Techniques for Evolution-Aware Runtime Verification

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Runtime Verification (RV)

- RV dynamically checks program executions against formal properties, whose violations can help find bugs
  - a.k.a. runtime monitoring, runtime checking, monitoring-oriented programming, typestate checking, etc.
- RV has been around for decades, now has its own conference (RV)
- Many RV tools:

JavaMOP: a representative RV tool

Example property: Collection_SynchronizedCollection (CSC)

https://docs.oracle.com/javase/7/docs/api/java/util/Collections.html#synchronizedCollection(java.util.Collection)

synchronizedCollection

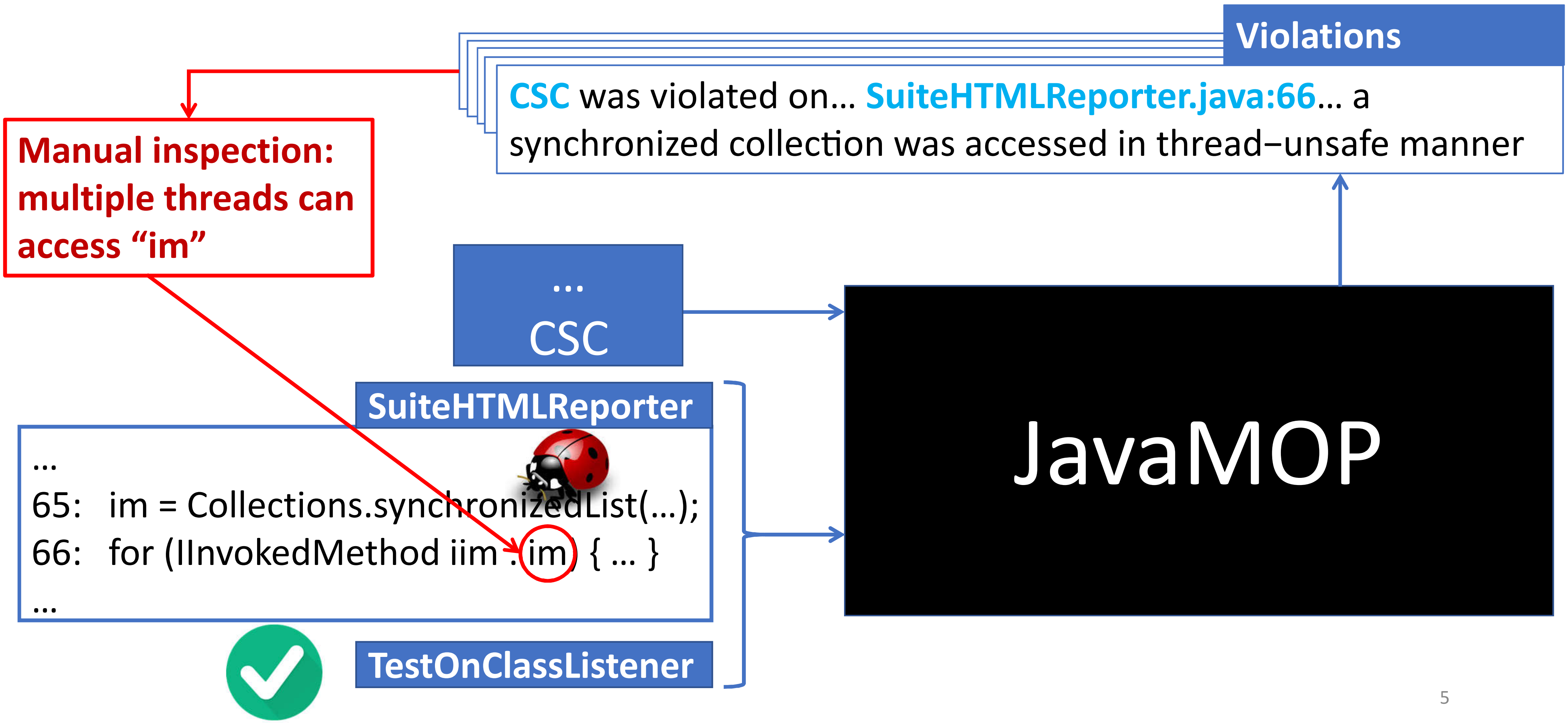
```
public static <T> Collection<T> synchronizedCollection(Collection<T> c)
```

It is imperative that the user manually synchronize on the returned collection when iterating over it:

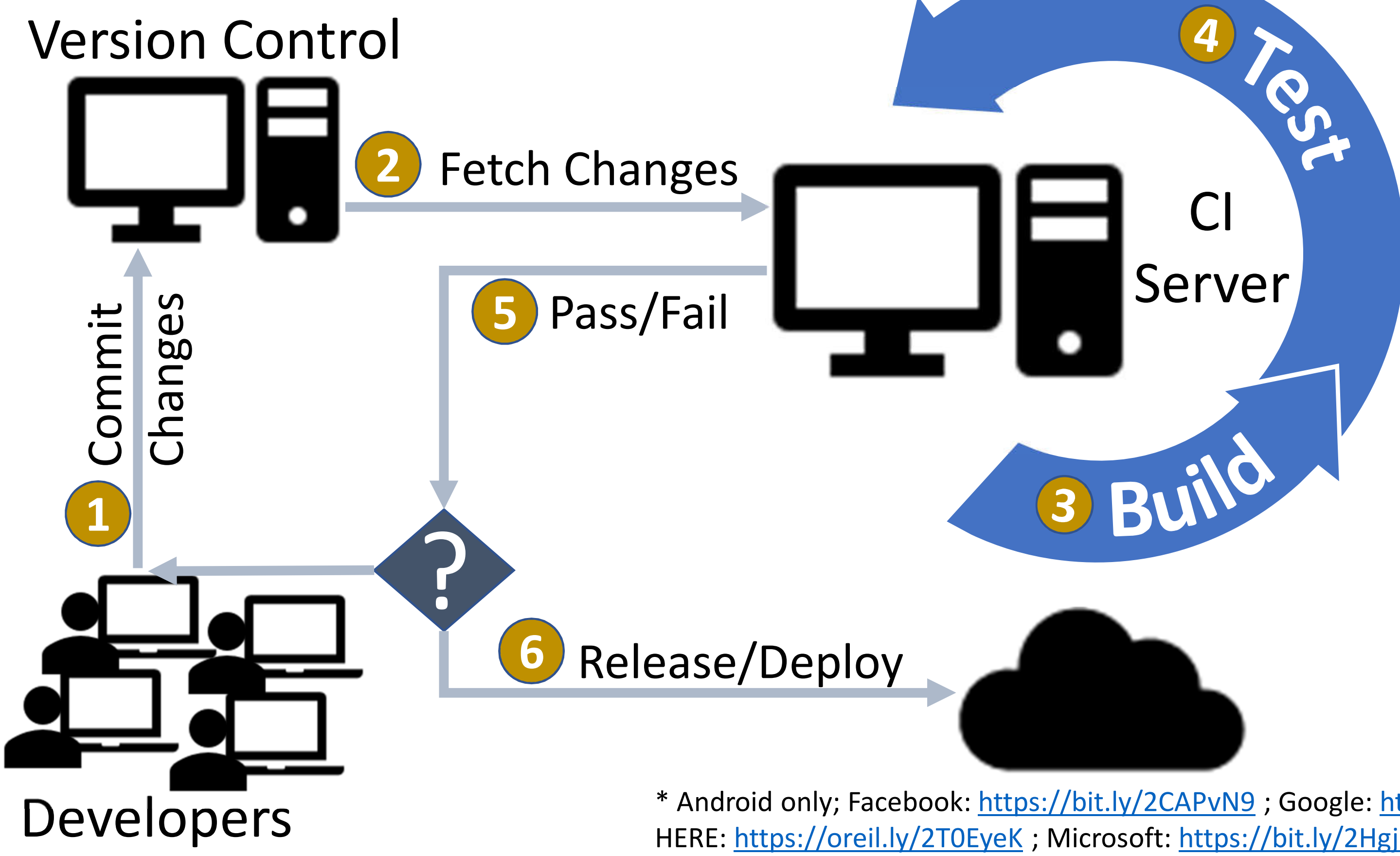
```
Collection c = Collections.synchronizedCollection(myCollection);
   ...
synchronized (c) {
    Iterator i = c.iterator(); // Must be in the synchronized block
    while (i.hasNext())
       foo(i.next());
}
```

Failure to follow this advice may result in non-deterministic behavior.

TestNG example: from RV of test executions to bugs



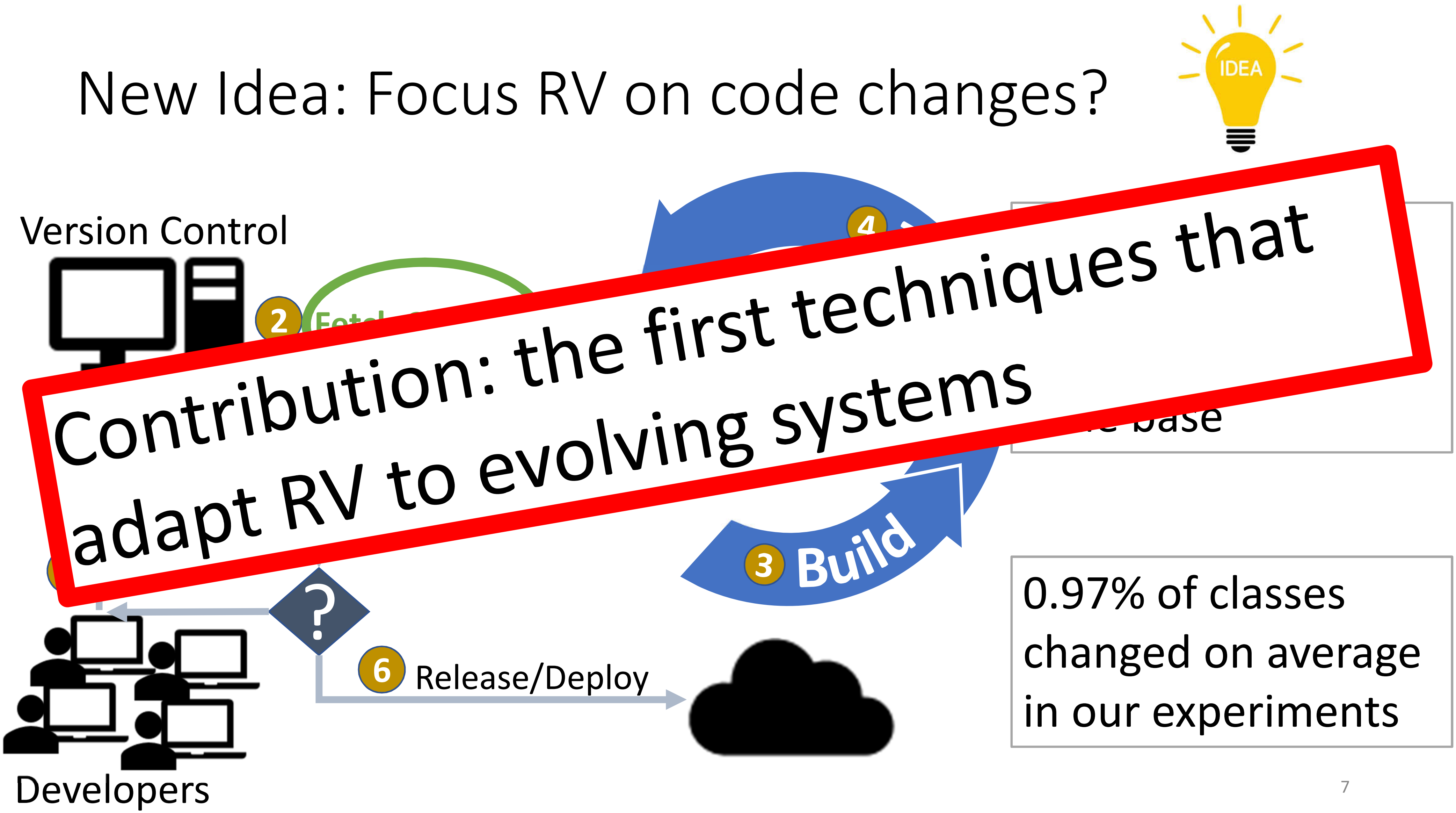
RV during Continuous Integration (CI)?



- Observation: All prior RV techniques are **evolution-unaware (Base RV)**
- **Base RV would re-incur entire overhead if re-run after each code change**

* Android only; Facebook: https://bit.ly/2CAPvN9 ; Google: https://bit.ly/2SYY4rR ; HERE: https://oreil.ly/2T0EyeK ; Microsoft: https://bit.ly/2HgjUpw ; Etsy: https://bit.ly/2IiSOJP ;

New Idea: Focus RV on code changes?



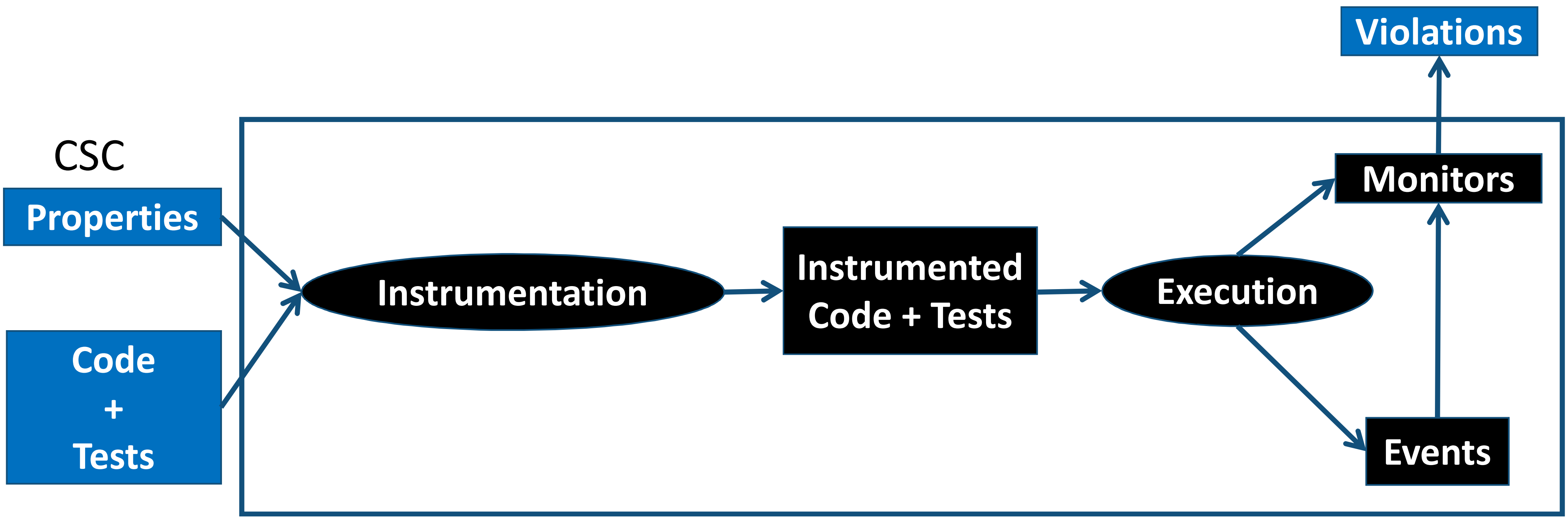
Contribution: Evolution-aware Runtime Verification

- Goal: leverage software evolution to scale RV better during testing

- Intended benefits:
  1. Reduce accumulated runtime overhead of RV across multiple program versions
  2. Show developers only new violations after code changes

- Complementary to techniques that improve RV on single program versions
  - Faster RV algorithms for single program versions
  - Running tests in parallel
  - Improve properties to have fewer false alarms

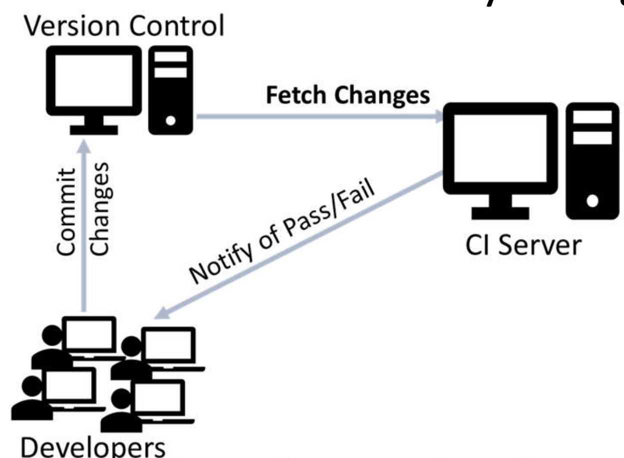
How JavaMOP works



Collections.synchronizedList()
Collection+.iterator()

We proposed three evolution-aware RV techniques

1. Regression Property Selection (RPS)
   - Re-monitors only properties that can be violated in parts of code affected by changes

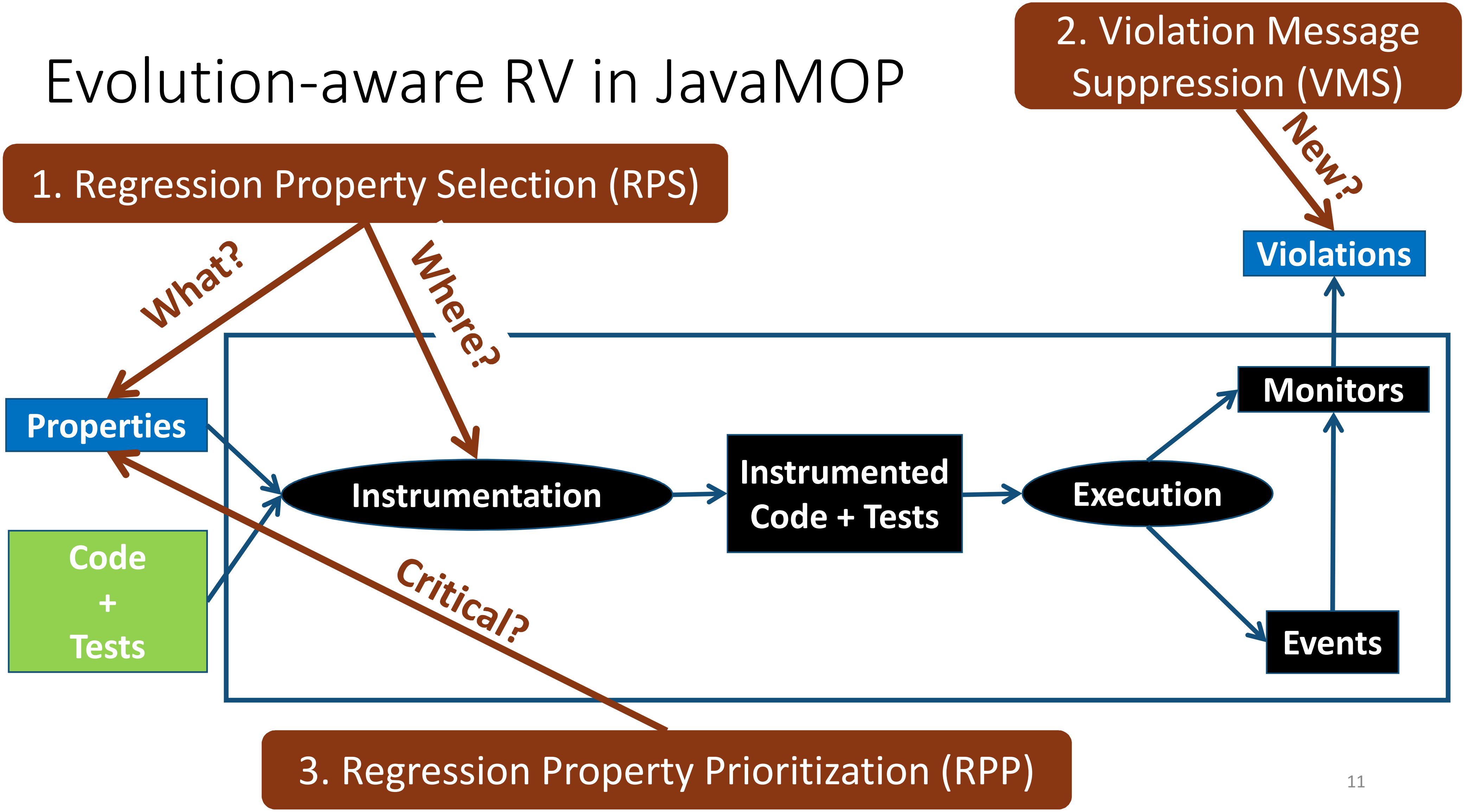


2. Violation Message Suppression (VMS)
   - Shows only new violations after code changes

3. Regression Property Prioritization (RPP)
   - Splits RV into two phases:
     - **critical phase:** check properties more likely to find bugs on developer's critical path
     - **background phase:** monitor other properties outside developer's critical path

The three techniques can be used together

Evolution-aware RV in JavaMOP

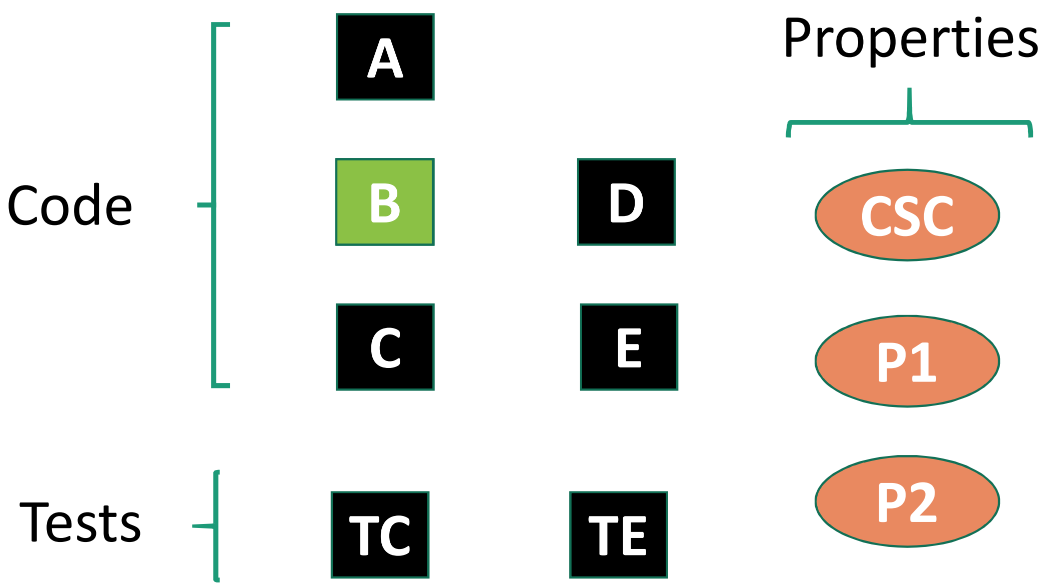


Evolution-aware RV – Result Overview

- RPS and RPP significantly reduced accumulated runtime overhead of Base RV
  - Average: from **9.4x** to **1.8x**
  - Maximum: from **40.5x** to **4.2x**
- VMS showed **540x fewer** violations than Base RV
- RPS did **not miss any new violation** after code changes
  - In theory can miss, but empirically it did not
- See paper for details on VMS and RPP

Base RV during software evolution

- Base RV re-monitors all properties after every code change
- No knowledge of dependencies in the code, or between code and properties

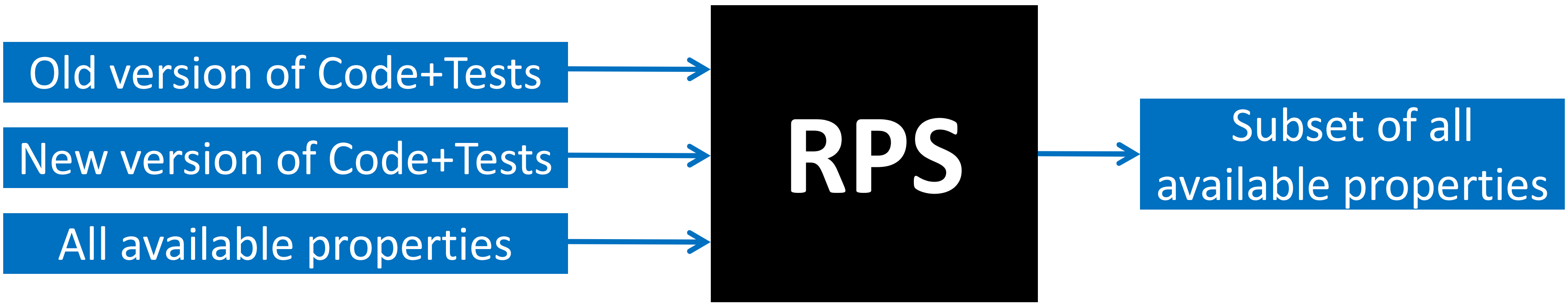


Old Version: monitor CSC, P1, P2

New Version: re-monitor CSC, P1, P2

$\Delta = \{B\}$

Regression Property Selection (RPS) Overview

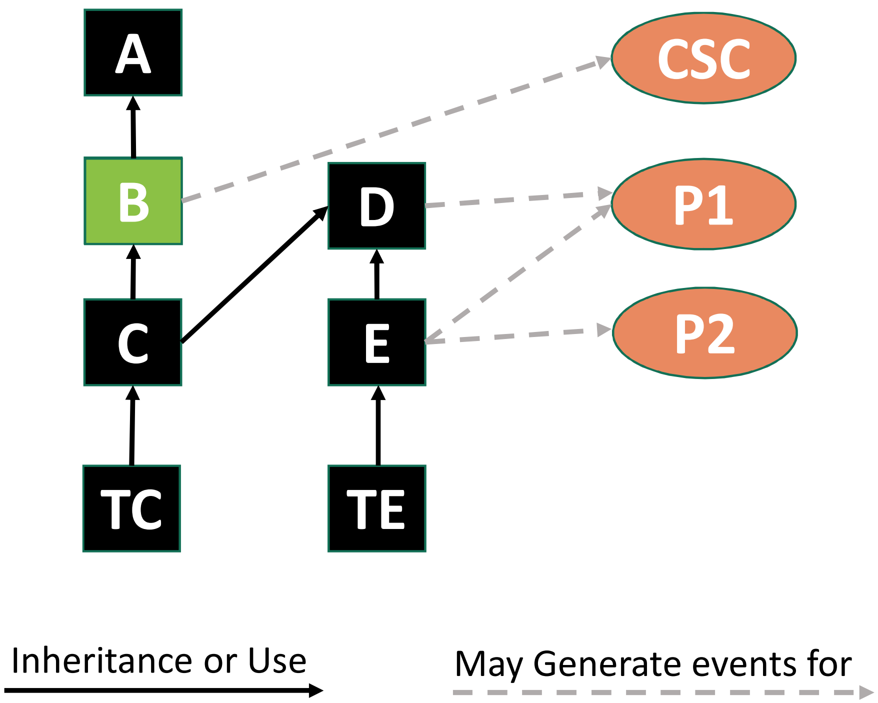


Selected subset of properties are those that may generate new violations

Regression Property Selection (RPS) – step 1

Re-monitors only properties that can be violated in parts of code affected by changes

$\Delta = \{B\}$



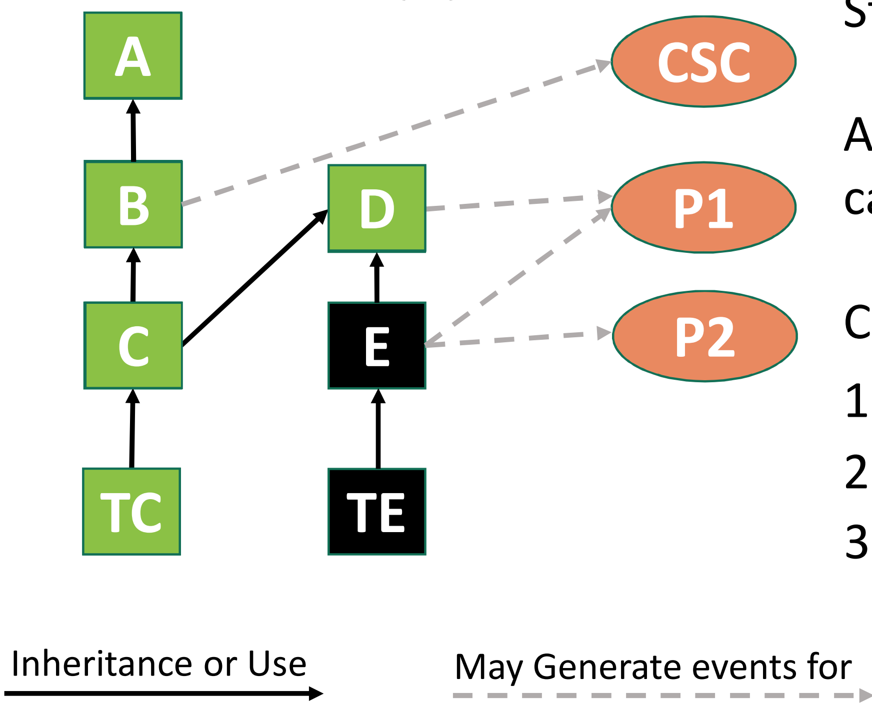
Step 1a: Build Class Dependency Graph (CDG) for new version

Step 1b: Map classes to properties for which the classes may generate events

Regression Property Selection (RPS) – step 2

Re-monitors only properties that can be violated in parts of code affected by changes

$\Delta = \{B\}$



Step 2: Compute affected classes

Affected classes: those that generate events that can lead to new violations after code changes

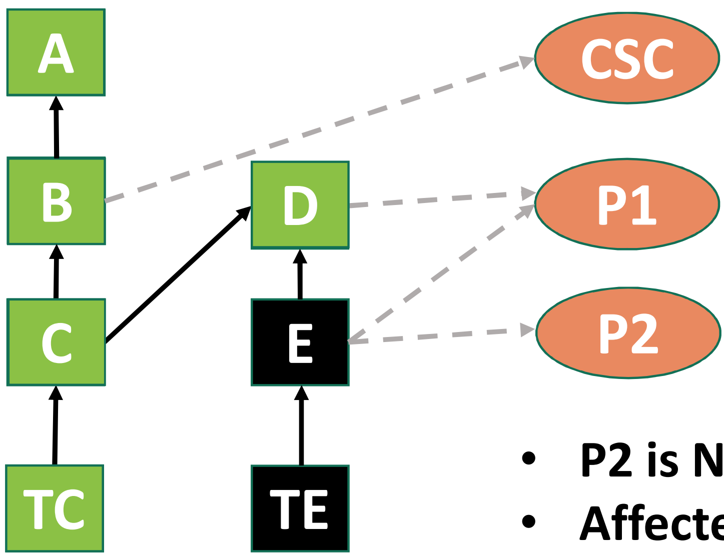
Class X is affected if

1. X changed or is newly added
2. X transitively depends on a changed class, or
3. Class Y that satisfies (1) or (2) can transitively pass data to X

Regression Property Selection (RPS) –Steps 3 & 4

Re-monitors only properties that can be violated in parts of code affected by changes

$\Delta = \{B\}$



Step 3: Select affected properties – those for which affected classes may generate events

Step 4: Re-monitor affected properties: **{CSC, P1}**

- **P2 is NOT re-monitored in the new version**
- **Affected classes cannot generate P2 events**
- **Saves time to monitor P2; does not show old P2 violations**

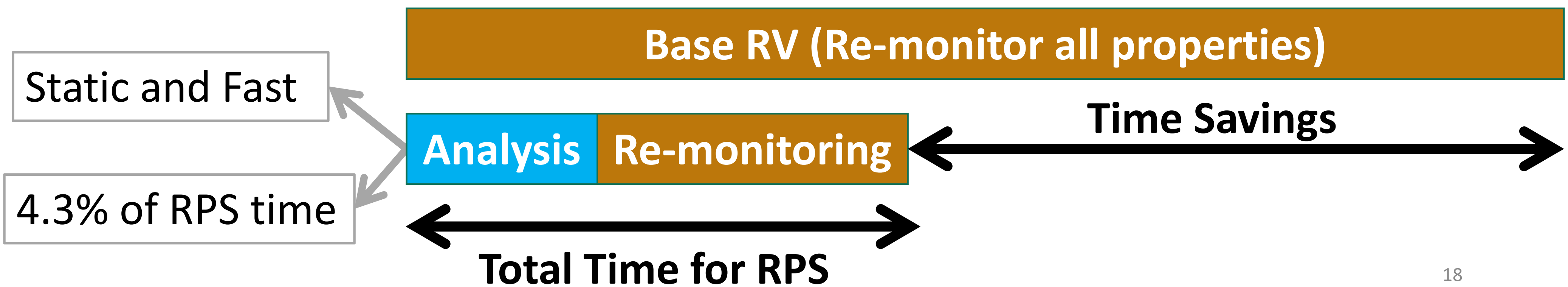
Inheritance or Use

May Generate events for

Total RPS time must be less than Base RV time

Analysis
- Step 1a: Build Class Dependency Graph (CDG) for new version
- Step 1b: Map classes to properties for which they may generate events
- Step 2: Compute affected classes
- Step 3: Select affected properties

Re-monitoring
- Step 4: Re-monitor only affected properties

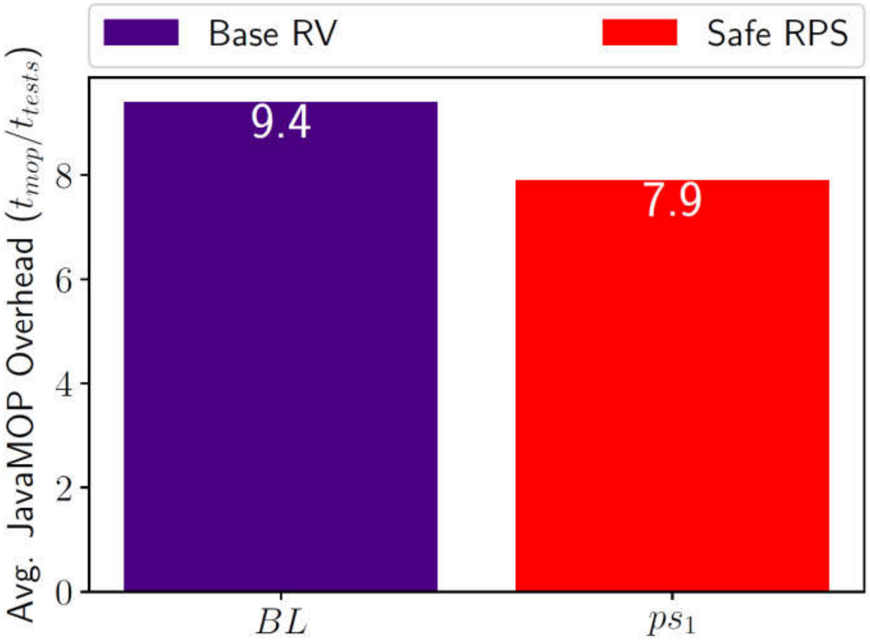


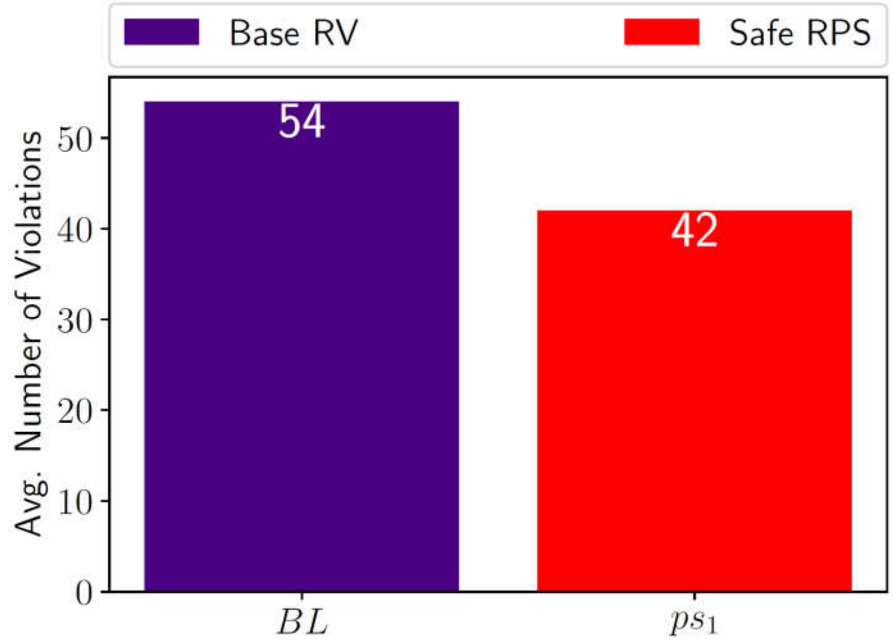
RPS Safety and Precision - Definitions

- Evolution-aware RV is **safe** if it finds all new violations that Base RV finds
- Evolution-aware RV is **precise** if it finds only new violations that Base RV finds
- RPS discussed so far is safe but not precise
  - Safe modulo CDG completeness, test-order dependencies, dynamic language features

Results of Safe RPS – ps_1

- 20 versions each of 10 GitHub projects
  - Average project size: 50 KLOC
  - Average test running time without RV: 51 seconds



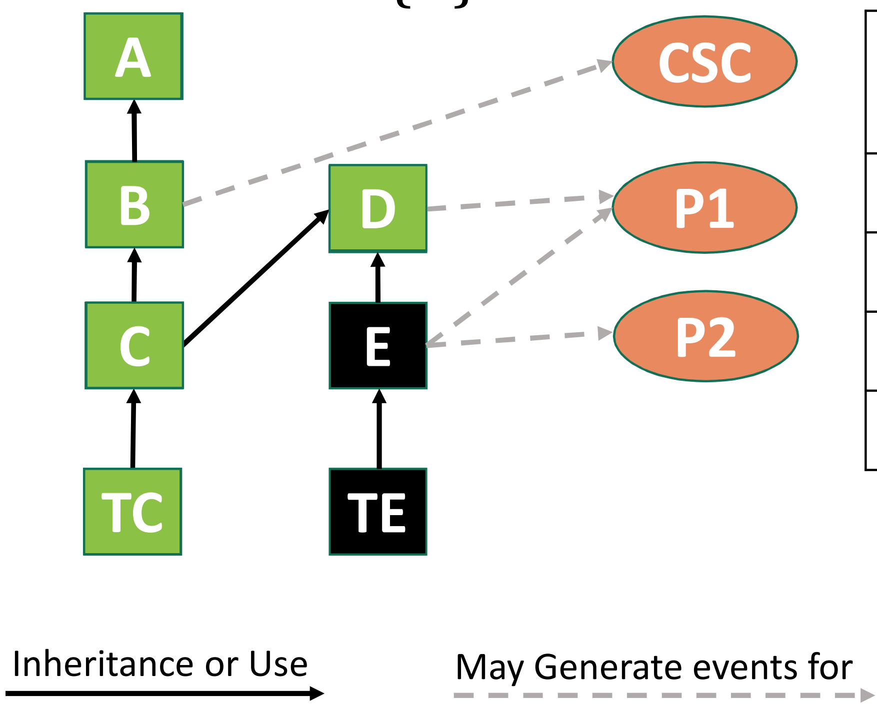


How can we improve these results?

RPS variants that use fewer affected classes

Goal: Reduce RV overhead by varying "what" set of affected classes is used to select properties

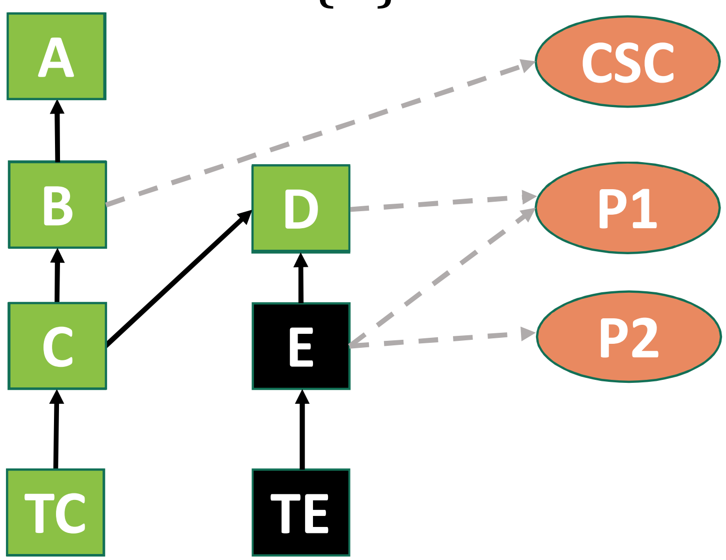
$\Delta = \{B\}$



What classes are used to select properties?	ps_1	ps_2	ps_3
Changed classes (i.e., Δ)	✓	✓	✓
Dependents of Δ	✓	✓	✓
Dependees of Δ	✓	✓	✗
Dependees of Δ's Dependents	✓	✗	✗

Using fewer affected classes can be (un)safe, e.g., ps_2

$\Delta = \{B\}$




```
class B {
 - public static boolean b = false;
 + public static boolean b = true;
}
```

```
class C {
  void getF() {
    D.foo(B.b);
}}
```

```
class D {
 static void foo(boolean b) {
    if (b) { // P1 events}
    else { // No P1 events}
}}
```

ps_2 can be safe if C does not pass data to D

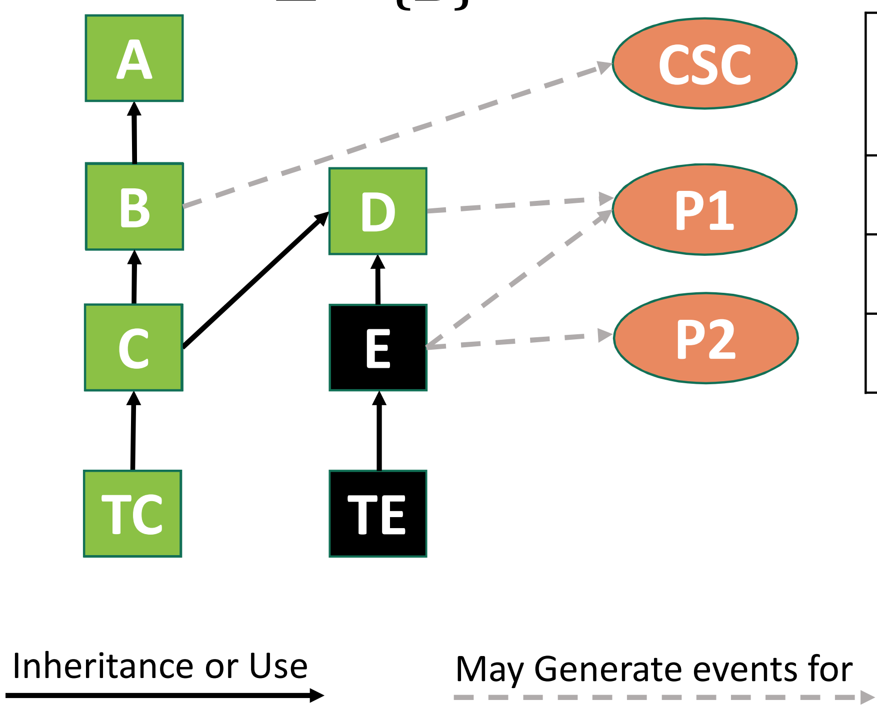
Inheritance or Use

May Generate events for

RPS variants that instrument fewer classes

Goal: Reduce RV overhead by varying "where" selected properties are instrumented

$\Delta = \{B\}$

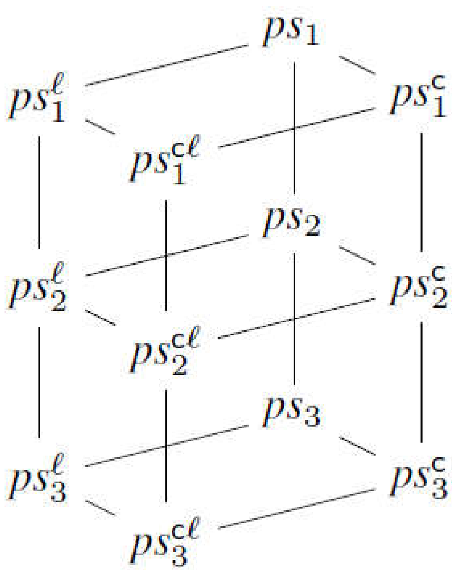


Where selected properties are instrumented ($i \in \{1,2,3\}$)	ps_i	ps_i^c	ps_i^l	ps_i^{cl}
affected(Δ)	✓	✓	✓	✓
affected(Δ)^c	✓	✗	✓	✗
third-party libraries	✓	✓	✗	✗

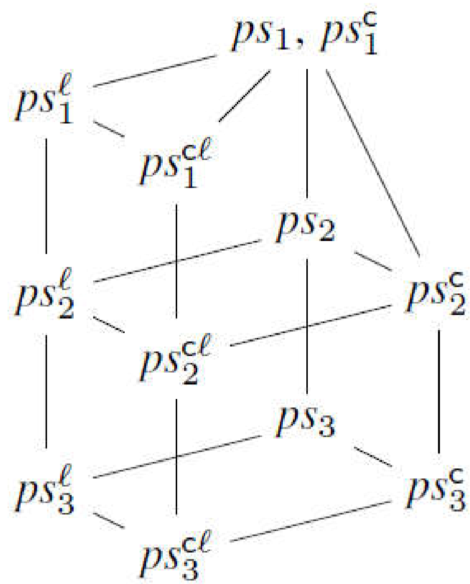
- have fewer violations
- ~36% of RV overhead
- excluding them can be safe

RPS Variants – Expected Efficiency/Safety Tradeoff

“more efficient than”



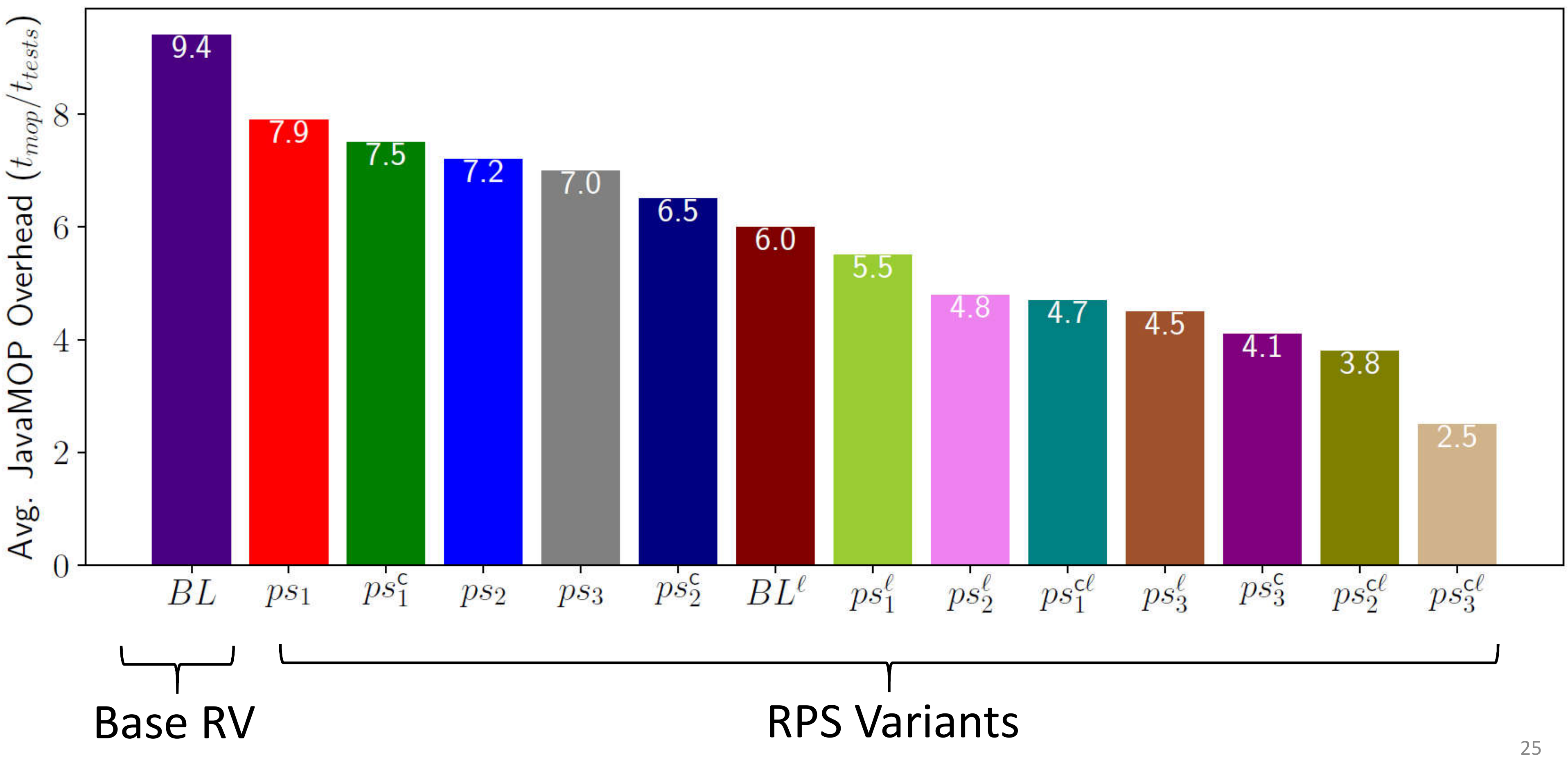
“less safe than”



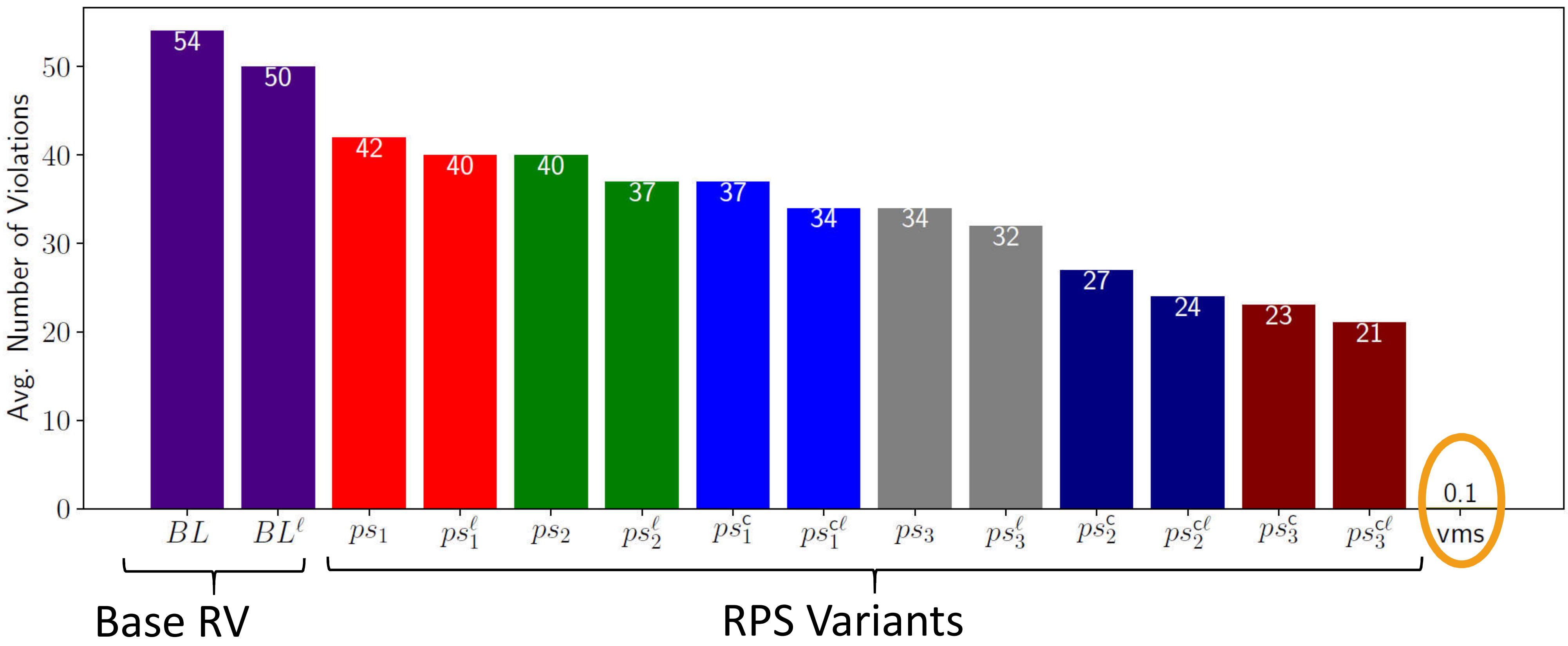
2 **Strong RPS** variants are safe under certain assumptions: ps_1 and ps_1^c

10 **Weak RPS** variants are unsafe; they trade safety for efficiency

RPS Results – Runtime Overhead



RPS Results – Violations Reported



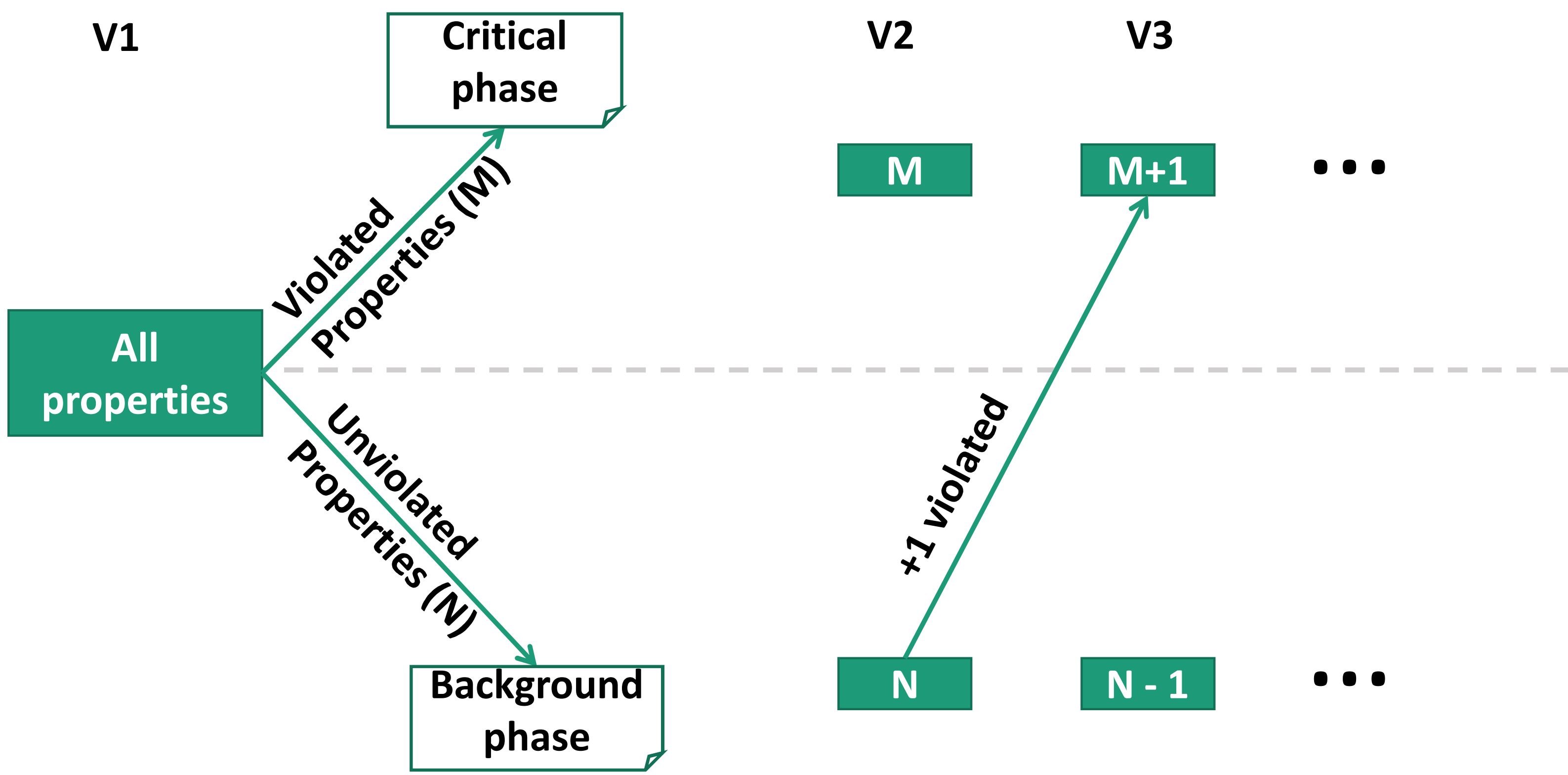
RPS Results – precision and safety

- VMS is precise – it shows only new violations
  - RPS is not precise – it shows two orders of magnitude more violations than VMS
- We manually confirmed whether all RPS variants find all violations from VMS
- Surprisingly, all weak RPS variants were safe in our experiments

Why weak RPS variants were safe in our experiments

- 75% of event traces observed by monitors involved only one class
- 32 of 33 new violations were due to changes whose effects are in ps_3
  - Additional scenarios captured by ps_1 and ps_2 did not lead to new violations
  - We may have missed old violations when not tracking ps_1 or ps_2 scenarios
- 87% of old violations missed by excluding third-party libraries did not involve any event from the code

Regression Property Prioritization (RPP)



Combining RPS+RPP reduced RV overhead to 1.8x (from 9.4x)

Conclusion

- We proposed three evolution-aware RV techniques: RPS, VMS, RPP
- Our techniques reduced Base RV overhead from 9.4× to as low as 1.8×
- Taking evolution into account can significantly reduce Base RV overhead during software evolution

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