Merging Equivalent Contexts for Scalable Heap-Cloning-Based Context-Sensitive Points-to Analysis∗

Guoqing Xu
Computer Science and Engineering
Ohio State University
xug@cse.ohio-state.edu

Atanas Rountev
Computer Science and Engineering
Ohio State University
rountev@cse.ohio-state.edu

Abstract

A context-sensitive points-to analysis maintains separate points-to relationships for each possible (abstract) calling context of a method. Previous work has shown that a large number of equivalence classes exists in the representation of calling contexts. Such equivalent contexts provide opportunities for context-sensitive analyses based on binary decision diagrams (BDDs), in which BDDs automatically merge equivalent points-to relationships. However, the use of a BDD “black box” introduces additional overhead for analysis running time. Furthermore, with heap cloning (i.e., using context-sensitive object allocation sites), BDDs are not as effective because the number of equivalence classes increases significantly. A further step must be taken to look inside the BDD black box to investigate where the equivalence comes from, and what tradeoffs can be employed to enable practical large-scale heap cloning.

This paper presents an analysis for Java that exploits equivalence classes in context representation. For a particular pointer variable or heap object, all abstract contexts within an equivalence class can be merged. This technique naturally results in a new non-BDD context-sensitive points-to analysis. Based on these equivalence classes, the analysis employs a last-k-substring merging approach to define scalability and precision tradeoffs. We show that small values for k can enable scalable heap cloning for large Java programs. The proposed analysis has been implemented and evaluated on a large set of Java programs. The experimental results show improvements over an existing 1-object-sensitive analysis with heap cloning, which is the most precise scalable analysis implemented in the state-of-the-art Paddle analysis framework. For computing a points-to solution for an entire program, our approach is an order of magnitude faster compared to this BDD-based analysis and to a related non-BDD refinement-based analysis.

Categories and Subject Descriptors

F.3.2 [Logics and Meaning of Programs]: Semantics of Programming Languages—Program Analysis

General Terms

Algorithms, measurement, experimentation

Keywords

Pointer analysis, points-to analysis, context sensitivity

1. INTRODUCTION

Context sensitivity in points-to analyses has been studied extensively; some of this work is summarized in [11, 8, 28]. Most such analyses compute a complete points-to solution for all variables in a program. Such algorithms usually have to sacrifice analysis precision for practical scalability. An alternative is a refinement-based approach that performs points-to analysis by answering pointer-related queries raised by a compiler or a client analysis on demand [32, 31]. The precision of this approach can be proportional to the resource constraints (such as time and memory) allowed to answer queries. The analysis can be more precise than those that compute a complete points-to solution, if its full precision is reached (i.e., the result is fully refined). However, this algorithm may not scale when computing solutions for a large number of variables [30], and therefore is not suitable for analyses that depend on points-to information for the entire program. In this paper we focus on analyses that compute complete points-to information, and propose an algorithm whose precision approaches that of the refinement-based algorithm, and that scales well to large Java programs.

In context-sensitive analyses a standard approach is to use a calling context abstraction that is a string of the call graph edges leading to the analyzed method. The length of each string is usually limited to a fixed number k. A different technique, used in [34, 36], does not limit the length of a context string, but excludes all contexts corresponding to call edges that are in a cycle in a precomputed call graph. Orthogonal to the context abstraction is the decision as to where to apply context sensitivity. All existing analyses use context-sensitive treatment of local variables, and some algorithms also do this for heap objects. Context-sensitive modeling of objects is sometimes also referred to as heap cloning [26]. Higher precision requires a longer context string, with enabled heap cloning. Of these two factors, heap cloning has been shown [20, 15] to be more important, because it allows analyses to distinguish different instances of a logical data structure. The importance of heap cloning can especially be seen in object-oriented programs [15].

To achieve scalability, binary decision diagrams (BDDs) have been employed [19, 34, 36, 3, 16] to avoid redundant representation of similar points-to relationships. A BDD provides an effective representation for context-sensitive analysis because many contexts are equivalent, in the sense that the points-to relationships computed under these contexts are the same [20]. A BDD automatically merges the representation of equivalent points-to relationships.
is possible to achieve scalable heap cloning. The analysis was evaluated for callstrings. By selecting small values for \( c \) such that for Java that can compute an whole-program solution in a scalable manner. Currently is the most precise publicly available points-to analysis based on object-sensitive analysis with heap cloning [16], which reduces memory usage and improves scalability.

Our proposal. The focus in this paper is a cloning-based context-sensitive analysis with arbitrary callstring length as the representation of contexts. We first present a characterization of equivalence classes of contexts for pointer variables and pointer targets. This can be captured by an abstraction function that takes as input a full context string \( c_p \) for a pointer variable \( p \) and a full context \( c_o \) for a pointer target \( o \), and produces a pair of context substrings \( (sub_1, sub_2) \) that defines an equivalence class. All pairs \( (c_p, c_o) \) such that \( c_p \) maps to \( sub_2 \) and \( c_o \) maps to \( sub_2 \) belong to the corresponding equivalence class. The points-to relationships under the contexts within an equivalence class are guaranteed to be the same, and all these contexts can be merged without loss of precision.

Based on this characterization, we propose a new flow-insensitive context-sensitive points-to analysis for Java. First, an intraprocedural phase builds a symbolic points-to graph for each method, using symbolic objects as placeholders for the objects that are not visible in the method. Next, an interprocedural phase performs bottom-up traversal of the call graph, cloning pointer variables and objects from callees to callers, computing points-to graphs, and making the call graph context-sensitive. The analysis takes advantage of equivalence classes: cloning of variables and objects is performed only for chosen context substrings. Since an additional top-down phase is not needed, the symbolic points-to graphs of callees can immediately be discarded when cloning is completed, which reduces memory usage and improves scalability.

Tailored for this analysis, a tradeoff technique is defined: last-\( k \)-substring merging for callstrings. By selecting small values for \( k \), it is possible to achieve scalable heap cloning. The analysis was evaluated using 19 programs. The experimental results show that even when \( k = 1 \), the results are more precise than an existing BDD-based 1-object-sensitive analysis with heap cloning [16], which currently is the most precise publicly available points-to analysis for Java that can compute an whole-program solution in a scalable manner. For computing a solution for an entire program, our approach is an order of magnitude faster compared to this analysis and to the refinement-based analysis discussed above.

2. EQUIVALENT CALLING CONTEXTS

Figure 1 shows an example adapted from [31], together with the corresponding call graph. The calling context abstraction is a string of call graph edge labels from main down to a certain method.

The term “equivalent context” was defined in [20] in terms of method-context pairs. Two such pairs \( (m_1, c_1) \) and \( (m_2, c_2) \) are equivalent if \( m_1 = m_2 \) and for every local pointer variable \( p \) in the method, the points-to set of \( p \) is the same under both contexts \( c_1 \) and \( c_2 \). In our running example, the method-context pairs \( (insert, ac) \) and \( (insert, bfc) \) are equivalent (the contexts use the edge labels from Figure 1) because the only AddrBook object on which \( insert \) is invoked is allocated in \( addName \), and this object does not affect and is not affected by the callers of \( addName \).

This definition is coarse-grained as it requires all pointer variables in a method to have the same equivalence classes. However, the equivalent contexts for different variables in a method can differ. Consider the constructor of Vector in the example. We denote a context-insensitive heap object abstraction by \( o_i \), where \( i \) is the line number for the allocation site. Similarly, a context-insensitive pointer variable abstraction is denoted by \( p_j \), where \( p \) is the name of the variable, and \( i \) is the line number where \( p \) is first used/defined. Using this notation, pointer variable \( t_3 \) can be decided to point to object \( o_2 \) within the constructor. Since no callers of the constructor can affect the points-to pair \( (t_3, o_3) \), all contexts for \( t_3 \) are equivalent (i.e., there is only one equivalence class of contexts for this variable). However, variable \( this_i \) points to objects outside the constructor and its points-to pair are affected by the callers of the constructor (e.g., the points-to sets for \( this \) in contexts containing call graph edge \( i \) and ones containing edge \( j \) are different). In general, the set of equivalence classes for a method \( m \) as defined in [20] treats uniformly all variables in \( m \), which may lead to unnecessary equivalence classes for some variables. Our goal is to provide a finer-grained definition of equivalent contexts in terms of pointer variables and heap objects, in order to exploit greater similarity (i.e., fewer equivalence classes for some variables).

Equivalence classes for recursion-free programs. Consider a context-insensitive points-to relationship of the form \( (p, o) \) where \( p \) is a pointer variable and \( o \) is an object allocation site. A context-sensitive points-to relationship in a heap-cloning analysis is a 4-tuple \( (p, c_p, o, c_o) \), where \( c_p \) is a full context (callstring) that goes from \( main \) to the method \( m \) that defines \( p, c_o \) is a full context that goes from \( main \) to the method \( m \), that contains \( o \), and \( p \) under context \( c_p \) may point to the objects created at \( o \) under context \( c_o \).

To characterize the equivalence of calling contexts, we outline two hypothetical analyses. These analyses are conceptual constructs, not our actual algorithm. The first analysis performs bottom-up traversal and method inlining. Each inlining step creates a copy of the callee’s body (this body itself has already been modified by earlier inlining steps) inside the caller, with the appropriate variable renaming, assignments for parameter passing, etc. The renaming attaches a context string to each pointer variable \( p \) and allocation site \( o \). For example, if the callee method \( m \) contains an assignment \( p := q \) where \( p \) and \( q \) are local variables, and the call graph contains an edge \( e \) from \( n \) to \( m \), this statement would be inlined in \( n \) as \( p(e) := q(e) \). If some method \( k \) calls \( n \) along a call graph edge \( f \), then the inlining step for \( f \) would create a statement \( p(f,e) := q(f,e) \) in \( k \), where \( (f,e) \) is a partial callstring. Eventually all methods are inlined in \( main \), all callstrings are complete, the original statement has been transformed to \( p(e_0,...,e_n) := q(e_0,...,e_n) \) where the source of \( e_0 \) is \( main \), and intraprocedural points-to analysis is applied to the body of \( main \).

The second hypothetical analysis is a variation of the first one. After a method \( n \) is processed to inline all its call sites, intraprocedural points-to analysis is applied to the new body. This analysis of \( n \) produces tuples \( (p, c_p, o, c_o) \) where \( c_p \) and \( c_o \) start with call graph edges whose source is \( n \). Suppose \( e \) is one of the edges from \( n \) to some callee \( m \). It is easy to see that for any \( (p, c_p, o, c_o) \) that was computed in the earlier analysis of \( m \) (here \( c_o \) and \( c_o \) start with edges whose source is \( m \), a corresponding \( (p, c_p, o, c_o) \) must exist in \( n \)'s solution; here \( c_p = (e) \circ c_p' \) and \( c_o = (e) \circ c_o' \) where \( \circ \) lists concatenation. This is because all statements in \( m \)'s body whose cumulative effects allowed the creation of \( (p, c_p, o, c_o) \) are also present in the body of \( n \), except that all pointer variables and allocation sites are tagged with updated contexts starting with \( e \).
However, not all tuples for $n$ have this property: for example, if the call site in the original body of $f$ is $p : = n$() and $m$ creates and returns a new object $o$, the solution for $n$ after inlining will contain $(p, e, o, (e))$, where $e$ is the empty context; for this tuple, there is no corresponding tuple in any callees of $n$. Furthermore, if originally $n$ also contains a call $p.m()$ for call graph edge $e$, after inlining we will have $\text{this}(e) : = p^*$ to represent parameter passing, and $(\text{this}, (e), o, (e))$ will be computed for $n$. Again, for this tuple there is no corresponding tuple in any callees of $n$.

The lifetime of a tuple consists of a single creation event in some method, followed by a sequence of inlining steps that increase both calling contexts in synch, until full contexts starting at $main$ are reached. For any $(p, e, o, (e))$ in the solution for $main$ (i.e., in the final points-to solution), the method in which the initial creation event happened will be referred to as the flow point (FP) for this tuple. This is the first method in which $o$ can flow to $p$; here “flow” is defined by the underlying intra-procedural analysis. The FP is unique and belongs to a common prefix of $o_p$ and $c_o$. If the common prefix ending at the FP were replaced with any chain from $main$ to the FP, the points-to relationship would still hold.

For example, in Figure 1 the FP for $(t_3, bi, o_3, bi)$, where $o_3$ is the object created at line 3, is the constructor of $Vector$. This is also the FP for $(t_3, aj, o_3, aj)$ and for $(t_3, bfej, o_3, bfej)$. In this case contexts $bi$, aj, and bfej are equivalent. The FP for $(p_{11}, adl, o_{34}, a)$, where $o_{34}$ is the string constant "Tom" at line 34, is $\text{addName}$; if all callees of $\text{addName}$ are transitively inline into it among chain $dl$, $o_{34}$ will flow to $p_{11}$ through a sequence of assignments within $\text{addName}$. Furthermore, this flow is independent of the callees of $\text{addName}$.

A key observation is that once a tuple in created for the first time in its FP, it will exist in all transitive callers of the FP (where it will be associated with longer context strings). For any contexts $c_p$ and $c_o$, the part that really contributes to $(p, c_p, o, c_o)$ are the suffixes starting at the call edges that leave the FP. This naturally leads to the definition of equivalence classes for contexts, based on the following abstraction functions $f_p$ and $f_o$:

\[
\begin{align*}
& f_p((p, (e_0, \ldots, e_{FP}, \ldots, e_p), o, c_o)) = (e_{FP}, \ldots, e_p) \\
& f_o((p, c_p, o, (e_0, \ldots, e_{FP}, \ldots, e_o)) = (e_{FP}, \ldots, e_o)
\end{align*}
\]

where the source of $e_{FP}$ and $c_{FP}$ is the FP and the source of $e_o$ is $main$. The suffix for $p$ or $o$ will be referred to as a unique replacement context (URC) for all contexts that map to it, with respect to the tuple. For example, the URCS for both $t_3$ and $o_3$ with respect to $(t_3, c, o_3, c)$, where $c$ is any chain from $main$ to $Vector<init>$, are an empty string $\epsilon$. The URCs for $p_{11}$ and $o_{34}$ with respect to $(p_{11}, adl, o_{34}, a)$ are $dl$ and $e$.

For each $(p, c_p, o, c_o)$ in the final analysis solution, one can conceptually replace the contexts with their URCS. Each distinct UR pair $(f_p(c_p), f_o(c_o))$ defines a context equivalence class for both pointer variables and pointer targets, and characterizes equivalent contexts under which the points-to relationship holds. A context-sensitive analysis only needs to explicitly represent points-to relationships with URCS. To answer a query “which objects may $p$ point to under context $e$”, one can inspect the set of URCS computed by $f_p$, compute a subset $U_p$ containing URCs that $c$ maps to, and return the union of object-context pairs $(o, c_o)$ such that $(p, c_p, o, c_o) \in U_p$. The set of distinct UR pairs can be much smaller than the set of all pairs of full contexts.

This definition of equivalence classes provides some insights into why a BDD implementation may be less effective in scaling an analysis with heap cloning than a non-heap-cloning analysis. Without heap cloning, an element of the solution is a 3-tuple and an equivalence class is defined by a single string $wrc_E$ rather than by a pair $(wrc_p, wrc_o)$. Thus, the number of equivalence classes is reduced significantly, and the number of times a pointer variable needs to be cloned is also greatly reduced. All these reductions lead to higher levels of similarity for a BDD to exploit.

**Equivalence classes in the presence of recursion.** In the presence of recursion we first consider a mapping of the infinite set of call chains to a finite set of repetition-free chains. TRIMCHAIN shown in Figure 2 provides an operational definition of this mapping. Given a call chain $(e_1, \ldots, e_j)$ in which a method could be repeated, the function scans the chain in reverse order, removes all substrings whose start point and end point are the same method, and returns a new string that is repetition-free. Note that this description is conceptual: the functionality defined by TRIMCHAIN could be implemented implicitly in an analysis algorithm.

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**Figure 1:** Running example: code and call graph.
similarly to how this was done for the recursion-free case. For a
solution we can define equivalence classes based on flowing points,
a flow graph: allocation site nodes

... means graph (PAG) in Spark [18]. There are three types of nodes in
S
variable nodes
extension of a standard points-to graph, with three types of nodes:
reference edge is (o
p
q
r
s
t
u
v
w
x
y
z
A variable points-to edge is (p
SO
Symbolic points-to graph. Based on the flow graph of a method,
we construct a symbolic points-to graph. A SPG for a method is an
extension of a standard points-to graph, with three types of nodes:
variable nodes V
, allocation nodes O
, and symbolic object nodes S
. A variable points-to edge is (v
for local variables and formal parameters) and field dereference nodes
∈ F
(nodes of the form v.fld, where v ∈ V)
. Edges in the graph
represent the flow of values: e.g., an assignment p := q where
p, q ∈ V
is represented by a flow graph edge e → p
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p, q ∈ V
is represented by a flow graph edge e → p
.

Figure 2: TrimChain for handling of recursion.

The hypothetical inlining analyses described earlier can be modi-
ified as follows. First, whenever a statement is inline from a callee
to a caller, the function from above is applied to ensure repetition-
free contexts. For example, if the callee has a statement p := q
where p and q are variables and e and d are contexts, inlining along
a call graph edge e will generate in the caller’s body a statement
p' := q' where e' = TrimChain(e) and d' is defined similarly.
Second, the inlining process will iterate through a SCC a suf-
ficient number of times to reach a fixed point for the set of unique
statements in the body of each (inlining-modified) SCC method.
There is a well-defined upper bound on the number of such iter-
ation steps [29]. After everything is inline in main
, intraprocedural
analysis computes a solution containing tuples
(p, c
, o
, c
)
in which c
and o
are repetition-free callstrings starting at main.
For this so-
lution we can define equivalence classes based on flowing points,
similarly to how this was done for the recursion-free case. For a
tuple (p
, c
, o
, c
)from the final solution, the FP is determined by
the earliest time when an “ancestor” tuple was created. This FP
defines the suffixes of c
and o
that are used as URCs.

3. POINTS-TO ANALYSIS

The approach from the previous section could potentially be ap-
plicated to different existing or future points-to analyses. In this sec-
tion we describe a new points-to analysis for Java that is based on
this idea. The analysis is flow-insensitive and context-sensitive,
with callstring contexts and heap cloning. Intraprocedurally the
value flow propagation is subset-based, and interprocedural prop-
gagation uses a combination of subset-based and unification-based
techniques. Our experiments indicate that this analysis is more
precise and more efficient than a subset-based 1-object-sensitive
analysis with heap cloning implemented with BDDs [16].

3.1 Intraprocedural Analysis

Flow graph. The intraprocedural phase first builds a flow graph
representing pointer assignments, similarly to the pointer assign-
ment graph (PAG) in Spark [18]. There are three types of nodes in
a flow graph: allocation site nodes ∈ O
, variable nodes ∈ V
for local variables and formal parameters) and field dereference nodes
∈ F
(nodes of the form v.fld, where v ∈ V)
. Edges in the graph
represent the flow of values: e.g., an assignment p := q where
p, q ∈ V
is represented by a flow graph edge e → p
.
Symbolic points-to graph. Based on the flow graph of a method,
we construct a symbolic points-to graph. A SPG for a method is an
extension of a standard points-to graph, with three types of nodes:
variable nodes V
, allocation nodes O
, and symbolic object nodes S
. A variable points-to edge is (v
→ o
) ∈ (V
→ (O
∪ S)
). A field reference edge is (o
1
→ o
2
) ∈ (O
∪ S)
.FIELDS
→ (O
∪ S)
).
The SPG of a method is constructed from the flow graph. First,
symbolic object nodes so ∈ S
are created to represent objects that
are not visible in the method. A symbolic object is created for each
formal parameter and each call site that returns a value, and edges
in the flow graph are added between the newly created objects and
the corresponding variable nodes (i.e., the formal parameter node
or the left-hand-side variable node of a call site). Second, closure
over flow graph edges is computed so that any two nodes that are
originally transitively connected are now directly connected.

Next, if there exists an edge between o ∈ O
∪ S
and n ∈ V
in the
flow graph, a new edge n → o is added to the SPG. Both nodes in
this edge are labeled with ϵ, signifying that the current callstring
context associated with them is empty. Following this, it is neces-
sary to propagate points-to relationships through object fields to
account for the effects of assignments to/from field dereferences
v.f
. This propagation is a worklist-based fixed-point computation
and the iteration stops when the SPG no longer changes. We use
the approach from [18] for this computation.

After this propagation, for each node v.f
in the flow graph, all
objects o in v’s points-to set are considered and their f fields are ex-
amined. If the points-to sets of all o.f are empty, a new symbolic
node so is introduced and SPG edges o ↓ so are added. Addi-
tional propagation is then performed to reach a final fixed point.
The SPG for method update from the example is shown in Figure
3. Symbolic object SO
1
is a placeholder for the unknown re-
ceiver object. Symbolic object SO
2
represents the object pointed-
to by this.names. Finally, SO
3
is a placeholder for the object
returned by the call to get. During the subsequent interprocedural
analysis, the three symbolic objects will be resolved to real objects.

A SPG is similar to the points-to escape graph from [35]. How-
ever, in a points-to escape graph, an outside node (similar to our
symbolic node) is created for each field dereference v.f if v points
to an escaped object, while we do not create a symbolic object node
for v.f if there already exists a symbolic or allocation node in the
points-to set of some o.f where v points to o.

Escape analysis. An object escapes a method if the object’s
lifetime exceeds the lifetime of the method [35, 6]. Since alloc-
ation nodes or symbolic nodes that do not escape a method are not
pointed to by variables defined in the callers of the method, we use
the results of the escape analysis to filter out such non-escaping
allocation or symbolic nodes, as described in the next subsection.

A node n can directly escape a method if n ∈ O
∪ S
and in the
method’s SPG there exists a points-to edge p → n, where p
represents a static field, a formal parameter of the method, or the
return variable of the method. (Our implementation also takes into
account escaping through exceptions.) A node n ∈ O
∪ S
indirectly escapes if in the SPG it is reachable from a node that
directly escapes the method. These definitions are extended from the
object escapement definitions in [35, 6], with the inclusion of symbolic
objects. Note that not all symbolic object nodes escape the method.
For example, symbolic nodes that do not escape may correspond to
objects created in the callees of the method, returned to the method,
and then not propagated any further.

3.2 Interprocedural Analysis

After intraprocedural analysis is performed on each method, the
interprocedural phase executes a bottom-up traversal of the SCC-
DAG of the call graph to inline variables and objects. We use an
initial imprecise call graph based on RTA [2]; during the analysis,
this graph may be refined as described later. The basic structure of
the algorithm is the following: edges from the callee’s SPG are
inlined ("cloned") in the caller’s SPG, with the corresponding up-
date of context information (i.e., context length increases by 1).
After this inlining, some symbolic nodes are merged with the cor-
responding real allocation nodes; this way, unresolved points-to-re-
lations involving these symbolic nodes are finally resolved. As
the bottom-up traversal progresses, the number of symbolic nodes
continuously decreases until all of them are replaced by allocation
nodes. Furthermore, whenever a FP is reached for some points-to
relationship, this relationship is excluded from further inlining and
is added to the final points-to solution for the program.

We first discuss the analysis of non-SCC methods, each of which
is processed by function PROCESSSPG shown in Figure 4. At
the time a method \( m \) is processed, all of \( m \)'s callees have already
been processed by this same function, and their SPGs have been
inlined in \( m \)'s SPG.

Resolving local points-to relationships. For a method \( m \), COMPUTELOCALPOINTSTOSolves local points-to and field reference
relationships and adds them to the final points-to solution produced
by the analysis. It also computes a set clonedEdges of SPG edges
that need to be cloned to (i.e., inlined in) \( m \)'s callees. The rules
used in this computation are shown in Figure 5(1).

The function resolves not only points-to relationships in \( m \), but
also relationships that were unresolved in \( m \)'s callees but now are
resolvable in \( m \). It searches for edges in \( m \)'s SPG, including edges
cloned from its callees, that can be resolved. Whenever such an
dge is found, the corresponding 4-tuple is added to the final points-
to solution for the program. Variables can point only to assignable
node is a symbolic object node
so is added to the final points-to solution for the program. Variables can point only to assignable

Cloning of SPG edges into calleers. After the set of SPG edges
that need to be cloned is computed, the edges are cloned for each
of \( m \)'s callees (lines 4-6 in Figure 4), and the newly cloned edges
are merged with corresponding SPG edges in the callee (line 7 in
Figure 4). Function CLONEEDGE is straightforward and its code
is not shown. Consider an edge \( ce \equal{} (p^e, q^e) \) in \( m \)'s SPG that
should be cloned due to some call graph edge \( e \), where \( e \)'s source
is \( n \) and \( e \)'s target is \( m \). A cloned node \( p^c \) is created in \( n \)'s SPG,
where the new context \( c' \) is the concatenation of \( (e) \) and \( e \). If many
cloned edges \( ce \) for \( e \) include \( p^c \), only one \( p^c \) is created. Similarly,
a cloned node \( q^d \) is created in \( n \)'s SPG. These nodes are connected
by new edges in \( n \)'s SPG.

(1) COMPUTELOCALPOINTSTO

(2) MERGENODES

Figure 5: Rules for interprocedural phase.
node of each of $so_2$’s outgoing edges. In (b), if one of the nodes is an allocation node, the symbolic node is replaced by the allocation node. In (c), if both $o_1$ and $o_2$ are allocation nodes, they must be preserved — for any node that is directly connected to one of these two nodes, the algorithm creates an edge to connect it with the other. A map replaced is maintained to map a node $p$ to the node $q$ by which $p$ is replaced, so that when $p$ is processed again, $q$ can be used instead. Merging of two nodes occurs only when the type of one node is assignable to the type of the other; otherwise the nodes can be used instead. Merging of two nodes occurs only when the type of one node is assignable to the type of the other; otherwise the nodes that have been replaced are eventually discarded after MERGENODES returns. In the presence of recursive data structures, of course, we need to check if an edge has been visited before its target node is merged.

After function MERGENODES finishes, a symbolic node cloned from the callee $m$ is instantiated by either a symbolic node or an actual object node in the caller $n$, and a symbolic node in $n$ is either instantiated by an actual object node from $m$ or is not affected by the merging. At this time, the SPG for $m$ can be safely destroyed, because all points-to relationships that can be resolved in $m$ (and its callees) have already been resolved and added to the final points-to solution for the program, and all relationships that are still unresolved have been cloned into $m$’s callers.

**Example.** Figure 7 illustrates the bottom-up phase of the analysis for $addName$ and its callees. The SPG for each method is shown; the shaded nodes need to be cloned to the callers of the method. We add a globally unique number after “SO” to name a symbolic node that has not been cloned, so that we can distinguish between nodes cloned from callees and nodes introduced in the SPG during the intraprocedural phase. For each SPG, the set of escaped nodes esc and the map for node replacement replaced are also shown. The map contains a pair $(o_1, o_2)$ if $o_1$ is replaced by $o_2$ during merging. When addName is processed, points-to pairs for all variables in it and its callees (except for its own this) under all contexts become fully resolved. All resolved points-to edges are immediately excluded from the propagation. For example, after COMPUTELOCALPOINTSTO completes for $addName$, only two nodes need to be cloned and merged into the callees of $addName$.

**Unification due to merging.** The merging process, although conservative, does not strictly correspond to the semantics of a subset-based analysis. In some cases unification may occur due to bidirectional value flow, as illustrated by the following example:
Points to solution, the observers of subject (r) to release this subject, because the corresponding call graph edge is text must be removed. Removing these nodes is difficult, because nodes that are propagated up through that edge in that specific context is based on RTA is used, a call graph edge could be de-

The approximations outlined above are due to the use of SPGs. While one could consider replacing SPGs with other more precise representations (e.g., flow graphs [18, 25, 32, 31]), it is not clear whether inlining along long call chains can be made scalable with such alternatives. Section 4 shows that our analysis has higher precision and lower cost than a fully subset-based 1-object-sensitive analysis. This indicates that the loss of precision due to unification may have been offset by the precision gains due to stronger context sensitivity. Furthermore, we have investigated some SPG enhancements to avoid such approximations, and found them to have no useful effect on analysis precision.

Dynamic dispatch. In the presence of dynamic dispatch, propagation occurs on all possible call graph edges. Since an imprecise call graph based on RTA is used, a call graph edge could be decided to be spurious in a certain context after it is processed. All nodes that are propagated up through that edge in that specific context must be removed. Removing these nodes is difficult, because they could be scattered in many SPGs. We use the observer pattern to solve this problem. For a call site that could involve more than one target method, suppose the variable pointing to the receiver is r. Each pair (r, t_i) is treated as a subject, where t_i is a subtype of r’s declared type. For each (r, t_i), all nodes that have been cloned into the current method from the callee corresponding to receiver type t_i are treated as observers of this subject. If r is cloned into a method m with a cloned node r', all observers that are also cloned in m need to replace r with the cloned node r' in their subject. Once a 4-tuple (r, c, o, d) is added to the final points-to solution, the observers of subject (r', o, type) are notified to release this subject, because the corresponding call graph edge is not spurious in the current context. If r' does not need to be cloned any more, a “remove” message is sent to all remaining observers of r'. An observer removes itself from the SPG it belongs to if it receives a “remove” message from any subject it observes. Once the interprocedural phase finishes, the entire call graph is scanned and call graph edges that are infeasible under all calling contexts are removed. Even though this approach is effective in avoiding spurious points-to relationships, it cannot completely eliminate them. For example, a symbolic object can still be merged with an object of an assignable type after being cloned along a spurious call chain.

Static fields. Many cloned nodes represent static fields. Since object nodes that can be pointed to by static fields always escape a method, they could be cloned a large number of times. A majority of these cloned (allocation or symbolic) nodes can only be pointed to by static fields, and cloning them does not contribute much to the precision of the analysis. Thus, static fields are treated context-insensitively: we only keep global copies of these field nodes, and do not create clones during propagation.

3.3 Last-k-Substring Merging

Although our analysis is efficient, it does not scale to large Java programs without applying any tradeoffs. The problem lies in the cloning of allocation and symbolic nodes — they have to be cloned upwards as long as they escape a method, since they could potentially be pointed to by variables. However, if a cloned object node could never be pointed to a variable, it becomes redundant. If a node is deep inside the merged subgraphs defined by set merge (i.e., a long reference distance away from the entry points of these subgraphs), it is less likely to be pointed directly by local variables in methods upward along the call chain.

A common tradeoff in a context-sensitive analysis is k-callstring-length, which limits the context to be the last k call graph edges. However, applying this approach may result in a large number of spurious points-to relationships that are computed along unrealizable paths, because nodes are not distinguished if the last k call graph edges of their contexts are the same. In fact, merging of nodes in unrealizable paths is one of the key factors that causes imprecision [20]. This tradeoff is also not suitable for our analysis. Although the number of nodes that need to be cloned can become smaller, the number of edges coming in/leaving each node could be significantly larger. This creates a large amount of work for function MERGENODES. In fact, we implemented the 3-callstring-limit technique in our analysis, and the analysis was very slow — it ran for more than an hour on the smallest benchmark — and less precise than the 1-object-sensitive analysis (discussed later).

Based on the observation that most redundant nodes are allocation and symbolic nodes, we propose a precision-scalability tradeoff referred to as last-k-substring merging. When an allocation or symbolic node n^m in a method m needs to be cloned to a caller of m, if there already exists a node n^c in the caller such that c_1 and c_2 share the last k call graph edges, we use n^c as the cloned node for n^m, instead of creating a new node. Applying this tradeoff has two advantages. First, last-k-substring merging does not limit the length of a context string. Second, node merging is caller-based, and cannot happen indiscriminately throughout the program. This significantly reduces the chances of nodes along unrealizable paths being merged. This approach has another desirable property: for a node, the longer its context string is, the more likely it will be merged with another node. The reason is that a node with a long context is cloned and propagated from a method “at the bottom” of the call graph, and there could be many call chains along which the (original) node is cloned. In the SPG of a method far from the node’s introducing method, such a node is usually deep and far from the local variables of the method, and is thus less likely to be directly pointed to by variables in this method or in its callers (i.e., it is more likely to be redundant).

Example. We use the following example to illustrate the difference between last-k-substring-merging and the commonly used k-callstring-length approach. Suppose there are two partial call chains where symbols represent methods: e → p → a → b → c and f → p → d → b → c. To simplify the example, assume that k = 1. Consider a symbolic or object node n originally introduced in method e, and assume that n needs to be cloned all the way up along the two call chains. The 1-callstring-length approach does not distinguish these two contexts, because they share the last
call graph edge \( b \rightarrow c \). In the setting of the bottom-up propagation described in this paper, after method \( b \) is processed in the inter-procedural phase, such an approximation would merge nodes \( n_{\text{bc}} \) and \( n_{\text{b}} \). The proposed \( k\)-substring-merging approach, however, will still create two distinct nodes in this case, because when \( n_{\text{bc}} \) is cloned, there does not exist a node \( n_{\text{bc}} \) in either method \( a \) or \( d \). Our approach merges nodes only at the caller method where these two call chains intersect (e.g., at method \( p \) in this example, where \( n_{\text{pabc}} \) and \( n_{\text{pabc}} \) share a common suffix).

The two properties of last-\( k \)-substring-merging discussed above can be seen in this example. First, it does not limit the length of a context. Although node \( n_{\text{pabc}} \) and node \( n_{\text{pabc}} \) are merged at \( p \), different clones of this node still need to be created for \( c \) and \( f \). However, by applying 1-callstring-length, all nodes of the form \( n_{\text{bc}} \) are merged. Second, in an “merge” method such as \( p \), nodes that have longer contexts (i.e., propagated from farther callees) are more likely to be merged than nodes that have shorter contexts (i.e., propagated from nearer callees). In our example, in method \( p \), instances of \( n \) (from \( c \)) are merged, while instances of nodes introduced in \( b \) are not. The reason why this is desirable is that in method \( p \), clones of \( n \) are more likely to be redundant (i.e., never pointed-to by a variable node) than clones of nodes introduced in \( b \).

### 3.4 Handling of Recursion

As described earlier, in the presence of recursion the infinite set of call chains is mapped to a finite set of repetition-free call chains in order to ensure termination. Of course, when processing a SCC the analysis propagates along all chains, not just along repetition-free ones. The definition of function TrimChain from Section 2 essentially provides an algorithm to handle an SCC — a cloned node \( n_{\text{ci}} \) does not need to be created in a caller if there already exists a node \( n_{\text{ci}} \) in this caller such that \( x_{\text{ci}} \) is a suffix of \( x_{\text{ci}} \). Any SPG edge that would have been created for \( n_{\text{ci}} \) during cloning is redirected to \( n_{\text{ci}} \). When a SCC is encountered in the bottom-up phase, all its methods are processed until the fixed point is reached (i.e., no nodes need to be cloned between any two methods in the SCC). If desired, the last-\( k \)-substring-merging approach can also be applied to speed up this computation.

### 4. EMPIRICAL EVALUATION

We implemented the analysis using the Soot 2.2.3 [33] framework. The analyses included the Sun JDK 1.3.1_20 libraries, in order to enable comparisons with the analyses implemented in Paddle [16]. All experiments were performed on a machine with an Intel Xeon 2.8GHz CPU, and run with 3G heap size (option Xmx3072m). The set of benchmarks, shown in Figure 1, includes the SPECjvm98 suite, programs from the Ashes suite [1], programs from the DaCapo suite [7], and several other programs. The programs from DaCapo were from version beta050224; this version is obsolete, but we used it to allow comparison with previous work [20, 31]. We did not include some programs from this version because we did not manage to deploy all library classes these programs depend on.

Table 1 shows the number of methods reachable from \( \text{main} \) in the call graph computed by Spark’s default context-insensitive points-to analysis [18]. The table also shows the number of statements in the largest SCC in the call graph. Library methods are included in these measurements, since the evaluated whole-program analyses have to analyze them together with the client code. For each benchmark, a SCC can contain more than 1000 methods. For some programs such as \texttt{compress} and \texttt{db}, the SCC contains almost half of all reachable methods. This shows the importance of context-sensitive modeling of recursion, which is impossible to achieve without careful merging of equivalent contexts.

We managed to run our analysis for some (relatively small) programs without applying any tradeoffs. However, the approach did not scale to larger programs such as \texttt{soot-c} and \texttt{sablecc-j}. By employing the last-\( k \)-sub-string merging with \( k \leq 2 \), the analysis was able to scale to all programs. We present experimental results for the following analyses: 1-object-sensitive analysis [23] with a (1- limited) context-sensitive heap abstraction, implemented with BDDs in Paddle [16] and referred to as \( 1H \) in their work; \texttt{Refine}, the refinement-based analysis described in [31] (run without any budget); \texttt{IEPA}, our equivalence-based points-to analysis with last-1-substring merging; 2\texttt{EPA}, our analysis with last-2-substring merging; and \texttt{Full}, our analysis with last-2-substring merging only within SCCs.

The \( 1H \) algorithm was chosen because [20] showed it to be the most precise of a set of analyses that included the algorithms from [36, 34] and \( k \)-callstring analyses. An analysis that could be even more precise than \( 1H \) is the 3-object-sensitive analysis implemented with BDDs in the data race detection tool from [24]. However, at present this tool is not publicly available, and the same analysis implemented in Paddle does not scale to any of our benchmarks.

Although it has been shown in [20] that the \( k \)-callstring analyses are less precise than \( 1H \), we implemented a 3-callstring analysis. As mentioned earlier, the analysis was very slow, and the results were imprecise compared to \( 1H \), which agreed with the conclusions from [20]. The \texttt{Refine} algorithm was chosen because it has been shown to be more precise than \( 1H \), although it may not perform well to compute a complete solution for the entire program [30].

### 4.1 Analysis Precision

**Downcasts safety.** The first set of experiments considered the number of downcasts for referenced-type variables proven to be safe. Table 2 shows the total number of casts (#Casts) and how many can be proven safe by the five analyses. A “*” is used if \texttt{Full} runs out of memory. For most programs, \texttt{Refine} is the most precise algorithm. Our \texttt{1EPA} and \texttt{2EPA} analyses are much more precise than \( 1H \), but are not as precise as \texttt{Refine}, because many nodes that represent different contexts are merged too early. Our analyses are more precise than \( 1H \) because they do not limit the lengths of context strings, which enables larger-scale heap cloning. As pointed out in [31], \( 1H \) cannot prove a cast as simple as \texttt{Iterator i = x.iterator(); o = (T)i.next();} because the elements contained in \( x \) are more than one (object) level far from \( i \). Cloning nodes for only one level does not suffice to precisely treat such

<table>
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<tr>
<th>Benchmark</th>
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<th>#Statements</th>
<th>Max SCC</th>
<th>Suite</th>
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<td>5278</td>
<td>95790</td>
<td>1711</td>
<td>DaCapo</td>
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</table>

Table 1: Java benchmarks.
widely used data structures. In addition, the last-k-substring merging approach to a large degree prevents nodes in unrealizable paths that share the same sub-context-strings from merging, by allowing nodes to be merged only in the same caller.

Note that IH produces much more precise result for ps. In this program, a large number of objects are read from a stack object that is pointed to by many variables. Our analysis with k = 2 cannot distinguish the elements in the stack, because many symbolic object nodes representing these elements are merged before the objects that the stack variables point to are merged. This is a typical problem of callstring-based analyses when they handle containers — in order to distinguish elements for different containers, nodes representing container elements must not be merged before the nodes representing containers are merged, and this is too expensive for analyzing large programs. Our result on this program also agreed with the explanation from [31], because Refine also fails to produce precise result for this particular program.

Virtual call resolution. The second set of experiments considered the numbers of virtual call sites that can be statically resolved to a unique target method. Table 3 shows the total number of virtual call sites (#VCS) and the number of resolved sites. Table 3: Number of virtual call sites resolved to a unique target.

4.2 Analysis Cost

Time and memory. Table 4 shows running time and peak memory consumption. We exclude the measurements for Full because it did not scale. IH was run using javabdd [12] as the backend to manipulate BDDs. According to [17] and also our own experience with small programs, running Paddle with BuDDy [4] as the backend can make the analysis run about 2 times faster. However, for most large programs in our benchmark set, BuDDy crashed the JVM for some unknown reasons. The column for Refine shows time and memory that the analysis used to answer queries for all variables in the programs.

Column Time-I EPA shows two numbers, representing the running times of the two analysis phases. Column Time-2 EPA column shows the total running time, since the first phases of the two analyses take the same time. The results indicate that both I EPA and 2 EPA are much faster than both IH and Refine. In fact, this would still be the case even if IH were run with BuDDy. The time reduction is achieved partially by the non-BDD-based implementation, and partially by the nature of a summary-based analysis — a non-SMC method is processed only once in the interprocedural phase.

In general, IH used less memory than I EPA and 2 EPA, especially for large programs such as soot-c and sablecc-j. The major reason is that our analysis, even with k = 1, cloned many more nodes than IH did. The majority of cloned nodes that reside in memory for a long time are allocation nodes and symbolic object nodes, as they have to be cloned and propagated up if they escape a method. Our analysis only merges equivalent contexts of a pair of variable and object, while a BDD may also be able to exploit the similarity of points-to sets of different variables (even for context-insensitive analysis [3]). This may also explain why the BDD analysis achieves more space efficiency than our analysis. Memory consumed by Refine is primarily for caching matched object pairs. Even though our experiments with Refine did not record points-to sets of variables (i.e. a points-to set for a variable was discarded immediately after being computed), Refine used more memory than our analysis for many programs.

Context string length. Table 5 shows the average context string length for variable nodes (VLen) and allocation nodes (OLen) in the final points-to sets. Thus, each context string associated with a variable or an object represents a URC for that variable or object. The average lengths of the URCs are quite small — for many programs, both lengths are smaller than 1. This supports the observation that a large number of contexts share similarities, which serves as the motivation of using BDDs to represent analysis information. Note that for every program in the table, the lengths of URCs for objects are larger than those for variables, which indicates that on average more clones are needed for objects than for variables.
Table 5: Average context string length.

5. RELATED WORK

There is a very large body of work on points-to analysis; useful summaries are available in [11, 8, 28]. The discussion in this section is restricted to context-sensitive algorithms that are most closely related to our technique.

Most early context-sensitive pointer analyses were designed for C programs. A recent analysis for C that is close to ours is the algorithm from [25]. This approach is based on the observation that context insensitivity does not lose precision if the program is free of procedural side effects. A bottom-up phase propagates procedure summaries from callees to callers to make the program free of procedural side effects, which is similar to cloning symbolic points-to graph nodes from callees to callers in our analysis. The top-down phase then context-insensitively composites the points-to pairs. The analysis can scale to large programs without applying any tradeoffs, which is impressive for a subset-based context-sensitive points-to analysis with full heap cloning.

One difference with this earlier work is that we propagate symbolic points-to graphs instead of flow graphs in the bottom-up phase, and the points-to relationships are computed during the propagation. As mentioned in Section 3.1, symbolic points-to graphs for callees are immediately removed after they are processed and nodes are cloned, whereas their analysis requires flow graphs of all reachable methods to reside in memory during the bottom-up propagation, which may cause the analysis to run out of memory. From our experience, it is impossible for a Java analysis to keep everything in memory until the bottom-up phase finishes. SPGs also allow us to introduce some unification during propagation, which also contributes to the good scalability of this analysis.

Liang and Harrold [21] propose a unification-based analysis for C that uses parameterized pointer information to compute summary information (similar to our symbolic points-to graph) for a procedure; this information can be instantiated at a client in a specific call site by binding the symbolic names. Lattner et al. [15] develop a context-sensitive, unification-based, heap-cloning-based analysis, and successfully applied it on the entire Linux kernel. Their experimental results suggest that heap-cloning greatly compensated the precision loss caused by unification. Kahlon [13] proposes a staged analysis algorithm that partitions the whole program into small subsets and uses a divide-and-conquer approach that concurrently finds solutions in these subsets. A summarization-based approach is used for scalable context-sensitive alias analysis.

Chatterjee et al. [5] develop a flow-sensitive context-sensitive relevant context inference technique for a Java-like subset of C++.

This approach constructs procedural summary functions in a bottom-up phase, and instantiates these functions in a top-down phase. Ruf [27] uses a flow-insensitive context-sensitive unification-based alias analysis to remove redundant Java synchronizations. This analysis uses method summaries to model context sensitivity, and also has a bottom-up phase followed by a top-down phase. Grove and Chambers [8] define a family of analyses that could provide points-to information for Java. In this general framework context sensitivity could be achieved either with functional or with call-string context abstractions [29].

Object-sensitive analysis [22, 23] uses the static abstraction of the receiver object as the abstract context, exploiting common patterns in object-oriented code. Studies have indicated [20, 24] that k-object-sensitive points-to analysis, even for small k, can produce more precise results than callstring-based approaches. We experimentally our callstring-based analysis with the BDD-based 1-object-sensitive analysis with heap cloning from [20]. The results indicate that our analysis achieves both better running times and higher precision.

Binary decision diagrams (BDDs) have been used recently to implement points-to analyses [3, 34, 36, 20, 16, 24, 10]. Representative context-sensitive analyses implemented with BDDs are [34, 36], which for the first time allow the use of arbitrary-length call-string contexts. However, these analyses use a context-insensitive heap abstraction, which leads to precision loss [20, 16]. Naik et al. present a race detection tool based on a 3-object-sensitive analysis implemented with BDDs [24]. Its precision relative to IH and ReFine remains to be studied. Lhoták and Hendren [20] identify and measure equivalence classes of abstract contexts, and suggest that the use of BDDs could be avoided if context equivalence classes can be found manually. Hardekopf and Lin [10] develop an optimized subset-based analysis and implement it using both BDDs and bitmaps. Their result suggest that the BDD implementation is two times slower than the bitmap implementation, but is much more space efficient. These two recent reports were the direct inspiration for this paper, leading to our techniques for explicit merging of calling contexts in order to achieve both time and space efficiency.

Refinement-based analyses have been proposed to generate relatively imprecise initial results and then refine parts of the solution based on needs of clients. Guyer and Lin [9] present a points-to analysis for C that takes a client-driven point of view and identifies statements that cause imprecision for this client. Additional analysis is then performed to achieve better sensitivity for those problematic statements. Sridharan and Bodik [31] present a combined demand-driven and refinement-based context-sensitive analysis. Their results suggest that the analysis has lower memory requirements and is more precise than the 1-object-sensitive analysis, when used to answer individual pointer-related queries. Although refinement-based analyses could potentially produce more precise results than analyses that compute a complete points-to solution for the entire program, they may have limited generality. As pointed out in [34], to answer queries as simple as "which variables point to a certain object" would require a complete solution to be computed, and the algorithms used by refinement-based analyses may not scale under these circumstances [30].

Recent work [14] proposes a variant of the classic callstring model of context sensitivity [29]; it would be interesting to see whether our analysis can be restated using this theoretical formulation.

6. CONCLUSIONS

This paper presents a technique that characterizes equivalence classes of calling contexts. Based on this technique, we design a new points-to analysis for Java that merges equivalent contexts
without relying on BDDs. We also propose a last-k-substring-merging tradeoff that allows tuning of analysis cost and precision. An experimental study show that with small values of k the analysis is able to run faster and achieve better precision than an 1-object-sensitive analysis. One direction of future work is to exploit the same ideas for efficient representation of context information for other interprocedural analyses (e.g., context-sensitive side-effect analysis and def-use analysis, similar to the approach used in [23]).

Acknowledgments. We would like to thank the ISSTA reviewers for their valuable and very thorough comments and suggestions.

7. REFERENCES