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An Efficient Tunable Selective Points-to Analysis for Large Codebases

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Objective

- Scaling object-sensitive points-to analysis with high precision
- A tuneable analysis framework
  - Utilizing the knowledge of the codebase
- Client Independent

Background

Points-to Analysis

- Variables → Objects
- Prerequisite to many analyses
- Andersen points-to implemented in Datalog
  - Flow-insensitive, inclusion-based
  - Heap-allocated objects
    - Creation-site as an abstraction for dynamically created objects
    - Heap-allocated object have fields

Background

Context-sensitivity

- Context insensitive (CI) points-to is imprecise
- Different flavors: type, callsite, objects
- 2O1H

2O1H

```
public class A{
    void foo(){                          //CalleeCtx =[o1,o2]
            o3: B b = new B();           // HeapCtx = [o2]
            b.bar();
    }
}
public class B{
    void bar(){                          //CalleeCtx = [o2,o3]
            o4: C c = new C();           // HeapCtx = [o3]
    }
}
```

Motivation

OpenJDK-b147

- 2O1H improves precision vs CI points-to
  - removes 97% of FP in PointsTo
  - removes 49% of FP call-graph edges
- High resource consumption
  - 6.8 hours execution time
- Only particular parts of the codebase are problematic
  - OpenJDK7 minus javax.swing
    - 8.8x faster
    - 45% memory reduction

Problem Statement

- Is it possible to selectively generate contexts?
- Which heap allocation sites need different context sensitivity?
- How deep should the contexts be?

State-of-Art in client-independent Points-to for Java

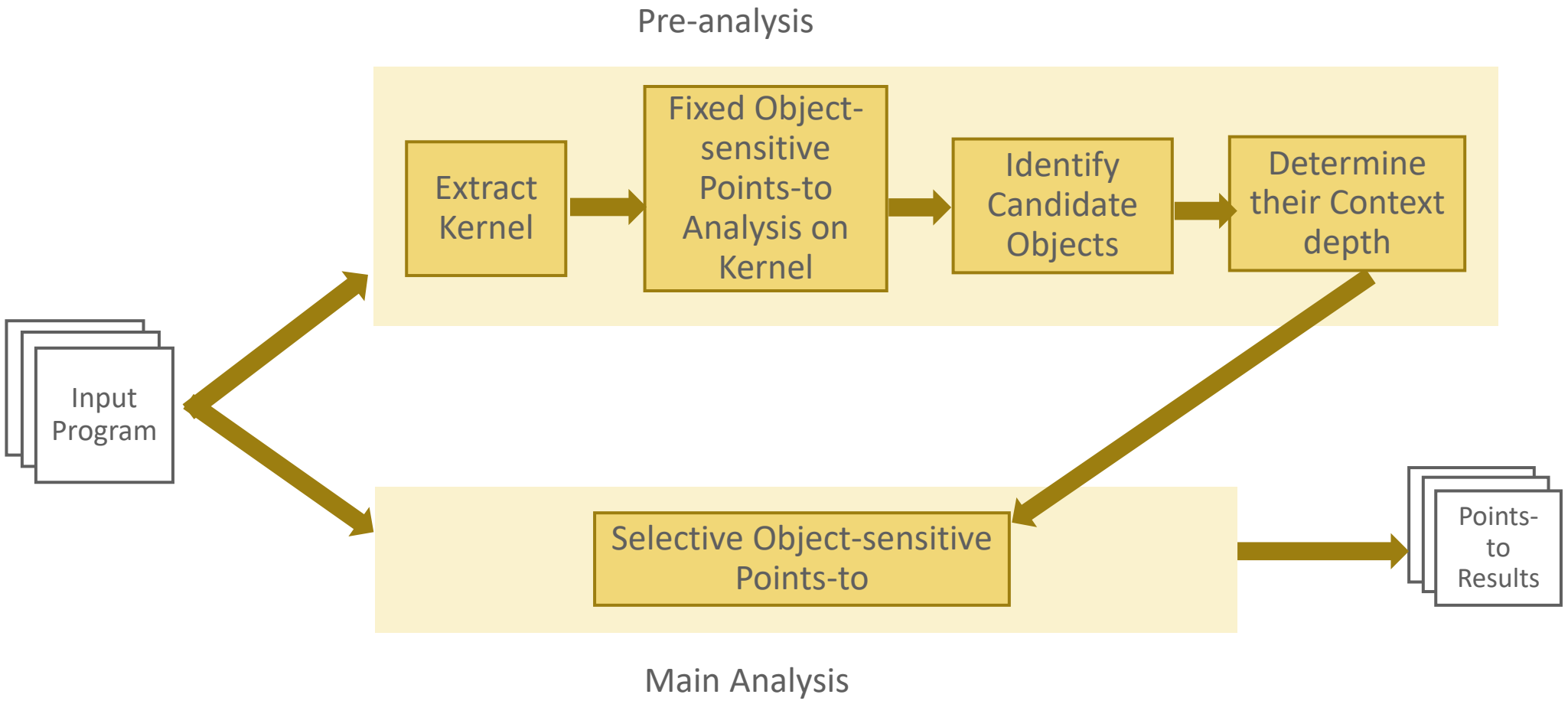
- Introspective context-sensitive points-to (Yannis et el., PLDI 2014)
  - Proposes two heuristics: HA, HB
  - Imprecise w.r.t. 2O1H
  - Case study: OpenJDK

Approach	Runtime	# VarPointsTo	#CallGraphEdge
2Obj+1H	6.8h	10M	261K
Context-insensitive	6.8m	318M	513K
HA	14m	206M	496K
HB	timeout	-	-

Our Contributions

- Identifying the *kernel*: the core problematic subset of input program
  - Based on CI points-to results
- Designing metrics on *kernel* for:
  - Evaluating effectiveness of generated contexts
  - Identifying candidate heap allocation sites
  - Identifying depth of the context needed
- A selective object-sensitive points-to
  - Going beyond 2O1H
- A general client independent framework

Tunable Selective Object-Sensitive Points-to Workflow



Automatically Extracting Kernel

Parameterized by P1, P2

1. A cheap context insensitive points-to
2. Kernel = Input program - RHA
3. RHA has heap allocation site o
   - where # PointedByVar(o) < P1 AND
   - which is NOT allocated in a method of class C where
     - o' has type C with #PointedByVar(o') >= P1 OR
     - C has method m with #MethodPointsTo(m) > P2

Analyzing Kernel

- 2O1H points-to on kernel
- Applying metrics to evaluate the effectiveness of contexts
- Finding candidate heap allocation sites
- Choosing context depth

Context Evaluation

Key insights

- False positives in 2O1H can be more expensive than in CI points-to
- Sources of imprecision
  - Certain program elements are handled by *smashing techniques* [1]
    - E.g., arrays, static fields, open world, exceptions, etc.
    - Due to array smashing, elements of the array are not distinguished
- Inappropriate contexts for these elements compounds *smashing effect*
  - Arrays cause 88% of VarPointsTo tuples in CS Points-to
  - Static fields cause 50% of VarPointsTo tuples in CS Points-to

1. B. Blanchet et al., Design and implementation of a special-purpose static program analyzer for safety-critical real-time embedded software. In The Essence of Computation: Complexity, Analysis, Transformation., pages 85–108. Springer-Verlag, 2002.

Context Evaluation

Metrics

- Given a program element *o* with smashing effect (e.g., array) in context *oc*

$$ContextValue(o, oc) = \min_{v} \frac{|InFlow(o)| \cdot |CtxInOutFlow(v, o, oc)|}{|OutFlow(v, o, oc)|}$$

- **InFlow:** objects of all contexts that are stored in *o* qualified by any context
- **OutFlow:** objects that v points to where v is loaded from *o*, with context *oc*
- **CtxInOutFlow**: contexts in which v is loaded from *o*, with context *oc*

Context Evaluation

Metrics

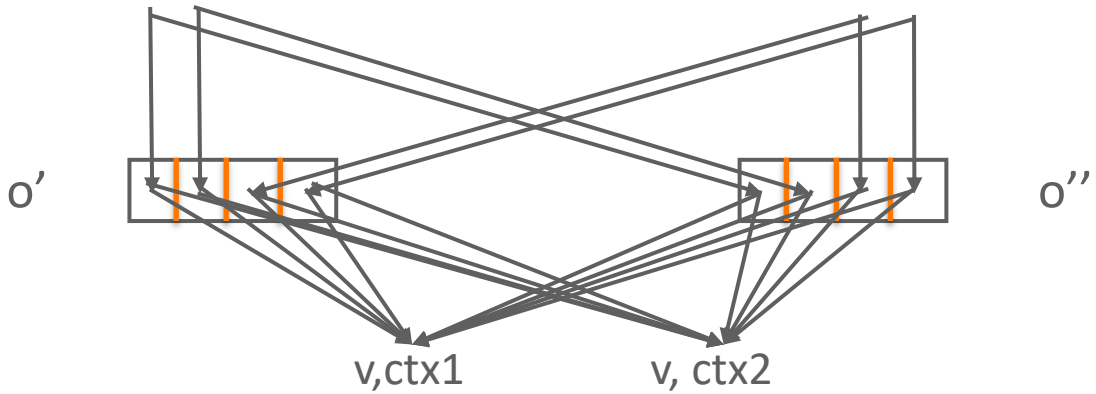
- Given a program element *o* with smashing effect (e.g., array) in context *oc*

$$ContextValue(o, oc) = \min_{v} \frac{|InFlow(o)| \cdot |CtxInOutFlow(v, o, oc)|}{|OutFlow(v, o, oc)|}$$

o: a = new … //oc = [o’]

a[i] = x

v = a[i]

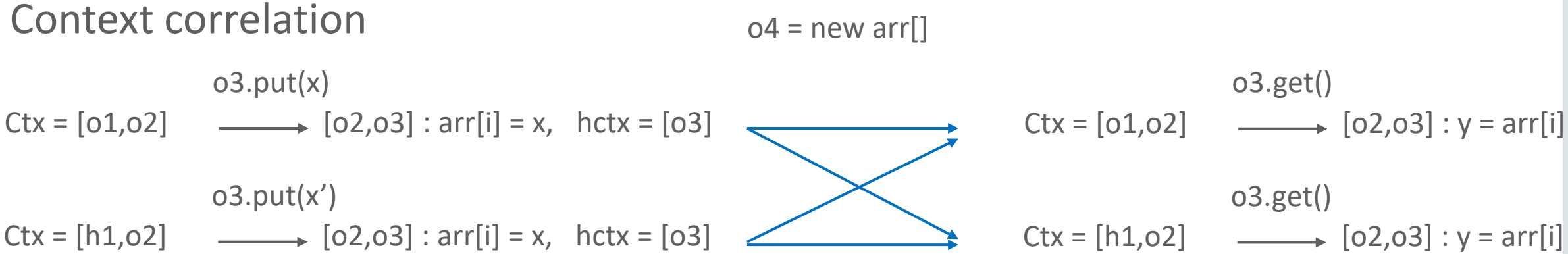


InFlow(o) = 4
CtxInOutFlow(v,o,o’) = 2
OutFlow(v,o,o’) = 8
=>
ContextValue(o,o’) = 1

Selective Context generation

General Algorithm

- Combining a subset of the metrics to:
  - Identifying candidates
  - Choosing context depth based on context correlation
- Context correlation



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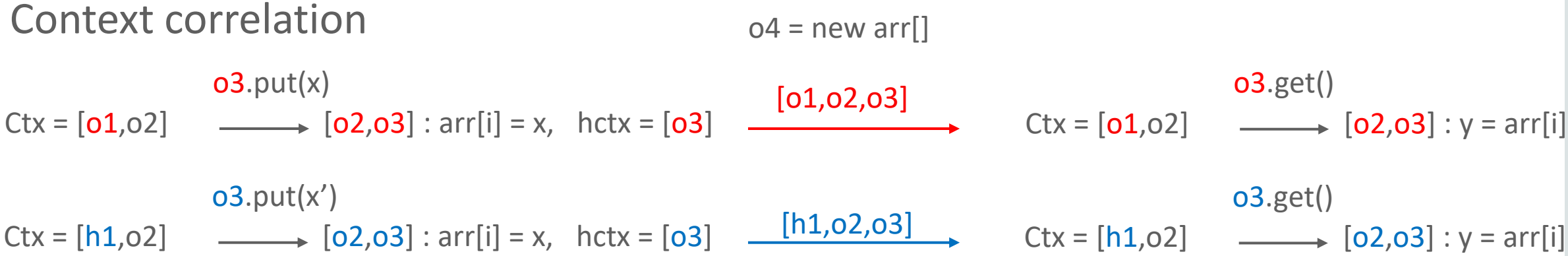


Selective Context Generation

Metrics Parametrized by P3 and P4

- Given *o* with context *oc* = [*o*']
- If ContextValue(*o*,*oc*) < P3 AND InFlow > P4
  - If extending oc results in context correlation
  - Else remove the context for *o*'.

Implementation

- Implementing
  - Datalog specification for DOOP points-to analysis
- Use Souffle as the Datalog engine
- SQLite relational database to compute the pre-processing metrics

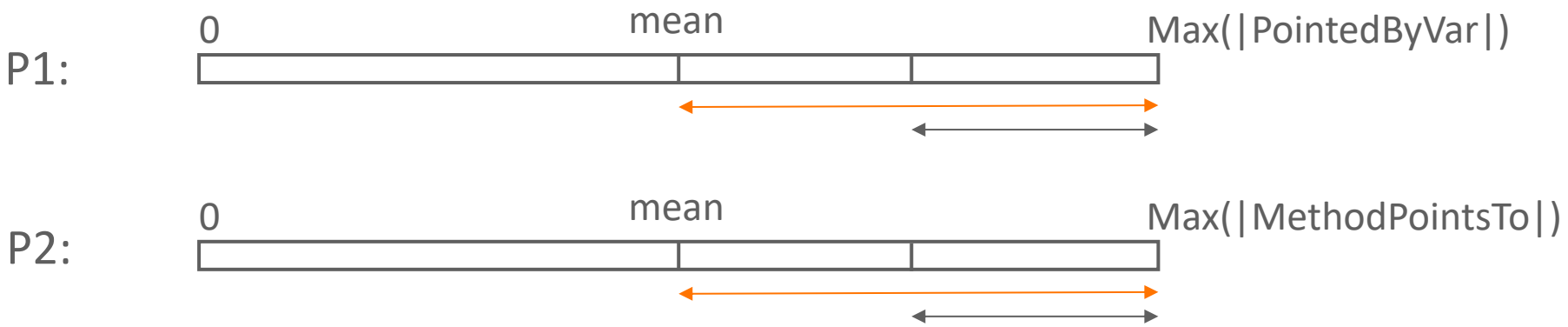
Evaluation

- Experimental setup:
  - Xeon E5-2699 2.30GHz, 8 threads running at a time, 396G RAM
  - P3 and P4 parameters are both 200
  - OpenJDK7-b147 and DaCapo 2006-10-MR2
    - No context refinement needed for objects of programs in DaCapo benchmarks, except for Jython

Benchmarks	#Variables	#Call-sites	#Heap-allocations
OpenJDK7	1440875	591262	185352
Jython	142641	59379	25608

Identifying the Kernel

Computing P1 and P2



Program	P1	P2
OpenJDK-b147	20K	50K
Jython	2149	1452

Evaluation

Performance

Benchmarks	Runtime (seconds)			Memory (GB)		
	2O1H	Ours	Imp.	2O1H	Ours	Imp.
OpenJDK	16200	11880	27%	186	153	18%
Jython	1280	109	91%	2.8	2.8	0%

Evaluation

Precision

Benchmarks	#VarPointsTo			#Alias			#ReachableMethods		
	2O1H	Ours	Loss	2O1H	Ours	Loss.	2O1H	Ours	Loss
OpenJDK	10100000	10400000	3%	845518	854600	1%	39909	39880	-0.1%
Jython	68519	68519	0%	28294	28294	0%	2876	2876	0%

Conclusion

- Designed a novel framework for scaling object-sensitive points-to analysis for large object-oriented programs
  - Involves identifying and experimenting on the kernel of program
  - Selective object-sensitive points-to analysis on the input program
- Client-independent
- Reduced the runtime of CS points-to with negligible precision loss

Questions/Suggestions

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