Techniques for Evolution-Aware Runtime Verification

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Abstract—Runtime Verification (RV) can help find bugs by monitoring program executions against formal properties. Developers should ideally use RV whenever they run tests, to find more bugs earlier. Despite tremendous research progress, RV still incurs high overhead in (1) machine time to monitor properties and (2) developer time to wait for and inspect violations from test executions that do not satisfy the properties. Moreover, all prior RV techniques consider only one program version and wastefully re-monitor unaffected properties and code as software evolves.

We present the first evolution-aware RV techniques that reduce RV overhead across multiple program versions. Regression Property Selection (RPS) re-monitors only properties that can be violated in parts of code affected by changes, reducing machine time and developer time. Violation Message Suppression (VMS) simply shows only new violations to reduce developer time; it does not reduce machine time. Regression Property Prioritization (RPP) splits RV in two phases: properties more likely to find bugs are monitored in a critical phase to provide faster feedback to the developers; the rest are monitored in a background phase.

We compare our techniques with the evolution-unaware (base) RV when monitoring test executions in 200 versions of 10 open-source projects. RPS and the RPP critical phase reduce the average RV overhead from 9.4× (for base RV) to 1.8×, without missing any new violations. VMS reduces the average number of violations 540×, from 54 violations per version (for base RV) to one violation per 10 versions.

Index Terms—runtime verification, regression testing, software evolution, specifications, software testing.

I. INTRODUCTION

Runtime Verification (RV) [4], [10], [11], [16], [21], [33], [34], [37], [43], [58] is a technique for monitoring program executions against formal properties. A property is a logical formula over a set of events, e.g., method calls; intuitively, it captures developers’ intent on correct API usage [76]. An RV tool takes a program, program inputs (e.g., tests), and properties. The tool instruments the program based on the properties so that executing the instrumented program generates events and creates monitors to listen to events and check properties. The outputs are violation messages (violations for short) which report that the execution violated some property at a code location. RV helped find many bugs but induces high runtime overhead in executing the instrumented program instead of the uninstrumented program, and some violations do not indicate true bugs but are false alarms [52], [76].

All prior RV techniques considered only a single program version, but software evolves over multiple versions. Developers should ideally use RV whenever they run tests, to find more bugs earlier in the development process. However, as software evolves, rerunning traditional, evolution-unaware RV (base RV) has unnecessarily high overhead: machine time can be wasted on repeatedly checking unchanged code, and developers can repeatedly see the same violations (even if they want to handle some violations later, they have no way to suppress those violations). It is therefore important to develop techniques that can reduce RV overhead—in both machine and developer time—during software evolution. This paper presents compelling evidence that taking software evolution into account can significantly reduce RV overhead across multiple program versions.

A. Techniques

We present three evolution-aware RV techniques: regression property selection (RPS), violation message suppression (VMS), and regression property prioritization (RPP). RPS, VMS, and RPP focus RV (and its users) on changed parts of code and new violations that are generated. RPS can reduce RV overhead in machine time and developer time, VMS can reduce the overhead in developer time but not machine time, and RPP can reduce time to see results for most critical properties, e.g., those historically more likely to find bugs.

RPS re-monitors only properties that can be violated in parts of code affected by changes, i.e., either directly changed or indirectly affected; these code parts may generate new events due to changes. Our current implementation of RPS re-monitors only properties whose events can come from affected classes. We focused on class-level RPS following recent evolution-aware techniques which showed greater overall benefits of performing analysis at class level than at finer granularity levels like methods or statements [9], [26], [51], [88].

VMS by itself re-monitors all properties in a new code version, but shows only new violations that were not in the old version. VMS collects violations from both versions and computes a mapping of code between new and old versions. VMS then filters out violations of the same property that occurred on the likely equivalent locations in both versions. VMS makes it easier to focus on new violations, and developers can decide whether to inspect only new or also old violations.

RPP partitions RV into two phases: it monitors some properties in the critical phase—so called because it is on the developer’s critical path from the moment of submitting code changes to getting the results—and monitors the remaining properties in the background phase. RPP reduces time to get feedback on critical properties but still monitors all properties. Developers select critical properties, e.g., those that helped find bugs or those for heavily-used APIs, etc. In our evaluation, critical properties become those that were previously violated.
We define safety and precision for evolution-aware RV techniques (Section III-A): an evolution-aware RV technique is safe if it does not miss a new violation, and precise if it shows only new violations. We develop two strong RPS variants that are safe under certain assumptions. We also develop 10 weak RPS variants that can trade some safety for more efficiency, i.e., reduced overhead. RPS variants differ in what properties they select and where they instrument the selected properties.

B. Results

We compared RPS, VMS, and RPP with base RV using 161 properties on 200 versions of 10 open-source projects (20 versions per project). The results showed that our evolution-aware RV techniques can substantially reduce the runtime overhead and number of violations shown, compared to base RV. We compute the runtime overhead and the number of shown violations per version, then average across versions of a project and then across all projects.

Base RV has average runtime overhead of 9.4×, showing 54 violations per version. The two strong RPS variants have runtime overhead of 7.5× and 7.9×, showing 37 and 42 violations. The 10 weak RPS variants have runtime overhead of 2.5×–7.5×, showing 21–37 violations. Surprisingly, all weak RPS variants were safe in our experiments although they can be unsafe in theory. Our manual inspection showed why: all new violations happened due to changes whose effects were in the classes considered affected by all weak RPS variants.

VMS has negligible extra runtime overhead and reduces the number of violations shown by two orders of magnitude relative to base RV; VMS shows, on average, 0.1 new violation per version, while base RV shows 54 violations per version.

RPP’s critical phase overhead is 1.8× (when combined with RPS), and our analysis of RPP showed that about 76% of base RV overhead goes into monitoring unviolated properties.

C. Contributions

This paper makes the following contributions:

* Evolution-Aware RV Techniques. We are the first to realize the RPS idea [53] and additionally propose VMS and RPP.
* RPS Variants. We develop two strong RPS variants, and 10 weak RPS variants that trade some safety for efficiency.
* Results. RPS and RPP reduced base RV overhead from 9.4× to as low as 1.8×, and VMS showed two orders of magnitude fewer violations than base RV.

II. Running Example

Our running example is necessarily detailed to show the specifics of RV that evolution-aware RV techniques exploit, and to highlight differences between the RPS variants in later sections. We illustrate properties, how evolution-unaware base RV works in the JavaMOP [40], [43], [58] tool used in our experiments, and violations.

A. Examples of Monitored Properties

In our running example, we use the three properties in figures 1a–1c, written in JavaMOP syntax [38]; they helped find several confirmed bugs [52]. Properties have three parts: (1) events: relevant method calls or field accesses, (2) a specification: logical formula over the events, and (3) a handler: action to take when events match (or violate) the specification.

**Collections_SynchronizedCollection (CSC):** CSC checks that code synchronizes on a synchronized Collection before iterating over it [18]. Not synchronizing on such Collection before iterating “may result in non-deterministic behavior” [17]. CSC defines four events in lines 3–10 of Fig. 1a: (1) sync (lines 3–4) occurs when Collections.synchronizedCollection is called to create a Collection, c, (2) syncMk (lines 5–6) occurs when c.iterator is called to obtain an Iterator i in a thread that holds the lock on c, (3) asyncMk (lines 7–8) occurs when c.iterator is called without first locking on c, and (4) access (lines 9–10) occurs when accessing i from a thread that does not hold c’s lock. When sync occurs, JavaMOP creates a monitor object to listen for CSC events (hence the creation event keywords).

CSC’s specification (line 11 of Fig. 1a) is an Extended Regular Expression which matches if the code either (1) creates c (sync event) and obtains i without first locking on c (asyncMk event), or (2) creates c (sync event) and obtains i from a thread that locks on c (asyncMk event) but accesses i from a thread that does not lock on c (access event). When a CSC monitor receives an event that causes its specification to match, its handler (line 12) is invoked. The handler can be any code, but most properties, including CSC, just print a violation to warn developers of a potential bug.

**StringTokenizer_HasMoreElements (STHEME):** STHEME checks that getting tokens from StringTokenizer, st, is only done after checking that st has more elements [82]. STHEME (Fig. 1b) defines two events: (1) hasnexttrue (lines 2–4) occurs when st.hasMoreTokens is invoked and returns true, and (2) next (lines 5–7) occurs when st.nextElement or st.nextToken is invoked. The STHEME specification (line 8) is a past-time LTL formula [57] stating that a next event on st must be preceded by a hasnexttrue event on st. When the STHEME specification does not hold, line 9 prints a violation.

**URLDecoder_DecodeUTF8 (URLD):** URLD checks that URLs are decoded from UTF-8, to avoid producing incompatible URLs [83], [84]. URLD’s only event, decode (lines 2–5 in Fig. 1c), occurs if URL is decoded with non-UTF-8 encoding. The handler on line 6 prints a violation on each decode event.

B. Base RV, Causes of Overhead, and Property Violations

We describe the example Java code in Fig. 1d and violations that occur when JavaMOP is used to monitor its execution against the CSC, STHEME, and URLD properties. The example code is hypothetical, created to illustrate our techniques.

**Example Code:** Fig. 1d shows five classes—A, B, C, D, and E—and two versions—line 11 in the old version is replaced with line 12 in the new version. A.a() concatenates the string
public class A {
    String s(List i, String sep) {
        String o = "";
        for (Object a : i) {
            if (a != null) 
                o += a.toString() + sep;
        }
        return o;
    }
}

class B extends A {
    String b(List l) {
        String o = "";
        for (Object a : l) 
            o += a.toString();
    return o;
}

(b) StringTokenizer_HasMoreElements (STHME) property

1 URLDecoder_DecodeUTF8() { 
2     event decode(String String) {
3         call(e = URLDecoder.decode(String, String)) && args(\*, \*enc) 
4         if (!enc.equalsIgnoreCase("utf-8") || !enc.equalsIgnoreCase("utf8")) 
5             return;
6         return;
7         return;
8         return;
9         /*violation message*/
10         String b(List l) {
11             String o = "";
12             for (Object a : l) 
13                 o += a.toString();
14             return o;
15         }
16         return;
17         return;
18         return;
19         /*violation message*/
20         String b(List l) {
21             String o = "";
22             for (Object a : l) 
23                 o += a.toString();
24             return o;
25         }
26         return;
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248         return;
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250         return;
Fig. 3: An example property violation

like in Fig. 3. A violation contains the violated property name, the location (i.e., fully qualified class name, method, source file name, and line number) of the last event that caused the violation, a URL for the property definition, and a sentence describing the violation. These help developers to reason whether a property violation is a true bug or false alarm.

We distinguish between violation instances, the list of violations, and the set of violations. Violation instances repeat, e.g., if property-violating code is in a loop or executed by multiple tests. We map violation instances of the same property that occur at the same location to the same violation. Developers may prefer to only see violations, but seeing all violation instances can help in debugging. Running tests in Fig. 2 on old version of Fig. 1d generates two violations from three violation instances. Lines 7 and 12 in Fig. 2 cause two instances of a STHME violation by executing `t.nextToken` on line 28 of Fig. 1d without calling `t.hasMoreTokens`. Line 12 in Fig. 2 causes one instance of a URLD violation by executing line 36 of Fig. 1d to decode a non-UTF-8 encoded URL. It can be time consuming to inspect/debug violations [52]. We next discuss evolution-aware RV techniques which aim to reduce runtime overhead of RV and show fewer violations as software evolves.

III. EVOLUTION-AWARE RV TECHNIQUES

We describe our evolution-aware RV techniques which leverage software evolution to reduce the runtime overhead of base RV across multiple program versions and to focus developers on new violations after a change. Base RV (illustrated through the example in Section II) is evolution-unaware. For example, running base RV on the new version of code in Fig. 1d would re-monitor all available properties and re-incur the entire overhead wastefully because the code change does not affect (i.e., alter the behavior of) all classes, e.g., `E` is unaffected. Further, properties whose events are only generated from unaffected classes cannot have any new violations after the code change. Finally, it may be desirable to monitor on the developer’s critical path, from when they launch tests to when they see the test results, only properties that are more likely to find bugs than others, e.g., based on a project’s history.

Section III-A defines safety and precision, two notions that we use in this paper to analyze and measure the quality of our evolution-aware RV techniques. Section III-B describes RPS, our technique to re-monitor only properties that can have new violations after a code change, and also includes our definition of affected classes and how RPS uses affected classes to select the subset of properties to re-monitor in a new program version. Section III-C describes various RPS variants. Sections III-D and III-E describe our other two evolution-aware RV techniques, VMS and RPP, respectively. RPS, VMS, and RPP can be used separately or together, and we illustrate them throughout this section using the example from Fig. 1.

A. Safety and Precision

Safety measures loss in violation-finding (and thus potential bug-finding) ability. Precision measures minimality. We define safety and precision relative to base RV and relevant violations. In this paper, relevant violations are new violations—violations that are in the new version, but not in the old version, after accounting for violations that merely changed line numbers in the code. Definition 1 allows developers to plug in other notions of relevant violations.

Definition 1. Relevant Violation: Relevant violations for an evolution-aware RV technique are those due to the changes. Relevant violations are those due to the changes.

Definition 2. Safety: An evolution-aware RV technique is safe if it finds all relevant violations that base RV finds.

Definition 3. Precision: An evolution-aware RV technique is precise if it finds only relevant violations that base RV finds.

B. Regression Property Selection (RPS)

RPS reduces accumulated base RV overhead by re-monitoring only properties that can be violated in parts of code affected by changes [53]. For RPS to be useful, its end-to-end time (i.e., time to select properties plus time to re-monitor selected properties) must be less than base RV time. Thus, we consider changes and affected parts of code at the class-level granularity, which was more effective than only finer-granularity levels (e.g., statements or methods) for other evolution-aware techniques [26], [51], [88]. The reason is that the analysis at the class level achieved a better balance of efficiency (class-level analysis is faster than analyses at finer granularity) and precision (class-level analysis may capture more than necessary because it is coarser grained).

The notion of affected classes is central to RPS, because it relates code changes with the properties. Intuitively, a property should be re-monitored only if its events can be generated from some class affected by the code change. That is, affected classes are those that can generate events that lead to new violations after code changes. Conversely, a class that is unaffected by a change cannot generate an event that leads to a new violation. Formally, RPS variants compute affected classes as those that satisfy some of the following conditions, which capture when a class may generate events that lead to new violations after a code change:

Definition 4. Affected Class: For RPS, a class C is affected by a change if (1) C changed, (2) C transitively depends (via inheritance or use) on a class that changed, or (3) a class that satisfies (1) or (2) can pass objects to C.

Condition 3 captures classes whose control flow may change (leading to new events and violations) if received objects change. For example, in Fig. 1d, `D` does not depend on the changed class (`B`) or its transitive dependents (`C` and `TC`); if only `B.flag()` changes to return `false` on line 14, then the
Fig. 4: Class dependency graph (CDG) for Figures 1d and 2. Edges mean “depends on”; the changed class is colored.

**Step 1:** RPS constructs the CDG in Fig. 4 for the new version of the code in Fig. 1d and the tests in Fig. 2.

**Step 2:** Strong RPS computes affected classes from the CDG as \( \Delta = \Delta \circ (E^{-1})^* \circ E^* \), where \( \Delta \) is the set of changed and new classes, \( E \) is the set of edges in the CDG, \( * \) is the reflexive and transitive closure, \( \circ \) is the relational image, and \( E^{-1} \) is the inverse relation. \( \Delta \) captures the three conditions in Definition 4. In our example, \( \Delta = \{ B \} \); only \( B \) changed (Condition 1). \( \Delta \circ (E^{-1})^* = \{ B, C, TC \} \).

TC and C transitively depend on \( \Delta \) (Condition 2). Lastly, \( \Delta \circ (E^{-1})^* \) since they cannot generate new events. Although elided in our example due to space limits, newly added classes are in \( \Delta \), so RPS re-monitors properties that may be violated in newly added classes.

**Steps 3 and 4:** RPS re-monitors only CSC and STHME in the new version. No (new) events for URLD are generated in affected(\( \Delta \)). So, RPS saves the time to re-monitor URLD (if both tests are run), and developer time for (re-)inspecting URLD violations. Any URLD violations must be in \( E \) and cannot be new violations, because \( E \notin \text{affected}(\Delta) \).

**Discussion of RPS:** If a property was not instrumented into the old version, but code changes cause it to be violated in affected(\( \Delta \)), RPS selects it, e.g., CSC is selected by strong RPS. Two CSC violation instances occur in the new version in Fig. 1d; lines 4–6 iterate over the synchronized Collection initialized on line 12 without locking on it, matching the left disjunct in CSC’s specification (line 11, Fig. 1a), so the handler (line 12) prints the violation in Fig. 3.

Base RV does not consider changes, dependencies, or classes that generate events for each property. After each change (e.g., from line 11 to line 12 in Fig. 1d), base RV re-monitors all properties and shows old and new violations. In our example, base RV shows three violations: the two STHME and URLD violations from the old version, plus the new CSC violation. RPS shows only the old STHME violation, plus the new CSC violation. Note that RPS by itself is not precise; it does not show only new violations. Showing only new violations is the goal of VMS (Section III-D).

**C. RPS Variants**

RPS determines (1) what properties to select and (2) where in the program to instrument selected properties. The strong RPS described in Section III-B is safe under certain assumptions: it selects to re-monitor all properties for which events can be generated from all affected classes (“what”), and instruments them throughout the program (“where”), including third-party libraries and even unaffected classes. However, that strong RPS variant is imprecise (it may instrument and monitor selected properties in unaffected classes). We describe here a second, more precise strong RPS variant. Weak RPS variants trade some safety for further overhead reduction. Weak RPS variants differ in what affected classes they use for selecting properties and where they instrument selected properties.

**Strong RPS Safety Assumptions:** Strong RPS is safe under the following assumptions: (1) the CDG is complete, (2) there are no test order dependencies [8], [29], [89], and (3) dynamic language features, e.g., reflection and classloading, do not introduce additional CDG edges.

**Notation:** Subscripts distinguish how affected classes are computed. \( ps_1 \) computes \( \text{affected}_1(\Delta) = \Delta \circ (E^{-1})^* \circ E^* \) (Definition 4). \( ps_2 \) computes \( \text{affected}_2(\Delta) = \Delta \circ ((E^{-1})^* \cup E^*) \), which consists of only classes that either depend transitively on \( \Delta \) (dependents) or \( \Delta \) transitively depends on (dependees); \( \text{affected}_2 \) is more unsafe than \( \text{affected}_1 \) because it omits condition 3 from Definition 4 to not include classes, e.g., D in Fig. 4, that may generate new events because they receive objects from dependents of \( \Delta \). \( ps_3 \) relaxes Definition 4 even further by omitting condition 3; it computes \( \text{affected}_3(\Delta) = \Delta \circ (E^{-1})^* \), i.e., only dependents of \( \Delta \).

Once the corresponding set of affected classes (\( \text{affected}(\Delta) \)) has been used to select the properties to re-monitor (namely properties whose events may be generated from \( \text{affected}(\Delta) \)), we obtain more variants by choosing “where” to instrument the selected properties. We can reduce where to instrument the selected properties, in order to obtain more reduction of base RV overhead, at two levels: (1) do not instrument the selected properties in unaffected classes in the program but still instrument all third-party library classes loaded into the JVM, and (2) do not instrument the selected properties in any third-party library class.

For the first level of instrumentation reduction, we use the superscript c to show that unaffected classes in the program (i.e., complement of \( \text{affected}(\Delta) \)) are not instrumented: \( ps_1^c \) excludes \( \text{affected}_1^c \), \( ps_2^c \) excludes \( \text{affected}_2^c \), and \( ps_3^c \) excludes \( \text{affected}_3^c \). To see the benefit of not instrumenting \( \text{affected}(\Delta)^c \), consider \( ps_1 \) and \( ps_2^c \), which are both safe. \( ps_2^c \) is safe because unaffected classes cannot generate any new events or alter the sequence of events for the selected
We denote weak RPS superscript. For example, affected

Efficiency/Safety Tradeoff: Weak RPS variants trade some means that (select properties, classes in assumptions of strong RPS do not hold, means inclusion, and means exclusion. Efficiency/Safety Tradeoff: Weak RPS variants trade some safety for lower runtime overhead. Fig. 5 shows two lattices of RPS variants; lower variants can be less safe (left lattice) but more efficient (right lattice) than higher ones. ps2 computes \{A, B, C, TC\} as affected\_d. D is not in affected\_2, so ps2 can miss new STHME violations, e.g., when changing only true to false on line 14 in Fig. 1d—ps3 does not even re-monitor STHME for this change. If such cases are rare, then ps3 can be safe but have lower overhead than strong RPS. In general, ps2 can be unsafe if there is data flow to classes that are not dependents or dependees of \(\Delta\). ps3 computes affected\_3 as \{B, C, TC\}—dependents of \(\Delta\)—which includes neither \(\Delta\)’s dependees, e.g., A, nor dependees of \(\Delta\)’s dependents, e.g., D. Therefore, ps3 can be more unsafe than ps2, e.g., if A changes such that a new violation results from events that are local to A, ps2 will find that new violation, but ps3 will not find it. Technique ps3 could miss new violations that ps2 finds. In fact, ps3 misses the new CSC violation after the change in Fig. 1d; it selects to re-monitor CSC but does not instrument A, so asyncMk is not triggered. Excluding third-party library classes from instrumentation can also be unsafe, e.g., if A or \(\Delta\) are third-party library classes. Weak RPS variants that do not instrument affected\_\(\Delta\)\^c can be faster but safe if changes only lead to new violations in \(\Delta\) and its dependents. Lastly, for weak RPS, false alarms can result from excluding classes from instrumentation. For example, if the STHME property’s hasnexttrue event is triggered from a third-party library class that is not instrumented, and the next event is triggered in affected\_\(\Delta\), a violation will occur even though the program satisfies the STHME property.

D. Violation Message Suppression (VMS)

VMS improves base RV by showing only new violations. Showing only new violations right after a change is more effective than showing old plus new violations to get developers to act—they are still in the mental context of the change and are the ones who can best address new violations [65].

Definition 7. Violation Message Suppression (VMS): A technique to show, in a new program version, only new violations that did not occur in an old version.

Base RV shows three violations in the new version of the example in Fig. 1d: line 4 (two instances), line 28 (two instances), and line 36 (one instance). The latter two were in the old version, and their line numbers did not change. (More generally, VMS does not simply check equality of line numbers but builds a likely mapping between old and new line numbers based on code context.) In the new version, VMS shows only the violation on line 4, instead of showing all three. VMS can be used with RPS to reduce the old violations shown by RPS. Running RPS on new version of Fig. 1d will show two violations (lines 4 and 28); VMS shows only one (line 4).

VMS’ inputs are the violations from the old and new versions, plus the source files in both versions. Each violation, \(v = (p, c, l)\), contains a triple of the property name \(p\) that was violated, and the class \(c\) and line number \(l\) of the last event that violated the property. Let \(V_1\) and \(V_2\) be the set of violations from monitoring the old version (\(P_1\)) and the new.
version \( (P_2) \), respectively. VMS computes \( V_{new} \), the set of new violations that are in \( P_2 \) but not in \( P_1 \). VMS does not simply compute \( V_2 \setminus V_1 \) that may report many old violations for which only the line numbers changed. Using only line numbers to match statements in two code versions performs poorly \([75]\).

For each class \( C_\delta \in \Delta \), where \( \Delta \) is the set of changed classes (including newly added and renamed classes), VMS first creates a mapping, \( M_{C_\delta} \), from line numbers in the source file of \( C_\delta \) in \( P_2 \) to line numbers with the likely same statement in the corresponding source file in \( P_1 \). Each line number in \( P_2 \) maps to at most one line number in \( P_1 \); some line numbers in \( P_2 \) may not be in \( M_{C_\delta} \). Note that \( M_{C_\delta} \) is likely (i.e., not exact) as it is based on simple syntactic and not semantic equivalence; the latter is rather challenging and does not scale currently \([28], [56]\). \( M_C \) is identity if \( C \) did not change. Then, \( V_{new}^{\Delta} = \cup_{C_\delta \in \Delta} VMS(V_1, V_2, M_{C_\delta}) \), where \( VMS(V_1, V_2, M_{C_\delta}) = \{(p, C_\delta, l) \in V_2 \mid \exists ! l' \in M_{C_\delta}(l) \lor (p, C_\delta, M_{C_\delta}(l)) \not\in V_1 \} \). Let \( \Delta' \) be the set of unchanged classes. New violations in \( \Delta' \) are \( V_{new}^{\Delta'} = \cup_{C \in \Delta'} VMS(V_1, V_2, M_C) \). \( V_{new} = V_{new}^{\Delta} \cup V_{new}^{\Delta'} \) is the output of VMS. \( V_{new}^{\Delta} \) is non-empty when interactions with changed classes cause new violations in \( \Delta' \), or when test non-determinism i.e., “flakiness” \([7], [9], [30], [58], [79]\) leads to non-determinism during monitoring.

**Discussion of VMS:** VMS can save developer time for inspecting violations but slightly increases machine time, e.g., VMS increases time by <1% in our experiments. As we showed with our example, VMS can further reduce violations shown by RPS.

**E. Regression Property Prioritization (RPP)**

Developers may be more interested in violations of critical properties than other violations, e.g., violations of properties that previously helped find bugs may be more critical. RPP partitions RV into two phases: a critical phase and a background phase. After a code change, the critical phase immediately re-monitors (manually or automatically selected) critical properties and provides results to developers. The background phase separately re-monitors other properties. Developers get delayed feedback if non-critical properties are violated. RPP allows (manually or automatically) moving properties between the phases as properties become more or less critical during software evolution. To evaluate RPP, we consider previously violated properties as critical. RPP is inspired by regression test prioritization \([22], [36], [78], [81], [87]\), but we are first to propose RPP for reducing RV overhead as software evolves.

**Discussion of RPP:** The benefit of RPP is to remove the re-monitoring of non-critical properties from developers’ critical path (from the moment of submitting code changes to the moment of getting feedback). RPP’s disadvantage is that it delays the time for developers to get feedback if non-critical properties are violated. RPS and VMS can be used with RPP—RPP merely first runs some subset of selected properties.

**IV. IMPLEMENTATION**

We present our implementation of RPS, VMS, and RPP.
average overheads of each phase. From the second version onward, if a property gets violated in the background phase, our RPP implementation moves it to the critical phase in the next version. We leave it as future work to investigate criteria for moving properties which have not been violated after a while from the critical phase back to the background phase.

V. EVALUATION

We list our research questions, describe our experimental setup, and answer the research questions.

A. Research Questions

We answer the following research questions: **RQ1:** How much does RPS reduce the machine time overhead of base RV? **RQ2:** How many violations does VMS show and how safe are RPS variants? **RQ3:** How much does RPP reduce time for developers to get feedback on critical properties?

B. Experimental Setup

**Projects:** Table III shows 10 open-source, Maven-based Java projects from GitHub used in our study, 9 of which we also used in prior work [51], [54], [80]. #Test is average number of test classes used (we skipped very few test classes from 6 projects due to problems with JavaMOP instrumentation), KLOC is average thousands of lines of code, Tests[s] is average test time, and $t_{mop}/t_{tests}$ is average base RV overhead.

**Properties:** We used 161 manually written properties found to be good in our prior study [52]. The properties were written to formalize Java APIs [50], [58] and are publicly available [70].

**Versions:** We started from a recent commit in each project and went back into the history, to select 20 commits/versions where (1) at least one `.java` file changed, (2) all tests pass without JavaMOP, and (3) all tests pass with JavaMOP.

**Running Experiments:** We wrote scripts to automate running tests, collect violations and measure time for three configurations on each version: (1) without JavaMOP, (2) with base RV, and (3) with each evolution-aware RV technique. For RPS, the most common case is that `.java` file changes modify the bytecode, so properties may need to be re-monitored. If `.java` file changes do not modify bytecode, we skip tests (no re-monitoring); time is only spent to check for changes. If changes affect bytecode, but no properties are selected to be re-monitored, all tests are run without JavaMOP, and the end-to-end time is the time to compute changes, find affected($\Delta$), check if properties need re-monitoring, and run tests.

C. RQ1: Overhead reduction from RPS

We present RV overhead in multiples ($\times$), as the ratio $t_{mop}/t_{tests}$, where $t_{mop}$ is time with JavaMOP and $t_{tests}$ is time without JavaMOP. We first show on a sample of 89 projects whether the high overhead induced by base RV can be seen in open-source projects with short- (<10s), medium- (10s–300s), and long-running (>300s) tests. These 89 projects were sampled from our prior studies [51], [52], [54], [80] and from the Apache continuous integration server. Fig. 6 plots $t_{mop}$ (x-axis, log scale, in seconds) vs. $t_{mop}/t_{tests}$ (y-axis). Projects in all three categories exhibit high overhead, so high base RV overhead is not a fixed cost that is more pronounced in projects with shorter-running tests. Squares show projects in this study. We did not evaluate our techniques on the other projects because (1) $t_{mop}$ is too small for RPS to be beneficial, (2) test-running times are high for long-running projects which requires more resources than we have to evaluate them, or (3) we could not get 20 versions that satisfy our criteria.

Solid bars in Fig. 7 show average runtime overhead of base RV ($BL$) and the RPS variants ($ps$) discussed in Section III-C. All overheads are computed from end-to-end time including time for analysis, running tests, and monitoring test executions. The results show several points. First, all RPS variants reduced the average base RV overhead, which is 9.4$\times$. Strong RPS variants, $ps_1$ and $ps_3$, have 7.9$\times$ and 7.5$\times$ overhead, respectively. As expected, weak RPS variants with fewer classes in affected($\Delta$) achieve more reduction. $ps_3$ is the most efficient weak RPS variant, with 2.5$\times$ overhead. Second, comparing $BL$ and $BL^*$ shows that base RV spends about 36% of overhead on third-party library code: $(BL−BL^*)/BL$. Since $ps_3^*$ is safe under certain assumptions, and, as we show in Section V-D, excluding unaffected and third-party library classes was safe in our experiments, $ps_3^*$ may, in general, achieve the best efficiency/safety tradeoff among weak RPS variants.

We also evaluated how much regression test selection (RTS) [14], [23], [24], [26], [27], [31], [51], [77], [87], [88]
can reduce base RV overheads during software evolution. RTS is a general approach (independent of RPS) for reducing the overhead of regression testing by re-running only a subset of tests whose behavior can differ after code changes. We previously noted that RTS can also reduce base RV overhead, since RTS already reduces testing overhead [53]. We evaluate a static class-level RTS technique, implemented in STARTS, which uses the same CDG as RPS. (Other RTS techniques compute dependencies dynamically [24], [26], [88], but it was challenging to evaluate them because their instrumentation often clashed with JavaMOP.) Since RTS can select more tests than those whose behavior differs after a code change, it may be imprecise as an evolution-aware RV technique (Section III-A). So, we also evaluated RPS plus RTS to see how these two can together further reduce base RV overhead.

The four rightmost solid bars in Fig. 7 show the overhead with RTS, with and without libraries. ts shows combination of RTS with base RV, i.e., rerun a subset of tests but re-monitor all properties, while ps indicates RTS (using variant ps) plus RTS, i.e., rerun a subset of tests and re-monitor a subset of properties. When measuring the overhead, we used end-to-end RTS time, which includes the time to select the tests. Combining base RV with RTS has $6.4 \times$ overhead, compared with $9.4 \times$ for base RV. RPS plus RTS gives lower overhead ($5.9 \times$) than RTS alone, showing that RPS can provide value even where RTS is used. Since RTS can be unsound, it may incorrectly miss to select tests [23], [26], [51], [77], which makes RTS an unsafe evolution-aware RV technique. Finally, as we show in RQ2, RTS by itself is imprecise; it should be combined with VMS to show only new violations.

D. RQ2: VMS and RPS Safety

We discuss the results of VMS, and how we used these results to guide our manual checking of RPS safety. The striped bars in Fig. 7 show average number of violations from all techniques evaluated in Section V-C; the vms bar shows VMS average. The most significant result is that VMS is orders of magnitude more precise than RPS. For four projects, no new violation occurred in the range of versions.

Further, library exclusion results in very little difference in the average number of violations, which is good, because most violations can still be found when libraries are excluded. Very few violations in the libraries makes sense because libraries are widely used and tend to be better tested. We manually checked all violations that are not generated when libraries are excluded and found 87.5% of them to be in the third-party libraries themselves, and not in the project code. Among these, only one was a new violation and it was due to a library version change—all events leading to the violation were in the new version of the library, so library exclusion did not lead to missing any new violation in the projects. All violations that are missed in projects when excluding libraries were not new violations, providing some justification for excluding libraries when one does not care about violations in libraries, and partial explanation for why library exclusion did not lead to missing new violations.

RPS Safety: We manually confirmed safety of RPS variants by checking if all new violations from VMS were also reported by each variant. VMS reported a total of 33 new violations in 16 of the 200 versions across all projects. Of these, 5 were due to flakiness, which we confirmed by re-running several times (i.e., these 5 violations could also have happened in the old version). All RPS variants found 27 of the new violations, but all missed one new violation. The one new violation that all variants missed was the aforementioned library version change. It is surprising that weak RPS variants were safe in our experiments, since they are theoretically unsafe. Therefore, we carried out further manual inspection of the changes involved...
We change. The rest of the time is spent on monitoring.

classes from which new events may be generated after a code
repackage the Jar file with selected properties, and to find the
properties (three times more than its overhead for monitoring critical
overhead for monitoring background properties (6)). The second finding is that overheads for
monitoring all properties together, (4) reduce RV overhead by sharing information among monitors (20), [58], [72], (5) support efficient monitoring of properties written in
different formalism [5], [32], [59], [60], (6) analyze observed
executions in monitors to infer characteristics of unseen executions [12], [13], (7) allow RV to monitor multiple properties in
one execution [44], [58], (8) reduce the time that RV wastes in
loops [71], etc. Tools include Eagle [3], JavaMOP [40], [43],
[58], jMonitor [45], JPaX [33], MarQ [74], MOPBox [10],
Mufin [20], Ruler [5], and TraceMatches [1], [11]. We used
JavaMOP because it is publicly available [40]. A complemen-
tary line of research is to automatically mine the properties
that RV can monitor [6], [15], [19], [25], [46], [48], [49],
[55], [62], [63], [67]–[69], [73], [76], [85], [86], [90].

Our recent large-scale study [52] showed that RV can find
many new bugs during testing, but at high overhead of 4.3×
for base RV, with the extra time incurred by JavaMOP (4.08s
– 12.48s) being too small for RPS to be beneficial.

VII. RELATED WORK

Many RV techniques and tools were proposed in almost
two decades since the first papers on RV [33], [34], mostly
concerned with speeding up RV on one program version.
Example techniques (1) improve the efficiency of synthesizing
monitors [35], (2) improve the efficiency of monitor garbage
collection [42], [44], [58], (3) create a virtual machine to
make RV more efficient in production [2], (4) reduce RV
overhead by sharing information among monitors [20], [58],
[72], (5) support efficient monitoring of properties written in
different formalism [5], [32], [59], [60], (6) analyze observed
executions in monitors to infer characteristics of unseen
executions [12], [13], (7) allow RV to monitor multiple properties in
one execution [44], [58], (8) reduce the time that RV wastes in
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for base RV, with the extra time incurred by JavaMOP (4.08s
– 12.48s) being too small for RPS to be beneficial.

VI. DISCUSSION

We highlight internal details of RPS and properties that
contributed the most monitors and events in each project.

RPS Internals: Our analysis of data from running RPS shows
that changes are small compared to the size of the program,
and that our analysis is very fast compared to the time for
monitoring. The data here is for ps1. The average CDG in our
experiments had 720 nodes and 3706 edges. On average, Δ
contained 7 nodes each version, leading to an average of 233
nodes in affected(Δ). The total analysis time was 4.3% of the
event time—this includes the time to find affected(Δ),
repackage the Jar file with selected properties, and to find the
classes from which new events may be generated after a code
change. The rest of the time is spent on monitoring.

Different properties dominated base RV overhead: We
measured the number of monitors created, events triggered,
and the top two properties that contribute the most monitors
(Top M) and events (Top E). No property always dominated
monitor creation or event generation, but two properties,
Iterator_HasNext and StringBuilder_ThreadSafe are
in Top M for all projects. No property dominates Top E.
Iterator_HasNext and StringBuilder_ThreadSafe are
quite common in Top E and generate most events in open-
tripplanner, the project with the highest base RV overhead.
Iterator_HasNext helped find several bugs [52], so devel-
opers may still want to monitor it. We are not aware that
StringBuilder_ThreadSafe previously helped find bugs.

E. RQ3: RPP Effectiveness

Fig. 8 shows RPP results, where the RPS variants do not
exclude libraries. The first finding is that RPP alone (noRPS)
overhead for monitoring background properties (bg) is roughly
three times more than its overhead for monitoring critical
properties (cr). The second finding is that overheads for cr
and bg do not sum up to base RV overhead. For all projects,
but one, cr+bg noRPS is greater than BL. Being greater is
expected because time to run tests is repeated between cr
and bg. The surprising project is opentripplanner, where the sum of
cr and bg is less than BL for monitoring all properties together,
likely due to reduced memory pressure when the properties are
split. Finally, cr with ps3y, has only 1.8× overhead, compared
with 9.4× for base RV.

V. CONCLUSIONS

We presented three evolution-aware RV techniques: RPS,
VMS, and RPP. Our techniques reduced base RV overhead
from 9.4× to as low as 1.8×, were safe, and showed two
orders of magnitude fewer violations than base RV. Our results
provide strong evidence that taking evolution into account can
significantly improve base RV.

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