Java Ranger: Static Regions for Efficient Symbolic Execution of Java

Abstract—Merging related execution paths is a powerful technique for reducing path explosion in symbolic execution. One approach, introduced and dubbed "veritesting" by Avgerinos et al., works by statically translating a bounded control flow region into a single formula. This approach is a convenient way to achieve path merging as a modification to a pre-existing single-path symbolic execution engine. Avgerinos et al. evaluated their approach in a symbolic execution tool for binary code, but different design considerations apply when building tools for other languages. In this paper we explore the best way to use a veritesting approach in the symbolic execution of Java.

Because Java code typically contains many small dynamically dispatched methods, it is important to include them in multi-path regions; we introduce a *higher-order* path-merging technique to do so modularly. Java's typed memory structure is very different from a binary, but we show how the idea of static single assignment (SSA) form can be applied to object references to statically account for aliasing. We extend path merging to summarize multiple exit points that return control flow from a multi-path region into a single such exit point. We have implemented our algorithms in Java Ranger, an extension to the widely used Symbolic Pathfinder tool for Java bytecode. Our empirical evaluation shows that Java Ranger greatly reduces the search space of Java symbolic execution benchmarks with its expanded path-merging capabilities providing a significant improvement.

Index Terms—multi-path symbolic execution; veritesting; Symbolic PathFinder; static analysis

I. INTRODUCTION

Symbolic execution is a popular analysis technique that performs non-standard execution of a program: data operations generate formulas over inputs, and branch constraints along an execution path are combined into a predicate. Originally developed in the 1970s [1], [2], symbolic execution is a convenient building block for program analysis, since arbitrary query predicates can be combined with the logical program representation, and solutions to these constraints are program inputs illustrating the queried behavior. Some of the applications of symbolic execution include test generation [3], [4], equivalence checking [5], [6], vulnerability finding [7], [8], and protocol correctness checking [9]. Symbolic execution tools are available for many languages, including CREST [10] for C source code, KLEE [11] for C/C++ via LLVM, JDart [12] and Symbolic PathFinder (SPF) [13] for Java, and S2E [14], FuzzBALL [15], and `angr` [8] for binary code.

Although symbolic analysis is a popular technique, scalability is a substantial challenge for many applications. In particular, symbolic execution can suffer from a *path explosion*: complex software has exponentially many execution paths, and baseline techniques that explore one path at a time are unable to cover all paths. Dynamic state merging [16], [17] provides one way to alleviate scalability challenges by opportunistically merging dynamic symbolic executors, effectively merging the paths they represent. Avoiding even a single branch point can provide a multiplicative savings in the number of execution paths, though at the potential cost of making symbolic state representations more complex.

Veritesting [18] is another recently proposed technique that can dramatically improve the performance of symbolic execution by effectively merging paths. Rather than explicitly merging state representations, veritesting encodes a local region of a program containing branches as a disjunctive region for symbolic analysis. This often allows many paths to be collapsed into a single path involving the region. In previous work [18], constructing bounded static code regions was shown to allow symbolic execution to find more bugs, and achieve more node and path coverage, when implemented at the X86 binary level for compiled C programs. This motivates us to investigate using static regions for symbolic execution of Java software (at the Java bytecode level).

Java programmers who follow best software engineering practices will write code in an object-oriented form with common functionality implemented as a Java class and multiple not-too-large methods used to implement small sub-units of functionality. This causes Java programs to make several calls to methods, such as getters and setters, to re-use small common sub-units of functionality. Merging paths within regions in such Java programs using techniques described in current literature is limited by not having the ability to inline method summaries. This is not a major impediment for compiled C code, as the C compiler will usually automatically inline the code for short methods such as `get`. However, Java has an *open world* assumption, and most methods are *dynamically dispatched*, meaning that the code to be run is not certain until a method is resolved at runtime; if inlining is performed at all, it is by the JRE, so it is not reflected in bytecode.

Not being able to summarize such dynamically dispatched methods can lead to poor performance for naïve implementations of bounded static regions. Thus, to be successful, we must be able to inject the static regions associated with the calls into the dispatching region [19]. We call such regions *higher order* as they require a region as an argument and can return a region that may need to be further interpreted. In our experiments, we demonstrate exponential speedups on benchmarks (in general, the more paths contained within a program, the larger the speedup) over the unmodified Java SPF tool using this approach.

Another common feature of Java code at the boundary of path merging is *exceptions*. If an exception can potentially be raised in a region, the symbolic executor needs to explore that exceptional behavior. But, it is possible for other unexceptional behavior to also exist in the same region. For example, it can be in the form of a branch nested inside another branch that raises an exception on the other side. Summarizing such unexceptional behavior while simultaneously guiding the symbolic executor towards potential exceptional behavior reduces the branching factor of the region. We propose a technique named *Single-Path Cases* for splitting a region summary into its exceptional and unexceptional parts.

A third common feature of Java at the frontier of path merging is the *return* instruction. For a region summary, a return instruction represents an *exit point* of the region. An exit point is a program location in the region at which paths in the region have been merged into a single path. If region has multiple exit points in the form of multiple return instructions, each predicated on a condition, the symbolic executor can construct a formula that represents all return values predicated on their corresponding conditions. Summarizing such multiple control-flow returning exit points of a region into a single exit point further reduces the branching factor of the region.

While summarizing higher-order regions, finding single-path cases, and converting multiple returning exit points into a single returning exit point is useful to improve scalability, representing such summaries in an intermediate representation (IR) that uses static single-assignment (SSA) form provides a few key advantages. (1) It allows region summaries to be constructed by using a sequence of transformations, with each transformation extending to add support for new features such as heap accesses, higher-order regions, and single-path cases. (2) It allows for simplifications such as constant propagation, copy propagation, constant folding to be performed on region summaries. (3) It makes the construction of region summaries more accessible to users of the symbolic execution tool, thereby making path merging more useful to end-users.

In this paper, we present Java Ranger, an extension of Symbolic PathFinder, that computes such region summaries over a representation we call Ranger IR. Ranger IR has support for inlining method summaries and for constructing SSA form for heap accesses. The paper also proposes Single-Path Cases as an alternative to multiple transition points as defined by Avgerinos et al. [18].

A. Motivating Example

Consider the example shown in Figure 1. The code counts the number of words where the concrete value 0 acts as a delimiter for words. The list object refers to an ArrayList of 200 Integer objects which have an unconstrained symbolic integer as a field. Checking the number of words delimited by one or more 0's requires 2^{200} execution paths because vanilla symbolic execution needs to branch on comparing every entry in the list to 0. However, we can avoid this path explosion by merge the two paths arising out of the
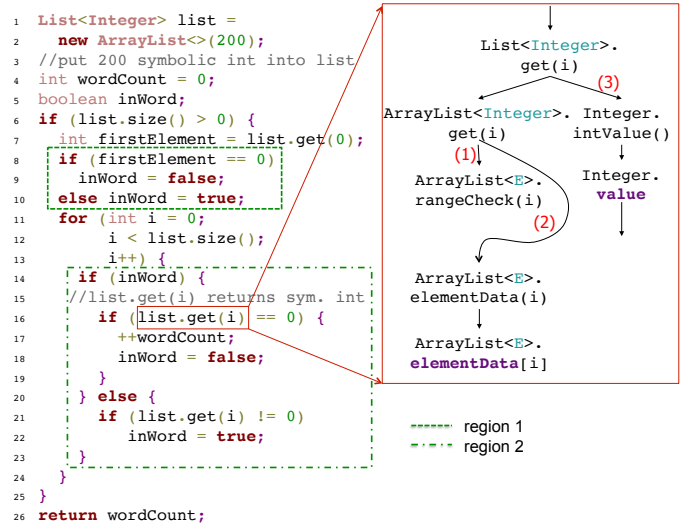


```
1  List<Integer> list =
2    new ArrayList<>(200);
3  //put 200 symbolic int into list
4  int wordCount = 0;
5  boolean inWord;
6  if (list.size() > 0) {
7    int firstElement = list.get(0);
8    if (firstElement == 0)
9      inWord = false;
10   else inWord = true;
11   for (int i = 0;
12        i < list.size();
13        i++) {
14     if (inWord) {
15       //list.get(i) returns sym. int
16       if (list.get(i) == 0) {
17         ++wordCount;
18         inWord = false;
19       }
20     } else {
21       if (list.get(i) != 0)
22         inWord = true;
23     }
24   }
25 }
26 return wordCount;
```

Fig. 1: An example where Java Ranger generates a multi-path region summary for two regions

list.get(i) == 0 branch. Such path merging requires us to compute a summary of all behaviors arising on both sides of the branch of the if-statement at line 16 in Figure 1. If we can construct such a summary beforehand, our symbolic executor can instantiate the summary by reading in inputs to the summary from the stack and/or the heap, and writing outputs of the summary to the stack and/or the heap. Unfortunately, constructing such a summary for this simple region is not straightforward. The call to list.get(int) which is actually a call to ArrayList<Integer>.get(int) which internally does the following: (1) It checks if the index argument accesses a value within bounds of the ArrayList by calling
ArrayList<E>.rangeCheck(int). If this access is not within bounds, it throws an exception. (2) It calls ArrayList<E>.elementData(int) to access an internal array named elementData and get the entry at position i. This call results in an object of class Integer being returned. (3) It calls Integer.intValue() on the object returned by the previous step. This call internally accesses the value field of Integer to return the integer value of this object.

The static summary of ArrayList<Integer>.get(int) needs not only to include summaries of all these three methods but also to include the possibility of an exception being raised by the included summary of ArrayList<E>.rangeCheck(i). The method whose summary is to be included depends on the dynamic type of the object reference on which the method is being invoked. In this example, the dynamic type of list is ArrayList, whereas it is declared statically as having the type List. Our contributions to path-merging uses the runtime type of list to inline such method summaries to merge path all 2^{200} paths into a single execution path in this

example. We walk through the transformations that allow such path merging on this example in Section III.

II. Related Work

Path explosion is a major cause of scalability limitations for symbolic execution, so an appealing direction for optimization is to combine the representations of similar execution paths, which we refer to generically as *path merging.* If a symbolic execution tool already concurrently maintains objects representing multiple execution states, a natural approach is to merge these states, especially ones with the same control-flow location. Hansen et al. [16] explored this technique but found mixed results on its benefits. Kuznetsov et al. [17] developed new algorithms and heuristics to control when to perform such state merging profitably. A larger departure in the architecture of symbolic execution systems is the MultiSE approach proposed by Sen et al. [20], which represents values including the program counter with a two-level guarded structure, in which the guard expressions are optimized with BDDs. The MultiSE approach achieves effects similar to state merging automatically, and provides some architectural advantages such as in representing values that are not supported by the SMT solver.

Another approach to achieve path merging is to statically summarize regions that contain branching control flow. This approach was proposed by Avgerinos et al. [18] and dubbed "veritesting" because it pushes symbolic execution further along a continuum towards all-paths techniques used in verification. A veritesting-style technique is a convenient way to add path merging to a symbolic execution system that maintains only one execution state, which is one reason we chose it when extending SPF. Avgerinos et al. implemented their veritesting system MergePoint to apply binary-level symbolic execution for bug finding. They found that veritesting provided a dramatic performance improvement, allowing their system to find more bugs and have better node and path coverage in a given exploration time. The static regions used by MergePoint are intra-procedural, but they can have any number of "transition points" at which control can be returned to regular symbolic execution. Avgerinos et al. do not provide details about how MergePoint represents memory accesses or integrates them with veritesting, though since MergePoint was built as an extension of the same authors' Mayhem system, it may reuse techniques such as symbolic representation of loads from bounded memory regions [21].

The veritesting approach has been integrated with another binary level symbolic execution engine named `angr` [8]. However angr's authors found that their veritesting implementation did not provide an overall improvement over their dynamic symbolic execution baseline: though veritesting allowed some new crashes to be found, they observed that giving more complex symbolic expressions slowed down the SMT solver enough that total performance was degraded. We have also observed complex expressions to be a potential cost of veritesting, but we believe that optimizations of the SMT solver interface and potentially heuristics to choose when to use static regions can allow them to be a net asset.

The way that Java Ranger and similar tools statically convert code regions into formulas is similar to techniques used in verification. In the limit where all relevant code in a program can be summarized, such as with WBS and TCAS in Section IV, Java Ranger performs similarly to a bounded symbolic model checker for Java. SPF and Java Ranger build on Java Pathfinder (JPF) [22], which is widely used for explicit-state model checking of Java and provides core infrastructure for instrumentation and state backtracking. Another family of Java analysis tools that use formula translation (also called verification condition generation) are ESC/Java [23], ESC/Java2 [24], and OpenJML [25], though these tools target static error checking and verification of annotated specifications.

Perhaps the most closely related Java model checking tool is JBMC [26], which has recently been built sharing infrastructure with the similar C tool CBMC. JBMC performs symbolic bounded model checking of Java code, transforming code and a supported subset of the standard library into SMT or SAT formulas that represent all possible execution paths. (The process by which JBMC transforms its internal code representation into SMT formulas is sometimes described as (static) symbolic execution, but it has more in common with how Java Ranger constructs static regions than with the symbolic execution that vanilla SPF performs.) In cases that Java Ranger can completely summarize, we would expect its performance to be comparable to JBMC's; an experimental comparison is future work. But static region summaries are more important as an optimization to speed up symbolic execution on software that is too large and/or complex to be explored exhaustively.

A wide variety of other enhancements to symbolic execution have been proposed to improve its performance, including caching and simplifying constraints, summarizing repetitive behavior in loops, heuristic guidance towards interesting code, pruning paths that are repetitive or unproductive, and many domain-specific ideas. A recent survey by Baldoni et. al. [27] provides pointers into the large literature. One approach that is most related to our higher-order static regions is the function-level compositional approach called SMART proposed by Godefroid [28]. Like Java Ranger's function summaries, SMART summarizes the behavior of a function in isolation from its calling context so that the summary can be reused at points where the function is used. But SMART uses single-path symbolic execution to compute its summaries, whereas Java Ranger uses static analysis: this makes Java Ranger's summary more compact at the expense of requiring more reasoning by the SMT solver. Because SMART was implemented for C, it does not address dynamic dispatch between multiple call targets.

III. Technique

Algorithm 1 describes how Java Ranger works. The main idea is that JR intercepts conditional branch instructions with symbolic operands and attempts to summarize instructions

Algorithm 1: Ranger general pseudocode

1 Input: (symbolic if-instruction inst);
2 $R_{initial}$ = jit-region-construction(inst);
3 R_{no_return} = early-return transformation($R_{initial}$);
4 R_{alpha} = alpha-renaming transformation(R_{no_return});
5 R_{before} = R_{alpha};
6 R_{after} = null;
7 repeat
8   **repeat**
9   **if** *($R_{after} \neq$ null)* **then**
10 | $R_{before} = R_{after}$
11 R_{sub} = substitution transformation(R_{before});
12 R_{ord} = higher-order transformation(R_{sub});
13 R_{field} = field references transformation(R_{ord});
14 R_{array} = array references transformation(R_{field});
15 R_{simple} = simplification transformation(R_{array});
16 $R_{after} = R_{simple}$;
17   **until** *($R_{before} = R_{after}$)*;
18 R_{after} = higher order transformation(R_{after});
19 until *($R_{before} = R_{after}$)*;
20 R_{single_path} = single-path cases transformation(R);
21 R_{linear} = linearization transformation(R);
22 R_{green} = to-green transformation(R);
23 if *is-canonical(R_{green})* **then**
24   populate outputs // `successful`
      `transformation`
25   skip region execution;
26 else
27   abort ; // `resume DSE of if-instruction`
28 end

$\langle stmt \rangle ::= \langle canonical\text{-}stmt \rangle \mid \lambda \text{ x}.\langle stmt \rangle$
$\mid \quad \langle stmt \rangle \; ; \; \langle stmt \rangle \mid \langle exp \rangle := \langle exp \rangle$
$\mid \quad \langle exit\_stmt \rangle \mid \text{if } \langle exp \rangle \text{ then } \langle stmt \rangle \text{ else } \langle stmt \rangle$
$\mid \quad \text{invoke}(\; \langle exp \rangle, \langle exp \rangle \;) \mid \text{exit}$

$\langle canonical\text{-}stmt \rangle ::= \langle canonical\text{-}stmt \rangle \; ; \; \langle canonical\text{-}stmt \rangle$
$\mid \quad \langle canonial\text{-}exp \rangle := \langle canonical\text{-}exp \rangle \mid \text{skip}$

$\langle exit\text{-}stmt \rangle ::= \text{new } \tau \mid \text{return } \langle exp \rangle \mid \text{throw } \langle exp \rangle$

$\langle exp \rangle ::= \langle canonical\text{-}exp \rangle \mid \text{get\_field}(\; \langle exp \rangle.\langle exp \rangle \;)$
$\mid \quad \text{put\_field}(\; \langle exp \rangle.\langle exp \rangle, \langle exp \rangle \;) \mid \text{array\_load}(\langle exp \rangle, \langle exp \rangle)$
$\mid \quad \text{array\_store}(\; \langle exp \rangle, \langle exp \rangle, \langle exp \rangle \;)$

$\langle canonical\text{-}exp \rangle ::= \langle val \rangle \quad \mid \quad \langle var \rangle \quad \mid \quad \langle canonical\text{-}exp \rangle \quad op_b$
$\quad \langle canonical\text{-}exp \rangle$
$\mid \quad op_u \quad \langle canonical\text{-}exp \rangle \quad \mid \quad \text{gamma}(\langle canonical\text{-}exp \rangle,$
$\quad \langle canonical\text{-}exp \rangle, \langle canonical\text{-}exp \rangle)$

$\langle op_b \rangle ::= + \mid - \mid * \mid \div \mid \& \mid \text{bitwise-or} \mid \oplus \mid \% \mid == \mid \neq \mid$
$\quad \leq \mid \geq \mid \&\& \mid \text{logical-or} \mid > \mid < \mid \ll \mid \gg \mid \ggg$

$\langle op_u \rangle ::= - \mid \tilde{} \quad \langle val \rangle ::= () \mid \mathbb{Z} \mid \mathbb{C} \quad \langle var \rangle ::= \text{ID\_}\mathbb{N}$

Fig. 2: Context Free Grammar for Java Ranger IR

These transformations perform operations, like for example inlining method summaries and supporting field accesses, that will allow the Ranger IR statement to ultimately be translated to a formula. But, dependencies between these transformations are not pre-determined. For example, a region can contain field accesses and a method invocation, the summary of which contains other field accesses. Using a nested fixed-point computation, JR ensures that such dependencies are taken into consideration.

If the transformations produce a canonical form of the region, then Java Ranger adds the canonical region summary to the path condition, populates the region's outputs, and sets the program counter (the next instruction to be executed) to the address of the instruction that is at the beginning of the immediate post-dominator. Otherwise, JR aborts and allows DSE to resume execution (lines 23-28).

In the following sections, we first describe Java Ranger grammar then we discuss just-in-time region construction then finally we talk about different JR transformations and their semantic meaning. We also show how each transformation is realized on the motivating example presented in Figure 1

A. Java Ranger Grammar

Figure 2 shows Java Ranger grammar, which can be thought of as a superset of Wala IR which is in turn a superset of Java bytecode instructions.

JR's grammar is composed of statements *stmt* and expressions *exp*. Statements include $\langle canonical\text{-}stmt \rangle$ used to describe the simplest form of statements in which different transformations of JR tries to reduces to. A region statement $\lambda x.\langle stmt \rangle$, which defines the binding of the input

that lie along every possible path in the region, up until the program location where all paths in the region merge. We call this summarization a "region" or just R. It is important to note that, R contains not only the summarization in form of a Ranger IR statement, it also contains other environment-related information, such as types, input and outputs of the region, explained later in this section.

Java Ranger uses Just-In-Time (JIT) analysis and, with the help of Wala [29], constructs the control-flow graph (CFG) of the method containing the intercepted symbolic conditional branch instruction. Then JR translates a part of the CFG, that begins from the node containing the symbolic conditional branch and ends at this node's immediate post-dominator, into a Ranger IR statement and an environment (line 2). We call this step "JIT region construction". The region is said to "begin" at the symbolic conditional branch instruction and "end" at the address of the first instruction in the immediate post-dominator of the node that contained the symbolic conditional branch instruction.

Next, Java Ranger then runs different transformations on R (lines 2-22) with the goal of reducing the region's IR statement into a canonical form that can be easily translated into a formula.

Value-maps	$\Delta_r : loc \rightarrow$	(val, exp)
	$\Delta_s : loc \rightarrow$	(val, exp)
Type-maps	$\Gamma_r : var \rightarrow$	τ
	$\Gamma_s : ref \rightarrow$	τ
Region-map	$\Psi : \tau \rightarrow$	$\lambda x.s$
path-subscript-map	$psm : v \rightarrow$	x
	$\Theta : var \rightarrow$	loc
Single-path-constraints	$\Sigma : \{exp\}$	
Early-return-constraints	$\Sigma_{ret} : x_{ret} \rightarrow$	exp
Nominal-next-instruction	$Next :$	$\mathbb{Z}$
Early-return-next-instruction	$Next_{ret} :$	$\mathbb{Z}$

Fig. 3: Environments used in Ranger.

parameter in the region statement. Other statements in JR IR also include: sequential composition ($stmt; stmt$), assignment ($exp := exp$), skip, exit ($exit\text{-}stmt$) (which determine single path cases, it includes $new\ \tau$, $throw\ exp$ and $return\ exp$ statements), if-then-else and finally $invoke$ statement to indicate call of a method.

JR expressions consist of $\langle canonical\text{-}exp \rangle$, which is analogous to canonical statements, which describes the simplest form of expressions that JR tries to reduce to. $\langle canonical\text{-}exp \rangle$ includes constants aka values (unit ( ) , positive and negative integers $\mathbb{Z}$, characters $\mathbb{C}$), variables (these are subscripted with integers to facilitate having SSA form for them ID_$\mathbb{N}$), binary and unary operations over canonical expressions as well as a special gamma expression, $gamma(exp, exp, exp)$. Gamma expression that allow Ranger IR to construct Gated Single Assignment (GSA) [] form for variables which intuitively describes conditional assignment of variables.

Java Ranger defines 4 types of variables, a field or array variable (created to maintain fields and arrays ssa), an early return variable (to carry early return values), variables that correspond to local variables, and variables used to represent intermediate computation. This distinction is abstracted away from the grammar but is referred to whenever necessary in the text.

Other forms of expressions include non-canonical expressions, this includes read and writes to fields and arrays.

B. JIT Region Construction

As mentioned before the construction of the region happens when Java Ranger detects a symbolic if-instruction during DSE, and thus an opportunity for path-merging. Using the recovered cfg of the method where the intercepted if-instruction resides, JR constructs two types of regions: *multi-path region* and *method-region*.

A *multi-path region*: contains a statement in JR IR and a coresponding environment. The IR statement represents the summarization of the instructions from the conditional instruction basic block, i.e, if-bytecode basic block, and down until the merge point, i.e, the phi basic block. The region environment that contains information about variables in the

region, such as types of variables, variables stack slot information, inputs of the region and output of the region.

A *method-region*: also contains a statement in JR IR and an environment. This time however the IR statement represents the summarization of the whole method. The environment for a method-region is almost similar to the multi-path region, except that the input and the stack slot of variables are defined in terms of the parameters to the method.

In the next subsections we describe the two main steps in constructing a region, the IR statement creation, which we call *IR statement recovery* and the environment creation for regions.

1) IR Statement Recovery: The algorithms used in this step are similar to those used for decompilation [30]. Starting from an initial basic block in a control-flow graph recovered by Wala [29], the algorithm first finds the immediate post-dominator of all *normal* control paths, that is, paths that do not end in an exception or return instruction. It then looks for nested self-contained subgraphs. If for any graph, the post-dominator is also a predecessor of the node, we consider it a loop and discard the region. The algorithm systematically attempts to build regions for every branch instruction, even if the branch is already contained within another region. The reason for this is that, it may not be possible to instantiate the larger region depending on whether summaries can be found for *dynamically-dispatched* functions, and whether references are *uniquely determinable* for region outputs. The outcome of this step is a statement in Java Ranger. For region 2 shown in the motivating example in Figure 1, the recovered statement is as follows where $x58$ corresponds to input from $inWord$, and $x54$, $x55$ correspond to outputs to $wordCount$, $inWord$ respectively.

```
if ((! (== x58 0 ) )) {
  x44 = invokeinterface < Application,
      Ljava/util/List,
      get(I)Ljava/lang/Object; >[x9,x59]
  x47 = invokevirtual < Application,
      Ljava/lang/Integer, intValue()I > x44
  if ((! (!= x47 0 ) )) {
    x48 := (+ x57 1 );
  }
} else { ... }
x54 := (Gamma !(x58==0) (Gamma !(x47!=0) x48
    x57) (Gamma !(x53==0) x57 x57));
x55 := (Gamma !(x58==0) (Gamma !(x47!=0) 0
    x58) (Gamma !(x53==0) 1 x58));
```

2) Environment Creation: Once the statement of a region has been recovered, i.e., a corresponding JR IR statement has been created, JR then tries to populate its corresponding environment. This includes identifying the region boundary, in terms of the region's local variable inputs and outputs, types, and stack slots of variables used in the region summary.

JR defines local variable inputs as variables in the region summary that make the first *use* of a given stack slot. This is called an input variable(s) to the region because, when the DSE hits a symbolic region where there is a opportunity

of path-merging, JR collects information (concrete/symbolic values) from the dynamic environment of DSE, and substitute them in the region's statements, i.e, substituting the first binding of variables to a stack slot with its actual concrete or symbolic value. Using these environment-related information JR continue trying to either dereference objects used in the IR statement or express them in a canonical form.

Similarly, local variable outputs are the last *def* of a JR IR variable in a region summary that maps to a given stack slot. JR uses this information to populate symbolic expression or concrete values that summaries the execution of the region. To do this, JR relies on Wala to provide stack slot information for intermediate variables. This is however not always available and therefore JR needs to try to infer the mapping of intermediates to stack slots. This is done using the observation that, if at one variable used in a ϕ-expression of Wala maps to a stack slot, then all variables used in that ϕ-expression must belong to the same stack slot. JR use this observation to propagate stack slots across all ϕ-expressions.

Formally we define the following structures:

Value-map: Δ_r and Δ_s maps a location (i.e, stack slots, heap entry), to concrete *val* or symbolic *exp* for Java Ranger and DSE respectively. This is used to collect the input of the region as well as to populate the output of the region.

Type-map: Γ_r and Γ_s maps vars or references, to types τ for Java Ranger and DSE respectively.

Region-map: Java Ranger defines a map Ψ from type τ to a parametric statement $\lambda x.s$ that defines the region's summary. This is used to bind the region type to its statement. The actually form of the region type is abstracted here, but really it is defined by class-name, method-name and instruction line number. This way, if a region is every hit again, i.e., executed again, then instead of re-running the jit-region construction, JR just pulls the region from the map.

Single-Path-Constraint-List: A list Σ of single-path constraints. This is later used to guide the DSE execution to particular paths that JR did not summarize, more information is in next section.

Early-Return-Constraint-map: A map Σ_{ret} from early-return vars x_{ret} to early-return constraints. This is used to set up the path condition for early return case, more information is in next section. **Nominal-next-instruction**: is a the instruction position that DSE should resume from, if path-merging was successful. **Early-next-instruction**: is a the instruction position that DSE should resume from, if path-merging was successful for early return case.

Figure 4 shows the semantics of different transformations, where the judgment describes a transformation step on some statement s, w.r.t. the maps, which usually yield a new statement s' and possibly some changes in the map.

C. Transformations

Early Return Transformation: In this transformation, Java Ranger converts multi-path region with *one or more* return statements or a method region with *more than one* return statement, into region that assigns a return variable x_{ret} *gamma* expression that evaluates to different return values depending on the return value predicated on the condition that would cause that value to be returned. The `early−return` describe the semantics of this transformation when the return statement is on one side of a multi-path region. In this case JR generates a new return variable x_{ret} and assign it to the return variable. Eventually if the path-merging of this region was successful JR will in this case generate two paths one to explore the early return choice and another to explore the nominal choice. Accordingly, the position where DSE needs to resume from needs to be changed depending on which choice is being executed.

Alpha-renaming Transformation: In this transformation, all Ranger IR variables are renamed by adding a subscript unique to each instantiation of the region. This transformation helps distinguish variables across multiple instantiations of the same region. To give an example of this transformation, line 2 in the recovered Ranger IR statement gets changed to:

```
x44$2 = invoke < Application,
    Ljava/util/List, get(I)Ljava/lang/Object;
    >[x9$2, x59$2]
```

Local Variable Substitution Transformation: During this transformation, local variable inputs in JR are substituted with their concrete or symbolic values obtained from the environment of DSE. The `substitution` rule in Figure 4 describes the semantics of this transformation where the location of an input variable l is used to lookup its value in the DSE environment Δ_s and is substituted in the region statement. Running this transformation on the previous Ranger IR statement causes $x9\$2$ to be resolved to a concrete integer value 375 to change the statement to

```
x44$2=
    invoke(ArrayList.get(I)Ljava.lang.Object,375,
    x59$2);
```

Higher-order Regions Transformation: This transformation is initiated when a method invocation after local variable substitution. At this point, we perform three steps. (1) The called method's region is retrieved, depending on the dynamic type obtained from DSE, if the region is not found then JIT-region construction is called for it. If a method region was finally constructed/retrieved then its variables are alpha-renamed. (2) For concrete object references that JR was able to substitute for callee objects (if it is non-static invocation, otherwise no object reference is need), JR uses expressions of IR parameters to substitute the formal parameters by repeatedly applying local variable substitution transformation over the method region. (3) When no more higher-order method summaries can be inlined, the resulting substituted method region is inlined into the outer region. Rules `high−order₁` and `high−order₂` describe the semantics of this transformation.

To show the effect of this transformation on the motivating example, regions that defines $ArrayList.get(I)java.lang.Object$ are inlined in the

$$\frac{Next = position(if_{inst}.next()) \qquad Next_{ret} = position(return_{inst}) \qquad gen\_id() = x_{ret}}{\Sigma\,;\, if\ e\ then\ (s_1; return\ v_1)\ else\ s_2\ \mapsto\ \Sigma\,;\, (if\ e\ then\ s_1; return\ v_1\ else\ s_2); x_{ret} = v_1}\ \text{get-return}$$

$$\frac{\Theta(x) = l, \qquad \Delta_s(l) = (v, e)}{\Theta, \Delta_s\,;\, \lambda x.s\ \mapsto_{sub}\ \Theta, \Delta_s\,;\, [(v,e)/x]s}\ \text{substitution} \qquad \frac{}{throw\ e\ \mapsto_{single}\ exit}\ \text{single-path}_1$$

$$\frac{\Gamma_r, \Delta_r\,;\, e_1\ \mapsto_{sub}\ \Gamma_r, \Delta_r'\,;\, v_1 \qquad \Gamma_s(v_1) = \tau, \qquad \Gamma_r', \Psi(\tau) = \lambda x.s_2, \qquad \Delta_r'\,;\, e_2\ \mapsto_{sub}\ \Delta_r''\,;\, v_2}{\Gamma_r, \Delta_r\,;\, s_1; invoke(e_1, e_2)\ \mapsto_{high}\ (\Gamma_r \cup \Gamma_r'), \Delta_r''\,;\, s_1; [v_2/x]s_1}\ \text{high-order}_1$$

$$\frac{\Gamma_r, \Delta_r\,;\, e_1\ \mapsto_{sub}\ \Gamma_r', \Delta_r'\,;\, v, \qquad \Gamma_s(v) = \tau, \qquad \Gamma_r', \Psi(\tau) = \lambda x.(s; return\ e'), \qquad \Delta_r'\,;\, e_2\ \mapsto_{sub}\ \Delta_r''\,;\, v_2}{\Gamma_r, \Delta_r\,;\, e = invoke(e_1, e_2)\ \mapsto_{high}\ (\Gamma_r \cup \Gamma_r'), \Delta_r''\,;\, [v_2/x]s; e = e'}\ \text{high-order}_2$$

$$\frac{}{\Sigma\,;\, if\ e\ then\ (s_1; exit; s_1')\ else\ s_2\ \mapsto\ (\Sigma \vee e)\,;\, s_2}\ \text{single-path}_2 \qquad \frac{}{\Sigma\,;\, if\ e\ then\ s_1\ else\ (s_2; exit; s_2')\ \mapsto\ (\Sigma \vee !e)\,;\, s_1}\ \text{single-path}_3$$

$$\frac{}{\Sigma\,;\, if\ e\ then\ (s_1; exit; s_1')\ else\ s_2; exit; s_2'\ \mapsto\ (\Sigma \vee true)\,;\, skip}\ \text{single-path}_4 \qquad \frac{}{if\ e\ then\ s_1\ else\ s_2\ \mapsto_{s_1\,;\,s_2}}\ \text{linearlization}$$

$$\frac{}{\Sigma\,;\, x := gamma(e_1, e_2, e_3)\ \mapsto\ \Sigma\,;\, (e_1 \wedge x = e_2) \vee (!e_1 \wedge x = e_3)}\ \text{to-green}$$

$$\frac{psm\,;\, e\ \mapsto_{any}\ psm\,;\, v \quad \Theta(v) = l \quad \Delta_s(v) = (v, e') \quad psm(v) = \phi}{psm\,;\, x := get\text{-}field(e)\ \mapsto_{field}\ psm\,;\, x := (v, e')}\ \text{get-field}_1 \qquad \frac{psm\,;\, e\ \mapsto_{any}\ psm\,;\, v \qquad psm(v) = x_r}{psm\,;\, x := get\text{-}field(e)\ \mapsto_{field}\ psm\,;\, x := x_r}\ \text{get-field}_2$$

$$\frac{\Gamma_r, psm\,;\, e\ \mapsto_{any}\ \Gamma_r, psm\,;\, v \qquad \Theta(v) = l \qquad psm(v) = \phi}{\Gamma_r, psm\,;\, x := put\text{-}field(e1, e2)\ \mapsto_{field}\ (\Gamma_r \cup (x_0, \Gamma_s v)), (psm \cup (v, x_0))\,;\, (x := x_0); (x_0 := e2)}\ \text{put-field}_1$$

$$\frac{psm\,;\, e\ \mapsto_{any}\ psm\,;\, v \qquad \Theta(v) = l \qquad psm(v) = x_{ref} \quad gen\_id() = x_{ref}'}{\Gamma_r, psm\,;\, x := put\text{-}field(e1, e2)\ \mapsto_{field}\ (\Gamma_r \cup (x_{ref}', \Gamma_r(x_{ref}))), (psm \cup (v, x_{ref}'))\,;\, (x := x_r); (x_{ref}' := e2)}\ \text{put-field}_2$$

$$\frac{\Gamma, psm\,;\, s_1\ \mapsto_{field}\ \Gamma', psm'\,;\, s_1' \qquad \Gamma', psm'\,;\, s_2\ \mapsto_{field}\ \Gamma'', psm''\,;\, s_2' \qquad gen\_id() = x_{ref}}{\Gamma, psm\,;\, if\ e\ then\ s_1\ else\ s_2\ \mapsto_{field}\ \Gamma''), psm''\,;\, if\ e\ then\ s_1'\ else\ s_2'; x_{ref} = create\text{-}gamma(s_1', s_2', psm)}\ \text{gamma-generation}_1$$

Fig. 4: Evaluation Rules for Ranger Transformations

original region to get the following Ranger IR statement. Please note that $x58$ from the originally recovered static summary has been substituted by $x40\$1$ because it was read as a local variable input ($inWord$) that had the symbolic value $x40\$1$ (a consequence of summarizing region 1 in Figure 1).

```
if ((! (== x40$1 0 ) )) {
 x4$4 = get(375.< Primordial,
     Ljava/util/ArrayList, size,
     <Primordial,I> >)
 if ((! (< 0 x4$4 ) )) {
  Throw Instruction
 }
 x4$5 = get(375.< Primordial,
     Ljava/util/ArrayList, elementData,
     <Primordial,[Ljava/lang/Object> >)
 x5$5 = x4$5[0:<Primordial,Ljava/lang/Object>]
 x6$3 = x5$5;
 x44$2 = x6$3;
 [x47$2] = invoke < Application,
     Ljava/lang/Integer, intValue()I >[x44$2]
 if ((! (!= x47$2 0 ) )) {
    x48$2 = (+ 0 1 );
 }
} else { ... }
x54$2 := (Gamma !(x40$1==0) (Gamma
    !(x47$2!=0) x48$2 0) (Gamma !(x53$2==0) 0
    0));
x55$2 := (Gamma !(x40$1==0) (Gamma
    !(x47$2!=0) 0 x40$1) (Gamma !(x53$2==0) 1
    x40$1));
```

Field References SSA Transformation: This transformation translates reads and writes of fields in Java bytecode into corresponding Ranger IR statements. In order to translate all field accesses to SSA form, this transformation creates a summary of the semantics represented by the field accesses in the region. This transformation constructs a new field access variable for every field assignment on every path within the region. This new field access variable construction makes use of two monotonically increasing subscripts. It uses a path subscript to distinguish between assignments to the same field on the same execution path. It uses a global subscript to distinguish between assignments to the same field across execution paths. At the merge point of the region, field assignments done on the same field are merged using Gated Single Assignment (GSA) [31]. To continue expanding the motivating example, the field references transformation on the above Ranger IR statement changes the assignments to $x4\$4$ and $x4\$5$ to assign them the concrete values 200 and 397 respectively. Since Java Ranger runs a simplification transformation (which has constant propagation and if-then-else statement simplification) within the same fixed point iteration, this Ranger IR statement is simplified to the following statement. Please note that the simplification transformation sets variables assigned to a constant value in a constant values map maintained in the region's instantiation environment. This causes uses of $x48\$2$ to be substituted by the constant 1.

```
if ((!= x40$1 0 )) {
```

```
x5$5 = 397[0:<Primordial,Ljava/lang/Object>]
x45$2 := x5$5;
[x47$2] = invoke < Application,
    Ljava/lang/Integer, intValue()I >[x5$5]
} else { ... }
x54$2 := (Gamma x40$1!=0 (Gamma x47$2==0 1 0)
    0);
x55$2 := (Gamma x40$1!=0 (Gamma x47$2==0 0
    x40$1) (Gamma x53$2!=0 1 x40$1));
```

Array References SSA Transformation: This transformation translates reads and writes of arrays in Java bytecode into corresponding Ranger IR statements. In order to translate all array accesses to SSA form, this transformation creates an execution path-specific copy of every array when it is first accessed within a region. Reads and writes of arrays are then done on a path-specific copy of the array. All array copies are merged at the merge point of multi-path regions. The merged array copy represents array outputs of the region. The effect of this transformation on the last shown Ranger IR statement produces the following statement where the value at index 0 in array reference 397 was 380 and the length of array at reference 397 was 200.

```
if ((!= x40$1 0 )) {
  if ((&& (< 0 200 ) (>= 0 0 ) )) {
    x5$5 := 380;
  } else {
    Throw Instruction
  }
  x45$2 := x5$5;
  [x47$2] = invoke < Application,
      Ljava/lang/Integer, intValue()I >[x5$5]
} else { ... }
x54$2 := (Gamma x40$1!=0 (Gamma x47$2==0 1 0)
    0);
x55$2 := (Gamma x40$1!=0 (Gamma x47$2==0 0
    x40$1) (Gamma x53$2!=0 1 x40$1));
```

Simplification of Ranger IR: This transformation uses constant propagation, copy propagation, and constant folding [32] to shorten the summary by representing constant assignments and copies in the region's instantiation environment. This transformation also simplifies if-then-else expressions and if-then-else statements where the choices are syntactically equal. Running simplification on the previous Ranger IR statement yields the following statement.

```
if ((!= x40$1 0 )) {
  [x47$2] = invoke < Application,
      Ljava/lang/Integer, intValue()I >[380]
} else { ... }
x54$2 := (Gamma x40$1!=0 (Gamma x47$2==0 1 0)
    0);
x55$2 := (Gamma x40$1!=0 (Gamma x47$2==0 0
    x40$1) (Gamma x53$2!=0 1 x40$1));
```

Single Path Cases: This transformation collects path predicates inside a region that lead to *non-nominal* exit point as an alternative to transition points [18]. We define non-nominal exit points to be program locations inside the region that either

cause exceptional behavior or use behavior that we cannot summarize, i.e, object creation. This helps the region instantiation proceed ahead with exploring unexceptional behavior in the region separately from exceptional behavior and potentially reduces the branching factor in the multi-path region. We use this pass of transformation to identify non-nominal exit points, collect their path predicates and prune them away from the Ranger IR statement. The formal rules of this transformation is defined in rule single−path₁ and single−path₂, where the former transforms statements that are considered exit points, then the later constructs the matching constraints to explore the single path of interest. The outcome of this process, is a more simplified and concise statement that represent the nominal behavior of the Ranger region. The collected predicate is later used to guide the symbolic execution to explore non-nominal paths.

Linearization: At the stage when this transformation is run, all GSA expressions have been computed, and so, Ranger IR statement need not have if-then-else statements anymore. The γ functions introduced by GSA are a functional representation of branching, which lets us capture the semantics of behavior happening on both sides of the branch. Running this transformation on the last shown Ranger IR statement (after another simplification and inlining of the summary of $Integer.intValue()$) produces the following statement. Please note that the $value$ field accessed by $Integer.intValue()$ in the object referenced by the value 380 was set to the symbolic integer $x1$. The variables $x54\$2$ and $x55\$2$ correspond to outputs to $wordCount$, $inWord$ in Figure 1 respectively.

```
x54$2 := (Gamma x40$1!=0 (Gamma x1==0 1 0) 0);
x55$2 := (Gamma x40$1!=0 (Gamma x1==0 0
    x40$1) (Gamma x1!=0 1 x40$1));
```

Translation to Green: At this point, the region summary contains only compositional statements with assignment statements that contain GSA expressions. Compositional statements are translated into conjunction, assignment statements are translated into Green [33] equality expressions. For assignment statements that have GSA expressions (shown in the to−green rule in Figure 4), these are translated into two disjunctive formulas that describes the assignment if the GSA condition or its negation were satisfied. We translate region summaries from Ranger IR to Green because we found Green constraints to be a more pliable interface for translation from Ranger IR to the solver than SPF's existing constraints.

IV. EVALUATION

A. Experimental Setup

We implemented the above mentioned transformations as a wrapper around the Symbolic PathFinder [13] tool. To make use of region summaries in Symbolic PathFinder, we use an existing feature of SPF named *listener*. A listener is a method defined within SPF that is called for every bytecode instruction executed by SPF. Java Ranger adds a path merging listener to SPF that, on every program location to be

executed, checks if the next instruction is a conditional branch instruction with at least one symbolic operand. On finding such a symbolic branch condition, Java Ranger attempts to compute a static summary of all multi-path regions in the method which contains the current program location. After this Just-In-Time static analysis, if Java Ranger summarized the multi-path region that begins at the current program location, Java Ranger computes the canonical region corresponding to the current program location by reading inputs from and writing outputs to the stack and the heap. Finally, it conjuncts the canonical region summary with the path condition and resumes symbolic execution at the bytecode offset of the end of the region. Java Ranger wraps around SPF and can be configured to either run SPF without any path merging or run SPF with the following four path-merging features enabled.

(1) Java Ranger only transforms multi-path regions with a single exit point to their canonical form. This includes multi-path regions that have local, stack, field, or array outputs. Java Ranger substitutes local inputs into the Ranger IR representation of the multi-path region, and constructs SSA form Ranger IR for all field and array accesses in the region using its runtime context. The SSA form representation of all field and array accesses allows the Ranger IR to be simplified uniformly across all variable types which reduces the size of the region summary and improves performance. While our current implementation of Java Ranger cannot transform summaries with symbolic object and array references, it is capable of summarizing reads and writes to arrays with symbolic indices. (2) Java Ranger uses multi-path region summaries that make method calls which have also been statically summarized. Method summaries are inlined into the multi-path region summary based on the dynamic type of the method. (3) Java Ranger uses single-path cases to allow regions to have more than one exit point. These exit points take the form of new object allocations and exceptional behavior present in the region. (4) Java Ranger converts multiple exit points that return control flow from the region to its caller into a single control flow-returning exit point. This feature allows summarization of multiple `return` instructions in a region into a single control-flow returning exit point. Instead of a single return value, such an exit point returns a formula to its caller, which predicates each return value on its corresponding condition in the region.

We used the control-flow graph recovered by Wala [29] to bootstrap our static statement recovery process. We ran the above implementation using the incremental solving mode of Z3 using the bitvector theory. The incremental solving mode provides only the last constructed constraint to the solver instead of passing the entire path condition every time a query is to be solved. Since path-merging can create large formulas in the path condition, the incremental solving mode provided a crucial benefit in reducing the number of times large formulas had to be passed to the solver.

B. Evaluation

In order to evaluate the performance of Java Ranger, we used the following nine benchmarking programs commonly used to evaluate symbolic execution performance. Eight of these programs were provided by Wang et al. [34] which also includes a translation of the Siemens suite to Java. (1) Wheel Brake System (WBS) [35] is a synchronous reactive component developed to make aircraft brake safely when taxing, landing, and during a rejected take-off. (2) Traffic Collision Avoidance System (TCAS) is part of a suite of programs commonly referred to as the Siemens suite [36]. TCAS is a system that maintains altitude separation between aircraft to avoid mid-air collisions. (3) Replace is another program that's part of the Siemens suite. Replace searches for a pattern in a given input and replaces it with another input string. (4) NanoXML is an XML Parser written in Java which consists of 129 procedures and 4608 lines of code. (5) Siena (Scalable Internet Event Notification Architecture) is an Internet-scale event notification middleware for distributed event-based applications [37] which consists of 94 procedures and 1256 lines of code. (6) Schedule2 is a priority scheduler which consists of 27 procedures and 306 lines of code. (7) PrintTokens2 is a lexical analyzer which consists of 30 procedures and 570 lines of code. (8) ApacheCLI [38] provides an API for parsing command lines options passed to programs. It consists of 183 procedures and 3612 lines of code. (9) MerArbiter models a flight software component of NASA JPL's Mars Exploration Rovers. We used the version made available by Yang et al. [39]. This benchmark consists of 268 classes, 553 methods, 4697 lines of code including the Polyglot framework.

We first ran each of these benchmarks using SPF with increasing number of symbolic inputs and obtained the most number of symbolic inputs with which SPF finished complete exploration of each benchmark within a 24 hour time budget. We then ran each benchmark with this number of symbolic inputs with Java Ranger. This evaluation allowed us to check if Java Ranger is faster than SPF at achieving complete path exploration of each benchmark. We report results from this evaluation for each benchmark in Table I. Table I shows that Java Ranger achieves a significant speed-up over SPF with 5 (WBS, TCAS, NanoXML, ApacheCLI, MerArbiter) of the 9 benchmarks in terms of both running time and number of execution paths. Java Ranger also achieves a modest 22% reduction in running time and 34% reduction in the number of execution paths with the PrintTokens2 benchmark.

Java Ranger is able to summarize the entire step function of WBS and TCAS into a single execution path. This step functions of WBS and TCAS take 3 and 12 symbolic inputs respectively. In WBS, Java Ranger summarizes multi-path regions with deeply nested `if` bytecode instructions, in one case summarizing a region that consisted of 9 branches nested within one another. In TCAS, Java Ranger inlines 28 method summaries in each step of TCAS, many of which summarize multiple return values into a single formula that represents all the return values of the method. While SPF does not finish more than 5 steps of WBS and 2 steps of TCAS within 24 hours, Java Ranger finishes 10 steps of both benchmarks within 2.81 seconds and 1.41 seconds respectively.

TABLE I: Comparing the performance of Java Ranger with Symbolic PathFinder on 9 benchmarks. "# sym inputs' indicates the total number of symbolic inputs that were given to each benchmark. For WBS and TCAS, we ran WBS and TCAS with path-merging using symbolic inputs corresponding to 10 steps of each. "path-merging enabled" indicates a comparison of no path-merging with path-merging with all the features turned on.

Benchmark name	# sym inputs	path-merging enabled?	total runtime (sec)	static analysis time (sec)	# exec. paths	# solver queries	solver time (sec)	# distinct regions used	# inlined method summaries	# canonical region summaries
WBS	15	NO	4427.66	0	7962624	15925246	3121.44	0	0	0
WBS	30	YES	2.81	3.73	1	0	0	16	0	140
TCAS	24	NO	353.07	0	39204	465262	296.23	0	0	0
TCAS	120	YES	1.41	2.29	1	0	0	4	560	40
replace	11	NO	1176.83	0	757261	4317642	749.77	0	0	0
replace	11	YES	4581.13	7.97	91983	1441674	3563.57	20	360	7334
NanoXML	8	NO	63554.90	0	33944190	77831662	30071.39	0	0	0
NanoXML	8	YES	28803.23	13.31	3637075	10363980	19742.50	10	8136	990022
Siena	7	NO	55027.94	0	35831808	91208236	26689.72	0	0	0
Siena	7	YES	57782.26	23.66	35831808	91208236	26945.8	0	0	0
Schedule2	3	NO	1.48	0	343	684	0.33	0	0	0
Schedule2	3	YES	2.52	3.42	343	684	0.32	0	0	0
PrintTokens2	4	NO	1716.27	0	166644	3491916	1305.59	0	0	0
PrintTokens2	4	YES	1338.85	4.01	109727	2404854	634.34	4	0	122504
ApacheCLI	6+1	NO	31886.46	0	4839812	64432586	9470.83	0	0	0
ApacheCLI	6+1	YES	5560.94	10.12	171818	756030	1904.21	5	0	977972
MerArbiter	28	NO	70876.22	0	2429568	6816406	3391.12	0	0	0
MerArbiter	28	YES	11087.11	5.96	276144	910023	475.49	16	0	411227

In the replace benchmark, while Java Ranger reduces the number of execution paths by about 88%, it incurs an increase in execution time. This increase occurs even when Java Ranger transforms 20 distinct regions into 7334 canonical region summaries. On manually investigating the set of instantiated regions in replace, we found that the outputs of most of these regions were being branched on later in the code causing the benefit from path-merging to be lost. In order to test this hypothesis, we ran an automated evaluation where we restricted Java Ranger to only a subset of regions. First, we determined the most number of symbolic inputs with which Java Ranger could explore all paths in replace in less than a minute. We found this number to be 6 symbolic inputs which took Java Ranger about 37 seconds while using 14 regions. Next, we constructed a list of region subsets sorted in increasing order of the subset size. This list began with 14 region subsets, each containing one region, and ended with a single set containing all 14 regions. The total number of region subsets present in this list was $2^{14} - 1$. Finally, we ran Java Ranger with every region subset in this list, where Java Ranger was allowed to only canonicalize regions within a given subset. After running this evaluation for 96 hours, we found that all possible region subsets containing up to 4 regions had been tested. But, no region subset up to 4 regions in size resulted with a reduction in the running time and number of execution paths. While it is possible that there is a larger set of regions in the replace benchmark that provides the most benefit from path-merging, our automated evaluation and a manual investigation did not reveal what such a set of

regions might be. In the future, we plan to integrate a query count estimated heuristic of the kind proposed by Kuznetsov et al. [17] to canonicalize only a beneficial set of regions in the replace benchmark.

On the NanoXML benchmark, Java Ranger finds several opportunities for execution path count reduction on account of the NanoXML benchmark having several methods with multi-path regions that have a control-flow returning instruction on every branch side. Since Java Ranger can convert such multiple control-flow returning exit points regions into a single control-flow returning exit point, Java Ranger is able to inline more than 8,000 method summaries when running NanoXML with 8 symbolic inputs and finish in about 8 hours while vanilla SPF needs about 18 hours to complete the same exploration.

Java Ranger has the same performance as SPF on Siena and Schedule2 with a minor overhead in running time that comes from Java Ranger's lookup of a region summary for every executed branch instruction and recording of metrics. We restrict our results with Siena to 7 symbolic inputs because 7 is the most number of symbolic inputs for which SPF finishes complete path exploration within a 24 hour time budget. On running Siena, the overhead of Java Ranger̃(about 5% in running time)results from running into concrete branch instructions that Java Ranger could have summarized, had these branches been symbolic.

In the PrintTokens2 benchmark, Java Ranger uses 4 distinct regions, 2 of which involve summarizing multi-path regions which have a `return` instruction at the end of every path in the region. Being able to summarize multiple control-flow

Benchmark name	multi-path region summ.	+ higher-order regions	+ single-path cases	+returns summ.
WBS	0.0002	0.0002	0.0002	0.0002
TCAS	0.347	0.002	0.002	0.002
replace	1.36	3.23	3.93	3.89
NanoXML	1.28	1.27	1.36	0.45
PrintTokens2	0.67	0.66	0.7	0.78
ApacheCLI	0.16	0.13	0.18	0.19
MerArbiter	0.15	0.16	0.17	0.16

(a) Comparing running time

Benchmark name	multi-path region summ.	+ higher-order regions	+ single-path cases	+returns summ.
WBS	1.30E-07	1.30E-07	1.30E-07	1.30E-07
TCAS	0.245	2.60E-05	2.60E-05	2.60E-05
replace	0.63	0.9	0.12	0.12
NanoXML	0.9998	0.9994	0.2655	0.1071
PrintTokens2	0.87	0.87	0.87	0.66
ApacheCLI	0.0035	0.0035	0.0035	0.0035
MerArbiter	0.11	0.11	0.11	0.11

(b) Comparing number of execution paths

Benchmark name	multi-path region summ.	+ higher-order regions	+ single-path cases	+returns summ.
WBS	0	0	0	0
TCAS	0.234	0	0	0
replace	0.74	1.13	0.33	0.33
NanoXML	0.9999	0.9995	0.2778	0.1332
PrintTokens2	0.92	0.92	0.92	0.69
ApacheCLI	0.05	0.05	0.05	0.05
MerArbiter	0.13	0.13	0.13	0.13

(c) Comparing number of solver queries

TABLE II: Presenting the ratio of three metrics, running time, number of execution paths, and number of solver queries, with path-merging to the same three metrics without path-merging for the 7 benchmarks where any path-merging was done. A ratio less than 1 indicates path-merging was useful in reducing the value of the metric (smaller is better). The "multi-path region summ." column represents path-merging was enabled only for multi-path regions that did not have a method invocation and had a single non-returning exit point. Every column in the next three columns adds a feature to the features enabled in the previous column. The "+ higher-order regions" column adds path-merging for regions containing method invocations. The "+ single-path cases" column adds path-merging for regions containing new object allocations, throwing of exceptions, and calls to unsummarized methods. The "+ returns summ." column adds path-merging for regions that have exit points that return control flow to the caller of the method in which the region is present.

returning exit points into a single such exit point proves to be a crucial feature in Java Ranger for this benchmark.

The ApacheCLI benchmark takes 9 inputs, the first 8 are 1-byte inputs used to construct command-line options and the last input controls whether ApacheCLI should stop on encountering an invalid option input. Since the 9th input is different from the first 8, we ran ApacheCLI with the first 6 inputs and the 9th input made symbolic. Java Ranger finishes exploration with this setup of ApacheCLI in about 1.5 hours whereas SPF finishes exploration in about 9 hours as shown in Table I When we ran SPF on ApacheCLI with the first 7 inputs and the 9th input made symbolic, it was unable to complete exploration within 24 hours. But, Java Ranger can complete this exploration in about 15 hours.

In the MerArbiter benchmark, the most significant benefit from Java Ranger comes from its ability to summarize multi-path regions that put their output on the stack directly. Such regions are common in Java bytecode since the JVM is both a stack machine and a register machine. All the multi-path regions that SPF (which is mode 1 in Java Ranger) needs to branch on but are summarized by Java Ranger are regions that compute a boolean value based on a symbolic branch and write it to the stack as an operand to be used by the following return instruction. Most of these multi-path regions lie inside several levels of nested classes and dynamically bound field references that necessitate a fixed-point computation over the field substitution and constant propagation transformations. Java Ranger summarizes such multi-path regions and does 411,000 instantiations with 7 steps of MerArbiter (each step takes 4 symbolic inputs), with more than 282,000 instantiations needing more than 8 iterations of the fixed-point computation.

Java Ranger has different path-merging features such as summarizing multi-path regions with a single non-returning exit point, inlining method summaries, exploring unsummarized behavior using single-path cases, and summarizing multiple control flow-returning exit points into a single such exit point. We wanted to evaluate the effect each feature has when it is added to a previous set of features. We set up an experiment where beginning with no path-merging (aka baseline SPF), we added path-merging features in the aforementioned order. For every benchmark where any path-merging was performed, we computed the ratio of three metrics with a set of path-merging features enabled to the same metrics without path-merging (aka when only baseline SPF was used). These three metrics were: the running time, the number of execution paths explored, and the number of solver calls made. We present the results of this comparison in Table **??**. Table **??** shows that merging of paths for regions that have a single non-returning exit point is most often useful. This observation matches our intuition that regions are most commonly present in Java. The addition of method summary inlining provides a major reduction in all three metrics in TCAS. This observation matches a observation made manually from TCAS' source code that multi-path regions in it often invoke methods that can be summarized by Java RangerThe addition of single-

path cases provides a major reduction in the number of solver queries in the replace and NanoXML benchmarks. But, it also causes a minor increase in the running time of both of these benchmarks. We attribute this increase to the fact that the reduction in the number of solver queries is not enough to compensate for the increase in complexity of the solver queries introduced with single-path cases. In the future, we plan to address this issue by transforming region summaries with more sophisticated term rewriting and context-specific simplification of canonical regions to reduce the complexity of solver queries. The addition of summarizing multiple control flow-returning exit points into a single such exit point provides a significant reduction in the number of execution paths and number of solver queries in the NanoXML, PrintTokens2 benchmarks. The benefit from this feature matches our observation that both of these benchmarks contain frequently-executed regions that contain multiple control-flow returning exit points.

V. FUTURE WORK

While Java Ranger was able to significantly outperform SPF in a majority of our benchmarks, there are a few directions along which it can further be extended. Java Ranger attempts to perform path merging as aggresively as possible. This path merging strategy doesn't optimize towards making fewer solver calls. We plan to work towards implementing heuristics that can measure the effect of path merging on the rest of the program.

While statically summarizing regions gives dynamic symbolic execution a performance boost to explore more paths efficiently, generating test cases that covers all summarized branches is one of the most useful applications of dynamic symbolic execution that is currently unsupported. We intend to extend Java Ranger towards test generation for merged paths in the future.

While path merging can potentially allow symbolic execution to explore interesting parts of a program sooner, the effect of path merging on search strategies, such as depth-first search and breadth-first search commonly used with symbolic execution, remains to be investigated. We plan to explore the integration of such guidance heuristics with path merging in the future. Java Ranger can summarize methods and regions in Java standard libraries. This creates potential for automatically constructing summaries of standard libraries so that symbolic execution can prevent path explosion originating from standard libraries.

VI. CONCLUSION

We presented an extension to veritesting implemented in a tool named Java Ranger. It works by systematically applying a series of transformations over a statement recovered from the CFG. Java Ranger's use of fixed-point computation over multiple transformations demonstrates a significant improvement over SPF. Java Ranger provides evidence that inlining summaries of higher-order regions can lead to a further reduction in the number of execution paths that need to be explored with path merging as shown by the TCAS benchmark. Java Ranger's use of return value summaries also demonstrates a significant benefit over SPF with the NanoXML benchmark. Java Ranger reinterprets path merging for symbolic execution of Java bytecode and allows symbolic execution to scale to exploration of real-world Java programs.

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VII. APPENDIX

We report results from our evaluations for each benchmark in Tables **??** and **??** Vaibhav: can you please check out the table