## A Proofs of Lemmas and Theorems

This section provides detailed proofs for the lemmas and theorems stated in the main paper. For clarity, some of the definitions, lemmas, and theorems are restated as needed.

THEOREM 4.1. (***Equivalence between Field and Variable Pointers under Object-Sensitive Analysis***). Under $k$-object-sensitive pointer analysis, a field $f$ of a heap object $h$ and a local variable $v$ in a method $m$ invoked on $h$ exhibit structural equivalence in their context-sensitive representations.

PROOF. Let us assume a $k$-object-sensitive pointer analysis.

*Context Representation for Field Pointers.* For a heap object $h$ allocated under context $[o_1, \dots, o_l]$, where $l \le k-1$, the field pointer $h.f$ is represented by as:

$$([o_1, \dots, o_l], h.f)$$

This indicates that the access to the field $f$ of object $h$ is resolved under the context in which $h$ was created, and the pointer name is tied to the field label $f$ and the base object $h$.

*Context Representation for Local Variables.* Suppose the method $m$ is invoked on the receiver object $h$ allocated under context $[o_1, \dots, o_l]$, where $l \le k-1$. Then, under object-sensitive analysis, the context of method $m$ becomes:

$$c_m = [o_1, \dots, o_{k-1}, h]$$

Let $v$ be a local variable within $m$. Its context-sensitive representation is then:

$$([o_1, \dots, o_{k-1}, h], v)$$

*Structural Equivalence.* Now, consider rewriting the field pointer representation. Note that the context-sensitive representation of $h.f$ can be rewritten by pushing the object $h$ into the context and separating the field label:

$$([o_1, \dots, o_{k-1}], h.f) \quad \equiv \quad ([o_1, \dots, o_{k-1}, h], f)$$

This reinterpretation is valid because object-sensitive pointer analysis uses abstract heap objects to construct contexts. Here, we merely shift the object $h$ from being the "base" of a field label to being part of the context sequence, while preserving the essential identity of the field.

*Conclusion.* Since both representations are of the same structural form, we conclude that *field pointers and local variables are structurally equivalent in their contextual representation* under $k$-object-sensitive analysis. □

THEOREM 4.2. The ground truth of selective context-sensitive objects must be precision-relevant: Precision $\uparrow (h) \implies \mathrm{PR}(h, k-1)$, where $k-1$ is the length limit of object contexts.

To facilitate the proof of Theorem 4.2, we first introduce the following lemma, whose proof is given afterwards to maintain the coherence of presentation.

LEMMA A.1. *Given the context-sensitive PFG $G_{\mathbb{O}}$, and a field $f$ of object $h$, the following formula always holds:*

$$\neg\textsc{Partial}(h, f) \implies \forall x \in \textsc{Pre}(h, f), \forall y \in \textsc{Suc}(h, f) : x \bowtie y$$

We now present the proof for Theorem 4.2 below.

PROOF FOR THEOREM 4.2. We prove by contraposition. That is, we assume $\neg\mathrm{PR}(h, k-1)$ and show that this implies $\neg$Precision $\uparrow (h)$, i.e., $h$ cannot contribute to precision improvement under context sensitivity.

From Definition 4.6, an object $h$ is *not* precision-relevant if for each field $f$ of $h$, one of the two cases below is satisfied: it is not partial or its corresponding flows are not distinguishable. We examine each case separately:

- **Not Partial:** If each field $f$ of $h$ is not partial, it is formalized as

$$\forall f \in \mathbb{F} \text{ of } h : \neg\textsc{Partial}(h, f)$$

By Lemma A.1, we have:

$$\neg\textsc{Partial}(h, f) \implies \forall x \in \textsc{Pre}(h, f), \forall y \in \textsc{Suc}(h, f) : x \bowtie y$$

By the nature of pointer analysis, we have in PFG $G_{\mathbb{O}\setminus\{h\}}$, for field $f$ of $h$, there is only one field pointer $(\emptyset, h.f)$, since all the contexts of $h$ are removed in $G_{\mathbb{O}\setminus\{h\}}$, hence we have $\forall x \in \textsc{Pre}(h, f), \forall y \in \textsc{Suc}(h, f) : x \bowtie y$ satisfied in $G_{\mathbb{O}\setminus\{h\}}$. This implies that $\forall x \in \textsc{Pre}(h, f), \forall y \in \textsc{Suc}(h, f) : x \bowtie z$ holds in both $G_{\mathbb{O}}$ and $G_{\mathbb{O}\setminus\{h\}}$. Consequently, the reachability related to the flows through $h.f$ remain the same in $G_{\mathbb{O}}$ and $G_{\mathbb{O}\setminus\{h\}}$, thus we have:

$$\forall v \in \mathbb{V}, \forall o \in \{o \mid o \rightsquigarrow_{G_{\mathbb{O}\setminus\{h\}}} v\} : o \rightsquigarrow_{G_{\mathbb{O}}} v$$

Therefore, we conclude $\neg$Precision $\uparrow (h)$.

- **Flow Not Distinguishable:**
If the corresponding flows of each field $f$ of $h$ are not distinguishable, it is formalized as:

$$\forall f \in \mathbb{F} \text{ of } h : \neg\textsc{DistObj}(h, f) \wedge \\ (\forall y \in \textsc{Pre}(h, f), \forall o \in pt(y) : \neg\mathrm{PR}(o, l') \vee \neg\textsc{DistCtx}(o, h, f) \vee l' \leq 0)$$

We discuss every condition below:
  - (1) By Definition 4.4, we have:

$$\neg\textsc{DistObj}(h, f) := \forall y \not\bowtie h.f, y' \in \textsc{Pre}(h, f), \forall c_y, c'_y \in \mathbb{C} : pt(c_y, y) = pt(c'_y, y')$$

    which means all the predecessors have the same objects, making the contexts of $h$ redundant for distinguishing these objects.
  - (2) By Definition 4.5, we have:

$$\neg\textsc{DistCtx}(o, h, f) := \forall y \not\bowtie h.f, y' \in \textsc{Pre}(h, f), \forall c_o, c_y, c'_y \in \mathbb{C} : \\ (c_o, o) \in \hat{pt}(c_y, y) \wedge (c_o, o) \in \hat{pt}(c'_y, y')$$

    which means all the predecessors have the identical contextual objects, making the contexts of $h$ redundant for distinguishing these contextual objects as well.
  - (3) By $l' \leq 0$, we have that the context length limit of $o$ is exceeded and the contexts of $h$ are invisible to $o$, making contexts of $h$ redundant for distinguishing the contextual objects of $o$.
  - (4) By $\neg\mathrm{PR}(o, l')$, we have the object $o$ is not *Precision-Relevant*, which leads to a recursive situation:
    * **Base:** $o$ is not *Precision-Relevant* due to $\neg\textsc{DistObj} \wedge (\neg\textsc{DistCtx} \vee l' \leq 0)$. In such scenarios, we have already shown that the contexts of $o$ are redundant for distinguishing pointer flows, implying that there is no need to differentiate the contextual replicas of $o$.
    * **Recursive:** $o$ is not *Precision-Relevant* due to $\neg\textsc{DistObj} \wedge \neg\mathrm{PR}$. This results in a recursive situation. However, by unrolling this recursion, we eventually reach one of the previously analyzed cases, which all establish that the contexts of $o$ are redundant for distinguishing pointer flows.

By the contradiction of all the conditions above, we have the contexts of $h$ redundant for distinguishing the pointer flows through its field pointers, thus, we have:

$$\forall x \in \textsc{Pre}(h, f), \forall y \in \{y | x \rightsquigarrow_{G_{\mathbb{O}\setminus\{h\}}} y\} : x \rightsquigarrow_{G_{\mathbb{O}}} y$$

further we have:

$$\forall v \in \mathbb{V}, \forall o \in \{o \mid o \rightsquigarrow_{G_{\mathbb{O}\setminus\{h\}}} v\} : o \rightsquigarrow_{G_{\mathbb{O}}} v$$

Therefore, we conclude $\neg$Precision $\uparrow (h)$.

In all possible cases where $\neg\text{PR}(h, k-1)$, we conclude that $\neg$Precision $\uparrow (h)$. Hence, the contrapositive $\neg\text{PR}(h, k-1) \implies \neg$Precision $\uparrow (h)$ holds, and so does the original implication Precision $\uparrow (h) \implies \text{PR}(h, k-1)$. □

In the following, we present the proof of Lemma A.1.

Proof for Lemma A.1. By Definition 4.3 , we have:

$$\neg\textsc{Partial}(h, f) \iff \forall x \in \textsc{Pre}(h, f), \forall y \in \textsc{Suc}(h, f) : x \bowtie h.f \vee h.f \bowtie y.$$

We aim to prove:

$$x \bowtie h.f \vee h.f \bowtie y \implies x \bowtie y$$

We consider the two disjunctive cases separately.

*Case 1:* $x \bowtie h.f$. By Definition 4.2, this means:

$$\forall c_x, c_h \in \mathbb{C} : (c_x, x) \rightarrow (c_h, h.f).$$

Furthermore, by Definition 4.1, for any $y \in \textsc{Suc}(h, f)$, we have:

$$\forall c_y \in \mathbb{C}, \exists c_h \in \mathbb{C} : (c_h, h.f) \rightarrow (c_y, y).$$

By composing these two reachability relations, we derive:

$$\forall c_x, c_y \in \mathbb{C} : (c_x, x) \rightsquigarrow (c_y, y),$$

which is the definition of $x \bowtie y$.

*Case 2:* $h.f \bowtie y$. This is symmetric to Case 1. We have:

$$\forall c_h, c_y \in \mathbb{C} : (c_h, h.f) \rightarrow (c_y, y),$$

and by Definition 4.1, for any $x \in \textsc{Pre}(h, f)$, we have:

$$\forall c_x \in \mathbb{C}, \exists c_h \in \mathbb{C} : (c_x, x) \rightarrow (c_h, h.f).$$

Therefore, composing again yields:

$$\forall c_x, c_y \in \mathbb{C} : (c_x, x) \rightsquigarrow (c_y, y),$$

which again implies $x \bowtie y$. □

Theorem 4.3. A *Precision-Relevant* object must be an *Applied Precision-Relevant* object: $\text{PR}(h, k-1) \implies \overline{\text{PR}}(h, k-1)$, where $k$ is the context length of methods, $k-1$ is the context length of objects.

To facilitate the proof of Theorem 4.3, we first introduce the following lemmas, whose proofs are given afterwards to maintain the coherence of presentation.

Lemma 4.1. Given a field load statement $y = x.f$, the following formula holds under context-sensitive analysis:

$$\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \hat{pt}(c_1, x) \neq \hat{pt}(c_2, x)$$

where $c_1, c_2 \in \mathbb{C}$.

Lemma 4.2. Under object-sensitive analysis, if a variable $y$ in method $m$ have different points-to sets under different contexts, we have $\overline{\textsc{DistObj2}}$ in $\overline{\text{PR}}$ satisfied on VFG $\mathcal{G}$:

$$\exists c_1, c_2 \in \mathbb{C} : pt(c_1, y) \neq pt(c_2, y) \implies \hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies this_m \rightsquigarrow_{\mathcal{G}} y \vee (\exists o \in \mathbb{O} : o \rightsquigarrow_{\mathcal{G}} y)$$

Lemma 4.3. Given a field $f$ of $h$, if $\textsc{Partial}(h, f)$ is satisfied on $G_{\mathbb{O}}$, we have $\overline{\textsc{Partial}}$ satisfied on VFG $\mathcal{G}$:

$$\textsc{Partial}(h, f) \implies \overline{\textsc{Partial}}$$

We now present the proof for Theorem 4.3.

Proof for Theorem 4.3. Both PR and $\overline{\text{PR}}$ defined in Definitions 4.6 and 4.8 rely on several atomic properties. Therefore, it suffices to prove each of the following atomic properties individually.

- **(1)** $\textsc{Partial}(h, f) \implies \overline{\textsc{Partial}}$
- **(2)** $\textsc{DistObj}(h, f) \vee (\exists y \in \textsc{Pre}(h, f), \exists o \in pt(y) : \text{PR}(o, l') \wedge \textsc{DistCtx}(o, h, f) \wedge l' > 0) \implies \overline{\textsc{DistObj1}} \vee \overline{\textsc{DistObj2}} \vee \overline{\textsc{DistCtx}}$

By Lemma 4.3, we have **(1)** proven, thus we only need to prove **(2)**, and we prove the two implications:

$$\textsc{DistObj}(h, f) \implies \overline{\textsc{DistObj1}} \vee \overline{\textsc{DistObj2}} \tag{3}$$

$$\begin{matrix} \exists y \in \textsc{Pre}(h, f), \exists o \in pt(y) : \\ \text{PR}(o, l') \wedge \textsc{DistCtx}(o, h, f) \wedge l' > 0 \end{matrix} \implies \overline{\textsc{DistObj1}} \vee \overline{\textsc{DistObj2}} \vee \overline{\textsc{DistCtx}} \tag{4}$$

(1) Implication (3): By Definition 4.4, we have:

$$\textsc{DistObj}(h, f) := \exists y \ntriangleleft h.f, y' \in \textsc{Pre}(h, f), c_y, c'_y \in \mathbb{C} : pt(c_y, y) \neq pt(c'_y, y')$$

When $y$ and $y'$ are different variables and they have different points-to sets, i.e., $\overline{\textsc{DistObj1}}$, thus we have:

$$\textsc{DistObj}(h, f) \implies \overline{\textsc{DistObj1}}$$

When $y$ and $y'$ are the same variable, which means the variable have different points-to sets under different contexts, by Lemma 4.2, we have:

$$\textsc{DistObj}(h, f) \implies \overline{\textsc{DistObj2}}$$

Thus, we have implication 3 satisfied.

(2) Implication (4), where the recursion on both sides can be unrolled within same steps: By Definition 4.5, we have:

$$\textsc{DistCtx}(o, h, f) := \begin{matrix} \exists y \ntriangleleft h.f, y' \in \textsc{Pre}(h, f), \exists c_o, c_y, c'_y \in \mathbb{C} : \\ (c_o, o) \in \hat{pt}(c_y, y) \wedge (c_o, o) \notin \hat{pt}(c'_y, y') \end{matrix}$$

According to Definition 4.5, a difference between the contextual points-to sets of $(c_y, y)$ and $(c'_y, y')$ is required. This discrepancy implies either the predicate $\overline{\textsc{DistObj1}}$ holds directly, or it can be over-approximated via the reachability criteria defined by $\overline{\textsc{DistObj2}}$ or by the context-sensitive distinction $\overline{\textsc{DistCtx}}$, as established in Lemma 4.2. Thus we have:

$$\begin{matrix} \exists y \in \textsc{Pre}(h, f), \exists o \in pt(y) : \\ \text{PR}(o, l') \wedge \textsc{DistCtx}(o, h, f) \wedge l' > 0 \end{matrix} \implies \overline{\textsc{DistObj1}} \vee \overline{\textsc{DistObj2}} \vee \overline{\textsc{DistCtx}}$$

□

In the following, we present our proof for Lemma 4.1.

Proof for Lemma 4.1. We proceed by contraposition. Suppose that:

$$\hat{pt}(c_1, x) = \hat{pt}(c_2, x) = P$$

where $P$ is the contextual points-to set pointed to by $x$ in both contexts $c_1$ and $c_2$.

By the **[Field-Load]** rule defined in Figure 3, for each contextual object $(c', h) \in P$, the following holds:

$$(c', h.f) \rightarrow (c_1, y) \quad \text{and} \quad (c', h.f) \rightarrow (c_2, y)$$

Since the same contextual points-to set $P$ is accessed under both $c_1$ and $c_2$, and each $(c', h.f)$ points to both $(c_1, y)$ and $(c_2, y)$ identically, it follows that the resulting contextual points-to sets for $y$ are also equal:

$$\hat{pt}(c_1, y) = \hat{pt}(c_2, y)$$

This contradicts the assumption that $\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y)$. Hence, by contraposition:

$$\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \hat{pt}(c_1, x) \neq \hat{pt}(c_2, x)$$

□

Before presenting the proof of Lemma 4.2, we first introduce the following lemmas, whose proofs are given afterwards.

Lemma A.2. *Under object-sensitive analysis, for any method $m$ and its associated receiver variable $this_m$, if method $m$ has two distinct contexts $c_1, c_2 \in \mathbb{C}$, then the context-sensitive points-to sets of $this_m$ are distinct, i.e., $\hat{pt}(c_1, this_m) \neq \hat{pt}(c_2, this_m)$.*

Lemma A.3. *Under object-sensitive analysis, given a variable $y$ in method $m$, the following formula holds:*

$$\exists c_1, c_2 \in \mathbb{C} : \hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \exists c_{n1}, c_{n2} \in \mathbb{C}, \exists n \in \mathcal{N} : \hat{pt}(c_1, n) \neq \hat{pt}(c_2, n) \land n \rightsquigarrow_{\mathcal{G}} y$$

Proof for Lemma 4.2. **Step 1.** We prove the implication:

$$\exists c_1, c_2 \in \mathbb{C} : pt(c_1, y) \neq pt(c_2, y) \implies \hat{pt}(c_1, y) \neq \hat{pt}(c_2, y)$$

By the definitions of $pt$ and $\hat{pt}$, we have:

$$pt(c_i, y) := \{o \mid (c, o) \in \hat{pt}(c_i, y) \text{ for some } c \in \mathbb{C}\}$$

Thus, the implication is naturally satisfied.

**Step 2.** We prove the implication:

$$\exists c_1, c_2 \in \mathbb{C} : \hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies this_m \rightsquigarrow_{\mathcal{G}} y \ \lor \ (\exists o \in \mathbb{O} : o \rightsquigarrow_{\mathcal{G}} y)$$

By Lemma A.3, we have:

$$\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \exists n \in \mathcal{N} : \hat{pt}(c_1, n) \neq \hat{pt}(c_2, n) \land n \rightsquigarrow_{\mathcal{G}} y$$

And the only root sources of pointer flow in $\mathcal{G}$ are:

- "this" variable $this_m$,
- some allocated heap objects $o \in \mathbb{O}$.

By Lemma A.2, $this_m$ carries distinct contextual points-to sets across different calling contexts, and so do the allocated heap objects due to the setting of context-sensitive objects. Hence, there must exist a path from either $this_m$ or some heap object $o$ to $y$, i.e.,

$$this_m \rightsquigarrow_{\mathcal{G}} y \ \lor \ \exists o \in \mathbb{O} : o \rightsquigarrow_{\mathcal{G}} y$$

□

We now present the proof for Lemma A.2 and A.3.

Proof for Lemma A.2. Let $m$ be a method. Under object-sensitive analysis, the context $c \in \mathbb{C}$ for a call to $m$ is constructed from a contextual receiver object $(c', o)$, where $o \in \mathbb{O}$ and $c' \in \mathbb{C}$, by a function cons illustrated in the rule **[Method-Call]** in Figure 3:

$$\textsc{cons}(c, o) = \lceil c :: o \rceil_k$$

Also, by rule **[Method-Call]**, we have:

$$(c', o) \longrightarrow (c, this_m)$$

which implies:

$$(c', o) \in \hat{pt}(c, this_m)$$

Now suppose $c_1 \neq c_2$ are two distinct contexts for $m$, and both were generated by CONS from pairs $(c'_1, o_1)$ and $(c'_2, o_2)$, respectively:

$$c_1 = \textsc{cons}(c'_1, o_1), \quad c_2 = \textsc{cons}(c'_2, o_2)$$

We show that $c_1 \neq c_2$ implies $(c'_1, o_1) \neq (c'_2, o_2)$. Suppose for contradiction that $(c'_1, o_1) = (c'_2, o_2)$. Then by definition of CONS, we would have:

$$c_1 = \textsc{cons}(c'_1, o_1) = \textsc{cons}(c'_2, o_2) = c_2$$

which contradicts $c_1 \neq c_2$. Hence, it must be the case that:

$$(c'_1, o_1) \neq (c'_2, o_2)$$

Now using the **[Method-Call]** rule again:

$$(c'_1, o_1) \in \hat{pt}(c_1, this_m), \quad (c'_2, o_2) \in \hat{pt}(c_2, this_m)$$

Since $(c'_1, o_1) \neq (c'_2, o_2)$, we conclude:

$$\hat{pt}(c_1, this_m) \neq \hat{pt}(c_2, this_m)$$

□

PROOF FOR LEMMA A.3. Assume $\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y)$. We begin by analyzing the possible derivation rules by which an edge $n \rightarrow_{\mathcal{G}} y$ could have been constructed in the VFG $\mathcal{G}$. We consider all VFG construction rules from Figure 6.

- **(a)** **[Assign]**$_{\mathcal{G}}$: Suppose $n \rightarrow_{\mathcal{G}} y$ is constructed due to an assignment $y = n$. Since assignment statements directly propagate pointer flows under different contexts, it follows that:

$$\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \hat{pt}(c_1, n) \neq \hat{pt}(c_2, n)$$

- **(b)** **[Field-Load]**$_{\mathcal{G}}$:
  (1) Suppose the edge arises from a field load $y = n.f$. By Lemma 4.1, if $\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y)$, then:

$$\hat{pt}(c_1, n) \neq \hat{pt}(c_2, n)$$

  (2) Suppose the edge arises from $n = y.f$, this does not affect the points-to set of $y$.
- **(c)** **[Field-Store]**$_{\mathcal{G}}$: Edges from statements of the form $n.f = y$ do not affect the points-to set of $y$.
- **(d)** **[Method-Call]**$_{\mathcal{G}}$: Suppose the edge $n \rightarrow_{\mathcal{G}} y$ is constructed when $y$ receives a return value from a callee called on $n$. By Theorem 4.1, the same reasoning as in case **(b)** applies, and we obtain:

$$\hat{pt}(c_1, n) \neq \hat{pt}(c_2, n)$$

  When the the edge $n \rightarrow_{\mathcal{G}} y$ is constructed when $n$ is an argument passed into a callee called on $y$, then same reasoning as in case **(c)** applies.
- **(e)** **[New]**$_{\mathcal{G}}$: Suppose the edge $n \rightarrow_{\mathcal{G}} y$ is constructed due to an allocation statement. Since allocation statements directly propagate pointer flows under different contexts, we have:

$$\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y) \implies \hat{pt}(\lceil c_1 \rceil_{k-1}, n) \neq \hat{pt}(\lceil c_2 \rceil_{k-1}, n)$$

In all relevant cases, we have shown that $\hat{pt}(c_1, y) \neq \hat{pt}(c_2, y)$ implies the existence of a predecessor node $n \in \mathcal{N}$ such that:

$$\exists c_{n1}, c_{n2} \in \mathbb{C}, \hat{pt}(c_{n1}, n) \neq \hat{pt}(c_{n2}, n) \quad \text{and} \quad n \rightarrow_{\mathcal{G}} y$$

We now apply this reasoning recursively: for such an $n$, if it is not a source node in $\mathcal{G}$, then it must itself have a predecessor under one of the VFG rules, and the same argument can be applied again, which completes the proof. □

Before presenting the proof of Lemma 4.3, we first introduce the following lemma, whose proof is given afterwards.

Lemma A.4. *Given a field store statement $x.f = y$, the following formula holds under context-sensitive analysis:*

$$\exists c_o, c_1, c_2 \in \mathbb{C}, o \in \mathbb{O}, (c_h, h) \in \hat{pt}(c_1, x), (c'_h, h') \in \hat{pt}(c_2, x) :$$
$$(c_o, o) \in \hat{pt}(c_1, y) \wedge (c_o, o) \notin \hat{pt}(c_2, y) \wedge (c_o, o) \in \hat{pt}(c_h, h.f) \wedge (c_o, o) \notin \hat{pt}(c'_h, h'.f)$$
$$\Longrightarrow$$
$$(c_h, h) \in \hat{pt}(c_1, x) \wedge (c'_h, h') \notin \hat{pt}(c_1, x)$$

Now we present the proof of Lemma 4.3.

Proof for Lemma 4.3. By Definition 4.8, we have:

$$\overline{\text{Partial}} := h \rightsquigarrow_{\mathcal{G}} this_m \vee \exists x \in \text{Base}(h, f) : h \rightsquigarrow_{\mathcal{G}} x$$

We prove the lemma by establishing the following two implications:

$$\text{Partial}(h, f) \implies \exists x \in \text{Base}(h, f), \exists c_h, c_x \in \mathbb{C} : (c_h, h) \notin \hat{pt}(c_x, x)$$
$$\exists x \in \text{Base}(h, f), \exists c_h, c_x \in \mathbb{C} : (c_h, h) \notin \hat{pt}(c_x, x) \implies h \rightsquigarrow_{\mathcal{G}} this_m \vee \exists x \in \text{Base}(h, f) : h \rightsquigarrow_{\mathcal{G}} x$$

**Step 1:** We prove the implication by contradiction:

$$\text{Partial}(h, f) \implies \exists x \in \text{Base}(h, f), \exists c_h, c_x \in \mathbb{C} : (c_h, h) \notin \hat{pt}(c_x, x)$$

Suppose that:

$$\text{Partial}(h, f) \quad \text{and} \quad \forall x \in \text{Base}(h, f), \forall c_x, c_h \in \mathbb{C} : (c_h, h) \in \hat{pt}(c_x, x)$$

By Definition 4.3, $\text{Partial}(h, f)$ is defined as:

$$\exists p \in \text{Pre}(h, f), \exists s \in \text{Suc}(h, f) : \; p \not\rightsquigarrow h.f \wedge h.f \not\rightsquigarrow s$$

We first consider the reachability regarding the predecessors, which is built by the rule **[Field-Store]** for statement $x.f = y$ in Figure 3, we have:

$$(c, y) \rightarrow (c_h, h.f) \iff (c_h, h) \in \hat{pt}(c, x)$$

From our assumption, we have:

$$\forall x \in \text{Base}(h, f), \forall c_x, c_h : (c_h, h) \in \hat{pt}(c_x, x)$$

This implies that for every field store $x.f = y$ and every $c$, we always have $(c, y) \rightarrow (c_h, h.f)$ in the PFG and no partial reachability can occur. The same rationale applies for the successors of field load statements as well. Thus, this contradicts the assumption, and we conclude:

$$\exists x \in \text{Base}(h, f), \exists c_x, c_h : (c_h, h) \notin \hat{pt}(c_x, x)$$

**Step 2:** We prove the implication:

$$\exists x \in \text{Base}(h, f), \exists c_h, c_x \in \mathbb{C} : (c_h, h) \notin \hat{pt}(c_x, x) \implies h \rightsquigarrow_{\mathcal{G}} this_m \vee \exists x \in \text{Base}(h, f) : h \rightsquigarrow_{\mathcal{G}} x$$

We assume $\exists x \in \textsc{Base}(h, f), \exists c_h, c_x \in \mathbb{C} : (c_h, h) \notin \hat{pt}(c_x, x)$, which means the distinction between contextual replicas of $h$ is preserved until reaching variable $x$. Thus, we can derive that such distinction at least is preserved within the method $m$ where $h$ is allocated. Since such distinction is naturally satisfied from the allocation site of $h$ (guaranteed by the **[New]** rule defined in Figure 3), thus, we only need such distinction either preserved at a base variable within method $m$, or at the exit of $m$, i.e., *this* variable. We then prove such distinction can be preserved along a VFG path starting from $h$.

The direct successor of $h$ (say $s$) must be built by **[New]**$_{\mathcal{G}}$, since this rule propagates objects within same contexts, thus we naturally have $\exists c_h, c'_h, c_s \in \mathbb{C} : (c_h, h) \in \hat{pt}(c_s, s) \wedge (c'_h, h) \notin \hat{pt}(c_s, s)$. We proceed by analyzing the possible derivation rules by which the path $h \rightarrow_{\mathcal{G}} s \rightarrow_{\mathcal{G}} x$ could have been constructed in the VFG $\mathcal{G}$. We consider all VFG construction rules from Figure 6.

**(a)** **[Assign]**$_{\mathcal{G}}$: Suppose $s \rightarrow_{\mathcal{G}} x$ is constructed due to an assignment $x = s$. Since assignments in VFG directly propagate pointer flows, it follows that:

$$\exists c_h, c'_h, c_s \in \mathbb{C} : (c_h, h) \in \hat{pt}(c_s, s) \wedge (c'_h, h) \notin \hat{pt}(c_s, s)$$

**(b)** **[Field-Load]**$_{\mathcal{G}}$: Suppose the edge $s \rightarrow_{\mathcal{G}} x$ arises from a field load $s = x.f$ or $x = s.f$, both cases do not affect the points-to set of $s$.

**(c)** **[Field-Store]**$_{\mathcal{G}}$: Suppose the edge $s \rightarrow_{\mathcal{G}} x$ arises from a field store statement of the form $x.f = s$, by Lemma A.4, we have the following condition must be satisfied:

$$\exists c_1, c_2 \in \mathbb{C} : \hat{pt}(c_1, x) \neq \hat{pt}(c_2, x)$$

**(d)** **[Method-Call]**$_{\mathcal{G}}$: Suppose the edge $s \rightarrow_{\mathcal{G}} x$ is constructed when $x$ receives a return value from a callee called on $s$. By Theorem 4.1, the same reasoning as in case **(b)** applies. Similarly, when the edge $s \rightarrow_{\mathcal{G}} x$ is constructed when $s$ is an argument passed into a callee called on $x$, then same reasoning as in case **(c)** applies.

We now apply this reasoning recursively and the same argument can be applied again, and we have the distinction preserved:

- naturally, if the VFG path contains only case **(a)**.
- conditionally, if the VFG path contains cases **(c)** or **(d)**, and the end node $x$ of VFG path must satisfy:

$$\exists c_1, c_2 \in \mathbb{C} : \hat{pt}(c_1, x) \neq \hat{pt}(c_2, x)$$

By Lemma A.2, *this* variable must have different contextual points-to sets under different contexts, thus we have either the contextual replicas of $h$ can reach any base variable like $x$ by assignment statements, or it must has a VFG path ending at *this* variable to reach out of the current method, which is:

$$h \rightsquigarrow_{\mathcal{G}} this_m \vee \exists x \in \textsc{Base}(h, f) : h \rightsquigarrow_{\mathcal{G}} x$$

□

And we present the proof of Lemma A.4.

Proof for Lemma A.4. By the **[Field-Store]** rule defined in Figure 3, for the field store statement $x.f = y$, we have a PFG edge $(c, y) \rightarrow (c', h.f)$ if and only if $(c', h) \in \hat{pt}(c, x)$. Since we already have:

$$(c_o, o) \in \hat{pt}(c_1, y) \wedge (c_o, o) \notin \hat{pt}(c_2, y) \wedge (c_o, o) \in \hat{pt}(c_h, h.f) \wedge (c_o, o) \notin \hat{pt}(c'_h, h'.f)$$

we naturally have:

$$(c_h, h) \in \hat{pt}(c_1, x) \wedge (c'_h, h') \notin \hat{pt}(c_1, x)$$

□

## B Detailed Comparison of Entire Analysis Time under 2-object-sensitive and 3-object-sensitive analysis

Table 5 and Table 6 provide the detailed analysis results for the entire analysis (including all three stages) under 2-object-sensitivity and 3-object-sensitivity, respectively, corresponding to the speedup comparisons presented in Figure 11a and Figure 11b in the main text.

Table 5. Precision and Efficiency results of entire analysis (including all three stages) of Cut-Shortcut, Zipper, Conch, DebloaterX and Moon, whereas CI and 2OBJ are presented as baselines.

| Program | Analysis | T | S | #MFC | #PCS | #RM | #CE | Program | Analysis | T | S | #MFC | #PCS | #RM | #CE | Program | Analysis | T | S | #MFC | #PCS | #RM | #CE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| antlr | 2obj | 26.5 | - | 510 | 1631 | 7806 | 51264 | avrora | 2obj | 18.8 | - | 568 | 933 | 10940 | 48361 | batik | 2obj | 810.7 | - | 2142 | 4956 | 20254 | 107822 |
| | ci | 4.8 | 5.5X | 1124 | 1976 | 8190 | 57341 | | ci | 5.5 | 3.4X | 1188 | 1372 | 11373 | 55476 | | ci | 13.3 | 61.0X | 3403 | 5810 | 20994 | 127604 |
| | CSC | 5.7 | 4.6X | 812 | 1896 | 8153 | 54460 | | CSC | 6.3 | 3.0X | 882 | 1283 | 11282 | 52535 | | CSC | 18.6 | 43.6X | 2846 | 5524 | 20819 | 121105 |
| | Z-2obj | 23.3 | 1.1X | 528 | 1650 | 7836 | 51391 | | Z-2obj | 18.0 | 1.0X | 595 | 948 | 10969 | 48466 | | Z-2obj | 427.8 | 1.9X | 2161 | 4968 | 20265 | 107892 |
| | C-2obj | 13.8 | 1.9X | 510 | 1631 | 7806 | 51264 | | C-2obj | 14.8 | 1.3X | 568 | 933 | 10940 | 48361 | | C-2obj | 430.3 | 1.9X | 2142 | 4956 | 20254 | 107822 |
| | D-2obj | 17.2 | 1.5X | 510 | 1631 | 7806 | 51264 | | D-2obj | 19.6 | 1.0X | 568 | 933 | 10940 | 48361 | | D-2obj | 297.1 | 2.7X | 2142 | 4958 | 20254 | 107824 |
| | M-2obj | 10.8 | 2.5X | 510 | 1631 | 7806 | 51264 | | M-2obj | 12.8 | 1.5X | 568 | 933 | 10940 | 48361 | | M-2obj | 230.9 | 3.5X | 2150 | 4962 | 20254 | 107828 |
| biojava | 2obj | 13.5 | - | 436 | 843 | 7440 | 34802 | bloat | 2obj | 352.9 | - | 1285 | 1566 | 9019 | 56577 | bytecode-viewer | 2obj | 2992.2 | - | 4064 | 4626 | 14210 | 100280 |
| | ci | 4.5 | 3.0X | 1046 | 1236 | 7910 | 41678 | | ci | 5.5 | 64.5X | 2082 | 2249 | 9454 | 67338 | | ci | 9.4 | 316.6X | 4723 | 5616 | 14637 | 110795 |
| | CSC | 5.7 | 2.4X | 687 | 1150 | 7853 | 38403 | | CSC | 7.6 | 46.4X | 1594 | 2166 | 9414 | 63909 | | CSC | 21.7 | 138.0X | 4366 | 5547 | 14601 | 106506 |
| | Z-2obj | 13.6 | 1.0X | 449 | 876 | 7487 | 34947 | | Z-2obj | 291.4 | 1.2X | 1309 | 1597 | 9061 | 56784 | | Z-2obj | 2146.0 | 1.4X | 4080 | 4644 | 14246 | 100443 |
| | C-2obj | 10.8 | 1.2X | 436 | 843 | 7440 | 34802 | | C-2obj | 214.4 | 1.6X | 1285 | 1566 | 9019 | 56577 | | C-2obj | 1693.2 | 1.8X | 4064 | 4626 | 14210 | 100280 |
| | D-2obj | 12.9 | 1.0X | 436 | 843 | 7440 | 34802 | | D-2obj | 30.2 | 11.7X | 1285 | 1566 | 9019 | 56577 | | D-2obj | 725.3 | 4.1X | 4064 | 4626 | 14210 | 100280 |
| | M-2obj | 8.8 | 1.5X | 436 | 843 | 7440 | 34802 | | M-2obj | 20.4 | 17.3X | 1285 | 1566 | 9019 | 56577 | | M-2obj | 243.4 | 12.3X | 4065 | 4629 | 14210 | 100283 |
| chart | 2obj | 100.2 | - | 1337 | 2027 | 15149 | 72650 | check-style | 2obj | OOM | - | - | - | - | - | classy-shark | 2obj | 22.3 | - | 564 | 1117 | 9393 | 44257 |
| | ci | 9.2 | 10.9X | 2560 | 2703 | 15923 | 86433 | | ci | 8.2 | >657.7X | 1939 | 2760 | 12766 | 80169 | | ci | 5.3 | 4.2X | 1323 | 1682 | 10178 | 56231 |
| | CSC | 10.4 | 9.6X | 1914 | 2405 | 15545 | 78847 | | CSC | 10.3 | >521.7X | 1503 | 2641 | 12713 | 74197 | | CSC | 7.1 | 3.1X | 876 | 1400 | 9489 | 48577 |
| | Z-2obj | 52.9 | 1.9X | 1376 | 2045 | 15234 | 72989 | | Z-2obj | 1489.6 | >3.6X | 1132 | 2249 | 12342 | 67170 | | Z-2obj | 22.2 | 1.0X | 581 | 1124 | 9412 | 44332 |
| | C-2obj | 70.5 | 1.4X | 1337 | 2027 | 15149 | 72650 | | C-2obj | 3822.0 | >1.4X | 1109 | 2216 | 12307 | 66970 | | C-2obj | 19.2 | 1.2X | 564 | 1117 | 9393 | 44257 |
| | D-2obj | 48.5 | 2.1X | 1337 | 2027 | 15149 | 72658 | | D-2obj | 43.3 | >124.7X | 1109 | 2216 | 12307 | 66970 | | D-2obj | 18.6 | 1.2X | 564 | 1117 | 9393 | 44257 |
| | M-2obj | 26.5 | 3.8X | 1337 | 2027 | 15149 | 72658 | | M-2obj | 24.9 | >216.8X | 1110 | 2216 | 12307 | 66970 | | M-2obj | 12.3 | 1.8X | 564 | 1117 | 9393 | 44257 |
| dcevm | 2obj | 374.1 | - | 2225 | 4417 | 20531 | 100557 | ddjava | 2obj | 10.9 | - | 367 | 815 | 6840 | 32248 | eclipse | 2obj | OOM | - | - | - | - | - |
| | ci | 13.5 | 27.7X | 3593 | 5669 | 21503 | 124314 | | ci | 4.1 | 2.7X | 880 | 1177 | 7249 | 38462 | | ci | 18.8 | >287.7X | 5090 | 10672 | 23386 | 182975 |
| | CSC | 15.2 | 24.6X | 2917 | 4932 | 20958 | 108001 | | CSC | 4.8 | 2.3X | 618 | 1093 | 7205 | 35797 | | CSC | 20.7 | >261.4X | 4282 | 10250 | 22977 | 172521 |
| | Z-2obj | 195.3 | 1.9X | 2316 | 4464 | 20573 | 100824 | | Z-2obj | 13.0 | 0.8X | 384 | 827 | 6855 | 32316 | | Z-2obj | OOM | - | - | - | - | - |
| | C-2obj | 245.1 | 1.5X | 2227 | 4425 | 20532 | 100594 | | C-2obj | 8.9 | 1.2X | 367 | 815 | 6840 | 32248 | | C-2obj | 1528.0 | >3.5X | 3612 | 9703 | 22627 | 162654 |
| | D-2obj | 214.2 | 1.7X | 2231 | 4431 | 20532 | 100608 | | D-2obj | 10.9 | 1.0X | 367 | 815 | 6840 | 32248 | | D-2obj | 598.6 | >9.0X | 3612 | 9703 | 22627 | 162654 |
| | M-2obj | 92.8 | 4.0X | 2241 | 4433 | 20535 | 100629 | | M-2obj | 8.4 | 1.3X | 367 | 815 | 6840 | 32248 | | M-2obj | 291.4 | >18.5X | 3612 | 9703 | 22627 | 162659 |
| findbugs | 2obj | 811.2 | - | 2013 | 3508 | 16264 | 87808 | fop | 2obj | 10.2 | - | 395 | 830 | 7591 | 34364 | h2 | 2obj | 17.0 | - | 398 | 911 | 7559 | 36261 |
| | ci | 9.7 | 83.7X | 3448 | 4435 | 16774 | 105576 | | ci | 4.0 | 2.5X | 911 | 1210 | 7997 | 40423 | | ci | 4.6 | 3.7X | 943 | 1274 | 7959 | 42799 |
| | CSC | 11.6 | 70.0X | 2766 | 4212 | 16705 | 96294 | | CSC | 4.5 | 2.2X | 653 | 1121 | 7944 | 37562 | | CSC | 5.2 | 3.3X | 687 | 1194 | 7914 | 40294 |
| | Z-2obj | 164.4 | 4.9X | 2044 | 3512 | 16276 | 87855 | | Z-2obj | 13.1 | 0.8X | 417 | 852 | 7621 | 34496 | | Z-2obj | 14.7 | 1.2X | 423 | 929 | 7591 | 36379 |
| | C-2obj | 76.2 | 10.6X | 2014 | 3508 | 16264 | 87808 | | C-2obj | 9.2 | 1.1X | 395 | 830 | 7591 | 34364 | | C-2obj | 11.6 | 1.5X | 398 | 911 | 7559 | 36261 |
| | D-2obj | 60.1 | 13.5X | 2014 | 3508 | 16264 | 87808 | | D-2obj | 11.9 | 0.9X | 395 | 830 | 7591 | 34364 | | D-2obj | 13.5 | 1.3X | 398 | 911 | 7559 | 36261 |
| | M-2obj | 35.7 | 22.7X | 2017 | 3511 | 16268 | 87838 | | M-2obj | 8.2 | 1.2X | 395 | 830 | 7591 | 34364 | | M-2obj | 8.9 | 1.9X | 398 | 911 | 7559 | 36261 |
| hsqldb | 2obj | 11.8 | - | 407 | 847 | 6981 | 34881 | jd | 2obj | 58.0 | - | 1592 | 2831 | 17000 | 82056 | JPC | 2obj | 65.3 | - | 1356 | 4237 | 15553 | 81294 |
| | ci | 4.4 | 2.7X | 922 | 1202 | 7386 | 41755 | | ci | 10.0 | 5.8X | 2714 | 3750 | 17878 | 95602 | | ci | 10.3 | 6.3X | 2252 | 4934 | 16138 | 94701 |
| | CSC | 5.0 | 2.3X | 657 | 1119 | 7331 | 38607 | | CSC | 11.8 | 4.9X | 2127 | 3278 | 17354 | 87467 | | CSC | 11.4 | 5.7X | 1790 | 4763 | 16034 | 87453 |
| | Z-2obj | 12.7 | 0.9X | 428 | 868 | 7015 | 35020 | | Z-2obj | 41.8 | 1.4X | 1686 | 2871 | 17045 | 82387 | | Z-2obj | 40.2 | 1.6X | 1382 | 4274 | 15582 | 81489 |
| | C-2obj | 9.4 | 1.3X | 407 | 847 | 6981 | 34881 | | C-2obj | 62.0 | 0.9X | 1592 | 2831 | 17000 | 82060 | | C-2obj | 56.8 | 1.2X | 1356 | 4238 | 15553 | 81307 |
| | D-2obj | 11.8 | 1.0X | 407 | 847 | 6981 | 34881 | | D-2obj | 52.3 | 1.1X | 1592 | 2832 | 17000 | 82061 | | D-2obj | 57.8 | 1.1X | 1356 | 4243 | 15554 | 81319 |
| | M-2obj | 8.6 | 1.4X | 407 | 847 | 6981 | 34881 | | M-2obj | 29.4 | 2.0X | 1597 | 2832 | 17000 | 82061 | | M-2obj | 31.2 | 2.1X | 1360 | 4243 | 15554 | 81321 |
| luindex | 2obj | 10.7 | - | 395 | 923 | 7019 | 33587 | lusearch | 2obj | 11.8 | - | 409 | 1119 | 7671 | 36464 | mindustry | 2obj | 9.3 | - | 378 | 778 | 6497 | 30844 |
| | ci | 3.9 | 2.7X | 920 | 1283 | 7409 | 39677 | | ci | 4.2 | 2.8X | 1032 | 1490 | 8094 | 43014 | | ci | 3.8 | 2.4X | 865 | 1136 | 6907 | 36808 |
| | CSC | 4.5 | 2.4X | 641 | 1201 | 7357 | 36882 | | CSC | 4.8 | 2.5X | 724 | 1411 | 8053 | 40001 | | CSC | 4.3 | 2.2X | 622 | 1051 | 6862 | 33970 |
| | Z-2obj | 12.1 | 0.9X | 417 | 944 | 7048 | 33718 | | Z-2obj | 13.7 | 0.9X | 434 | 1143 | 7700 | 36598 | | Z-2obj | 11.9 | 0.8X | 398 | 805 | 6540 | 30984 |
| | C-2obj | 8.8 | 1.2X | 395 | 923 | 7019 | 33588 | | C-2obj | 9.3 | 1.3X | 409 | 1119 | 7671 | 36464 | | C-2obj | 8.4 | 1.1X | 378 | 778 | 6497 | 30844 |
| | D-2obj | 11.1 | 1.0X | 395 | 923 | 7019 | 33588 | | D-2obj | 13.2 | 0.9X | 409 | 1119 | 7671 | 36464 | | D-2obj | 9.8 | 1.0X | 378 | 778 | 6497 | 30844 |
| | M-2obj | 7.9 | 1.4X | 395 | 923 | 7019 | 33588 | | M-2obj | 8.4 | 1.4X | 409 | 1119 | 7671 | 36464 | | M-2obj | 7.3 | 1.3X | 378 | 778 | 6497 | 30844 |
| open-telemetry | 2obj | 9.2 | - | 351 | 767 | 6303 | 29976 | pmd | 2obj | 32.5 | - | 1398 | 2354 | 11851 | 59910 | recaf | 2obj | 475.3 | - | 3247 | 5701 | 27823 | 142265 |
| | ci | 3.9 | 2.4X | 825 | 1117 | 6713 | 35944 | | ci | 6.5 | 5.0X | 2265 | 2950 | 12365 | 69505 | | ci | 20.4 | 23.3X | 5127 | 7402 | 29038 | 187415 |
| | CSC | 4.2 | 2.2X | 581 | 1035 | 6668 | 33157 | | CSC | 7.6 | 4.3X | 1748 | 2710 | 12273 | 64834 | | CSC | 34.0 | 14.0X | 4138 | 6702 | 28300 | 161535 |
| | Z-2obj | 10.8 | 0.9X | 365 | 789 | 6335 | 30086 | | Z-2obj | 31.8 | 1.0X | 1428 | 2375 | 11882 | 60047 | | Z-2obj | 261.6 | 1.8X | 3378 | 5732 | 27857 | 142450 |
| | C-2obj | 7.9 | 1.2X | 351 | 767 | 6303 | 29976 | | C-2obj | 33.2 | 1.0X | 1398 | 2354 | 11851 | 59910 | | C-2obj | 296.4 | 1.6X | 3249 | 5716 | 27823 | 142326 |
| | D-2obj | 9.9 | 0.9X | 351 | 767 | 6303 | 29976 | | D-2obj | 25.6 | 1.3X | 1398 | 2354 | 11851 | 59910 | | D-2obj | 268.5 | 1.8X | 3249 | 5722 | 27823 | 142332 |
| | M-2obj | 7.4 | 1.3X | 351 | 767 | 6303 | 29976 | | M-2obj | 16.8 | 1.9X | 1398 | 2354 | 11851 | 59910 | | M-2obj | 161.7 | 2.9X | 3257 | 5722 | 27826 | 142365 |
| sqlite-jdbc | 2obj | 8.7 | - | 351 | 768 | 6322 | 30094 | sunflow | 2obj | 35.7 | - | 1172 | 1965 | 13313 | 61168 | tesseract | 2obj | 11.7 | - | 399 | 843 | 7743 | 37267 |
| | ci | 3.8 | 2.3X | 826 | 1118 | 6732 | 36062 | | ci | 8.2 | 4.3X | 2146 | 2553 | 13981 | 72716 | | ci | 4.6 | 2.5X | 1013 | 1291 | 8313 | 45068 |
| | CSC | 4.4 | 2.0X | 581 | 1036 | 6687 | 33275 | | CSC | 9.0 | 4.0X | 1660 | 2359 | 13797 | 67237 | | CSC | 6.1 | 1.9X | 747 | 1216 | 8270 | 41968 |
| | Z-2obj | 11.5 | 0.8X | 365 | 790 | 6354 | 30204 | | Z-2obj | 27.2 | 1.3X | 1215 | 1988 | 13401 | 61537 | | Z-2obj | 13.8 | 0.8X | 421 | 867 | 7775 | 37383 |
| | C-2obj | 7.9 | 1.1X | 351 | 768 | 6322 | 30094 | | C-2obj | 32.1 | 1.1X | 1186 | 1994 | 13346 | 61442 | | C-2obj | 10.0 | 1.2X | 399 | 843 | 7743 | 37267 |
| | D-2obj | 9.8 | 0.9X | 351 | 768 | 6322 | 30094 | | D-2obj | 31.2 | 1.1X | 1172 | 1965 | 13314 | 61173 | | D-2obj | 12.3 | 1.0X | 399 | 843 | 7743 | 37267 |
| | M-2obj | 7.2 | 1.2X | 351 | 768 | 6322 | 30094 | | M-2obj | 19.1 | 1.9X | 1172 | 1965 | 13314 | 61173 | | M-2obj | 8.9 | 1.3X | 399 | 843 | 7743 | 37267 |
| tomcat | 2obj | 16.8 | - | 402 | 871 | 6978 | 33095 | trade-beans | 2obj | 26.7 | - | 466 | 967 | 8021 | 39111 | xalan | 2obj | 372.9 | - | 592 | 1643 | 9666 | 46782 |
| | ci | 4.0 | 4.1X | 931 | 1320 | 7388 | 39513 | | ci | 4.7 | 5.7X | 1095 | 1420 | 8652 | 47885 | | ci | 5.2 | 71.3X | 1298 | 2084 | 10092 | 54001 |
| | CSC | 4.6 | 3.6X | 665 | 1243 | 7340 | 37125 | | CSC | 5.5 | 4.9X | 786 | 1314 | 8546 | 44610 | | CSC | 6.0 | 61.6X | 884 | 1967 | 10034 | 50747 |
| | Z-2obj | 13.8 | 1.2X | 421 | 895 | 7022 | 33248 | | Z-2obj | 22.2 | 1.2X | 501 | 1017 | 8213 | 40042 | | Z-2obj | 194.5 | 1.9X | 609 | 1665 | 9697 | 46916 |
| | C-2obj | 10.0 | 1.7X | 402 | 871 | 6978 | 33095 | | C-2obj | 14.9 | 1.8X | 481 | 999 | 8065 | 39461 | | C-2obj | 218.4 | 1.7X | 592 | 1643 | 9666 | 46782 |
| | D-2obj | 11.3 | 1.5X | 402 | 871 | 6978 | 33095 | | D-2obj | 15.4 | 1.7X | 466 | 967 | 8021 | 39111 | | D-2obj | 27.7 | 13.5X | 592 | 1643 | 9666 | 46782 |
| | M-2obj | 8.2 | 2.1X | 402 | 871 | 6978 | 33095 | | M-2obj | 10.5 | 2.6X | 466 | 967 | 8021 | 39111 | | M-2obj | 14.3 | 26.0X | 592 | 1643 | 9666 | 46782 |

Table 6. Precision and Efficiency results of entire analysis (including all three stages) of Cut-Shortcut, Zipper, Conch, DebloaterX and Moon, whereas CI and 3OBJ are presented as baselines.

| Program | Analysis | T | S | #MFC | #PCS | #RM | #CE |
|---|---|---|---|---|---|---|---|
| antlr | 3obj | 526.2 | - | 450 | 1624 | 7805 | 51237 |
| | ci | 4.8 | 108.7X | 1124 | 1976 | 8190 | 57341 |
| | CSC | 5.7 | 92.0X | 812 | 1896 | 8153 | 54460 |
| | Z-3obj | 235.8 | 2.2X | 473 | 1643 | 7835 | 51364 |
| | C-3obj | 127.1 | 4.1X | 450 | 1624 | 7805 | 51237 |
| | D-3obj | 19.2 | 27.3X | 450 | 1627 | 7805 | 51240 |
| | M-3obj | 11.1 | 47.4X | 450 | 1626 | 7805 | 51239 |
| biojava | 3obj | 1053.9 | - | 347 | 837 | 7439 | 34756 |
| | ci | 4.5 | 232.7X | 1046 | 1236 | 7910 | 41678 |
| | CSC | 5.7 | 186.5X | 687 | 1150 | 7853 | 38403 |
| | Z-3obj | 211.7 | 5.0X | 369 | 870 | 7486 | 34901 |
| | C-3obj | 190.3 | 5.5X | 347 | 837 | 7439 | 34756 |
| | D-3obj | 15.3 | 69.0X | 347 | 839 | 7439 | 34758 |
| | M-3obj | 9.2 | 114.8X | 347 | 838 | 7439 | 34757 |
| chart | 3obj | OOM | - | - | - | - | - |
| | ci | 9.2 | >587.6X | 2560 | 2703 | 15923 | 86433 |
| | CSC | 10.4 | >519.7X | 1914 | 2405 | 15545 | 78847 |
| | Z-3obj | 428.9 | >12.6X | 1280 | 2021 | 15204 | 72544 |
| | C-3obj | OOT | - | - | - | - | - |
| | D-3obj | 183.8 | >29.4X | 1230 | 2005 | 15119 | 72228 |
| | M-3obj | 52.8 | >102.2X | 1230 | 2004 | 15119 | 72227 |
| dcevm | 3obj | OOM | - | - | - | - | - |
| | ci | 13.5 | >399.4X | 3593 | 5669 | 21503 | 124314 |
| | CSC | 15.2 | >355.0X | 2917 | 4932 | 20958 | 108001 |
| | Z-3obj | OOM | - | - | - | - | - |
| | C-3obj | OOT | - | - | - | - | - |
| | D-3obj | 1125.9 | >4.8X | 2131 | 4396 | 20493 | 100083 |
| | M-3obj | 504.9 | >10.7X | 2131 | 4396 | 20493 | 100084 |
| findbugs | 3obj | OOM | - | - | - | - | - |
| | ci | 9.7 | >557.3X | 3448 | 4435 | 16774 | 105576 |
| | CSC | 11.6 | >465.9X | 2766 | 4212 | 16705 | 96294 |
| | Z-3obj | OOT | - | - | - | - | - |
| | C-3obj | 524.3 | >10.3X | 1632 | 3477 | 16217 | 86892 |
| | D-3obj | 64.4 | >83.9X | 1652 | 3478 | 16217 | 86899 |
| | M-3obj | 37.4 | >144.3X | 1652 | 3478 | 16219 | 86915 |
| hsqldb | 3obj | 588.8 | - | 355 | 840 | 6980 | 34854 |
| | ci | 4.4 | 134.7X | 922 | 1202 | 7386 | 41755 |
| | CSC | 5.0 | 116.8X | 657 | 1119 | 7331 | 38607 |
| | Z-3obj | 168.2 | 3.5X | 382 | 861 | 7014 | 34993 |
| | C-3obj | 161.6 | 3.6X | 355 | 840 | 6980 | 34854 |
| | D-3obj | 13.9 | 42.5X | 355 | 843 | 6980 | 34857 |
| | M-3obj | 8.9 | 65.8X | 355 | 842 | 6980 | 34856 |
| luindex | 3obj | 376.2 | - | 341 | 916 | 7018 | 33560 |
| | ci | 3.9 | 96.5X | 920 | 1283 | 7409 | 39677 |
| | CSC | 4.5 | 82.9X | 641 | 1201 | 7357 | 36882 |
| | Z-3obj | 138.8 | 2.7X | 364 | 937 | 7047 | 33691 |
| | C-3obj | 124.5 | 3.0X | 341 | 916 | 7018 | 33561 |
| | D-3obj | 13.8 | 27.3X | 341 | 919 | 7018 | 33564 |
| | M-3obj | 8.3 | 45.3X | 341 | 918 | 7018 | 33563 |
| open-telemetry | 3obj | 325.3 | - | 296 | 760 | 6303 | 29955 |
| | ci | 3.9 | 83.2X | 825 | 1117 | 6713 | 35944 |
| | CSC | 4.2 | 77.5X | 581 | 1035 | 6668 | 33157 |
| | Z-3obj | 104.9 | 3.1X | 318 | 783 | 6335 | 30066 |
| | C-3obj | 108.6 | 3.0X | 296 | 760 | 6303 | 29955 |
| | D-3obj | 11.5 | 28.3X | 296 | 762 | 6303 | 29957 |
| | M-3obj | 7.7 | 42.4X | 296 | 762 | 6303 | 29957 |
| sqlite-jdbc | 3obj | 310.9 | - | 296 | 761 | 6322 | 30073 |
| | ci | 3.8 | 81.0X | 826 | 1118 | 6732 | 36062 |
| | CSC | 4.4 | 70.3X | 581 | 1036 | 6687 | 33275 |
| | Z-3obj | 102.4 | 3.0X | 318 | 784 | 6354 | 30184 |
| | C-3obj | 106.2 | 2.9X | 296 | 761 | 6322 | 30073 |
| | D-3obj | 11.2 | 27.7X | 296 | 763 | 6322 | 30075 |
| | M-3obj | 7.5 | 41.2X | 296 | 763 | 6322 | 30075 |
| tomcat | 3obj | 687.6 | - | 345 | 866 | 6977 | 33068 |
| | ci | 4.0 | 169.8X | 931 | 1320 | 7388 | 39513 |
| | CSC | 4.6 | 149.1X | 665 | 1243 | 7340 | 37125 |
| | Z-3obj | 167.6 | 4.1X | 374 | 891 | 7022 | 33226 |
| | C-3obj | 143.0 | 4.8X | 345 | 866 | 6977 | 33068 |
| | D-3obj | 13.1 | 52.6X | 345 | 868 | 6977 | 33070 |
| | M-3obj | 8.8 | 78.1X | 345 | 868 | 6977 | 33070 |

| Program | Analysis | T | S | #MFC | #PCS | #RM | #CE |
|---|---|---|---|---|---|---|---|
| avrora | 3obj | 2592.0 | - | 496 | 929 | 10939 | 48330 |
| | ci | 5.5 | 470.4X | 1188 | 1372 | 11373 | 55476 |
| | CSC | 6.3 | 409.5X | 882 | 1283 | 11282 | 52535 |
| | Z-3obj | 890.2 | 2.9X | 536 | 944 | 10969 | 48439 |
| | C-3obj | 587.3 | 4.4X | 496 | 929 | 10939 | 48330 |
| | D-3obj | 22.0 | 117.9X | 496 | 931 | 10939 | 48332 |
| | M-3obj | 13.0 | 199.2X | 496 | 930 | 10939 | 48336 |
| bloat | 3obj | OOT | - | - | - | - | - |
| | ci | 5.5 | >987.2X | 2082 | 2249 | 9454 | 67338 |
| | CSC | 7.6 | >710.5X | 1594 | 2166 | 9414 | 63909 |
| | Z-3obj | 4784.5 | >1.1X | 1215 | 1583 | 9045 | 56555 |
| | C-3obj | 1458.7 | >3.7X | 1188 | 1552 | 9003 | 56348 |
| | D-3obj | 34.6 | >156.3X | 1188 | 1555 | 9003 | 56351 |
| | M-3obj | 20.4 | >264.3X | 1188 | 1554 | 9003 | 56350 |
| check-style | 3obj | OOM | - | - | - | - | - |
| | ci | 8.2 | >657.7X | 1939 | 2760 | 12766 | 80169 |
| | CSC | 10.3 | >521.7X | 1503 | 2641 | 12713 | 74197 |
| | Z-3obj | OOT | - | - | - | - | - |
| | C-3obj | OOT | - | - | - | - | - |
| | D-3obj | 50.1 | >107.9X | 996 | 2172 | 12260 | 66188 |
| | M-3obj | 27.9 | >193.3X | 1000 | 2171 | 12260 | 66188 |
| ddjava | 3obj | 398.8 | - | 312 | 810 | 6840 | 32226 |
| | ci | 4.1 | 98.0X | 880 | 1177 | 7249 | 38462 |
| | CSC | 4.8 | 83.4X | 618 | 1093 | 7205 | 35797 |
| | Z-3obj | 126.2 | 3.2X | 336 | 823 | 6855 | 32290 |
| | C-3obj | 119.2 | 3.3X | 312 | 810 | 6840 | 32226 |
| | D-3obj | 13.3 | 30.1X | 312 | 812 | 6840 | 32228 |
| | M-3obj | 8.5 | 46.9X | 312 | 812 | 6840 | 32229 |
| fop | 3obj | 363.4 | - | 336 | 824 | 7591 | 34344 |
| | ci | 4.0 | 91.1X | 911 | 1210 | 7997 | 40423 |
| | CSC | 4.5 | 80.0X | 653 | 1121 | 7944 | 37562 |
| | Z-3obj | 120.3 | 3.0X | 370 | 846 | 7621 | 34476 |
| | C-3obj | 108.1 | 3.4X | 336 | 824 | 7591 | 34344 |
| | D-3obj | 13.0 | 27.9X | 336 | 826 | 7591 | 34346 |
| | M-3obj | 8.4 | 43.2X | 336 | 825 | 7591 | 34345 |
| jd | 3obj | OOM | - | - | - | - | - |
| | ci | 10.0 | >538.4X | 2714 | 3750 | 17878 | 95602 |
| | CSC | 11.8 | >459.2X | 2127 | 3278 | 17354 | 87467 |
| | Z-3obj | 265.0 | >20.4X | 1600 | 2818 | 16979 | 81855 |
| | C-3obj | 281.9 | >19.2X | 1491 | 2751 | 16875 | 81318 |
| | D-3obj | 99.9 | >54.1X | 1491 | 2754 | 16875 | 81326 |
| | M-3obj | 39.7 | >136.2X | 1491 | 2754 | 16875 | 81327 |
| lusearch | 3obj | 582.3 | - | 357 | 1112 | 7670 | 36437 |
| | ci | 4.2 | 139.6X | 1032 | 1490 | 8094 | 43014 |
| | CSC | 4.8 | 121.6X | 724 | 1411 | 8053 | 40001 |
| | Z-3obj | 180.8 | 3.2X | 382 | 1136 | 7699 | 36571 |
| | C-3obj | 151.3 | 3.8X | 357 | 1112 | 7670 | 36437 |
| | D-3obj | 14.5 | 40.2X | 357 | 1115 | 7670 | 36440 |
| | M-3obj | 9.6 | 61.0X | 357 | 1114 | 7670 | 36439 |
| pmd | 3obj | 872.1 | - | 1333 | 2348 | 11851 | 59851 |
| | ci | 6.5 | 133.3X | 2265 | 2950 | 12365 | 69505 |
| | CSC | 7.6 | 114.3X | 1748 | 2710 | 12273 | 64834 |
| | Z-3obj | 287.6 | 3.0X | 1374 | 2369 | 11882 | 59988 |
| | C-3obj | 170.7 | 5.1X | 1333 | 2348 | 11851 | 59851 |
| | D-3obj | 27.8 | 31.3X | 1333 | 2350 | 11851 | 59853 |
| | M-3obj | 19.5 | 44.6X | 1333 | 2349 | 11851 | 59852 |
| sunflow | 3obj | OOM | - | - | - | - | - |
| | ci | 8.2 | >654.5X | 2146 | 2553 | 13981 | 72716 |
| | CSC | 9.0 | >600.7X | 1660 | 2359 | 13797 | 67237 |
| | Z-3obj | 779.3 | >6.9X | 1116 | 1976 | 13382 | 61274 |
| | C-3obj | 606.2 | >8.9X | 1083 | 1976 | 13325 | 61154 |
| | D-3obj | 53.2 | >101.4X | 1071 | 1955 | 13294 | 60907 |
| | M-3obj | 20.3 | >266.5X | 1071 | 1954 | 13294 | 60919 |
| trade-beans | 3obj | 4379.4 | - | 401 | 962 | 7989 | 38931 |
| | ci | 4.7 | 927.8X | 1095 | 1420 | 8652 | 47885 |
| | CSC | 5.5 | 799.2X | 786 | 1314 | 8546 | 44610 |
| | Z-3obj | 1685.7 | 2.6X | 448 | 1015 | 8209 | 39991 |
| | C-3obj | 1152.1 | 3.8X | 417 | 991 | 8040 | 39276 |
| | D-3obj | 18.1 | 241.6X | 401 | 964 | 7989 | 38933 |
| | M-3obj | 11.3 | 387.9X | 401 | 963 | 7991 | 38941 |

| Program | Analysis | T | S | #MFC | #PCS | #RM | #CE |
|---|---|---|---|---|---|---|---|
| batik | 3obj | OOM | - | - | - | - | - |
| | ci | 13.3 | >406.3X | 3403 | 5810 | 20994 | 127604 |
| | CSC | 18.6 | >290.2X | 2846 | 5524 | 20819 | 121105 |
| | Z-3obj | OOT | - | - | - | - | - |
| | C-3obj | OOM | - | - | - | - | - |
| | D-3obj | OOM | - | - | - | - | - |
| | M-3obj | 777.5 | >6.9X | 2044 | 4930 | 20243 | 106779 |
| bytecode-viewer | 3obj | OOT | - | - | - | - | - |
| | ci | 9.4 | >571.4X | 4723 | 5616 | 14637 | 110795 |
| | CSC | 21.7 | >249.0X | 4366 | 5547 | 14601 | 106506 |
| | Z-3obj | OOT | - | - | - | - | - |
| | C-3obj | OOT | - | - | - | - | - |
| | D-3obj | OOT | - | - | - | - | - |
| | M-3obj | 1858.6 | >2.9X | 3661 | 4195 | 14042 | 94460 |
| classy-shark | 3obj | 3020.7 | - | 484 | 1106 | 9384 | 44166 |
| | ci | 5.3 | 566.7X | 1323 | 1682 | 10178 | 56231 |
| | CSC | 7.1 | 425.4X | 876 | 1400 | 9489 | 48577 |
| | Z-3obj | 1407.2 | 2.1X | 512 | 1113 | 9407 | 44251 |
| | C-3obj | 1058.6 | 2.9X | 484 | 1106 | 9384 | 44166 |
| | D-3obj | 21.9 | 137.9X | 484 | 1108 | 9384 | 44168 |
| | M-3obj | 13.3 | 226.9X | 484 | 1107 | 9386 | 44176 |
| eclipse | 3obj | OOM | - | - | - | - | - |
| | ci | 18.8 | >287.7X | 5090 | 10672 | 23386 | 182975 |
| | CSC | 20.7 | >261.4X | 4282 | 10250 | 22977 | 172521 |
| | Z-3obj | OOT | - | - | - | - | - |
| | C-3obj | OOM | - | - | - | - | - |
| | D-3obj | OOM | - | - | - | - | - |
| | M-3obj | 3739.3 | >1.4X | 3484 | 9661 | 22572 | 161716 |
| h2 | 3obj | 1942.4 | - | 336 | 907 | 7557 | 36232 |
| | ci | 4.6 | 423.2X | 943 | 1274 | 7959 | 42799 |
| | CSC | 5.2 | 376.4X | 687 | 1194 | 7914 | 40294 |
| | Z-3obj | 650.3 | 3.0X | 373 | 925 | 7590 | 36354 |
| | C-3obj | 427.4 | 4.5X | 336 | 907 | 7557 | 36232 |
| | D-3obj | 17.0 | 114.5X | 336 | 909 | 7558 | 36237 |
| | M-3obj | 10.0 | 193.9X | 336 | 908 | 7558 | 36236 |
| JPC | 3obj | 1438.2 | - | 1204 | 4101 | 15206 | 79620 |
| | ci | 10.3 | 139.5X | 2252 | 4934 | 16138 | 94701 |
| | CSC | 11.4 | 125.9X | 1790 | 4763 | 16034 | 87453 |
| | Z-3obj | 194.6 | 7.4X | 1234 | 4139 | 15233 | 79803 |
| | C-3obj | 168.0 | 8.6X | 1204 | 4102 | 15206 | 79633 |
| | D-3obj | 67.9 | 21.2X | 1204 | 4105 | 15207 | 79641 |
| | M-3obj | 25.4 | 56.7X | 1204 | 4119 | 15209 | 79684 |
| mindustry | 3obj | 325.0 | - | 321 | 771 | 6495 | 30815 |
| | ci | 3.8 | 85.1X | 865 | 1136 | 6907 | 36808 |
| | CSC | 4.3 | 75.2X | 622 | 1051 | 6862 | 33970 |
| | Z-3obj | 111.3 | 2.9X | 352 | 799 | 6540 | 30962 |
| | C-3obj | 109.1 | 3.0X | 321 | 771 | 6495 | 30815 |
| | D-3obj | 11.5 | 28.2X | 321 | 773 | 6495 | 30817 |
| | M-3obj | 7.7 | 42.4X | 321 | 773 | 6495 | 30817 |
| recaf | 3obj | OOM | - | - | - | - | - |
| | ci | 20.4 | >265.1X | 5127 | 7402 | 29038 | 187415 |
| | CSC | 34.0 | >158.6X | 4138 | 6702 | 28300 | 161535 |
| | Z-3obj | OOM | - | - | - | - | - |
| | C-3obj | OOM | - | - | - | - | - |
| | D-3obj | 1172.3 | >4.6X | 3037 | 5651 | 27467 | 140236 |
| | M-3obj | 498.0 | >10.8X | 3038 | 5646 | 27468 | 140249 |
| tesseract | 3obj | 733.4 | - | 341 | 836 | 7743 | 37221 |
| | ci | 4.6 | 159.1X | 1013 | 1291 | 8313 | 45068 |
| | CSC | 6.1 | 120.0X | 747 | 1216 | 8270 | 41968 |
| | Z-3obj | 198.5 | 3.7X | 372 | 861 | 7775 | 37339 |
| | C-3obj | 185.6 | 4.0X | 341 | 836 | 7743 | 37221 |
| | D-3obj | 14.1 | 52.1X | 341 | 838 | 7743 | 37223 |
| | M-3obj | 9.4 | 77.8X | 341 | 838 | 7743 | 37223 |
| xalan | 3obj | OOM | - | - | - | - | - |
| | ci | 5.2 | >1032.5X | 1298 | 2084 | 10092 | 54001 |
| | CSC | 6.0 | >892.6X | 884 | 1967 | 10034 | 50747 |
| | Z-3obj | 1545.4 | >3.5X | 561 | 1658 | 9696 | 46887 |
| | C-3obj | 464.5 | >11.6X | 539 | 1636 | 9665 | 46753 |
| | D-3obj | 31.7 | >170.2X | 539 | 1639 | 9665 | 46756 |
| | M-3obj | 15.7 | >343.5X | 539 | 1638 | 9665 | 46755 |