CS 5154
Integrating Runtime Verification with Software Testing

Spring 2021

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Software has become more critical to most aspects of our daily lives

The risk posed by software failure has also grown

The New York Times

Airline Blames Bad Software in San Francisco Crash

GOOGLE SELF-DRIVING CAR CAUSED FREEWAY CRASH AFTER ENGINEER MODIFIED ITS SOFTWARE

BY JASON MURDOCK ON 10/17/18 AT 11:34 AM

Newsweek

Hard Questions Raised When A Software 'Glitch' Takes Down An Airliner

Forbes

Nest thermostat bug leaves users cold

By Jane Wakefield
Technology reporter

14 January 2016

BBC

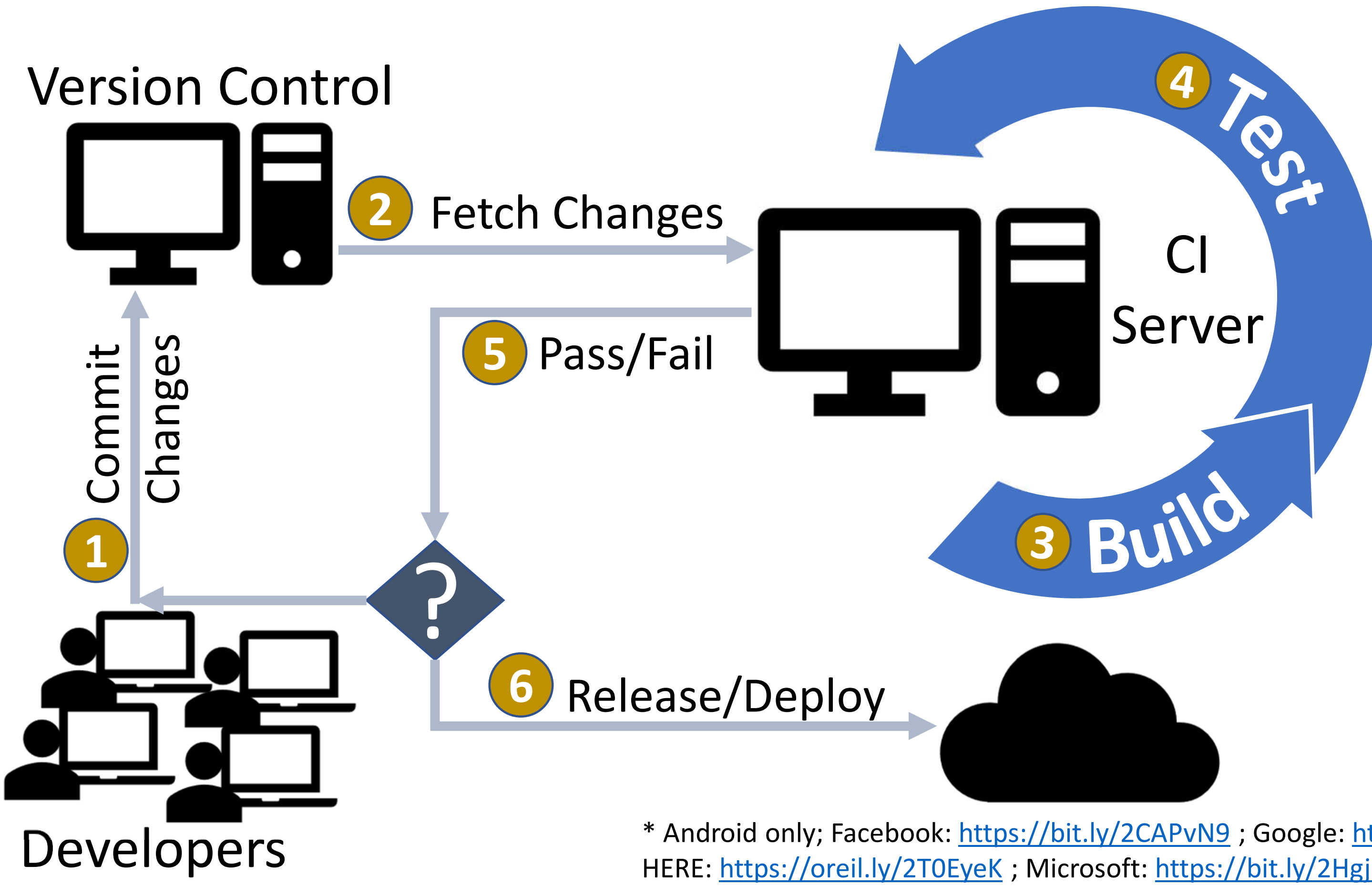
Report: Software failure caused $1.7 trillion in financial losses in 2017

TechRepublic.

Software testing company Tricentis found that retail and consumer technology were the areas most affected, while software failures in public service and healthcare were down from the previous year.

By Scott Matteson | January 26, 2018, 7:54 AM PST

Continuous Integration (CI): rapid test/release cycles



Builds per day:

- Facebook: 60K*
- Google: 17K
- HERE: 100K
- Microsoft: 30K
- Single open-source projects: up to 80

Releases per day

- Etsy: 50

* 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 ;

Several important problems exist in these cycles

P1: Passing tests miss bugs

S1: Find more bugs from tests that developers already have

P3. Testing can be very slow

S3: Find bugs faster by speeding up testing

P2. Failed tests, no buggy changes

S2: Find bugs more reliably by detecting such failures

P4. How to test in new domains?

S4: Find bugs in emerging application domains

HERE: https://oreil.ly/2T0EyeK ; Microsoft: https://bit.ly/2HgJUpw ; Etsy: https://bit.ly/2IiSOJP ;

The problem that we'll talk about today

Problem: Passing tests miss bugs

Our Solution: Use Runtime Verification to find more bugs from tests that developers <u>already</u> have

Developers

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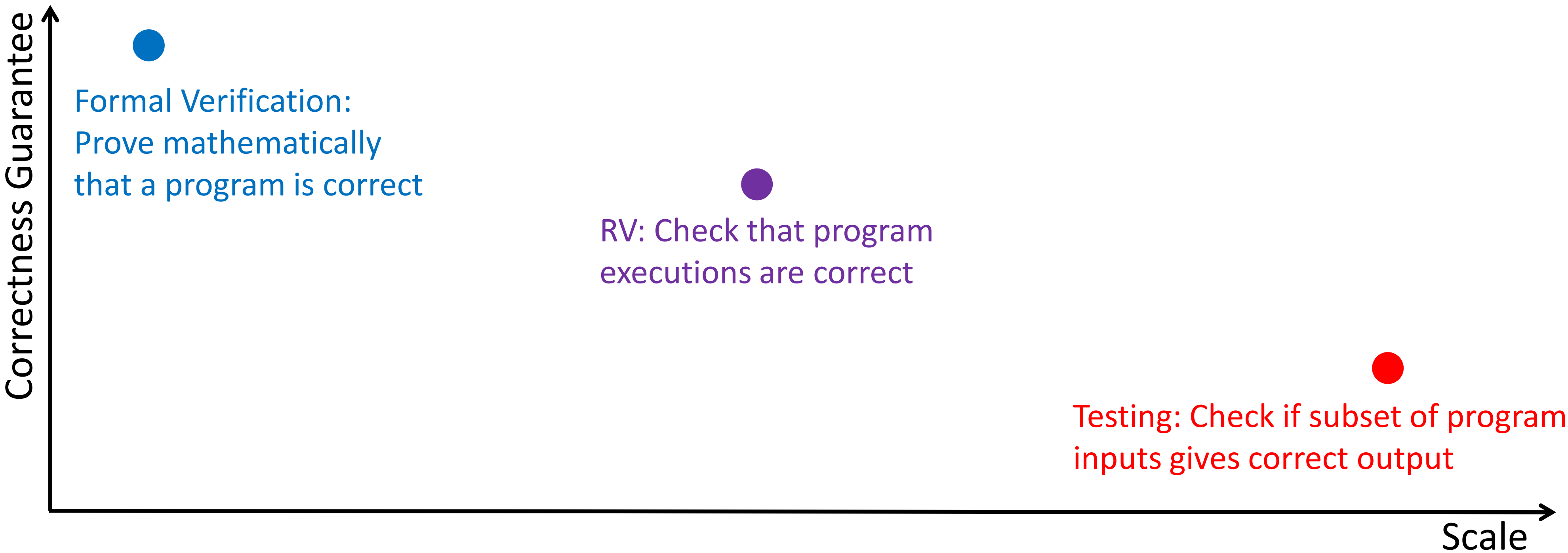
In this lecture

- Integrating a lightweight formal method called runtime verification with everyday software testing
  - Benefits (find more bugs earlier)
  - Challenges (high overheads)
  - Progress on resolving some of the challenges

Introduction to Runtime Verification (RV)

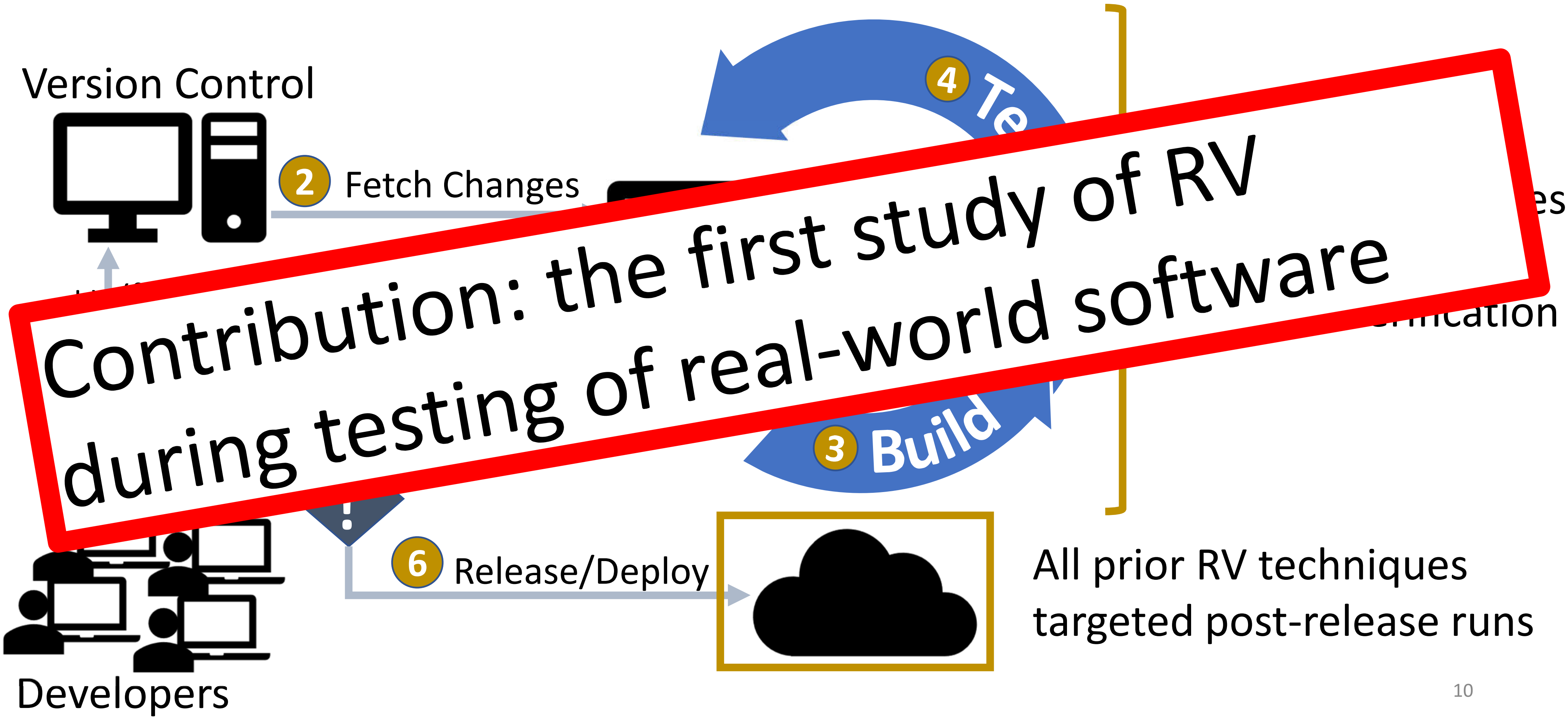
- RV dynamically checks program executions against formal properties, whose violations can help find bugs
  - a.k.a. runtime monitoring, runtime checking, monitoring-oriented programming, typestate checking, etc.
- RV has been around for decades, now has its own conference
- Many RV tools:

One reason why RV is appealing

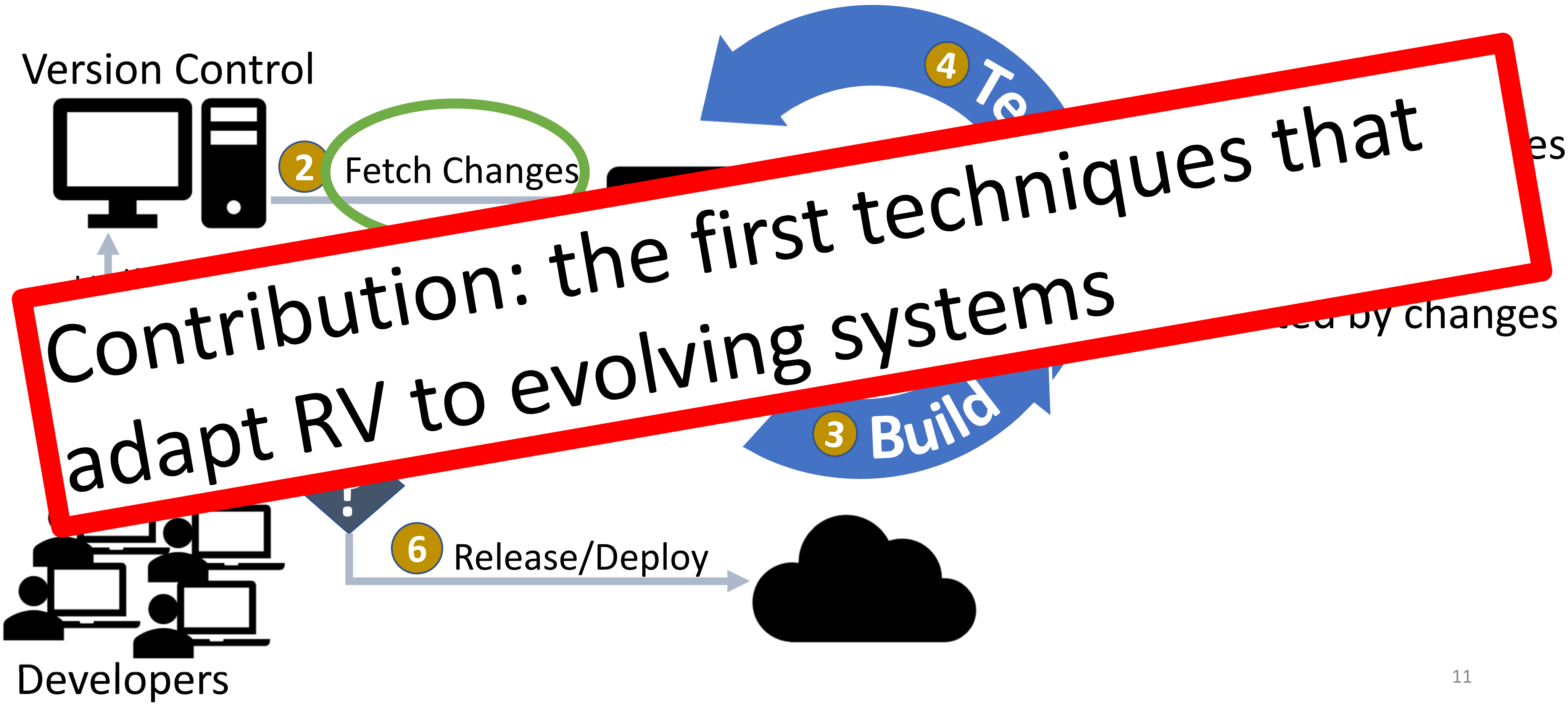


Can RV help bring some of the mathematical rigor of formal verification to everyday software development?

No study of RV during testing of real-world software



No previous RV techniques for evolving systems



Contribution: the first techniques that adapt RV to evolving systems

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.

CSC property in JavaMOP

Parameters

```
Collections_SynchronizedCollection (Collection c, Iterator i) {
 Collection c;
 creation event sync after() returning (Collection c):
   call (Collections.synchronizedList(Collection)) ...
 event syncMk after (Collection c) returning (Iterator i):
   call (Collection+.iterator()) && target (c) && condition (Thread.holdsLock(c)) {}
 event asyncMk after (Collection c) returning (Iterator i):
   call ( Collection+.iterator() && target(c) && condition (!Thread.holdsLock(c)) {}
 event access before (Iterator i):
   call ( Iterator.*(..)) && target (i) && condition (!Thread.holdsLock(this.c)) {}
   ere : ( sync asyncMk) | (sync syncMk access)
   @match { RVMLogging.out.println ( Level.CRITICAL, __DEFAULT_MSG); ... }
}
```

Events: related method calls or field accesses

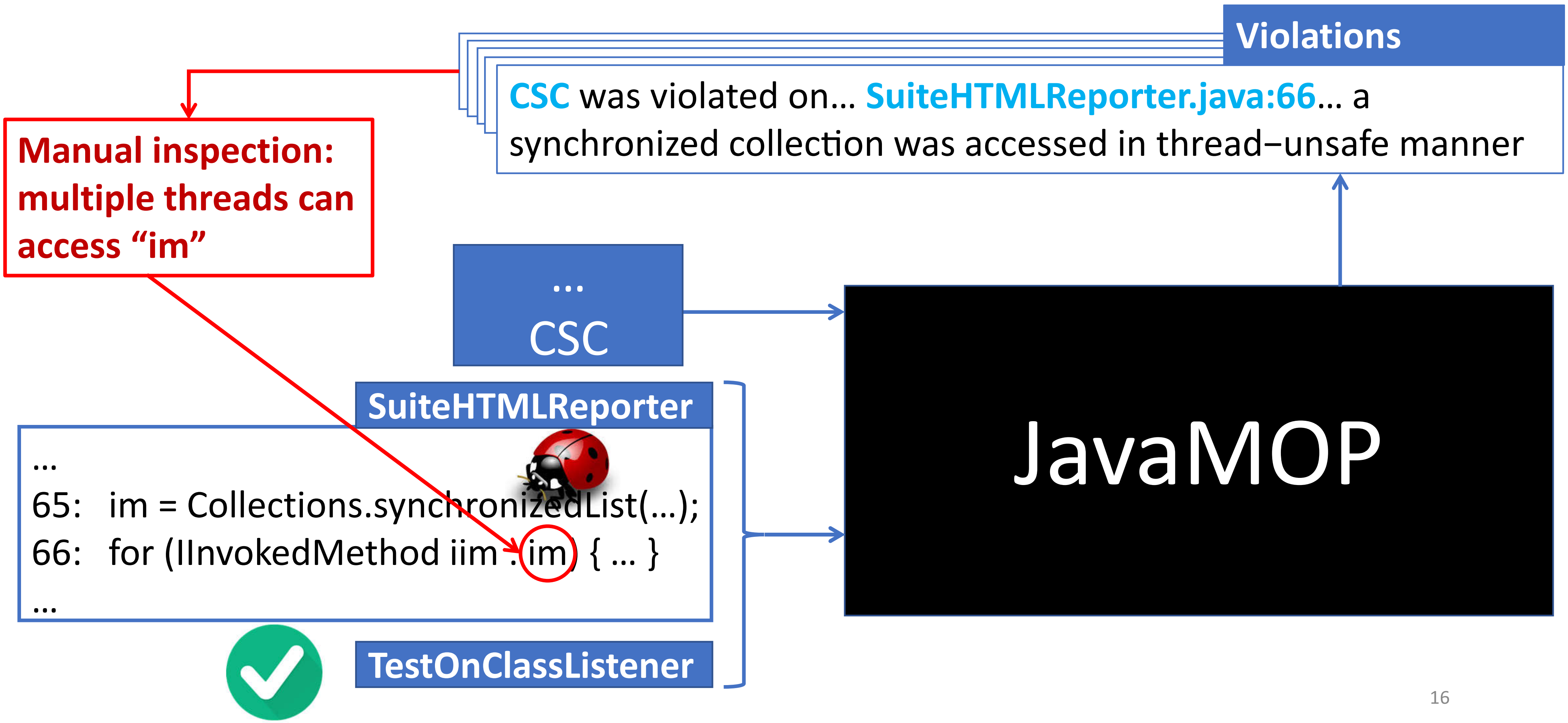
Specification: logical formula over the events

Handler: action taken after specification is violated

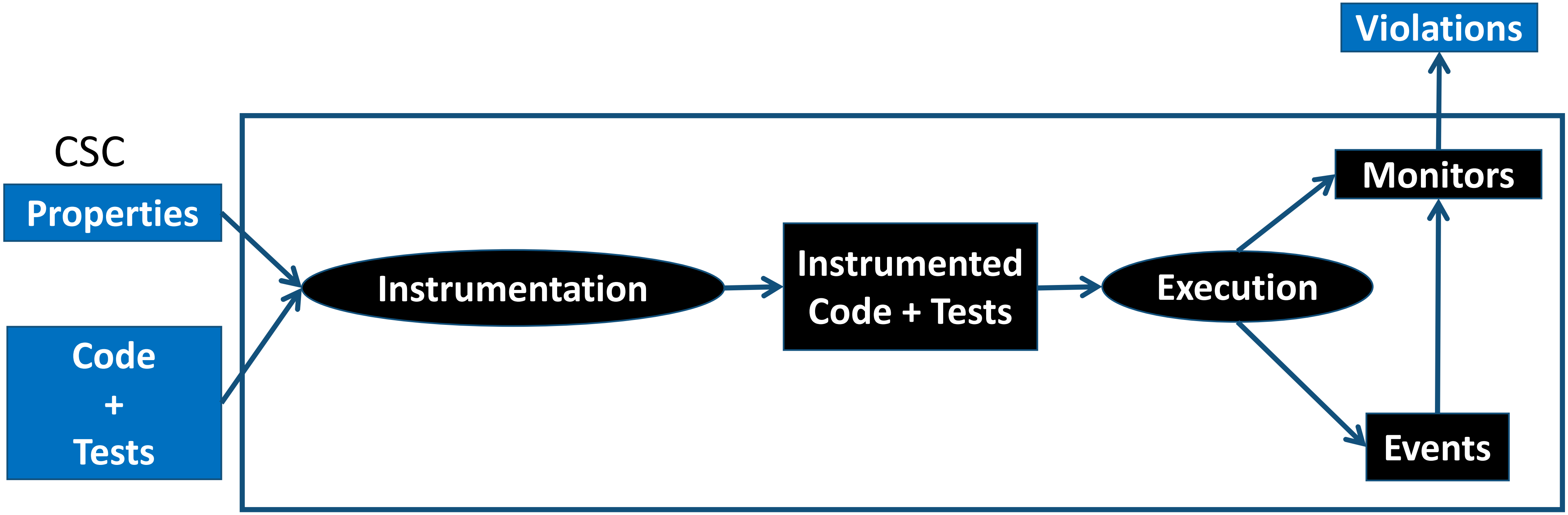
Other example properties

Property Name	Nature of bug found
StringTokenizer_HasMoreElements	**Crash:** don’t fetch elements from an empty collection
ByteArrayOutputStream_FlushBeforeRetrieve	**Correctness:** don’t read streams with incomplete data
InetSocketAddress_Port	**Performance:** don’t use too many ephemeral ports

TestNG example: from RV of test executions to bugs

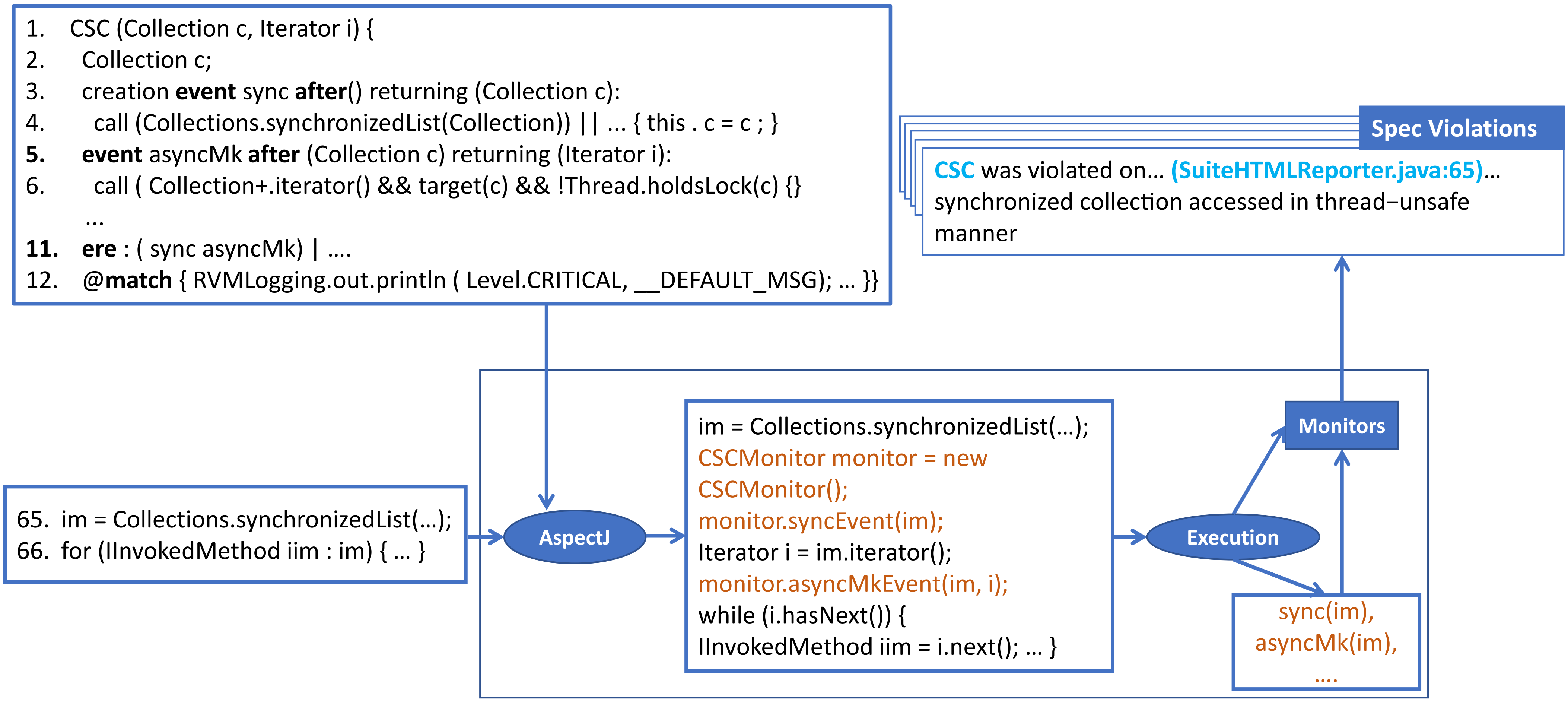


How JavaMOP works

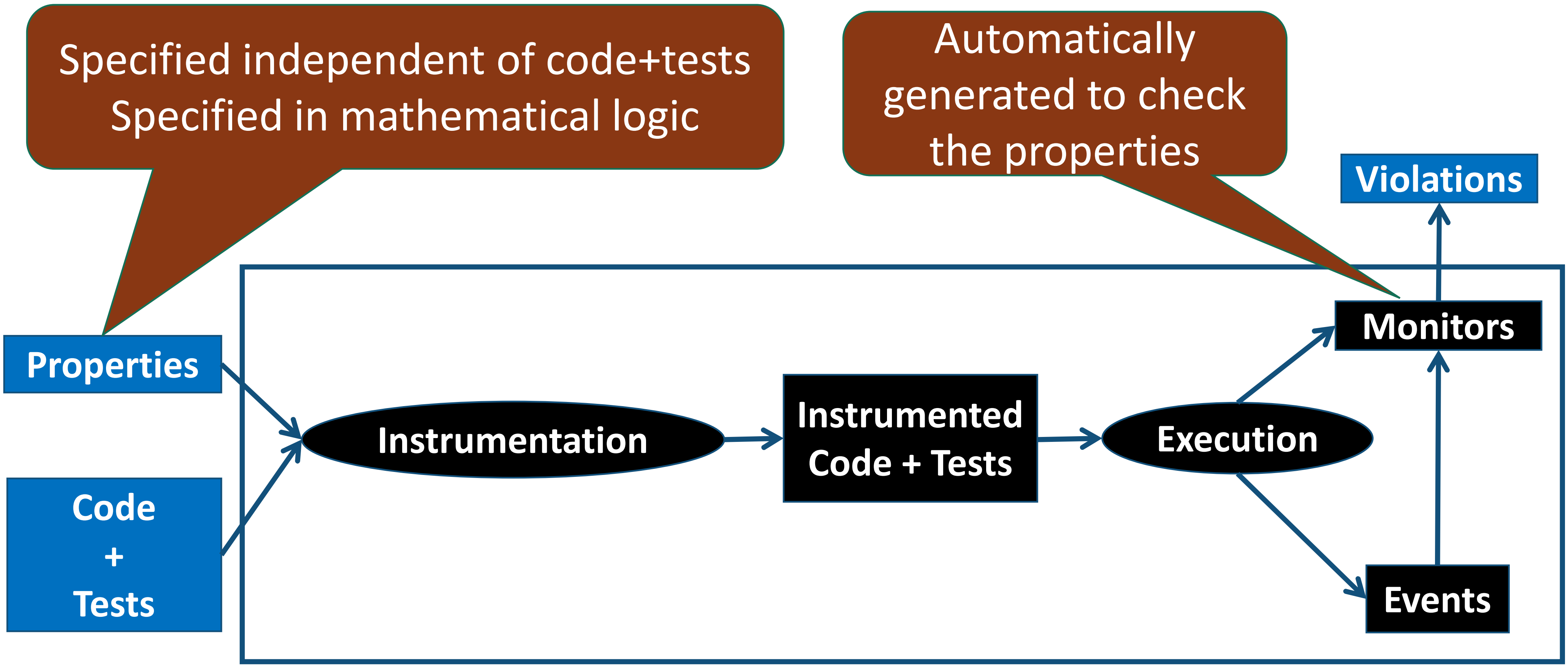


Collections.synchronizedList()
Collection+.iterator()

Example: finding bugs from RV of test executions



How is RV different from testing?



Contribution: large-scale study of RV during testing

We conducted our study to answer the following questions:

- How many additional bugs does RV help find during testing?

- How high is RV overhead during testing?

- How often do property violations <u>not</u> indicate true bugs?

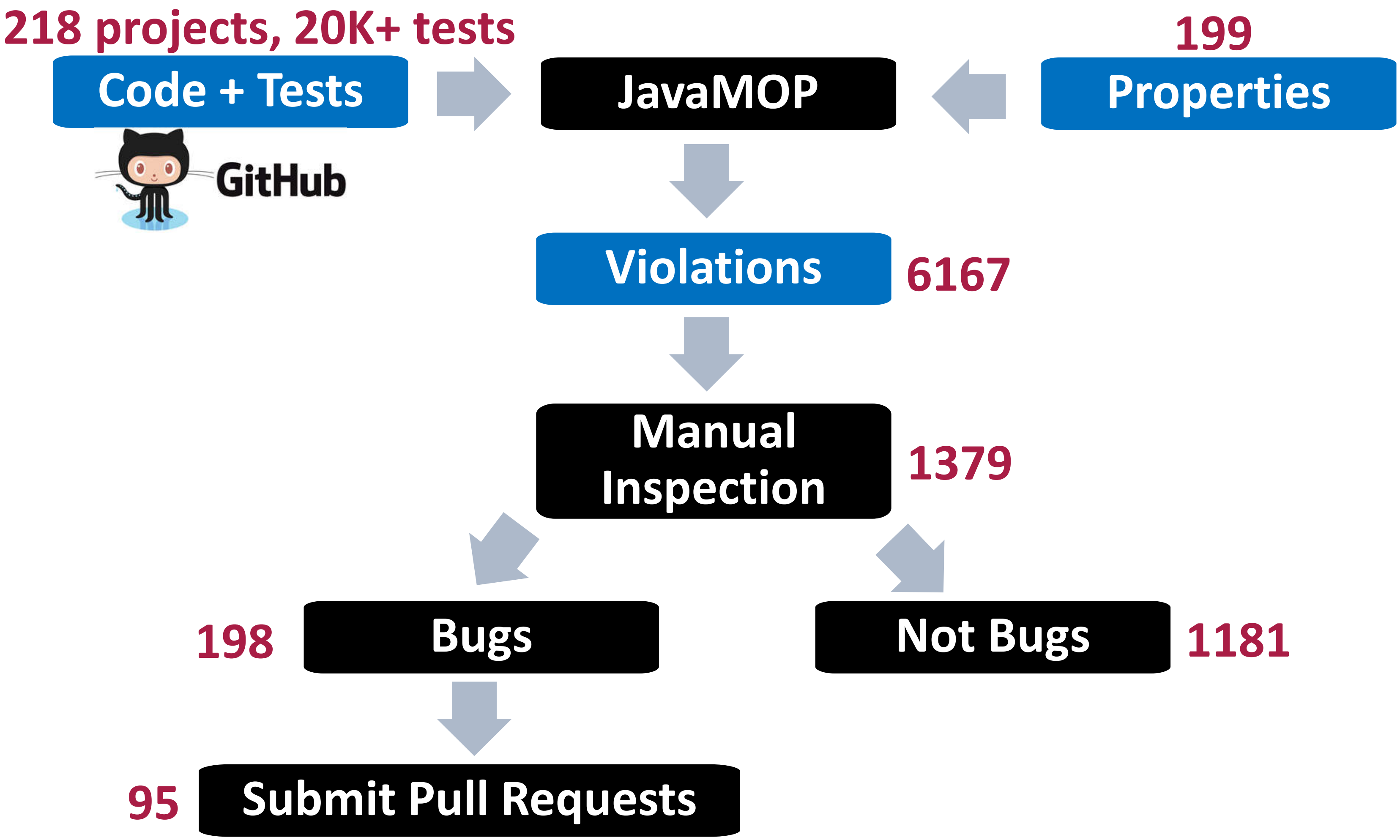
Properties used in our study

- Formal specifications of correct standard Java library API usage
- Manually written[1] or automatically mined [2] by other researchers
- 161 manually written properties from 4 packages: java.lang, java.io, java.util, and java.net
- JavaMOP supports different formalism: LTL, CFG, FSM, ERE, SRS, etc.

[1] Q. Luo, Y. Zhang, C. Lee, D. Jin, P. O. Meredith, T. F. Serbanuta, and G. Rosu. RV-Monitor: Efficient parametric runtime verification with simultaneous properties. RV 2014

[2] M. Pradel, C. Jaspan, J. Aldrich, and T. R. Gross. Statically checking API protocol conformance with mined multi-object specifications. ICSE 2012

Overview of our study



Some of the projects where we found bugs

Joda Time

commons Math

ImgLib2

Apache Camel

commons lang

hadoop

GeoServer

TestNG

GORA

APACHE HBASE

Summary of study results

- How many additional bugs does RV help find during testing?
  - ✓ Total bugs found so far: 198
  - ✓ So far: 95 bugs reported, 74 accepted, 3 rejected
- How high is RV overhead during testing?
  - ✗ Up to 40x
  - e.g., 1min to 40min, 30mins to 10hours
- How often do property violations <u>not</u> indicate true bugs?
  - ✗ 86% of ~1.4K violations were not bugs

Why are some violations (not) bugs?

```
65:  im = Collections.synchronizedList(…);
66:  for (IInvokedMethod iim : im) { … }
```

Pull Request

```
65:    im = Collections.synchronizedList(…);
66: +  synchronized (im) {
67:        for (IInvokedMethod iim : im) { … }
68: +  }
```

TestNG accepted our pull requests for 13 CSC violations

XStream developers rejected our pull request for similar CSC bug

- "...there's no need to synchronize it... as explicitly stated ..., XStream is not thread-safe ... this is documented ..."

Properties do not capture enough program context[1]

[1] S. Thummalapenta and T. Xie. Alattin: Mining Alternative Patterns for Detecting Neglected Conditions. ASE 2009

Logistics

- Homework 4 is released
  - Work in your project group
  - Due 5/10/2021
- Project Sprint 2 will be released soon
  - Focus: using testing JavaMOP and/or Randoop
  - Due 5/14/2021 (last day of classes)

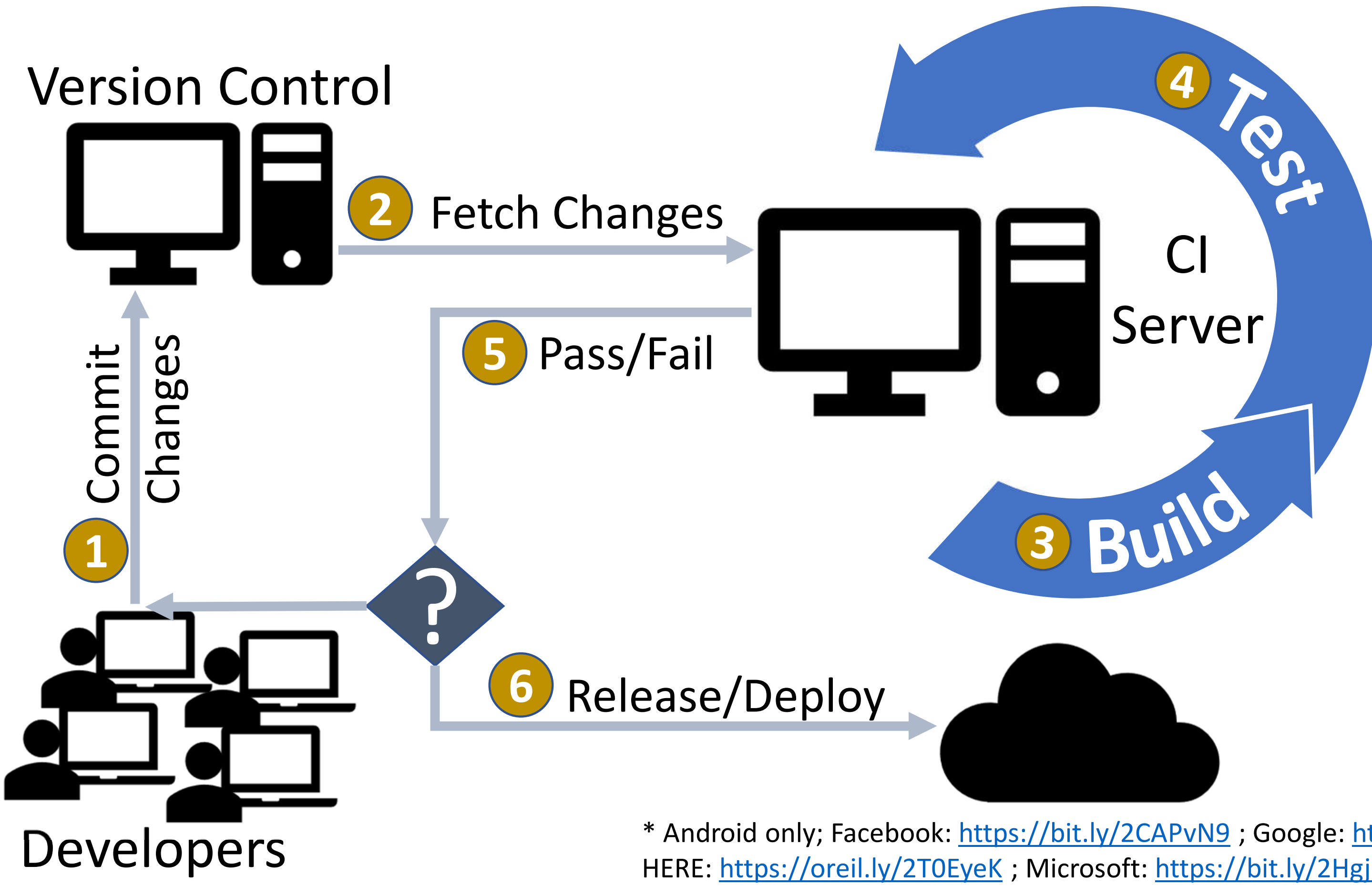
Reflecting on the study results

- RV overhead is still high despite decades of tremendous research progress
  - Overhead in machine time (up to 40x)
  - Overhead in developer time to inspect violations (1200 hours / 1379 violations)
  - Yet, RV helped find many bugs from existing tests

- Do we need faster RV algorithms and better properties? Yes!

- But what if we also consider how developers are likely to use RV?

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**

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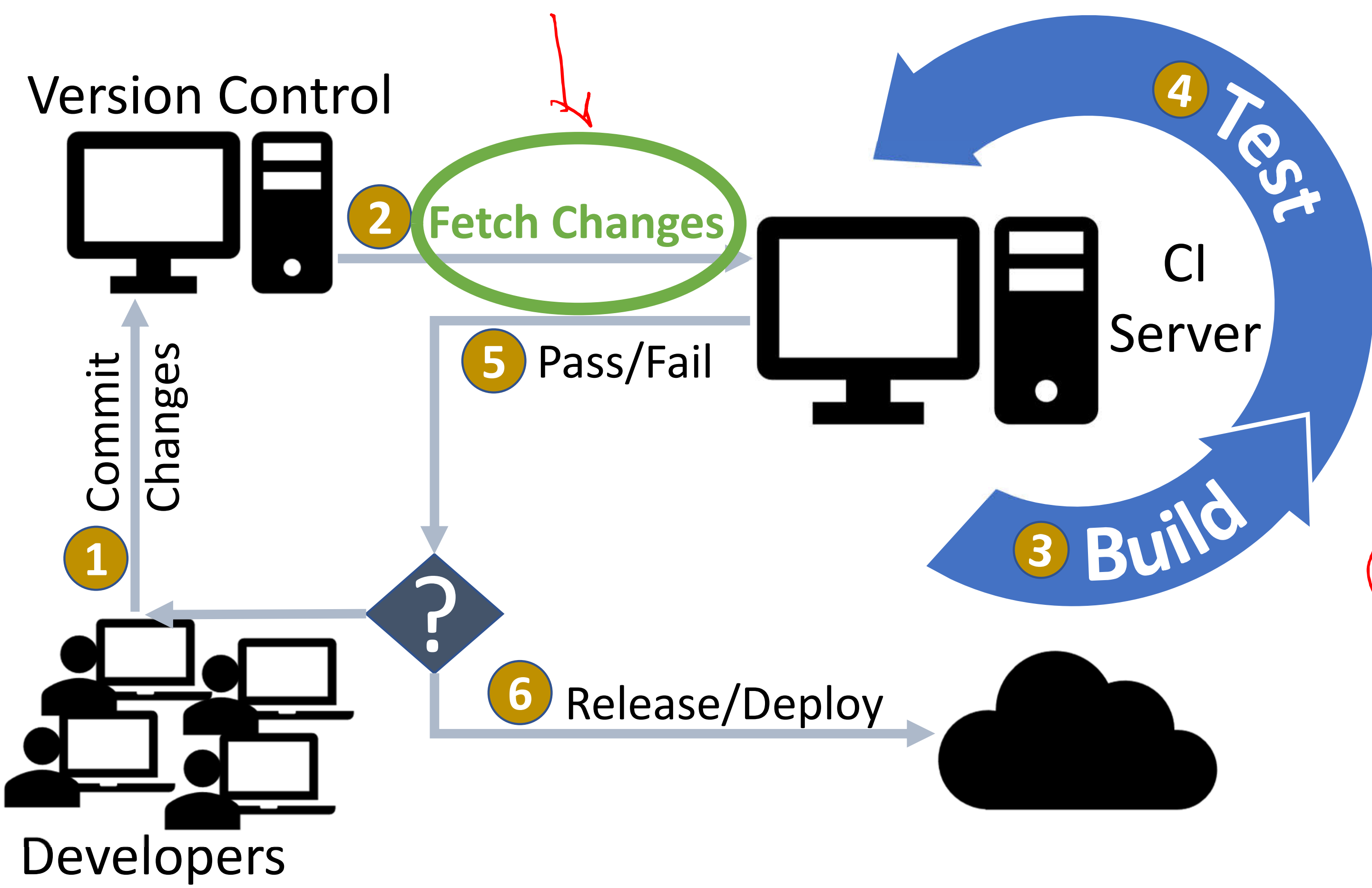
New Idea: Focus RV on code changes?



Code changes are typically very small relative to entire code base

0.97% of classes changed on average in our experiments

Contribution: Evolution-aware Runtime Verification

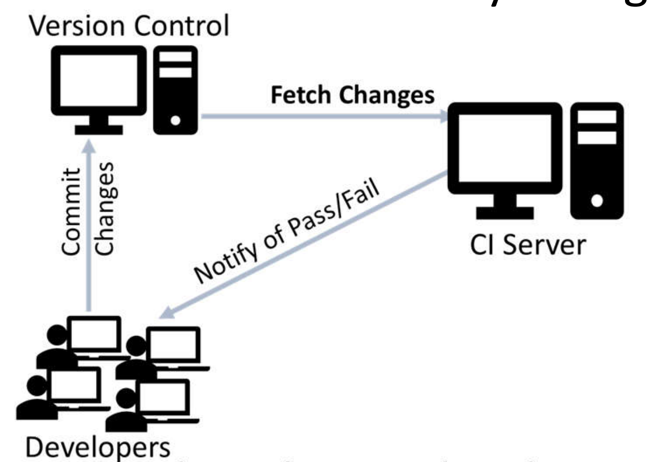
- Goal: leverage software evolution to scale RV better during testing

- 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

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

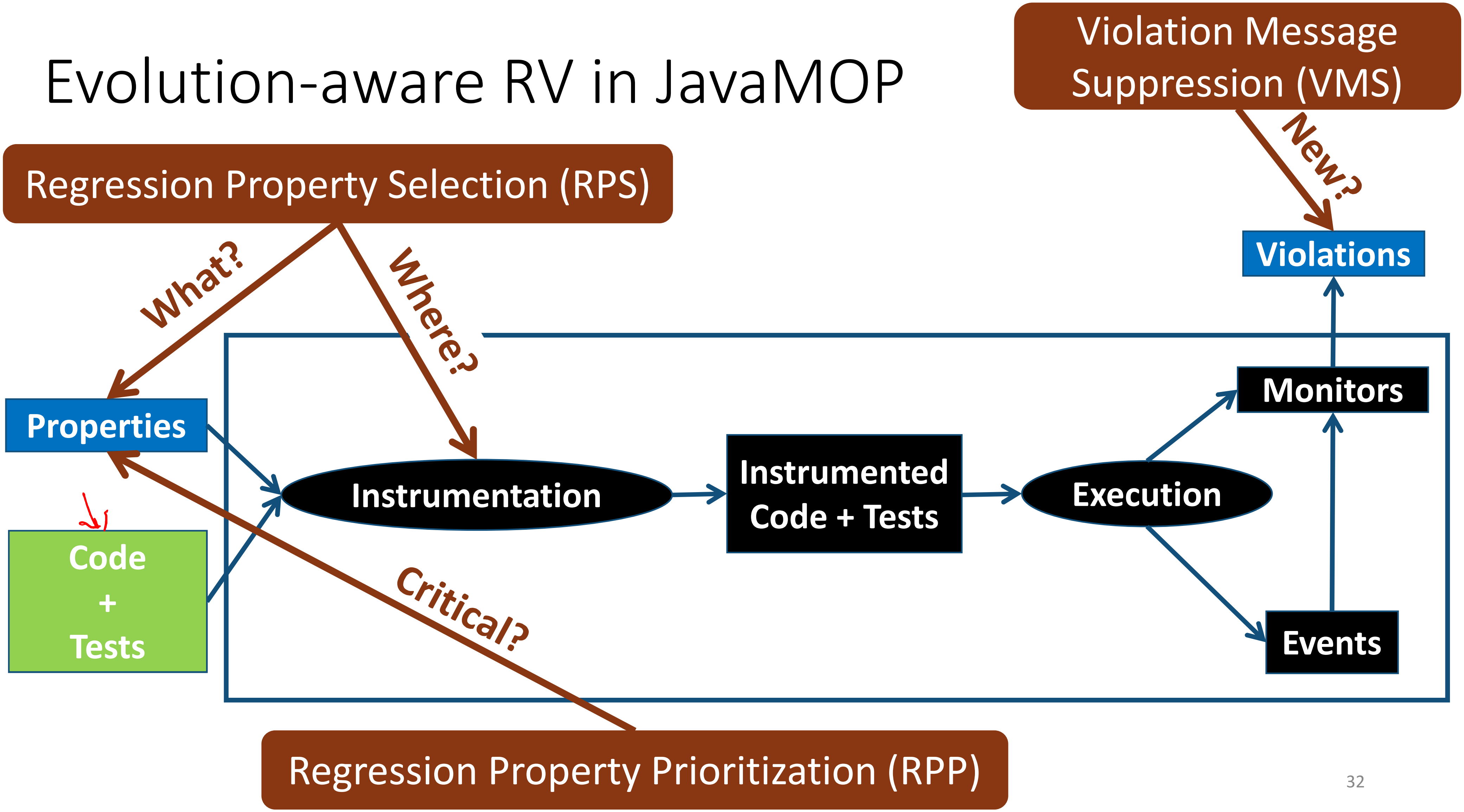


2. Violation Message Suppression (VMS) ✓
   - Shows only new violations after code changes

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

→ 1% 99x 5x

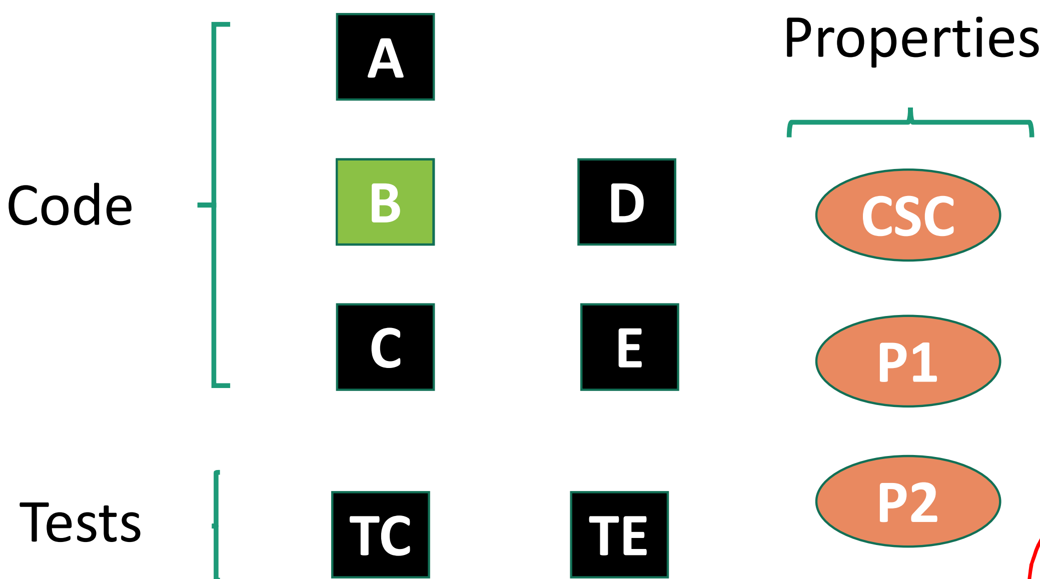
- RPS and RPP significantly reduced accumulated runtime overhead of Base RV
  - Average: from **9.4x** to **1.8x**
  - Maximum: from **40.5x** to **4.2x**

- VMS showed **540x fewer** violations than Base RV

- RPS did **not miss any new violation** after code changes

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

Old version of Code+Tests

New version of Code+Tests

All available properties

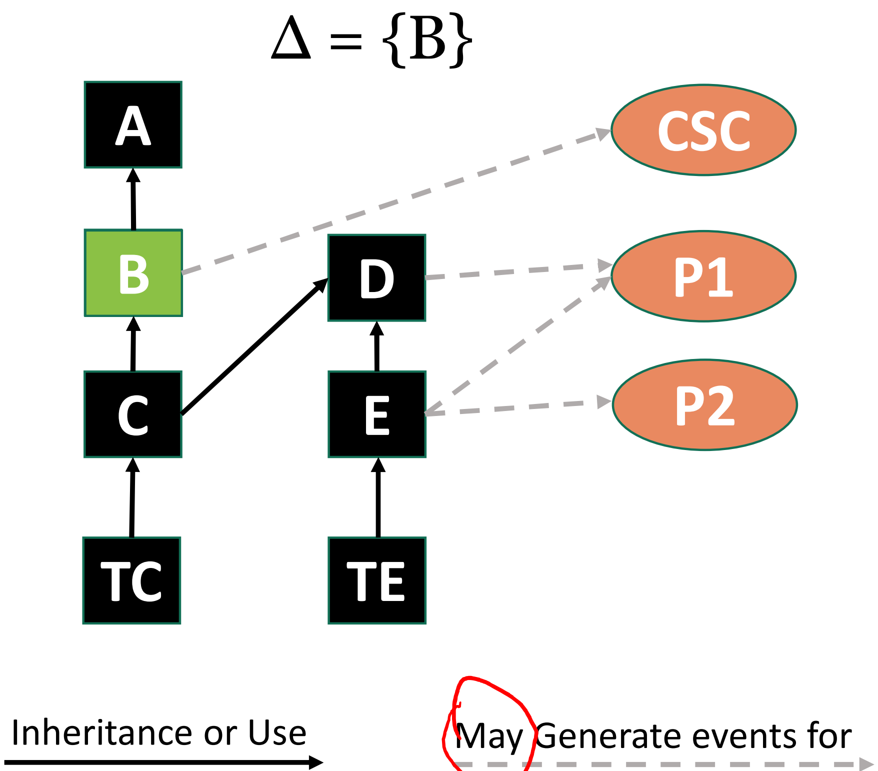
RPS

Subset of all available properties

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



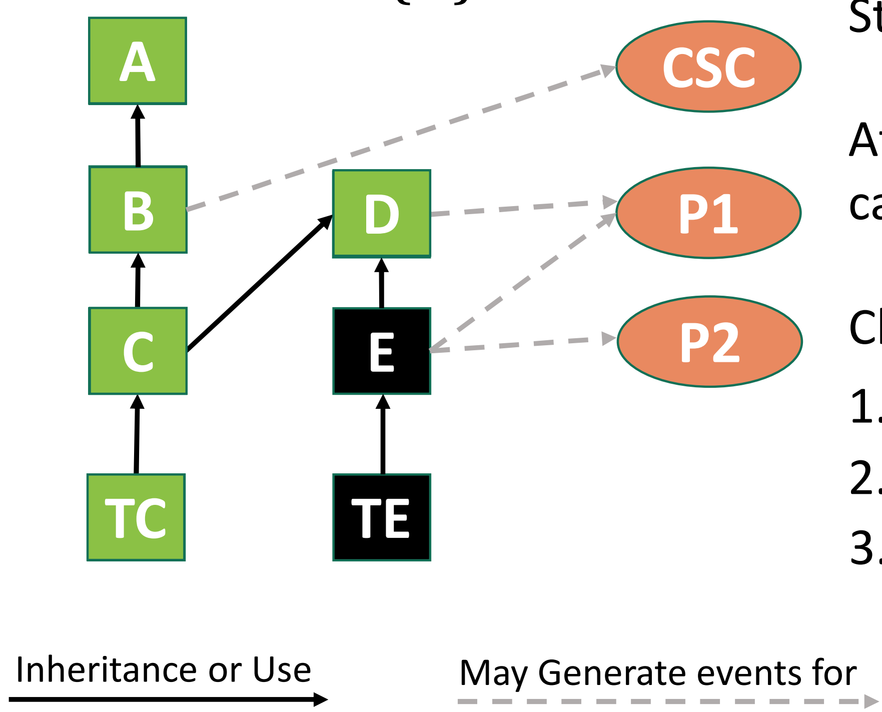
Step 1a: Build Class Dependency Graph (CDG) for new version

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

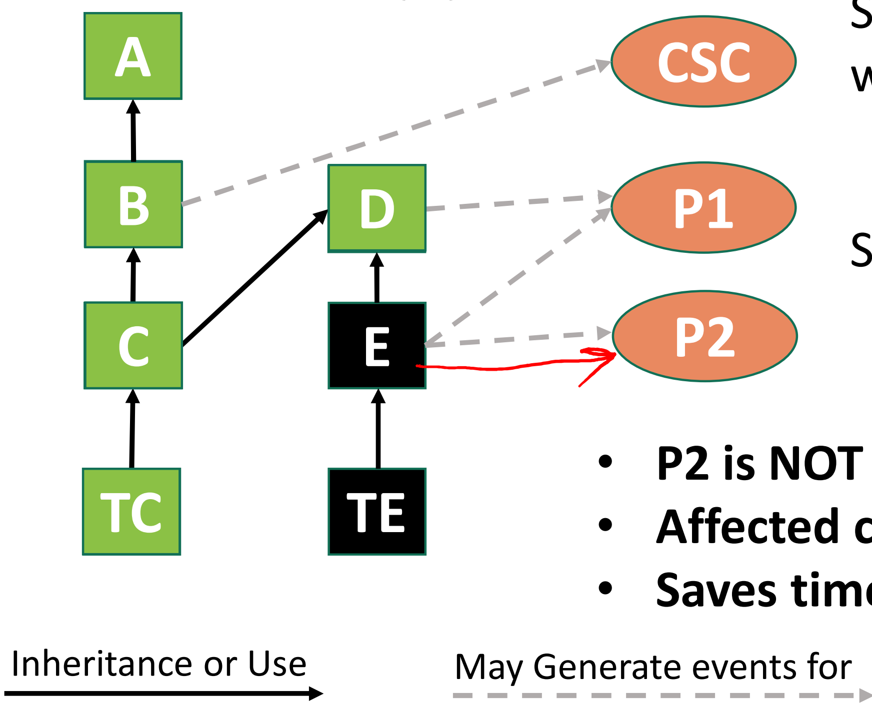
Class X is affected if

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**

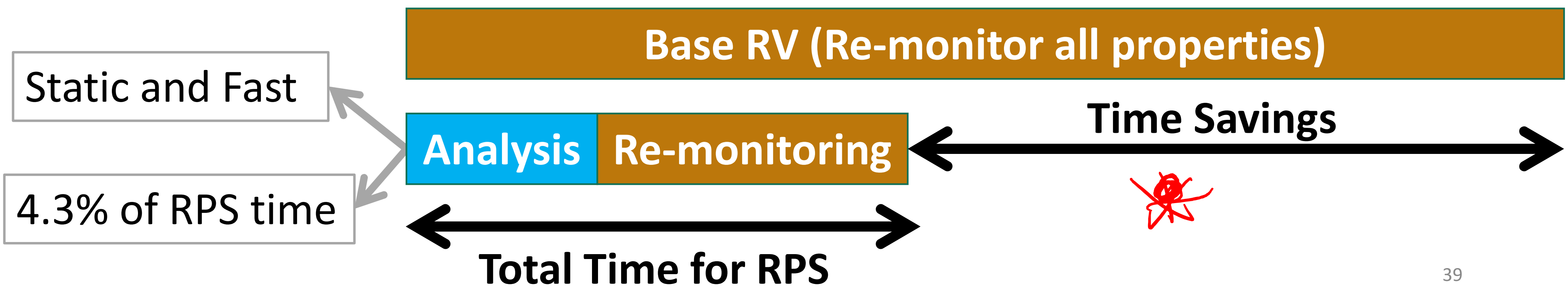
Total RPS time must be less than Base RV time

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

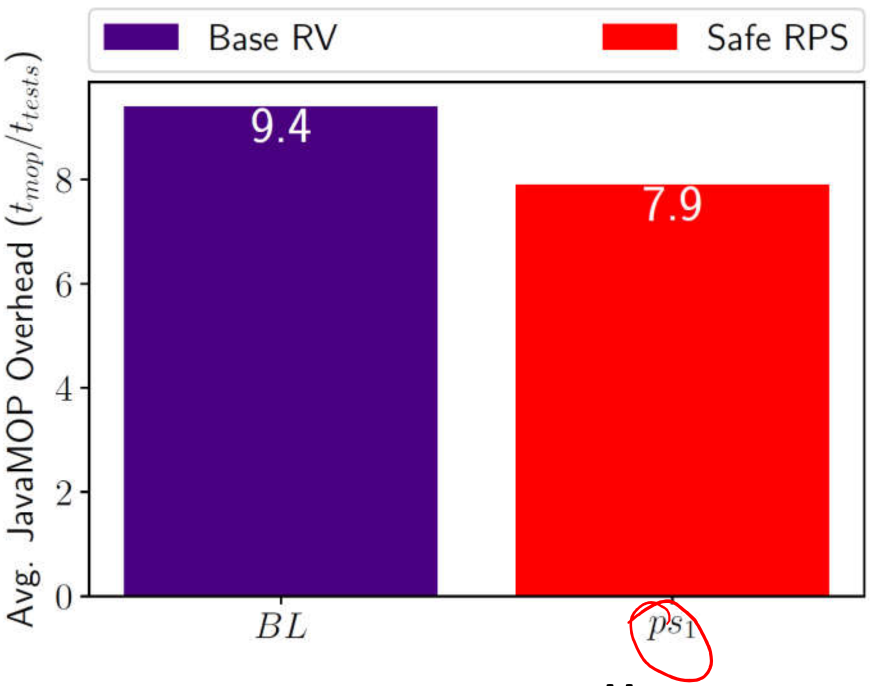


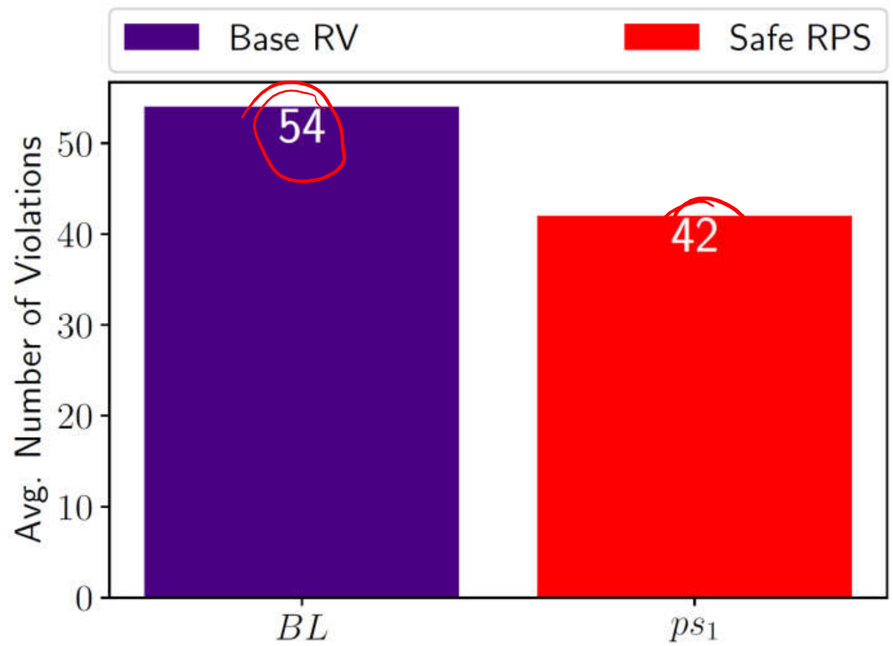
RPS Safety and Precision - Definitions

- 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

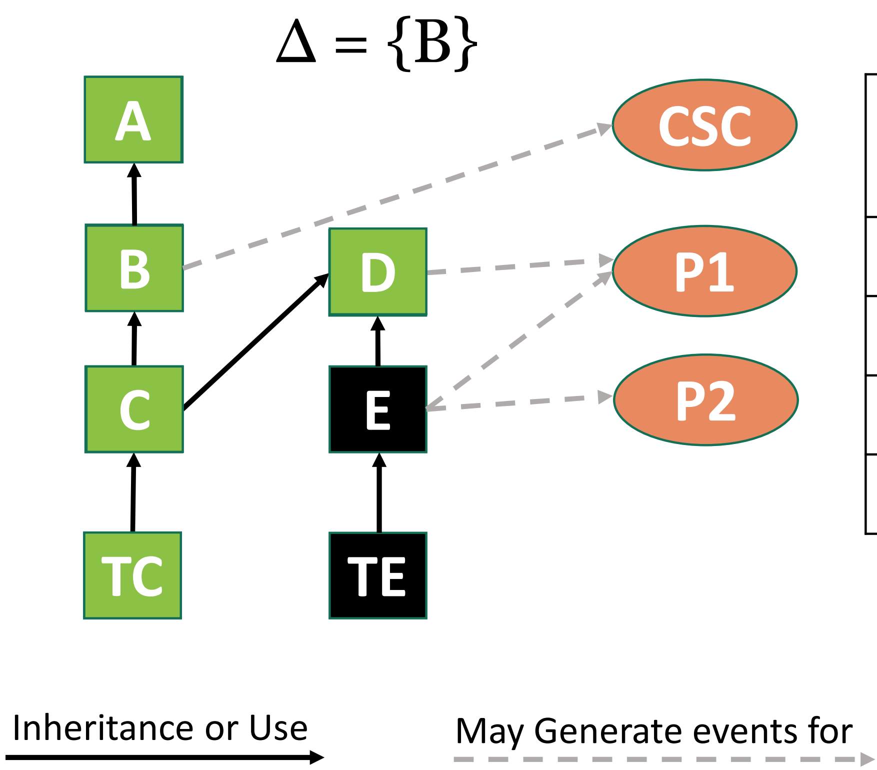




How can we improve these results?

RPS variants that use fewer affected classes

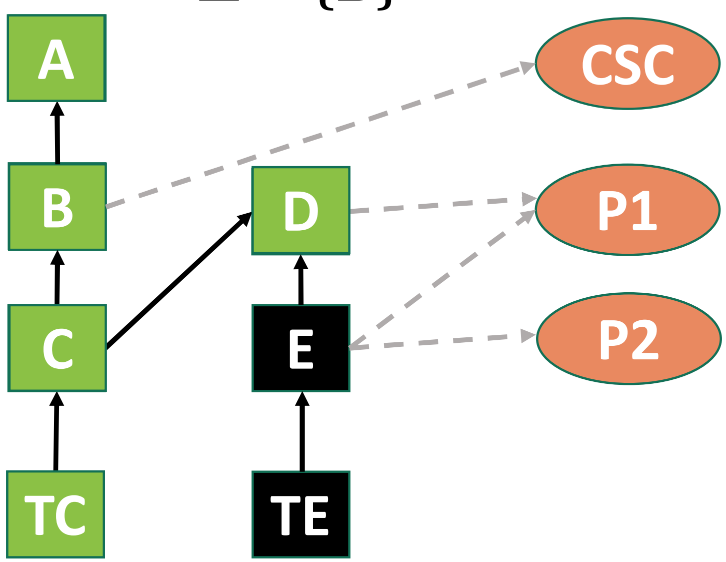
Goal: Reduce RV overhead by varying "what" set of affected classes is used to select properties



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

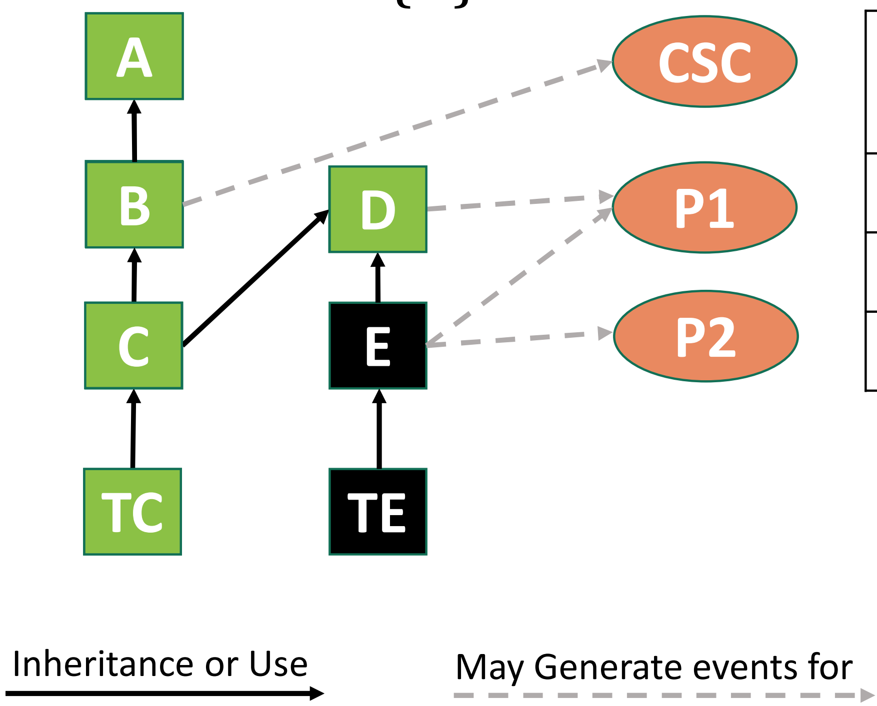
Inheritance or Use

May Generate events for

RPS variants that instrument fewer classes

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

$$\Delta = \{B\}$$

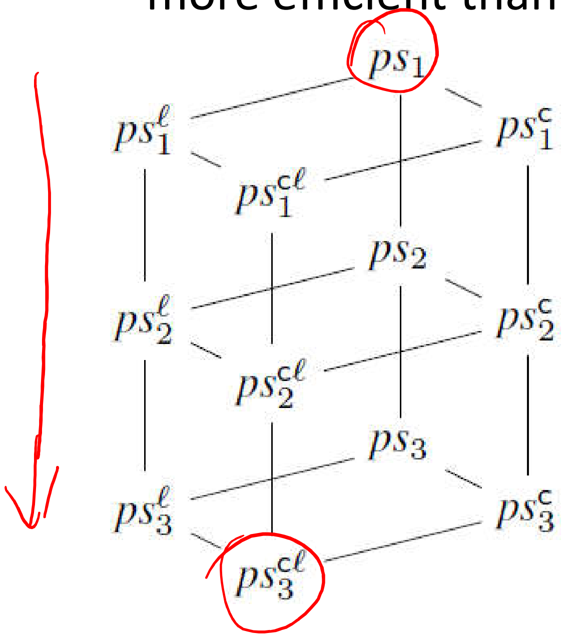


Where selected properties are instrumented ($i \in \{1,2,3\}$)	ps_i	ps_i^c	ps_i^l	ps_i^{cl}
affected(Δ)	✓	✓	✓	✓
affected(Δ)^c	✓	✘	✓	✘
third-party libraries	✓	✓	✘	✘

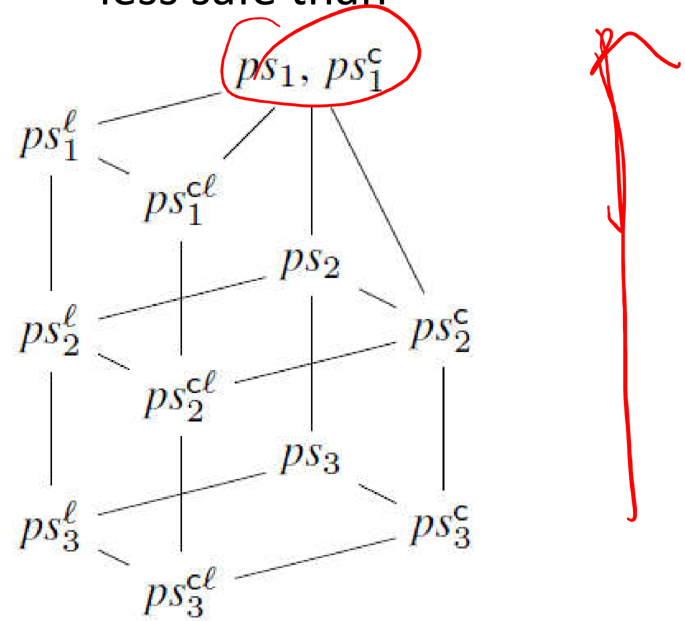
- have fewer violations
- ~36% of RV overhead
- excluding them can be safe

RPS Variants – Expected Efficiency/Safety Tradeoff

“more efficient than”



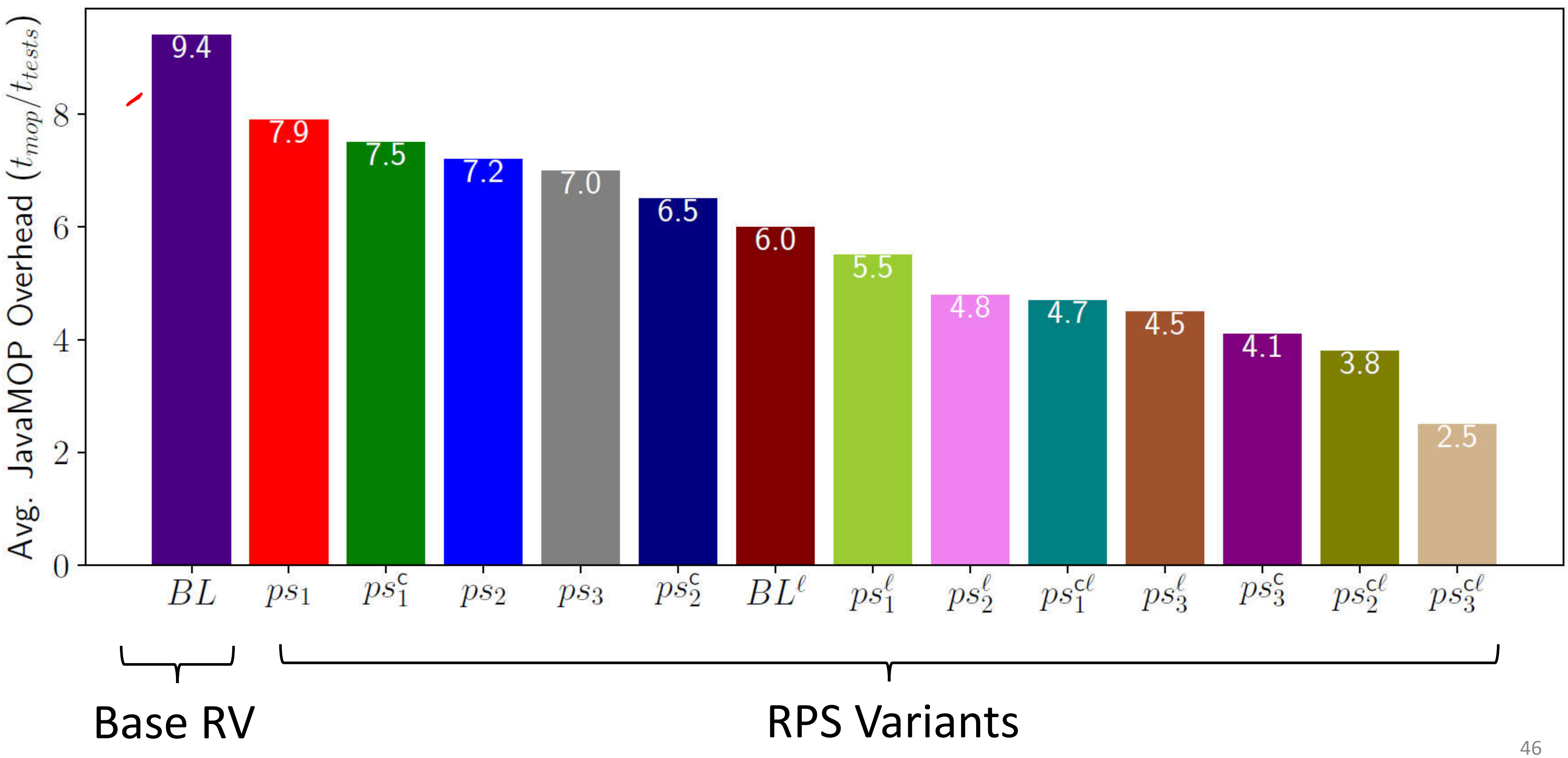
“less safe than”



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

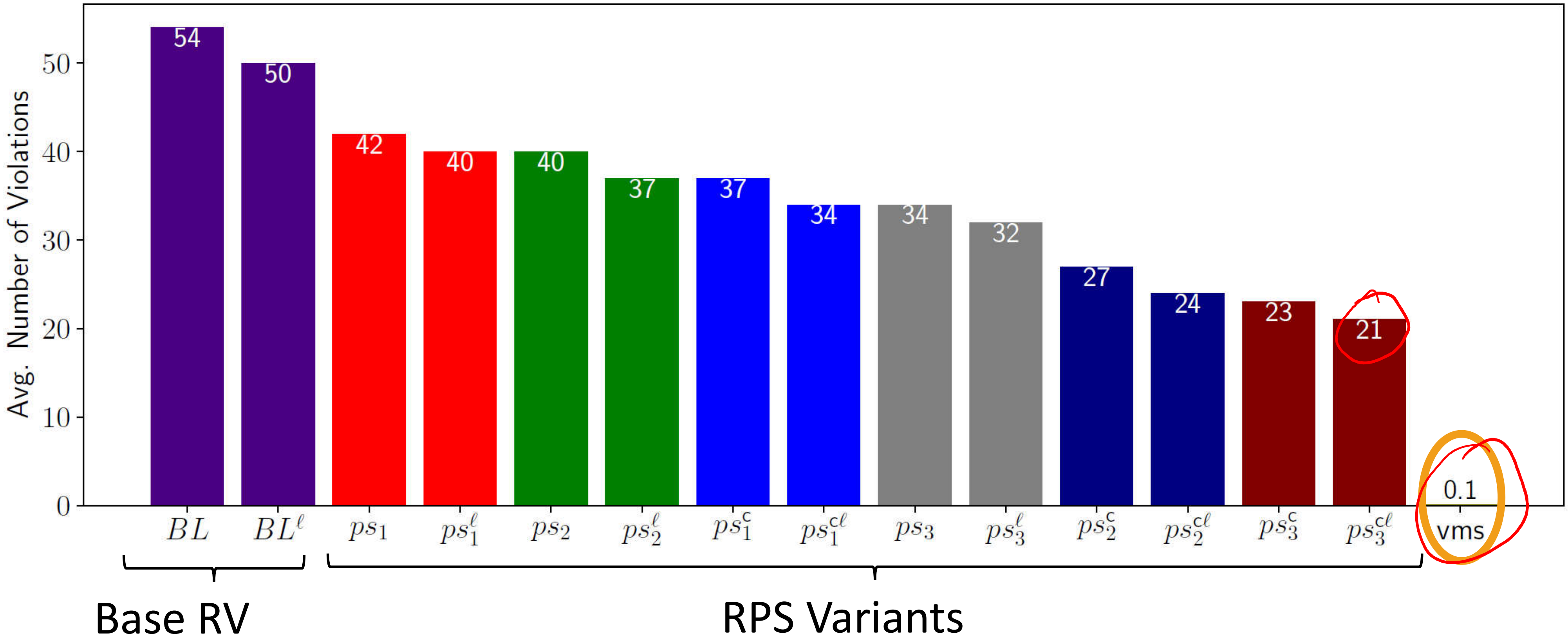
10 **Weak RPS** variants are unsafe; they trade safety for efficiency

RPS Results – average runtime overhead



RPS Results – no. of violations reported

Excluding third-party libraries does not miss many violations on average



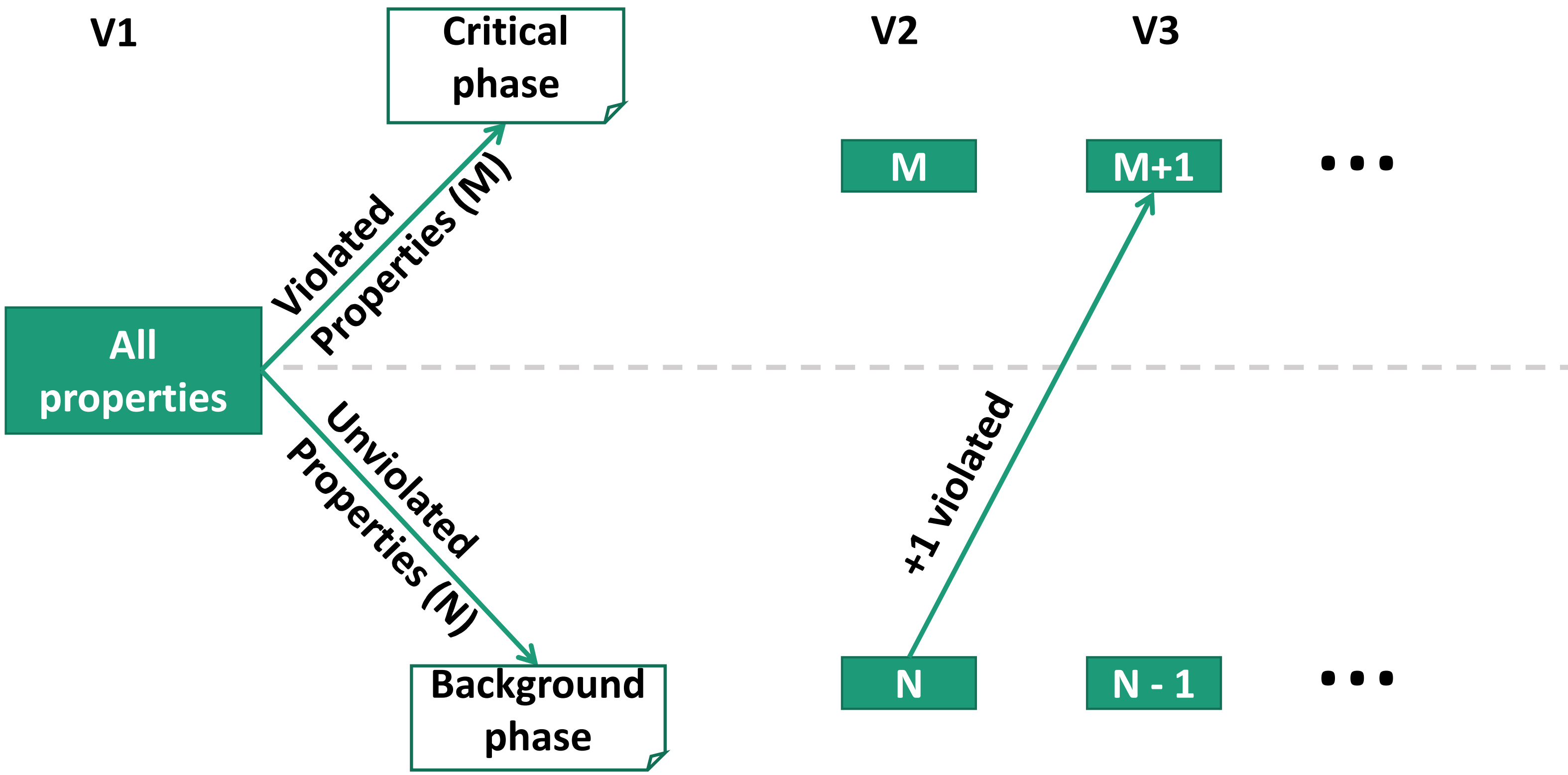
RPS Results – precision and safety

- 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

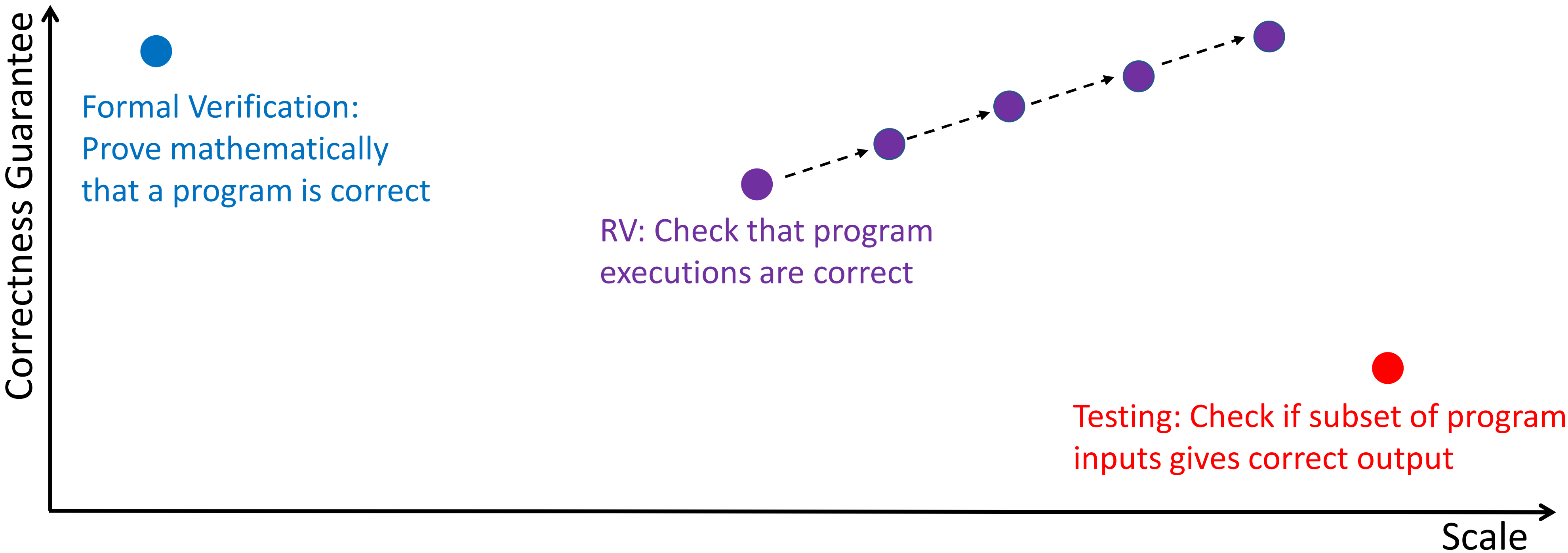
- 75% of event traces observed by monitors involved only one class
- 32 of 33 new violations were due to changes whose effects are in ps_3
  - Additional scenarios captured by ps_1 and ps_2 did not lead to new violations
  - We may have missed old violations when not tracking ps_1 or ps_2 scenarios
- 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)

Where do we (want to) go from here?

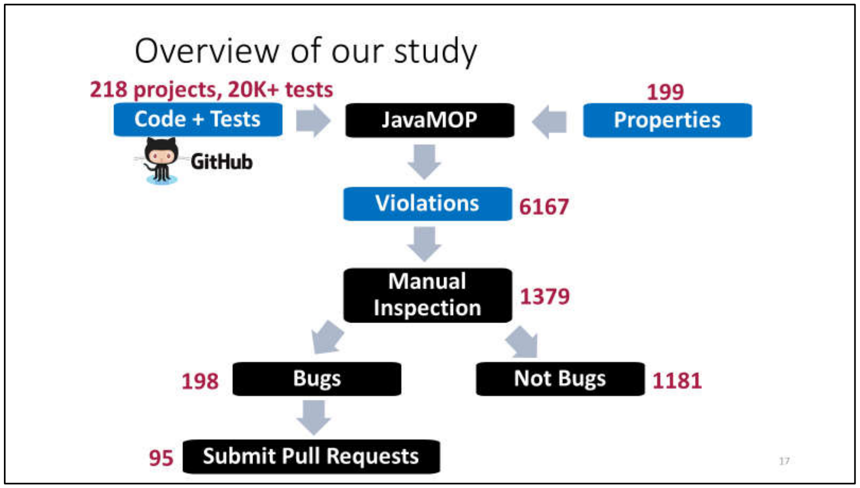


Can we make RV scale like testing and have guarantees of verification?

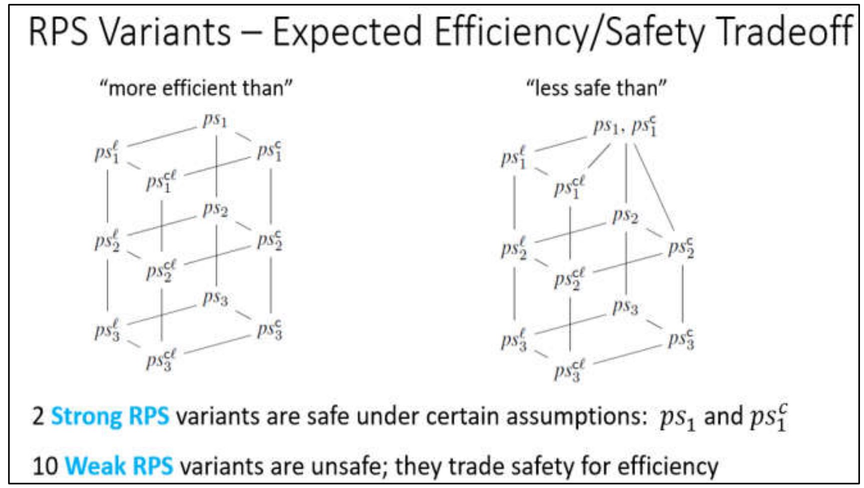
Some steps that can get us closer…

- Obtain better properties to monitor
  - 85% false alarm rate is a very hard sell!
- Reduce the developer overhead of inspecting violations
  - Hint: We already tried Machine Learning (ICST'20)
- Scale RV to (ultra-)large software ecosystems
  - Most important software are being developed in **monorepositories**
- Improve the coverage of the tests (wrt to the properties)
  - Otherwise, we cannot have high guarantees

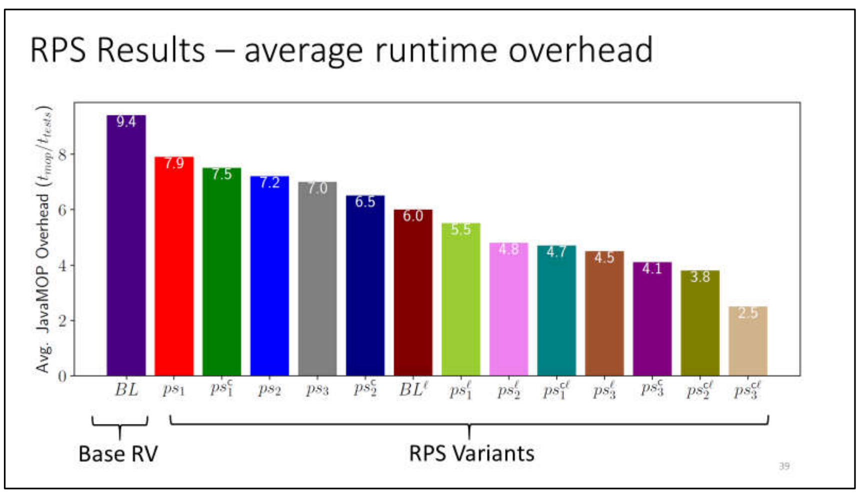
Summary



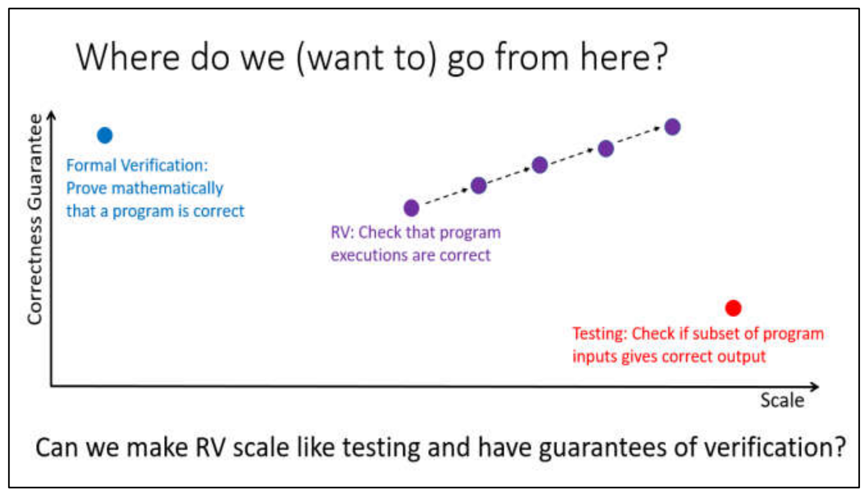
Overview of our study
218 projects, 20K+ tests
Code + Tests
GitHub
JavaMOP
199
Properties
Violations
6167
Manual Inspection
1379
198
Bugs
Not Bugs
1181
95
Submit Pull Requests



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 – average runtime overhead
Avg. JavaMOP Overhead (t_{mop}/t_{tests})
9.4
7.9
7.5
7.2
7.0
6.5
6.0
5.5
4.8
4.7
4.5
4.1
3.8
2.5
Base RV
RPS Variants



Where do we (want to) go from here?
Correctness Guarantee
Formal Verification: Prove mathematically that a program is correct
RV: Check that program executions are correct
Testing: Check if subset of program inputs gives correct output
Scale
Can we make RV scale like testing and have guarantees of verification?