximations

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type-based exception analyses [Robillard, Jex]

- do not determine where an exception comes from
- conservative/unsound for 'computed' exceptions

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doop compared to other datalog-based points-to analysis

- full end-to-end analysis in datalog
- first precise declarative exception analysis

what have we seen?

- joint points-to and exception analysis

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what more is in the paper?

- computing exception handlers
- experiments
- background on datalog and points-to analysis