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

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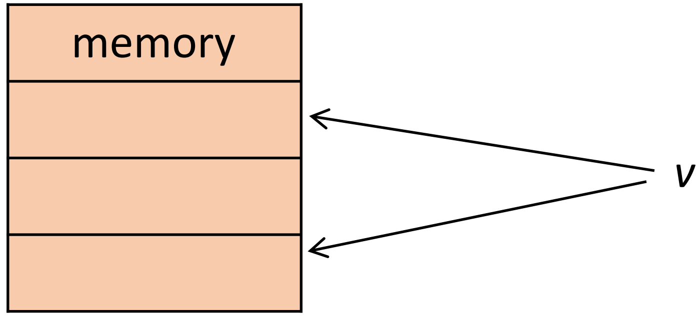
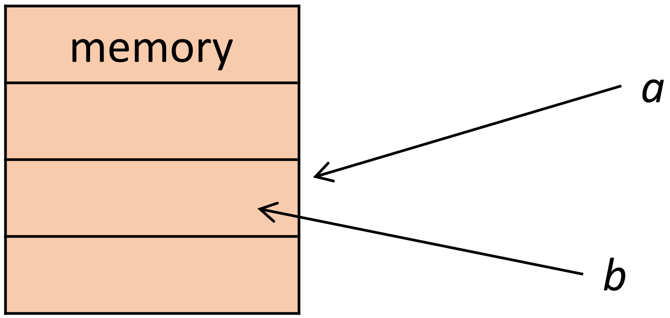
Pointer Analysis

- ❑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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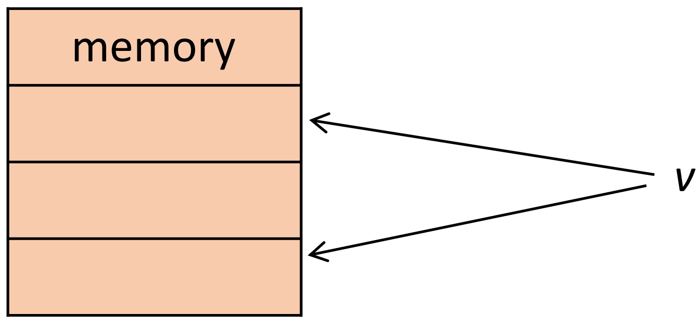

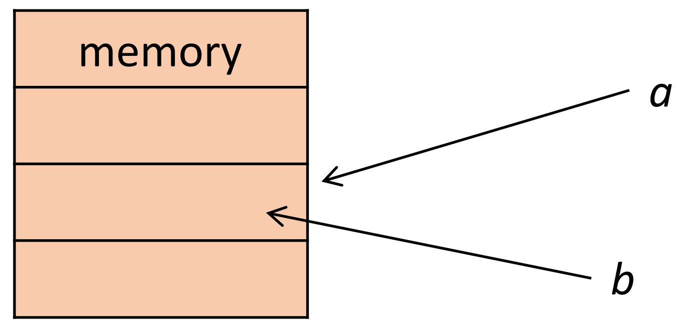

(1) What can a pointer point to?

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

- ❑Foundation of many Static Program Analysis

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

- ❑Implementations 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
  - E.g., $[o_1, o_2, \cdots, o_k]$

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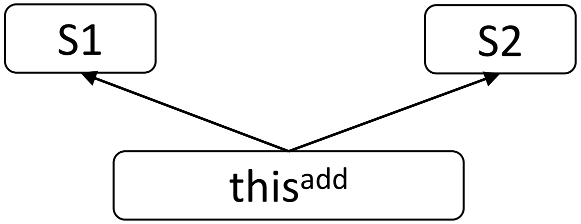
- ❑An example
  - two contexts of **HashSet.add** : [S1] and [S2].

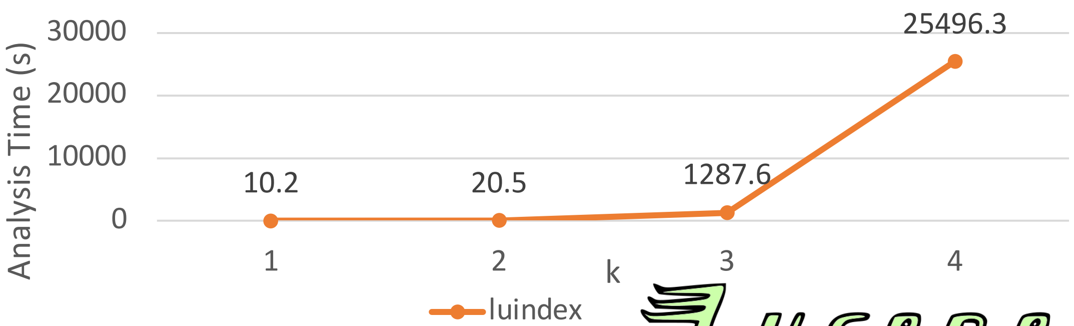
```
HashSet s1 = new HashSet();// S1
HashSet s2 = new HashSet();// S2
s1.add(new Object()); // O1
s2.add(new Object()); // O2
```

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



Exponential Explosion Issue

- Increasing k makes kOBJ less Efficient or even Unscalable



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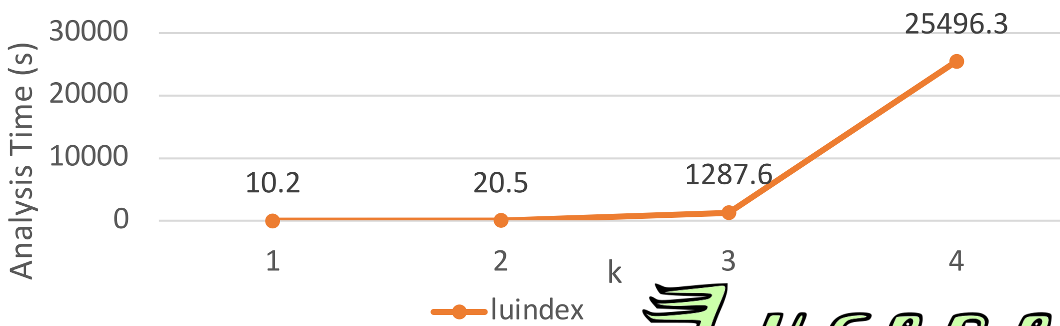
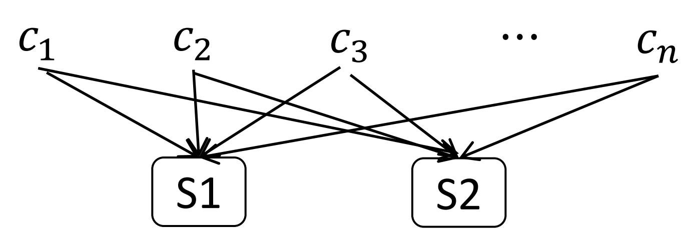


- Contexts of kOBJ grow exponentially with k
  - **HashSet.add :** $2n$ contexts, i.e., [S1, c_i] and [S2, c_i] ($1 \leq i \leq n$).

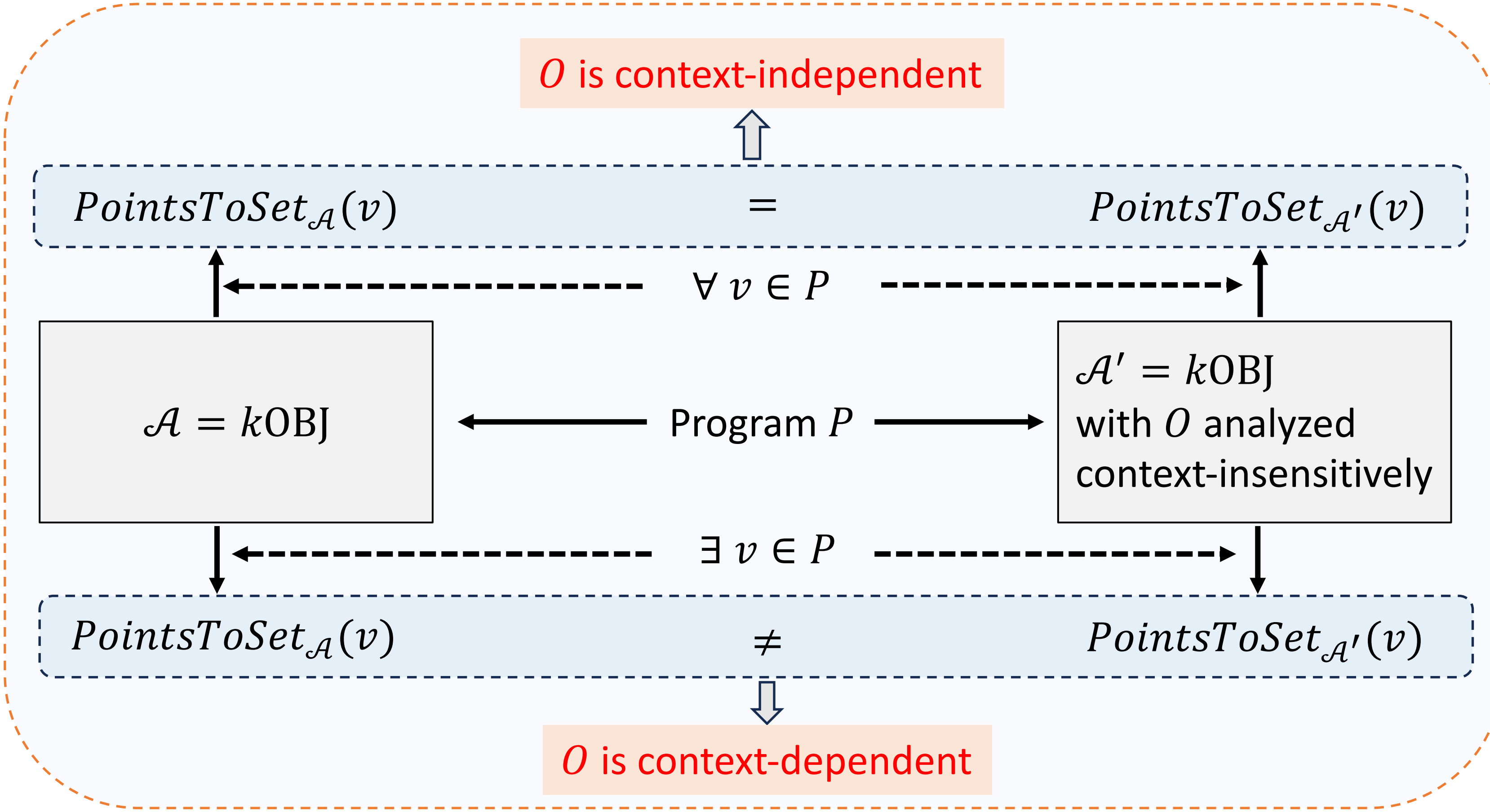
```
HashSet s1 = new HashSet();// S1
HashSet s2 = new HashSet();// S2
s1.add(new Object()); // O1
s2.add(new Object()); // O2
```

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



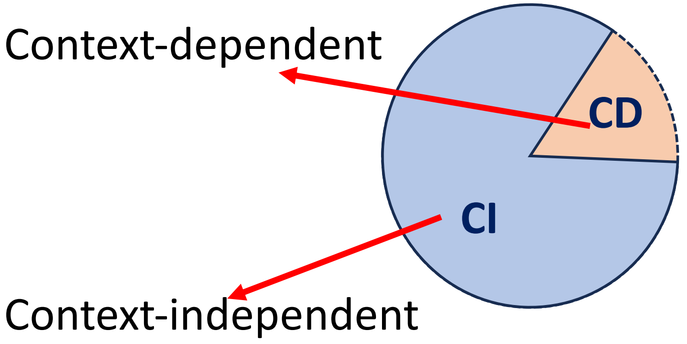
Review: Context Debloating

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



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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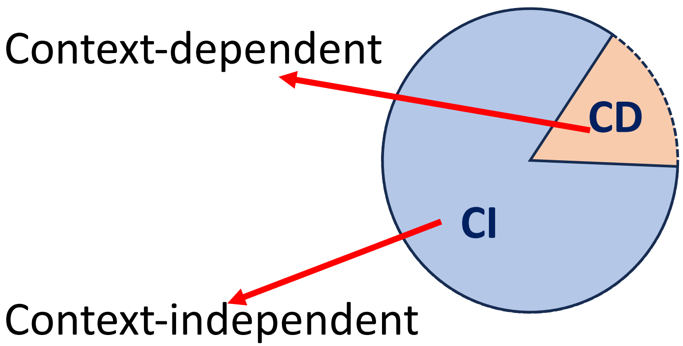
analyzed under n contexts, $c_1, \cdots c_n$

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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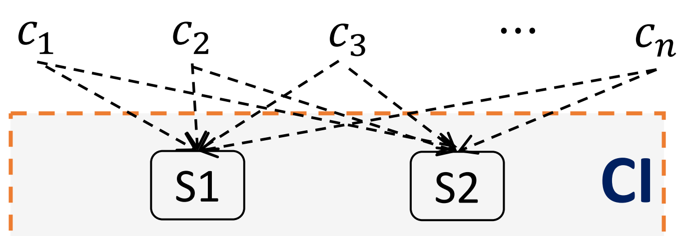
analyzed under n contexts, $c_1, \cdots c_n$

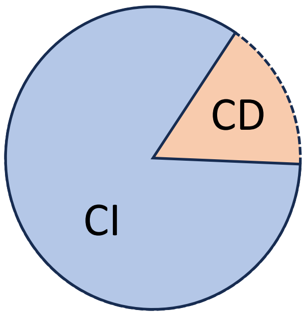
- **Key Idea： inhibit context combinations on CI elements**
  - # contexts of **HashSet.add: $2n$ -> 2**

Precise and Efficient!

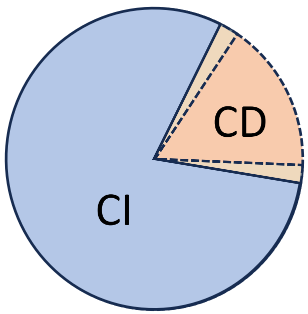


The Challenge in Context Debloating

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

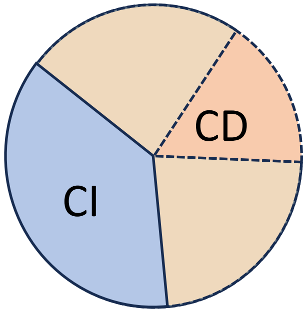


Ideal (Oracle)



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

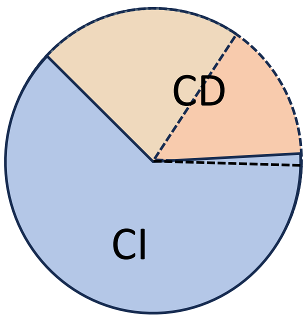


Eagle

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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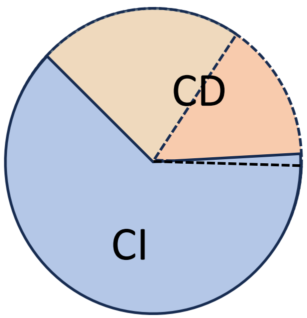

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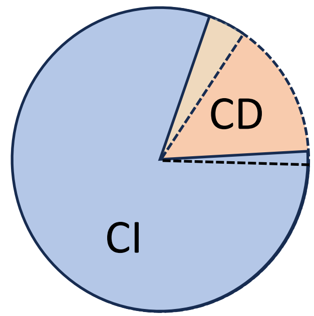

DebloaterX

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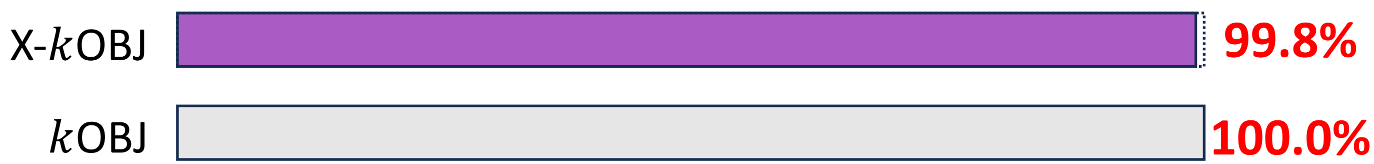
- Three Container-Usage Patterns
  - Inner Containers
  - Factory-Created Containers
  - Container Wrappers

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 the real world.



DebloaterX: Overall Algorithm

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

Input : P (Input Program)
Output : $\mathcal{I}$ (Context-Independent Objects)

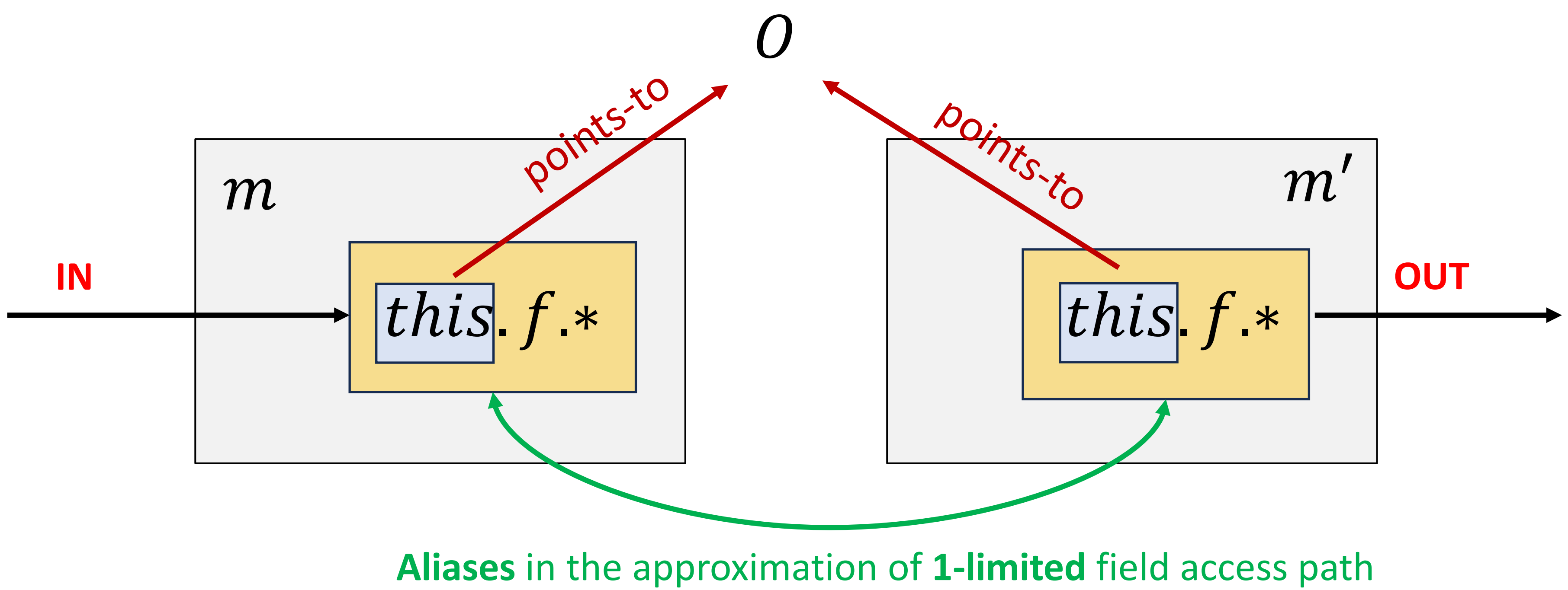
begin
- $\boxed{\text{Step 1:}}$ Find container objects in P and collect them in `containers`.
- $\boxed{\text{Step 2:}}$ Find context-dependent objects according to container-usage patterns.
  - $\mathcal{D} \leftarrow \emptyset$; `// Initialize the set for collecting Context-dependent Objects`
  - **foreach** `object` $o \in$ `containers` **do**
    - $\boxed{\text{Step 2.1:}}$ **if** *o is an inner container* **then** $\mathcal{D} \ni o$;
    - $\boxed{\text{Step 2.2:}}$ **if** *o is a factory-created container* **then** $\mathcal{D} \ni o$;
    - $\boxed{\text{Step 2.3:}}$ **if** *o is a container wrapper* **then** $\mathcal{D} \ni o$;
- $\boxed{\text{Step 3:}}$ **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

Containers

- An object O is a **container object** if it has at least
  - One **pointer field** $\boldsymbol{f}$ of an **open** (or abstract/raw/coarse) **type**,
  - 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



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  - m and m' are methods invoked on O
- 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

Containers

❑Rules for identifying Container Objects

$$\frac{O \in \mathbb{H} \quad t = \mathtt{typeof}(O) \quad t \text{ is an instance type} \\ f \in \mathtt{fields}(O) \quad t' = \mathtt{typeof}(f) \quad t' \in \mathtt{openTypes} \\ \mathtt{hasInFlow}\ (\mathrm{O, f}) \quad \mathtt{hasOutFlow}\ (\mathrm{O, f})}{O \in \mathtt{containers}}$$

$$\frac{O \in \mathbb{H} \quad t = \mathtt{typeof}(O) \\ t \text{ is an array type} \quad t \in \mathtt{openTypes}}{O \in \mathtt{containers}} \ [\textsc{Con}]$$

$$\frac{m \in \mathtt{methodsInvokedOn}(O) \quad f \in \mathtt{fields}(O) \\ p \in \mathtt{params}(m) \cap \mathtt{inParams}(f)}{\mathtt{hasInFlow}(O, f)}$$

$$\frac{a.f = \_ \text{ is a store in method } m \quad O \in \overline{\mathtt{pts}}(a) \\ O \text{ not allocated in } m \quad a \notin assign^*(\mathtt{this}^m)}{\mathtt{hasInFlow}(O, f)} \ [\textsc{In}]$$

$$\frac{m \in \mathtt{methodsInvokedOn}(O) \quad f \in \mathtt{fields}(O) \\ v \in \mathtt{paramsRet}(m) \cap \mathtt{outParamsRets}(f)}{\mathtt{hasOutFlow}(O, f)}$$

$$\frac{\_ = a.f \text{ is a load in method } m \quad O \in \overline{\mathtt{pts}}(a) \\ O \text{ not allocated in } m \quad a \notin assign^*(\mathtt{this}^m)}{\mathtt{hasOutFlow}(O, f)} \ [\textsc{Out}]$$

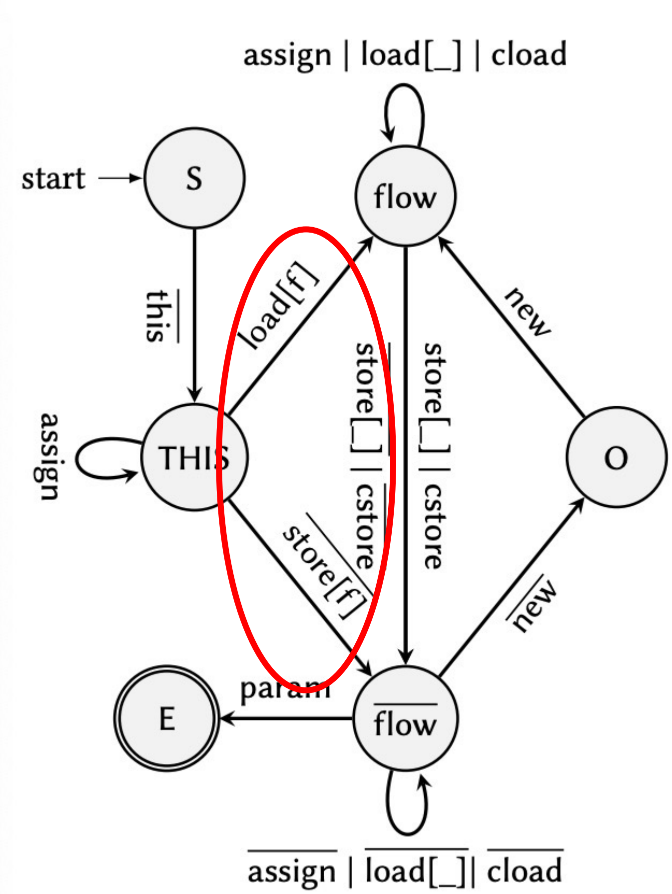
❑Rules for Open Types

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

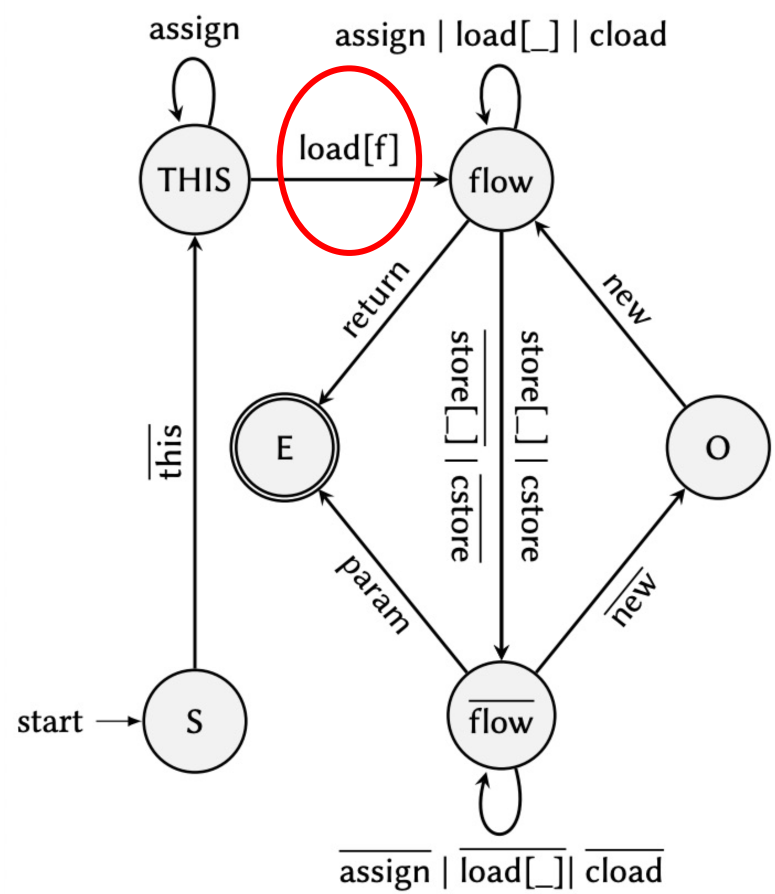
$$\frac{t \in \mathtt{openTypes}}{[t] \in \mathtt{openTypes}} \qquad \frac{t \in \mathbb{T} \quad f \in \mathtt{fields}(t) \quad \mathtt{typeof}(f) = t' \quad t' \in \mathtt{openTypes}}{t \in \mathtt{openTypes}}$$

Containers

- DFAs for computing incoming/outgoing value flows



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



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

- 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

```java
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

1

2

```
// in com.google.common.collect;
1 class Sets {
2   static HashSet newHashSet() {
3     return new HashSet(); // S
4 }}
```

❑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

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

- Rule for identifying factory-created containers

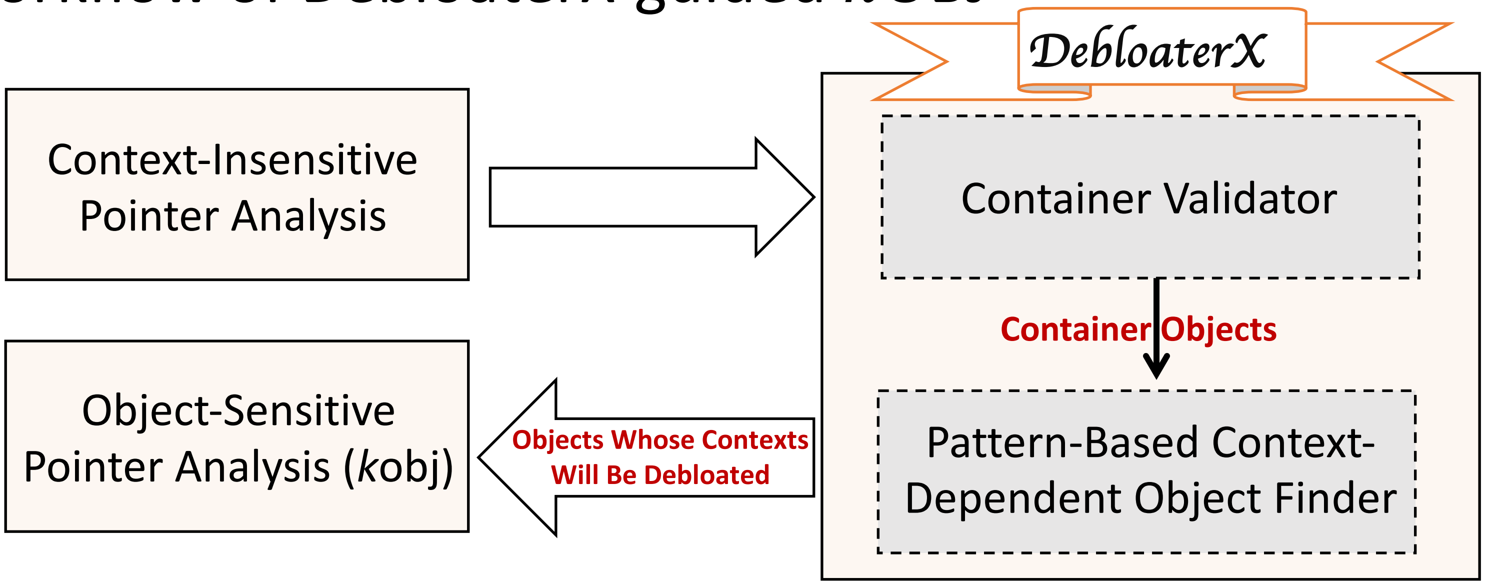
$$\frac{m \text{ is a static method} \quad m = \texttt{methodof}(O) \quad \texttt{isDirectlyReturned}(O)}{\texttt{isAFactoryCreatedContainer}(O)} \qquad \frac{O \xrightarrow{\text{new}} x \text{ is an edge in XPAG} \quad m = \texttt{methodof}(O) \quad \texttt{ret}^m \in \mathit{assign}^*(x)}{\texttt{isDirectlyReturned}(O)}$$

- Rule for identifying container wrappers

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

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

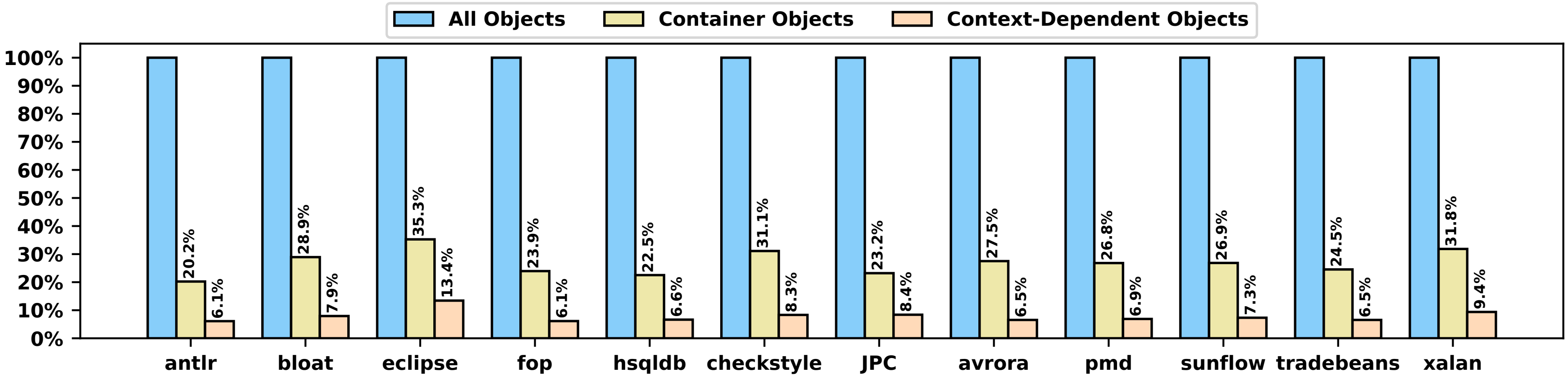
JREs

JPC

- 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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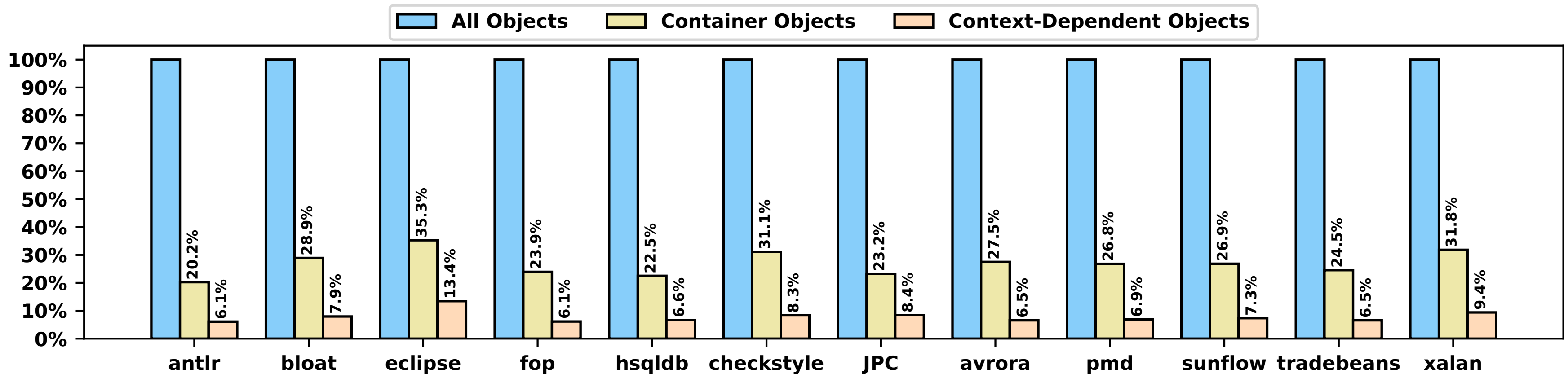
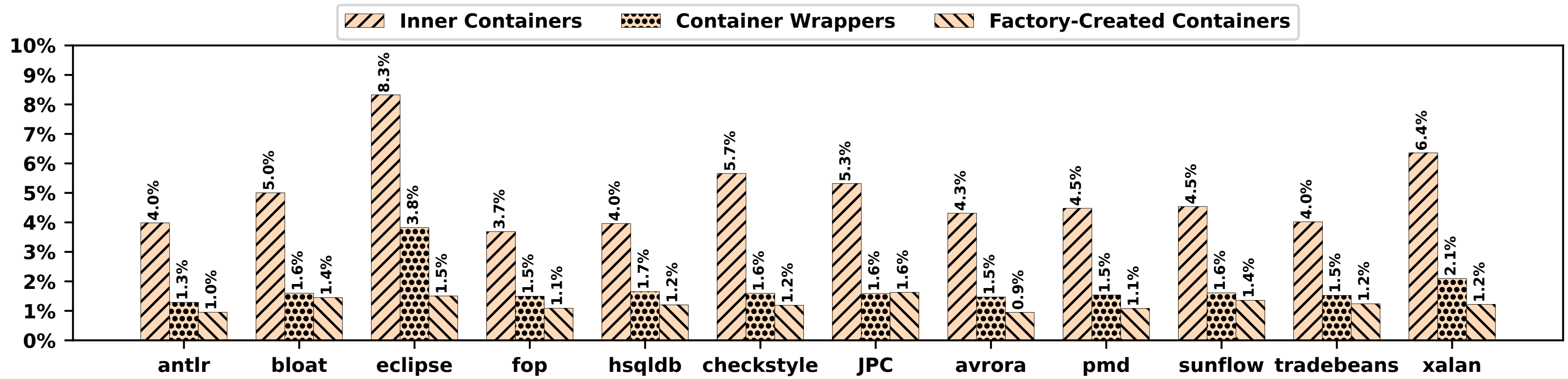
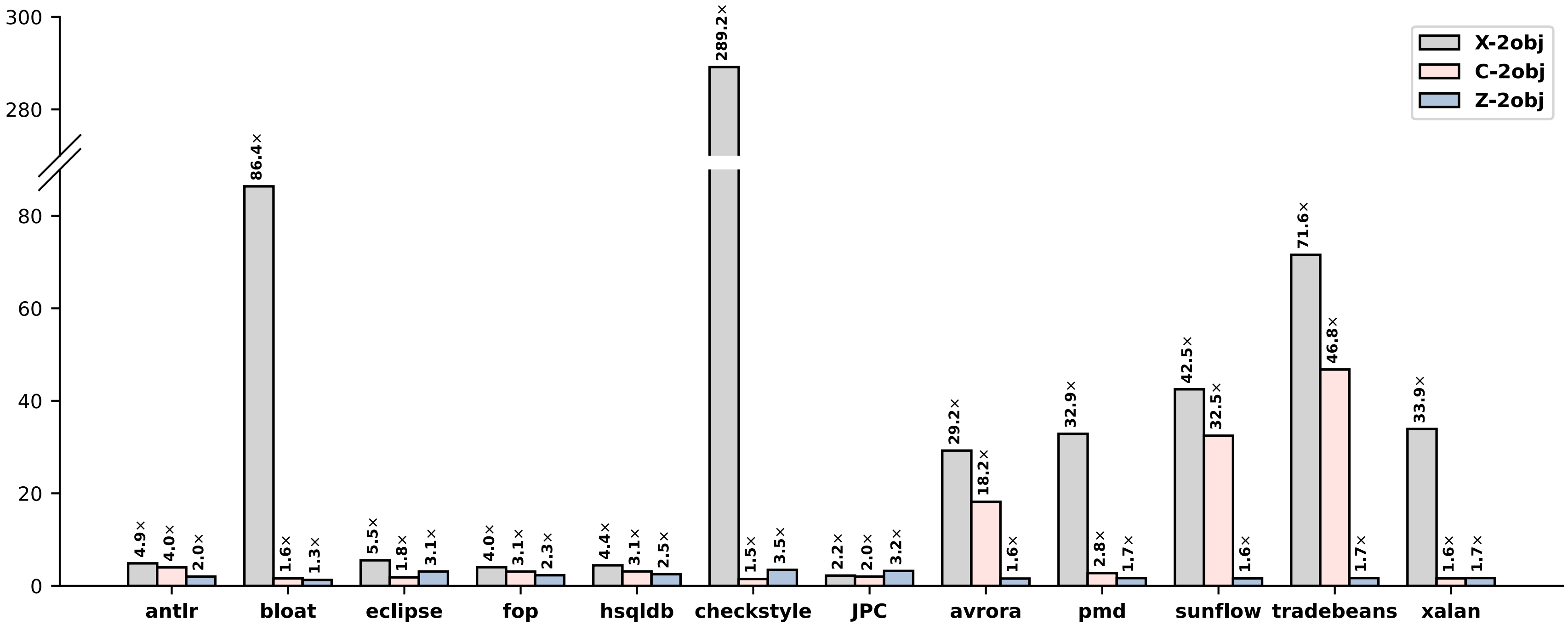


- ❑ Inner containers: 4.8% , factory-created containers: 1.2%, container wrappers: 1.7%



Evaluation: Efficiency

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

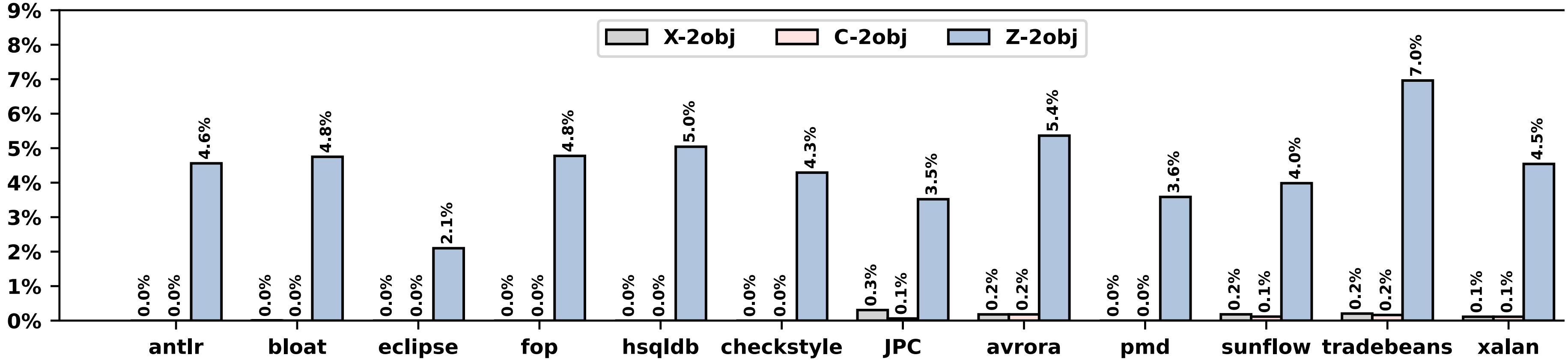


The enabled Speedup of DebloaterX, Conch, and Zipper over 2OBJ

- 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
- enable kOBJ to be more efficient than state-of-the-art while preserving nearly all of its 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!