A Container-Usage-Pattern-Based Context Debloating Approach for Object-Sensitive Pointer Analysis

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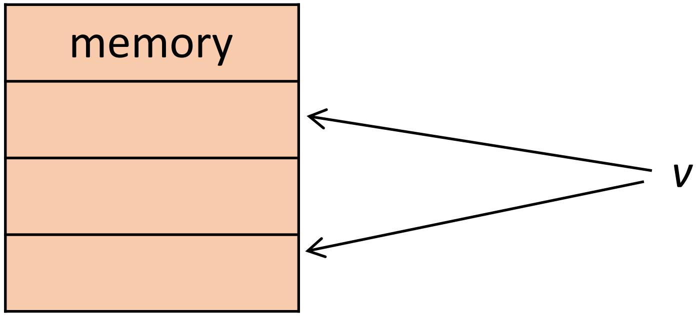
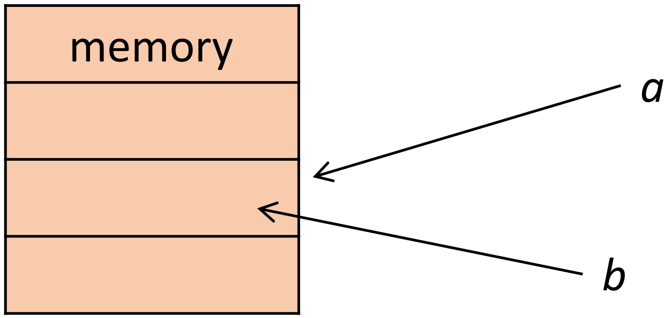
Pointer Analysis

- ❑ Programs (in C/C++/Java, …) are full of **pointers** or **references**
- ❑ Answer the following two problems



(1) What can a pointer point to?



(2) Can *a* and *b* be aliases?

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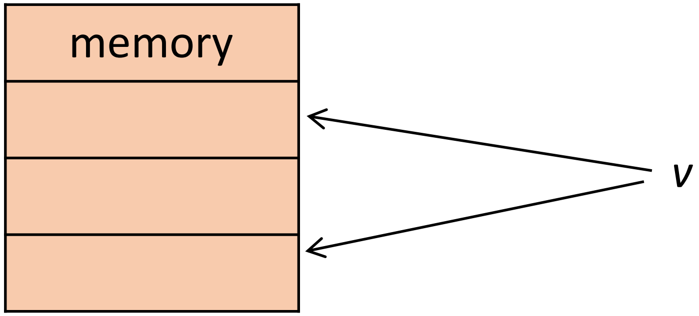

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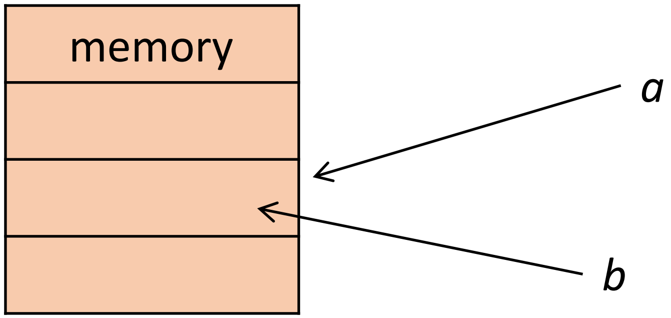


(2) Can *a* and *b* be aliases?

- Foundation of many Static Program Analysis

Compiler Optimization | Call-graph Construction | Program Verification | Program Understanding | Bug Detection | …

- Implemented in many popular frameworks

Qilin Soot WALA (T. J. WATSON LIBRARIES FOR ANALYSIS) DOOP SVF

Object Sensitive Pointer Analysis (kOBJ)

❑An effective technique to improve the precision

❑Context elements are receiver objects

  - $[o_1, o_2, \cdots, o_k]$

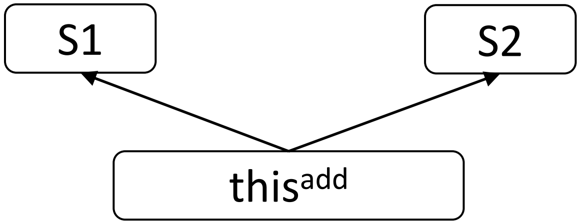
Object Sensitive Pointer Analysis (kOBJ)

- An effective technique to improve the precision
- Context elements are receiver objects
    - $[o_1, o_2, \cdots, o_k]$

- An example
    - two contexts of **HashSet.add** **:** [S1] and [S2].

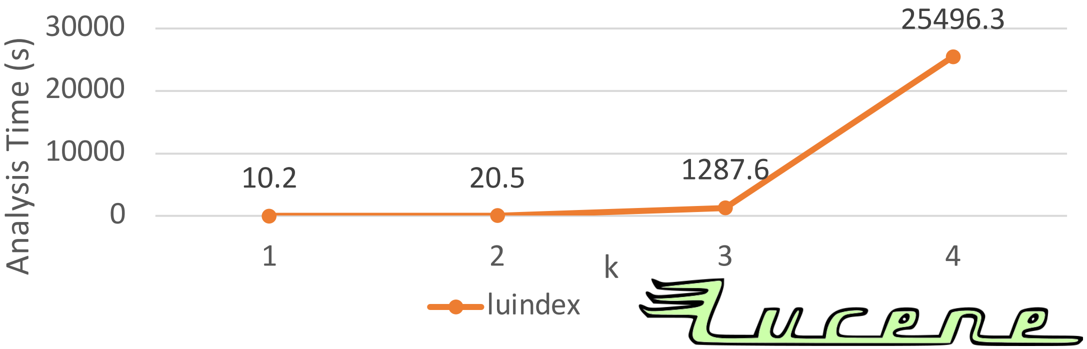
```
HashSet s1 = new HashSet();// S1
HashSet s2 = new HashSet();// S2
s1.add(new Object()); // O1
s2.add(new Object()); // O2
```

In **main()**, analyzed under empty context []



Exponential Explosion Issue

- Increasing k makes kOBJ less Efficient or even Unscalable



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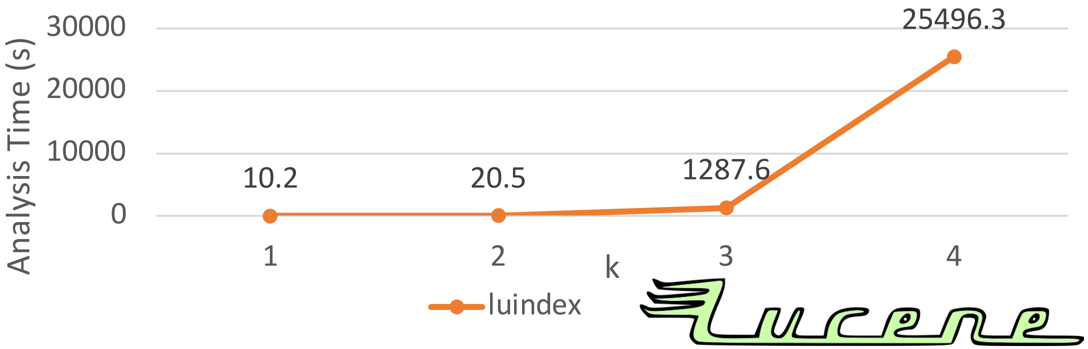


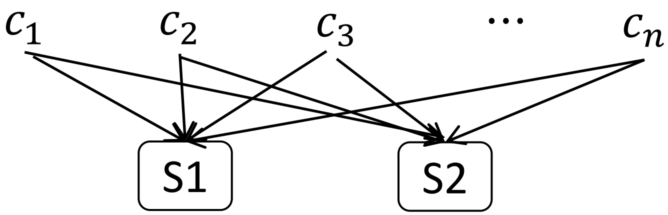
Lucene

❑ Contexts of kOBJ grow exponentially with k

- **HashSet.add :** $2n$ contexts, i.e., [S1, c_i] and [S2, c_i] ($1 \leq i \leq n$).

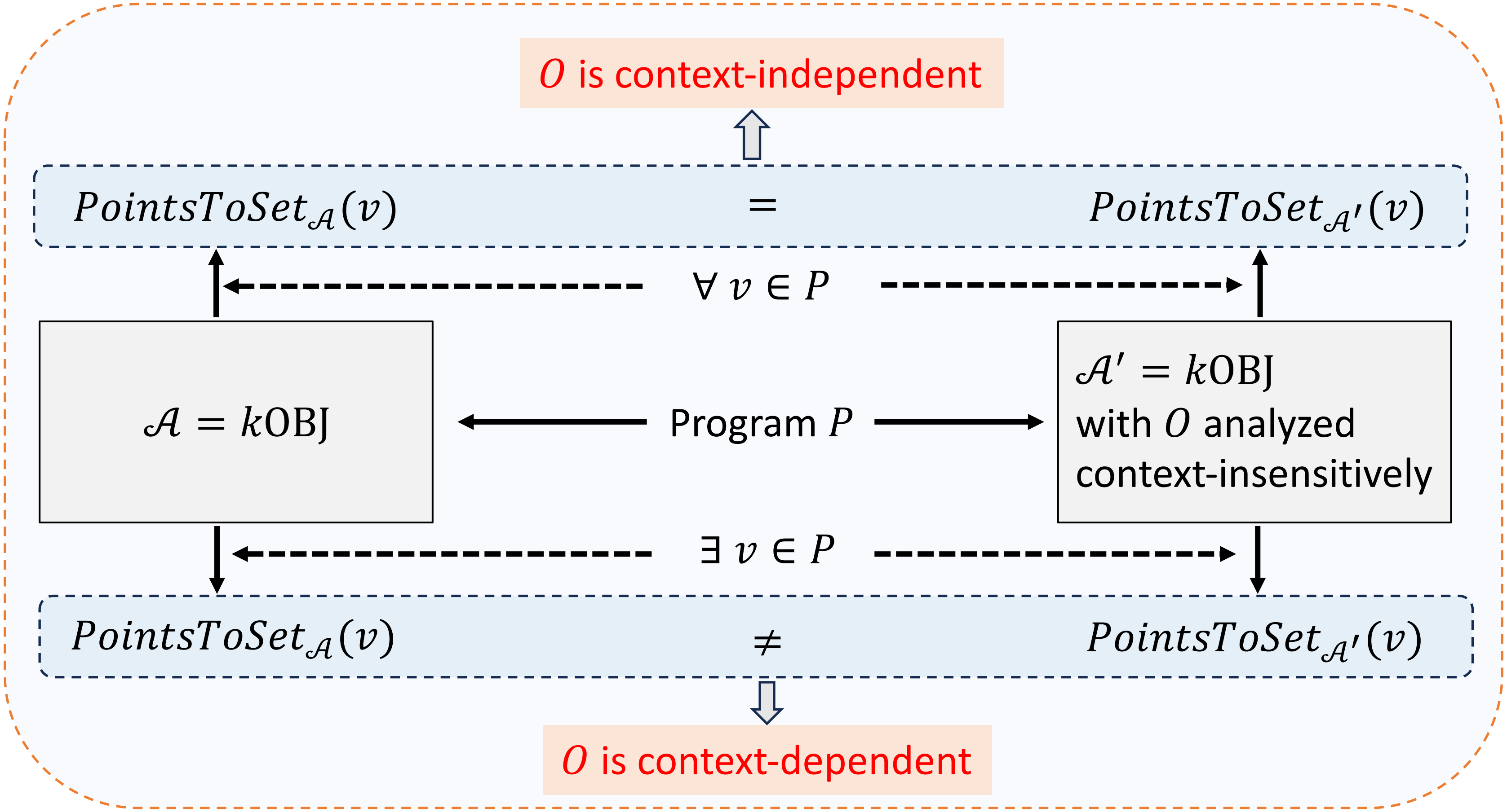
```
HashSet s1 = new HashSet();// S1
HashSet s2 = new HashSet();// S2
s1.add(new Object()); // O1
s2.add(new Object()); // O2
```

analyzed under n different contexts, c_1, $\ldots c_n$



Review: Context Debloating

- ❑ An object (or context element) O is context-dependent if
  - ○ analyzing it context-insensitively in kOBJ will cause some program variables to lose precision.



O is context-independent

$PointsToSet_{\mathcal{A}}(v) = PointsToSet_{\mathcal{A}'}(v)$

$\forall\, v \in P$

$\mathcal{A} = k\text{OBJ}$

Program P

$\mathcal{A}' = k\text{OBJ}$
with O analyzed
context-insensitively

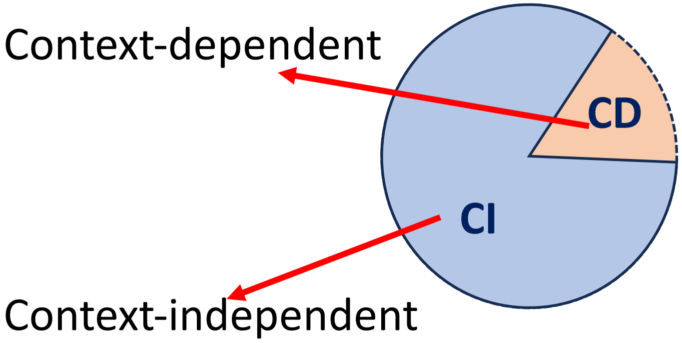
$\exists\, v \in P$

$PointsToSet_{\mathcal{A}}(v) \neq PointsToSet_{\mathcal{A}'}(v)$

O is context-dependent

Review: Context Debloating

- Key Observation:
  - Most **(90%+)** objects are Context-independent
  - E.g., S1 and S2 are locally used and independent of their contexts.
  - Allowing context combinations on them **only** increases analysis time



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HashSet s1 = new HashSet();// S1
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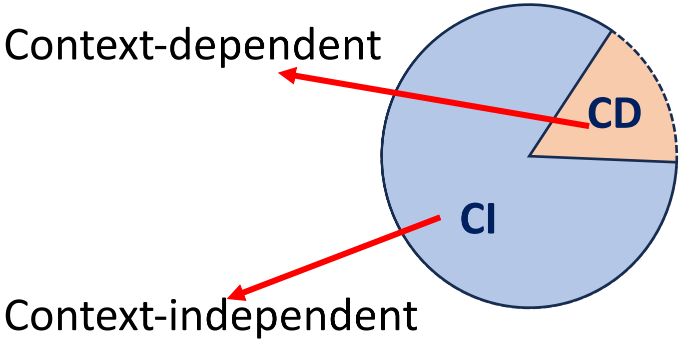
analyzed under n contexts, $c_1, \cdots c_n$

Review: Context Debloating

❑ Key Observation:

- **90%+** Context elements (i.e., Objects in kOBJ) are Context-independent
- E.g., S1 and S2 are locally used and independent of their contexts.
- Allowing context combinations on them **only** increases analysis time



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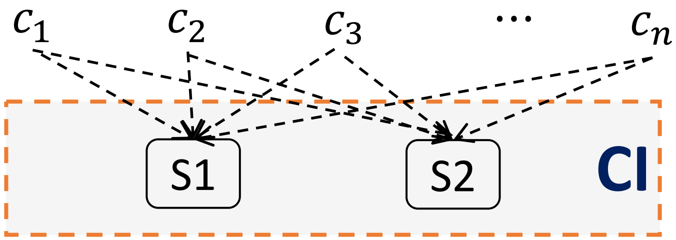
❑Key Idea： inhibit context combinations on CI elements

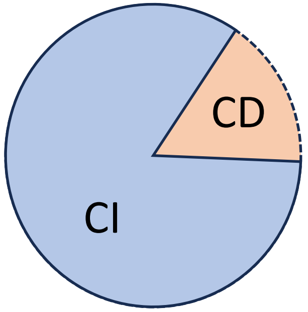
- # contexts of **HashSet.add: $2n$ -> 2**

Precise and Efficient!

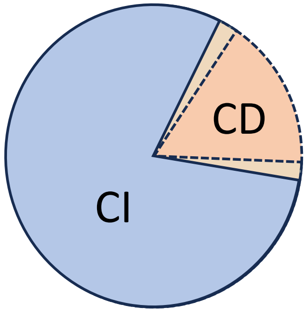


The Challenge in Context Debloating

- ❑How to precisely identify context-(in)dependent objects?

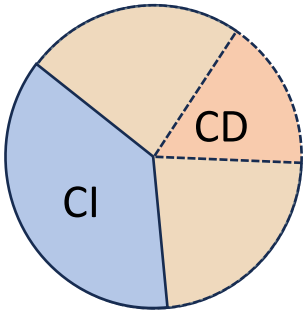


Ideal (Oracle)



Context-free-language(CFL)-based

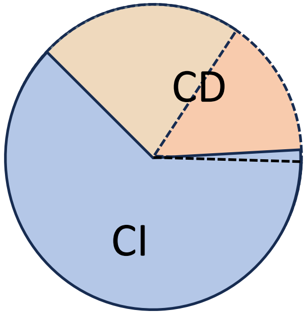
- CFL-based approach is undecidable (OOPSLA’19, TOPLAS’00)
- Eagle, Over-approximation of CFL (OOPSLA’19)
  - selects almost all non-trivial **CI**s as **CD**s
  - Very limited speedups, e.g., 1.5X



Eagle

Context Debloating Approaches

- ☐ **Conch:** approximates CFL with three linearly verifiable conditions
  - ○ field-insensitive (still too conservative)
  - ○ **limits further performance improvement**



Conch (ASE’21, TOSEM’23)

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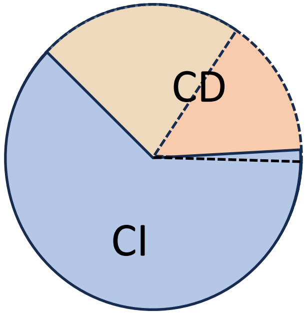

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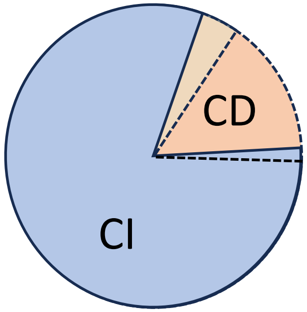

DebloaterX

- ❑ **DebloaterX**
  - 1-limited field-sensitive (e.g, O.f.*)
  - **significant performance improvement with negligible precision loss**

	k = 1	k = 2	k = 3	k = 4
X-kOBJ	10.2s	5.7s	10.3s	14.3s
kOBJ	10.2s	20.5s	1278.6s	25496.3s
C-kOBJ	10.2s	7.6s	363.1s	555.0s

luindex

DebloaterX: Our Approach

- ❑Identify context-dependent objects by usage patterns
  - ○ We believe Patterns are **finite**!

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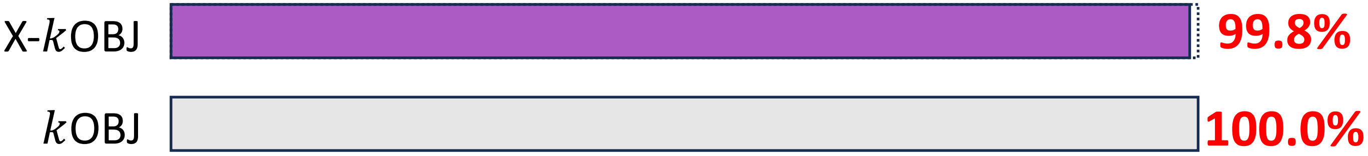
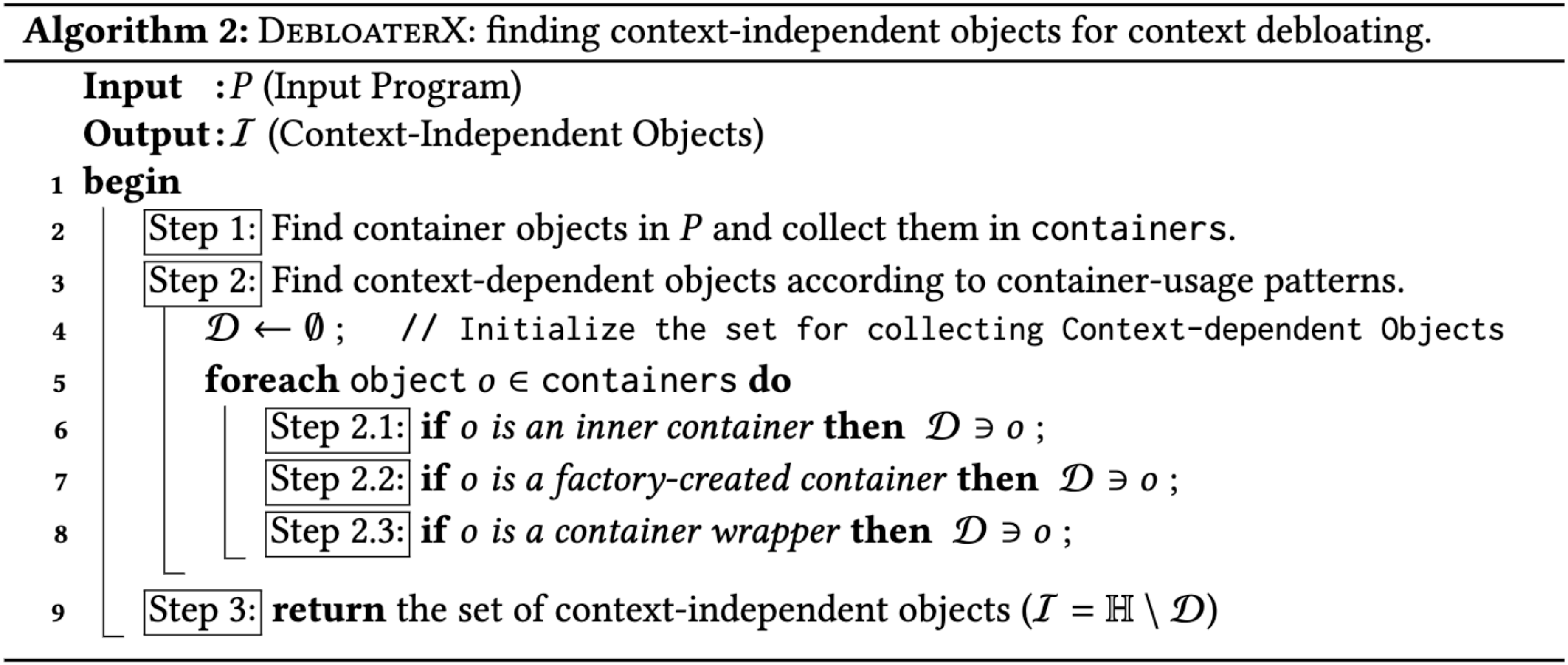
- ❑ Three Container-Usage Patterns
  - ○ Inner Containers
  - ○ Factory-Created Containers
  - ○ Container Wrappers

DebloaterX: Our Approach

- Identify context-dependent objects by usage patterns
  - We believe Patterns are **finite**!
- Three Container-Usage Patterns
  - Inner Containers
  - Factory-Created Containers
  - Container Wrappers
- The above **three** Patterns are enough to preserve **99.8%** of precision in real-world programs.



DebloaterX: Overall Algorithm



Algorithm 2: DEBLOATERX: finding context-independent objects for context debloating.

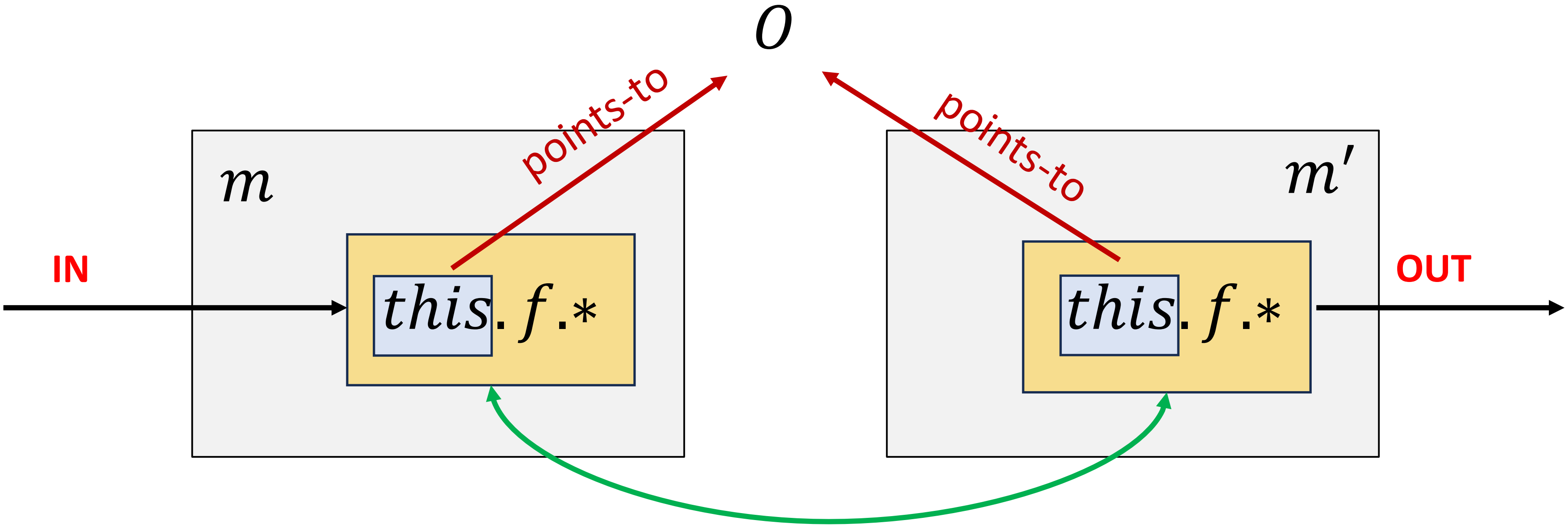
```
Input  : $P$ (Input Program)
Output : $\mathcal{I}$ (Context-Independent Objects)
begin
    Step 1: Find container objects in $P$ and collect them in containers.
    Step 2: Find context-dependent objects according to container-usage patterns.
        $\mathcal{D} \leftarrow \emptyset$ ;    // Initialize the set for collecting Context-dependent Objects
        foreach object $o \in$ containers do
            Step 2.1: if $o$ is an inner container then $\mathcal{D} \ni o$ ;
            Step 2.2: if $o$ is a factory-created container then $\mathcal{D} \ni o$ ;
            Step 2.3: if $o$ is a container wrapper then $\mathcal{D} \ni o$ ;
    Step 3: return the set of context-independent objects ($\mathcal{I} = \mathbb{H} \setminus \mathcal{D}$)
```

- **CI** objects in $\mathcal{I}$ will be used for **context debloating**

inhibit context combinations on CI elements

Container objects

- ❑An object O is a **container object** if it has at least
  - ○ One **pointer field** f,
  - ○ An **incoming value flow** s.t. $this^{m}.f.* = p\ (p \in \{p_i^{m}\})$, and
  - ○ An **outgoing value flow** s.t. $v.* = this^{m'}.f.*\ (v \in \{ret^{m'}, p_i^{m'}\})$
  - ○ m and m' are methods invoked on O



Aliases in the approximation of **1-limited** field access path

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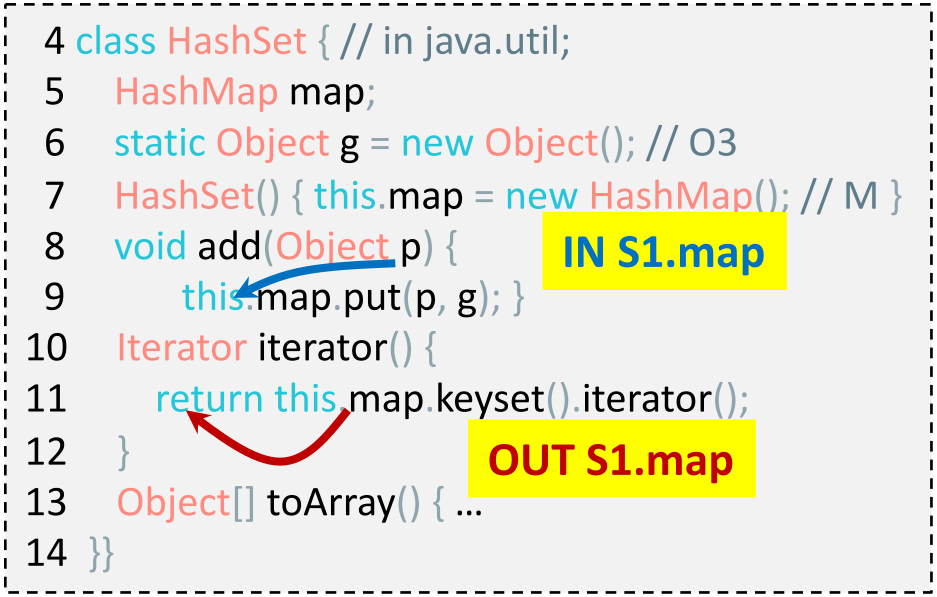
- ❑ An example
  - ○ **S1** is a container object

```
HashSet s1 = new HashSet();// S1
s1.add(new Object()); // O1
Object o1 = s1.toArray()[0];
```



```
class HashSet { // in java.util;
  HashMap map;
  static Object g = new Object(); // O3
  HashSet() { this.map = new HashMap(); // M }
  void add(Object p) {
     this.map.put(p, g); }
  Iterator iterator() {
    return this.map.keyset().iterator();
  }
  Object[] toArray() { …
}}
```

IN S1.map

OUT S1.map

Container objects

❑Rules for identifying Container Objects

$$\frac{\begin{array}{c} O \in \mathbb{H} \quad t = \mathsf{typeof}(O) \quad t \text{ is an instance type} \\ f \in \mathtt{fields}(O) \quad t' = \mathsf{typeof}(f) \quad t' \in \mathsf{openTypes} \\ \mathtt{hasInFlow}\ (O, f) \quad \mathtt{hasOutFlow}\ (O, f) \end{array}}{O \in \mathtt{containers}} \qquad \frac{\begin{array}{c} O \in \mathbb{H} \quad t = \mathsf{typeof}(O) \\ t \text{ is an array type} \quad t \in \mathsf{openTypes} \end{array}}{O \in \mathtt{containers}}\ [\textsc{Con}]$$

$$\frac{\begin{array}{c} m \in \mathtt{methodsInvokedOn}(O) \quad f \in \mathtt{fields}(O) \\ p \in \mathtt{params}(m) \cap \mathtt{inParams}(f) \end{array}}{\mathtt{hasInFlow}(O, f)} \qquad \frac{\begin{array}{c} a.f = \_ \text{ is a store in method } m \quad O \in \overline{\mathtt{pts}}(a) \\ O \text{ not allocated in } m \quad a \notin assign^*(\mathtt{this}^m) \end{array}}{\mathtt{hasInFlow}(O, f)}\ [\textsc{In}]$$

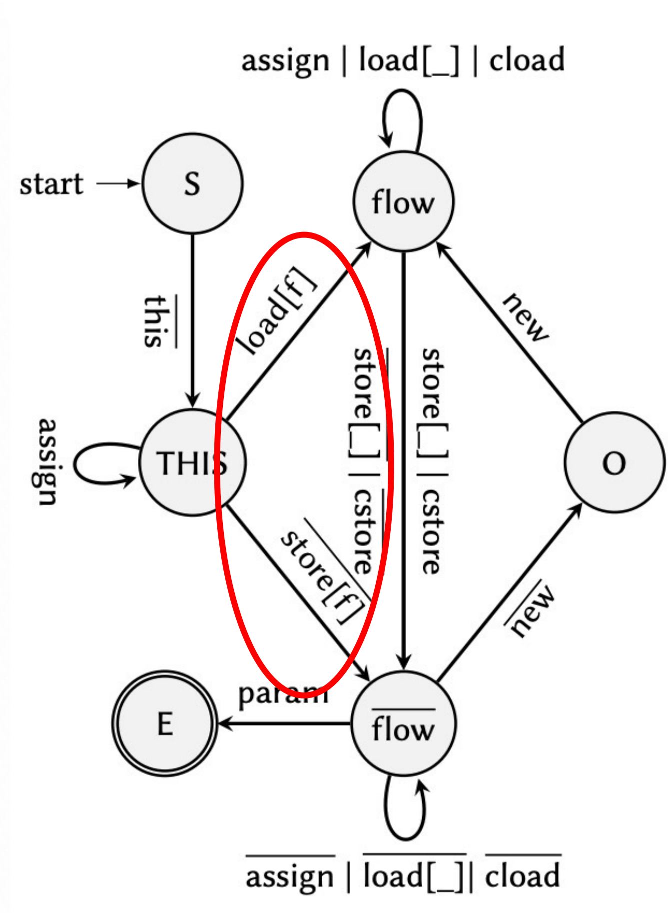
$$\frac{\begin{array}{c} m \in \mathtt{methodsInvokedOn}(O) \quad f \in \mathtt{fields}(O) \\ v \in \mathtt{paramsRet}(m) \cap \mathtt{outParamsRets}(f) \end{array}}{\mathtt{hasOutFlow}(O, f)} \qquad \frac{\begin{array}{c} \_ = a.f \text{ is a load in method } m \quad O \in \overline{\mathtt{pts}}(a) \\ O \text{ not allocated in } m \quad a \notin assign^*(\mathtt{this}^m) \end{array}}{\mathtt{hasOutFlow}(O, f)}\ [\textsc{Out}]$$

$$\frac{t \in \mathbb{T} \text{ is java.lang.Object}}{t \in \mathsf{openTypes}} \qquad \frac{t \in \mathbb{T} \text{ is an abstract type}}{t \in \mathsf{openTypes}} \qquad \frac{t \in \mathbb{T} \text{ is an interface type}}{t \in \mathsf{openTypes}}$$

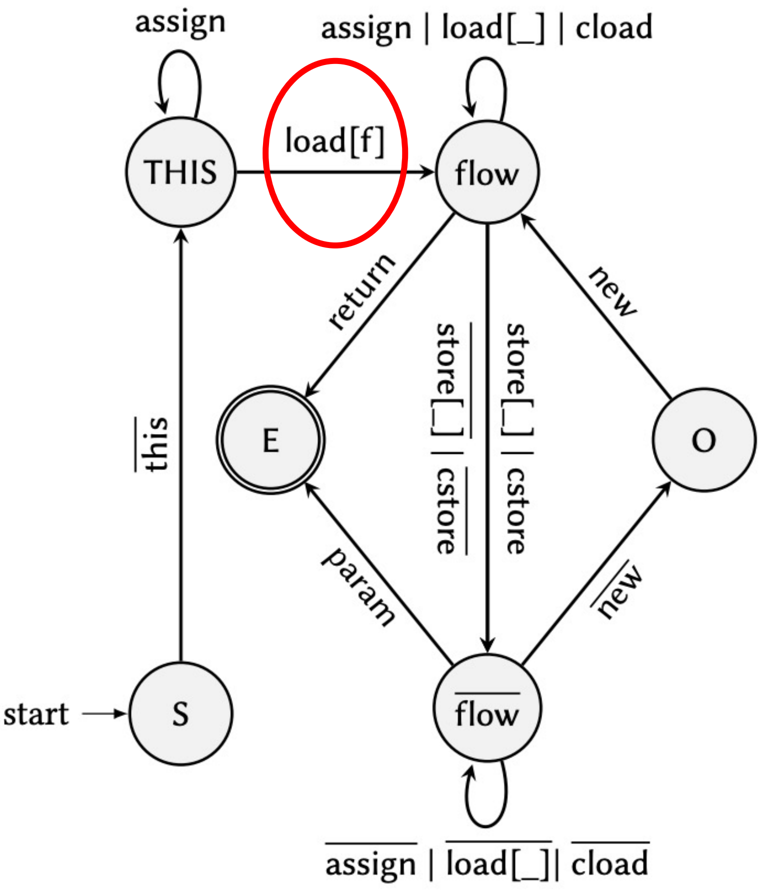
$$\frac{t \in \mathsf{openTypes}}{[t] \in \mathsf{openTypes}} \qquad \frac{t \in \mathbb{T} \quad f \in \mathtt{fields}(t) \quad \mathsf{typeof}(f) = t' \quad t' \in \mathsf{openTypes}}{t \in \mathsf{openTypes}}$$

Container objects

- ❑DFAs for computing incoming/outgoing value flows



$\mathcal{A}^{f}_{in}$

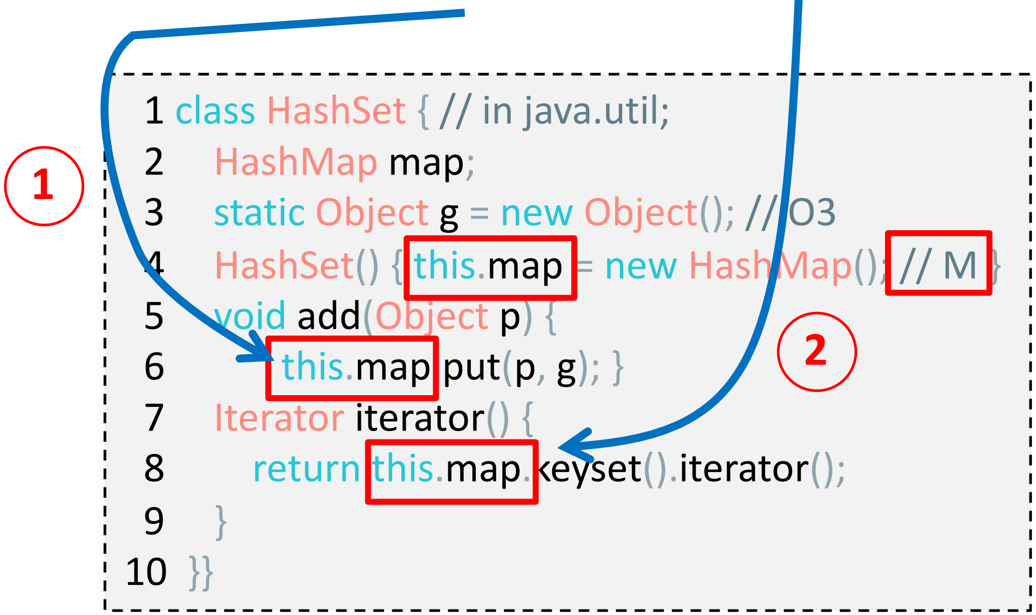


$\mathcal{A}^{f}_{out}$

- ❑1-limited field sensitive

Container-Usage Patterns

- ❑ Pattern I: Inner Containers
  - ○ Accessed by outer containers via a field
  - ○ Used by outer containers for storing and retrieving data



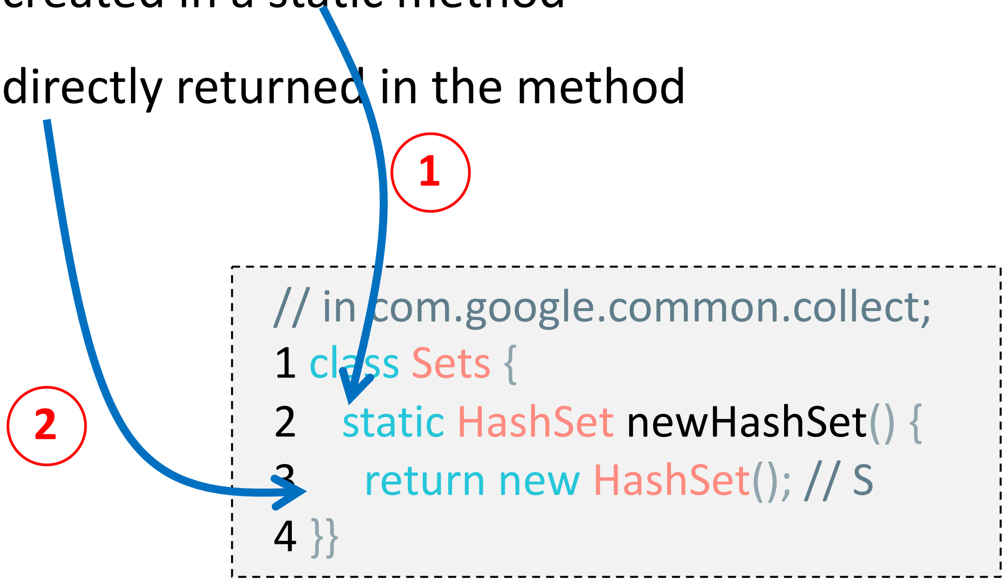
```
class HashSet { // in java.util;
    HashMap map;
    static Object g = new Object(); // O3
    HashSet() { this.map = new HashMap(); // M }
    void add(Object p) {
        this.map.put(p, g); }
    Iterator iterator() {
        return this.map.keyset().iterator();
    }
}}
```

- ❑ Inner containers are context-dependent
  - ○ Distinguish the data stored by its different outer container objects

Container-Usage Patterns

❑Pattern II: Factory-Created Containers

- created in a static method
- directly returned in the method



```
// in com.google.common.collect;
class Sets {
  static HashSet newHashSet() {
    return new HashSet(); // S
}}
```

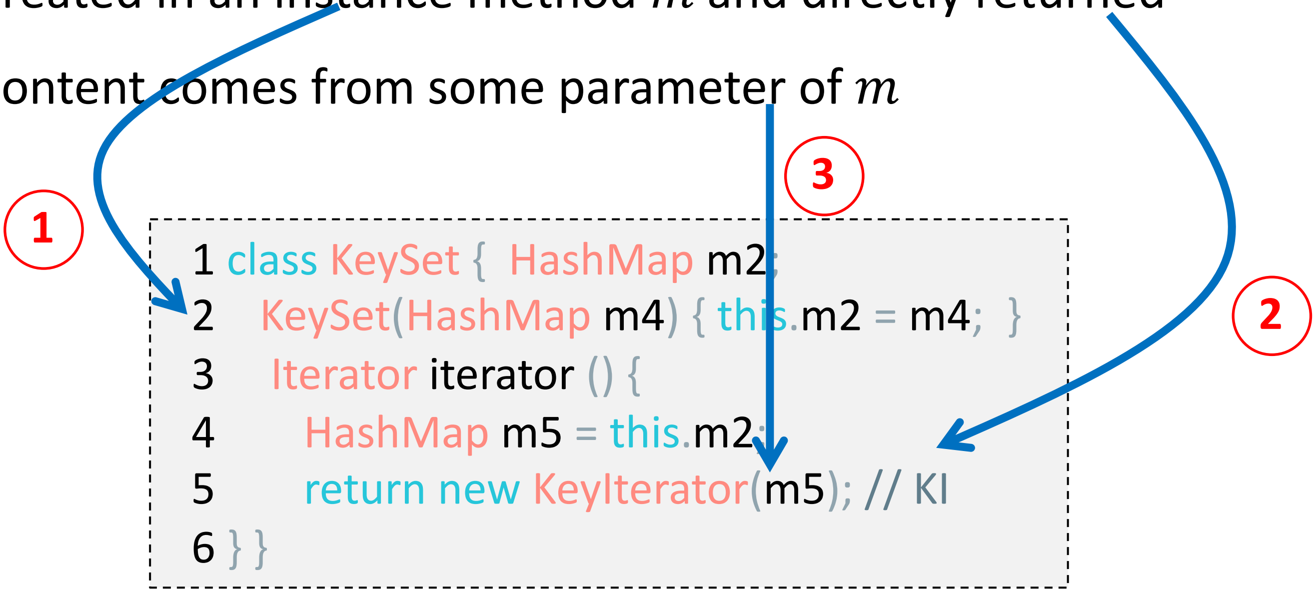
❑Factory-created containers are context-dependent

- Differentiate the data coming from different calling contexts

Container-Usage Patterns

❑Pattern III: Container Wrappers

- often are iterators, enumerators, …
- created in an instance method m and directly returned
- content comes from some parameter of m



```
class KeySet {  HashMap m2;
  KeySet(HashMap m4) { this.m2 = m4;  }
   Iterator iterator () {
      HashMap m5 = this.m2;
      return new KeyIterator(m5); // KI
} }
```

❑Container wrappers are context-dependent

- Differentiate the wrapped content coming from different calling contexts

Rules for Identifying Usage Patterns

- Rule for identifying inner containers

$$\frac{\begin{array}{c} O \in \mathbb{H} \quad m = \texttt{methodof}(O) \quad m \text{ is an instance method} \quad f \in \texttt{objectStoredInto}(O) \quad t = \texttt{typeof}(f) \\ t \in \texttt{openTypes} \quad O' \in \texttt{receiverObjects}(m) \quad \texttt{hasInFlow}(O', f) \quad \texttt{hasOutFlow}(O', f) \end{array}}{\texttt{isAnInnerContainer}(O)}$$

- Rule for identifying factory-created containers

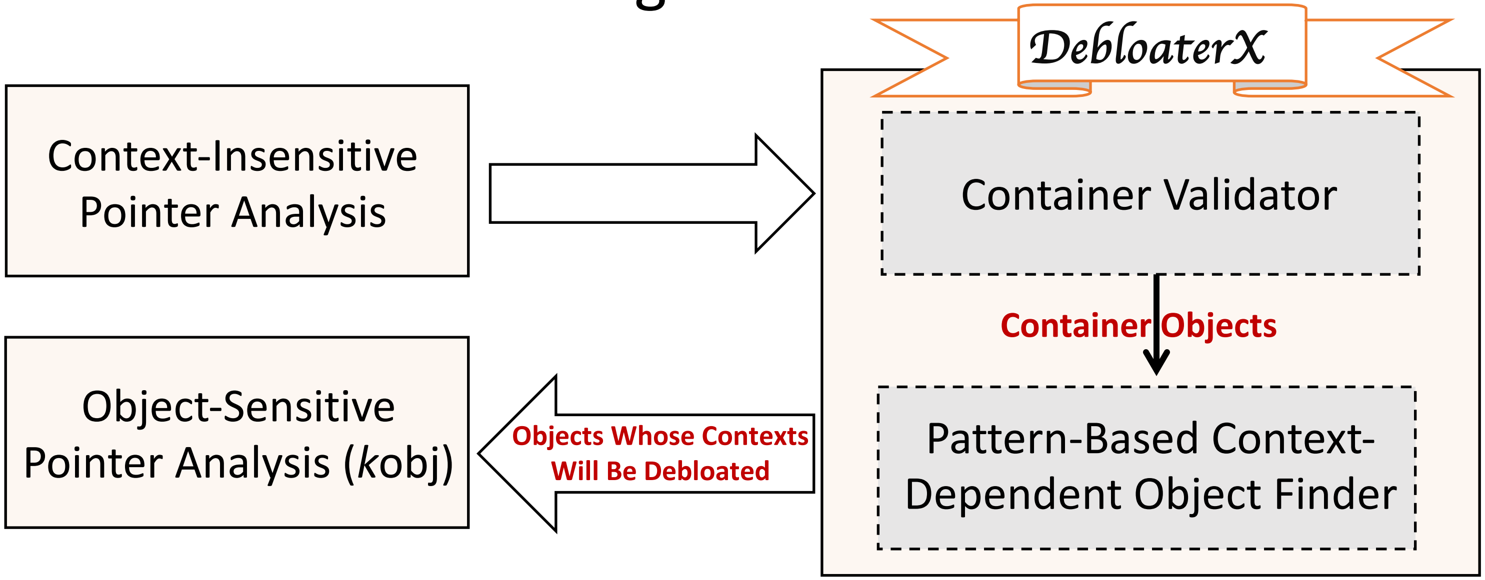
$$\frac{\begin{array}{c} m \text{ is a static method} \quad m = \texttt{methodof}(O) \\ \texttt{isDirectlyReturned}(\mathrm{O}) \end{array}}{\texttt{isAFactoryCreatedContainer}(O)} \qquad \frac{\begin{array}{c} O \xrightarrow{\text{new}} x \text{ is an edge in XPAG} \\ m = \texttt{methodof}(O) \quad \texttt{ret}^{m} \in \textit{assign}^{*}(x) \end{array}}{\texttt{isDirectlyReturned}(O)}$$

- Rule for identifying container wrappers

$$\frac{\begin{array}{c} m = \texttt{methodof}(O) \quad m \text{ is an instance method} \\ \texttt{isDirectlyReturned}(O) \quad \texttt{isContentFromParam}(O) \end{array}}{\texttt{isAContainerWrapper}(O)}$$

Workflow and Implementation

❑Workflow of DebloaterX-guided kOBJ



❑Implementation (~1500 LOC in Java)

- Source: https://github.com/DongjieHe/DebloaterX
- Artifact: https://hub.docker.com/r/hdjay2013/debloaterx
- Released in Qilin framework (https://qilinpta.github.io)

Evaluation

- Benchmarks
  - 5 dacapo 2006 benchmarks + JRE1.6
  - 2 real-world applications + JRE1.6
  - 5 dacapo-9.12 benchmarks + JRE1.8

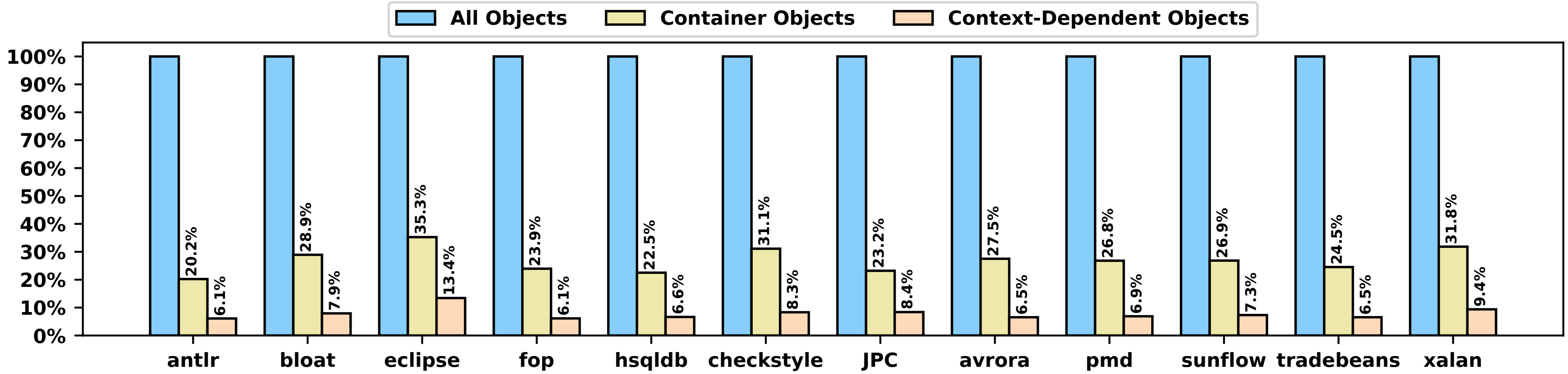
JPC

JREs

- Linux server with 512GB memory, 16 cores
- Time budget: 12 hours
- Metrics
  - Efficiency: *analysis time*
  - Precision: *#fail-casts, #reachable, #call-edges, #poly-calls*

Evaluation: Objects Identification

- Containers: 26.6%, context-dependent objects: 7.6%



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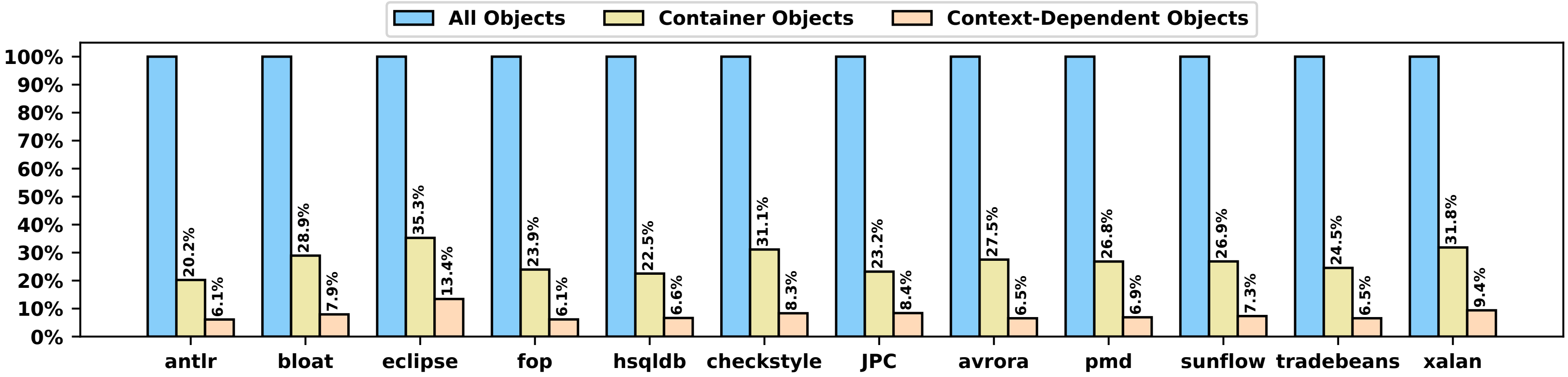
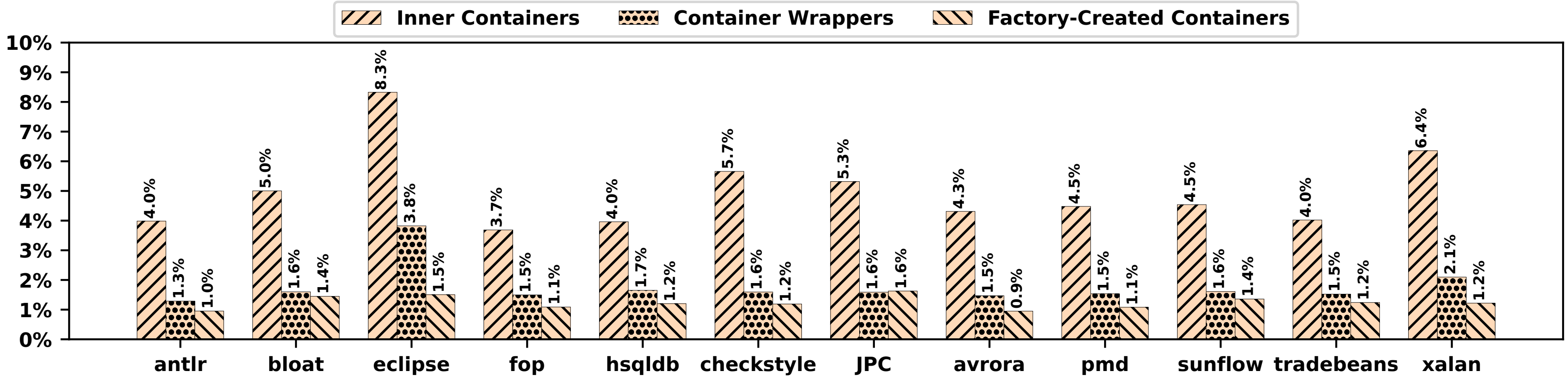
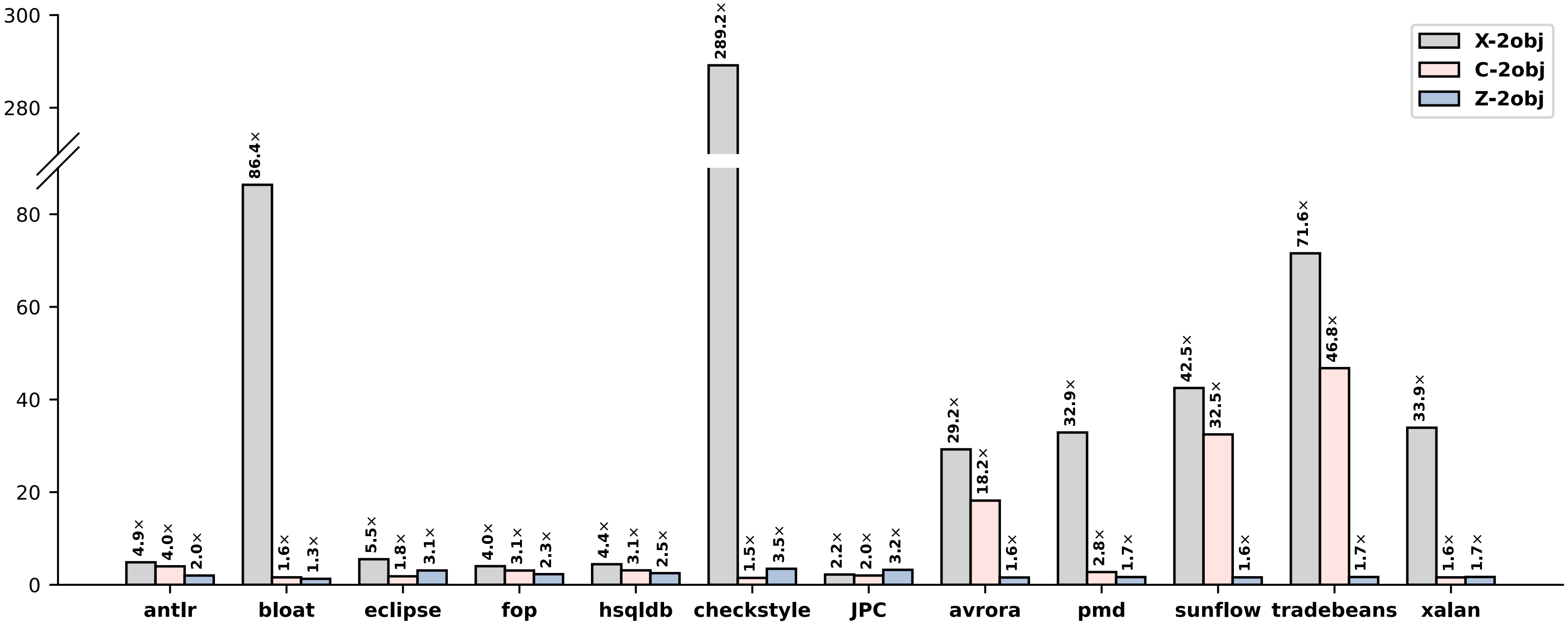


- Inner containers: 4.8% , factory-created containers: 1.2%, container wrappers: 1.7%



Evaluation: Efficiency

- 19.3x (150.2x) when k = 2 (3), faster than Conch and Zipper

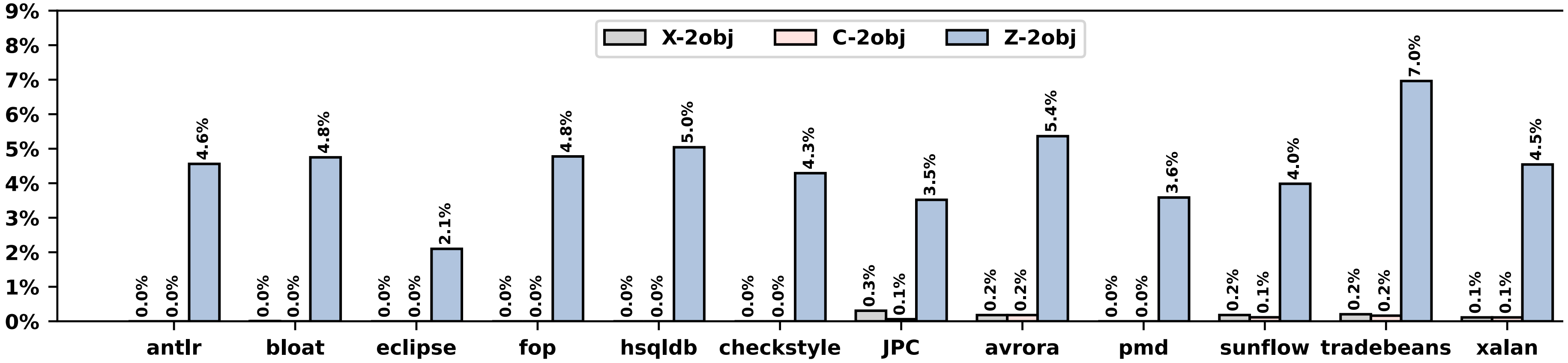


The enabled Speedup of **DebloaterX**, **Conch**, and **Zipper** over 2OBJ

- Better scalability
  - Scale 1 more than Conch, 6 more than Zipper
  - Scale 7 more than standard kOBJ

Evaluation: Precision

- ☐ Negligible precision loss (**<0.2%**), similar to Conch
- ☐ Precise than Zipper (**~4.5%** loss)



The precision loss of **DebloaterX**, **Conch**, and **Zipper**-guided 2OBJ over 2OBJ

Summary

- ❑ A new context debloating technique, DebloaterX
  - ○ Based on three container usage patterns
- ❑ enable kOBJ to be more efficient than state-of-the-art while preserving nearly all of the precision.

X-kOBJ: A precise yet efficient pointer analysis ☑

- ❑ Future work
  - ○ Investigate performance issues on extremely larger programs, e.g., eclipse
  - ○ Develop context-debloating techniques for other context-sensitivity

Q & A

Thank You!