Using Controlled Numbers of Real Faults and Mutants to Empirically Evaluate Coverage-Based Test Case Prioritization

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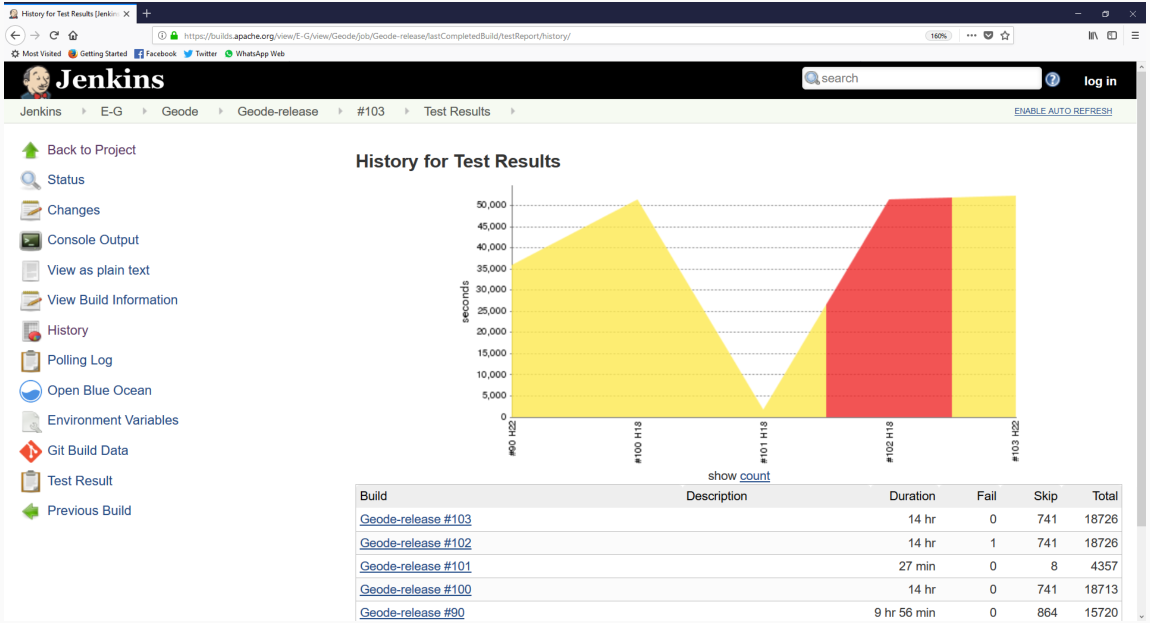
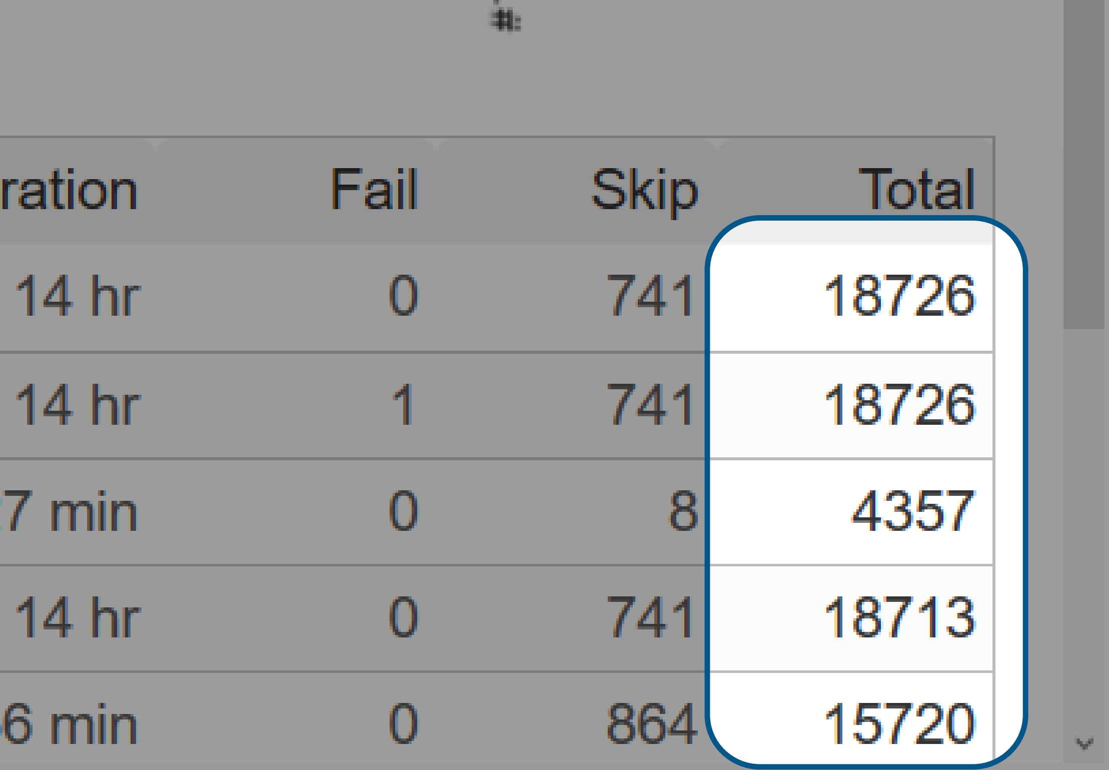
Test Case Prioritization

- Testing is required to ensure the correct functionality of software
- Larger software → more tests → longer running test suites



History for Test Results

Build	Description	Duration	Fail	Skip	Total
Geode-release #103		14 hr	0	741	18726
Geode-release #102		14 hr	1	741	18726
Geode-release #101		27 min	0	8	4357
Geode-release #100		14 hr	0	741	18713
Geode-release #90		9 hr 56 min	0	864	15720



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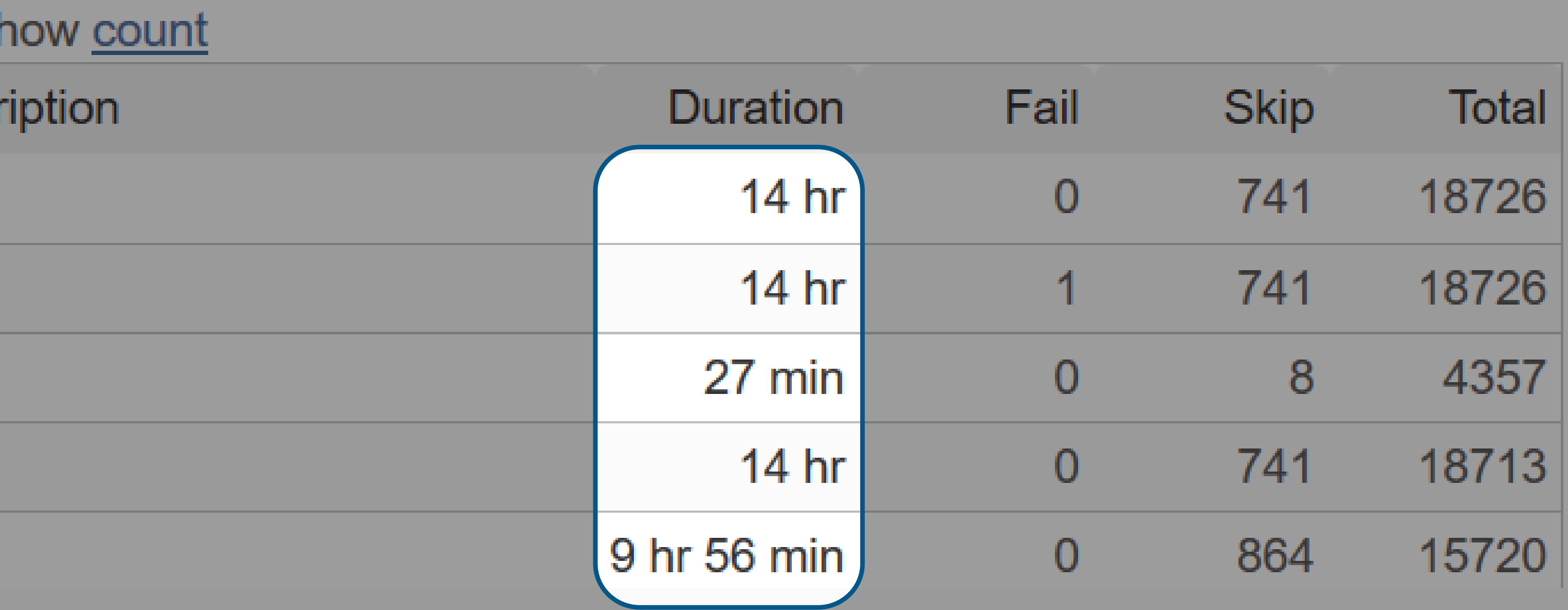
14 hr	0	741	18713
6 min	0	864	15720



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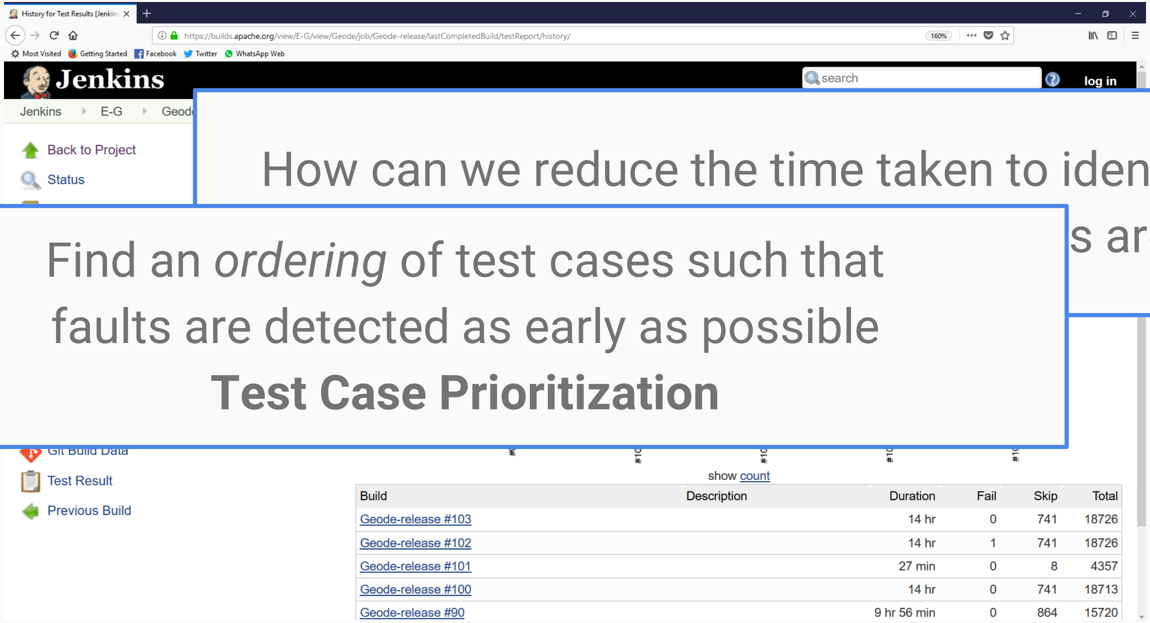

History for Test Results [Jenkins

https://builds.apache.org/view/E-G/view/Geode/job/Geode-release/lastCompletedBuild/testReport/history/

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How can we reduce the time taken to identify new

s are found?

Find an *ordering* of test cases such that faults are detected as early as possible

Test Case Prioritization

Types of Fault

Real

Artificial

Test Case Prioritization

Strategy A

- 100 subjects
- Evaluated on **mutants**
- **Score = 0.75**

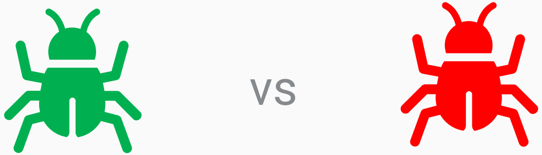
Strategy B

- 100 subjects
- Evaluated on **real faults**
- **Score = 0.72**

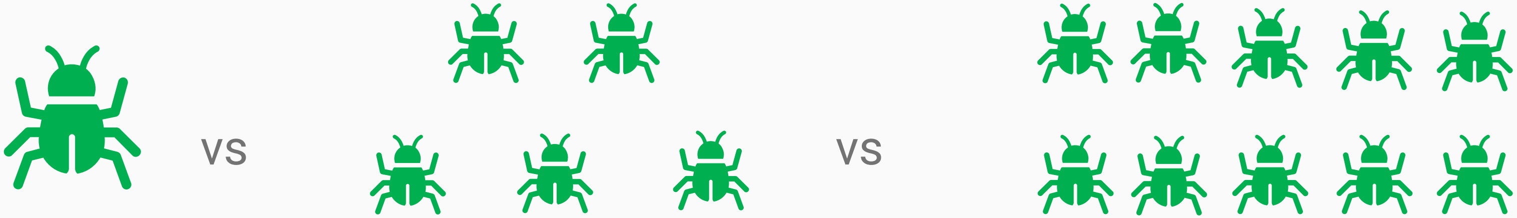
Which strategy performs the best?

Research Objectives

1. Compare prioritization strategies across fault types



2. Investigate the impact of multiple faults



Evaluating Test Prioritization

Average Percentage of Faults Detected (APFD)

- % Faults Found vs % Test Suite executed

- $APFD = 1 - \frac{\sum_{i=1}^{m} TF_i}{mn} + \frac{1}{2n}$

Evaluating Test Prioritization

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$$PFD = 1 - \frac{\sum_{i=1}^{m} \boxed{TF_i}}{mn} + \frac{1}{2n}$$

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% Faults Found vs % Test Suite executed

$$APFD = 1 - \frac{\sum_{i=1}^{m} TF_i}{\boxed{mn}} + \frac{1}{2n}$$

e of Faults Detected (APFD)

vs % Test Suite executed

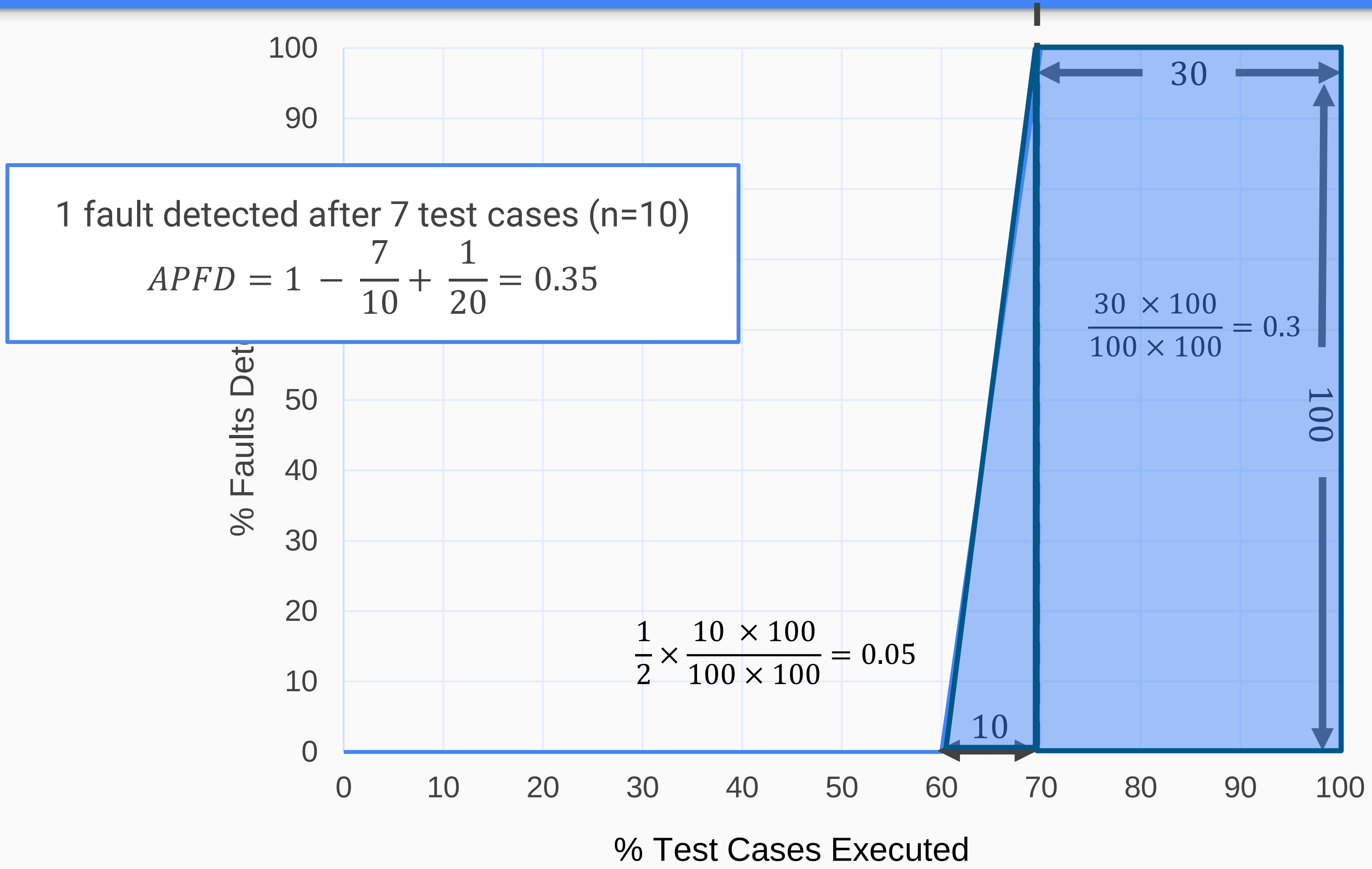
$$= 1 - \frac{\sum_{i=1}^{m} TF_i}{mn} + \frac{1}{\boxed{2n}}$$

Evaluating Test Prioritization

Average Percentage of Faults Detected (APFD)

- % Faults Found vs % Test Suite executed
- $APFD = 1 - \frac{\sum_{i=1}^{m} TF_i}{mn} + \frac{1}{2n}$
- TCP aims to **maximize** APFD by **minimizing** TF_i

Evaluating Test Prioritization



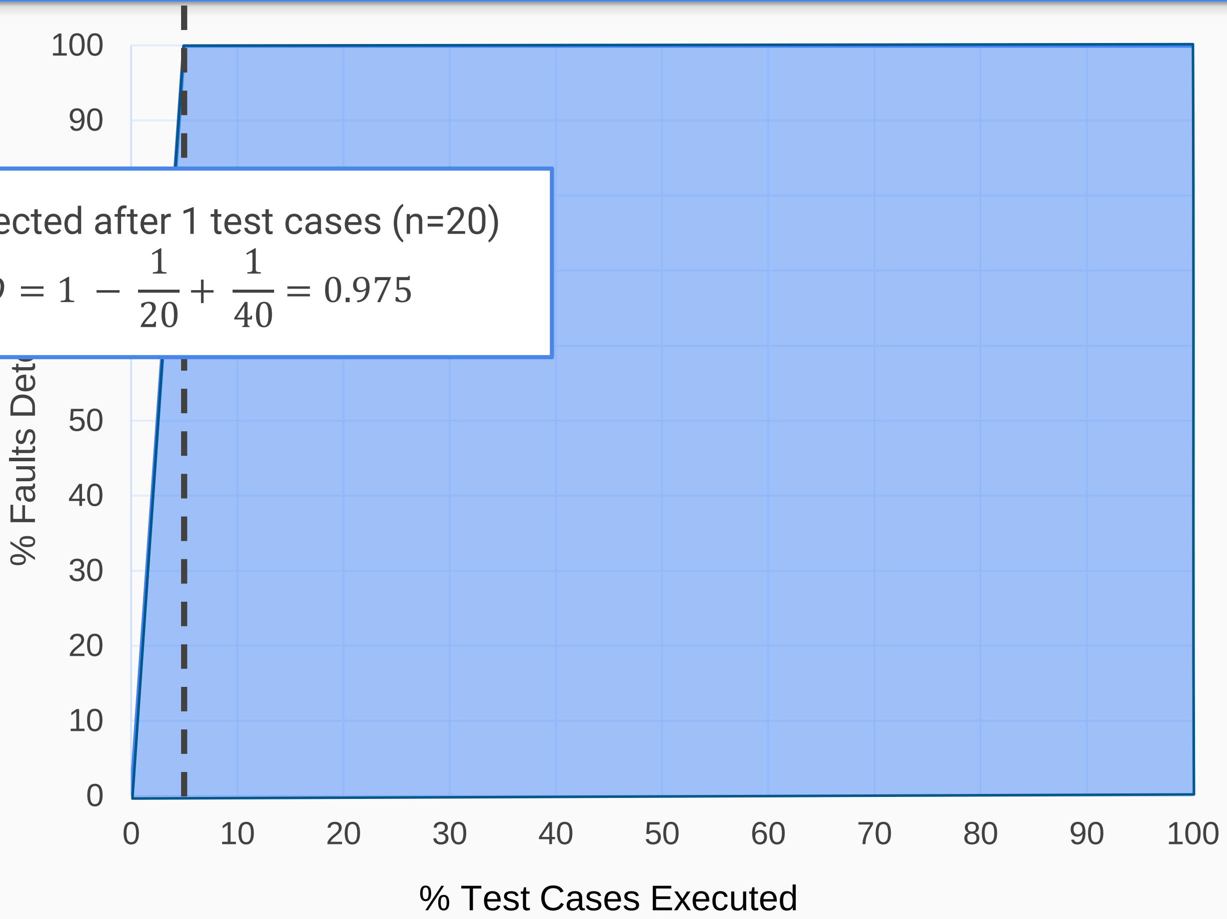
1 fault detected after 7 test cases (n=10)

$$APFD = 1 - \frac{7}{10} + \frac{1}{20} = 0.35$$

$$\frac{30 \times 100}{100 \times 100} = 0.3$$

$$\frac{1}{2} \times \frac{10 \times 100}{100 \times 100} = 0.05$$

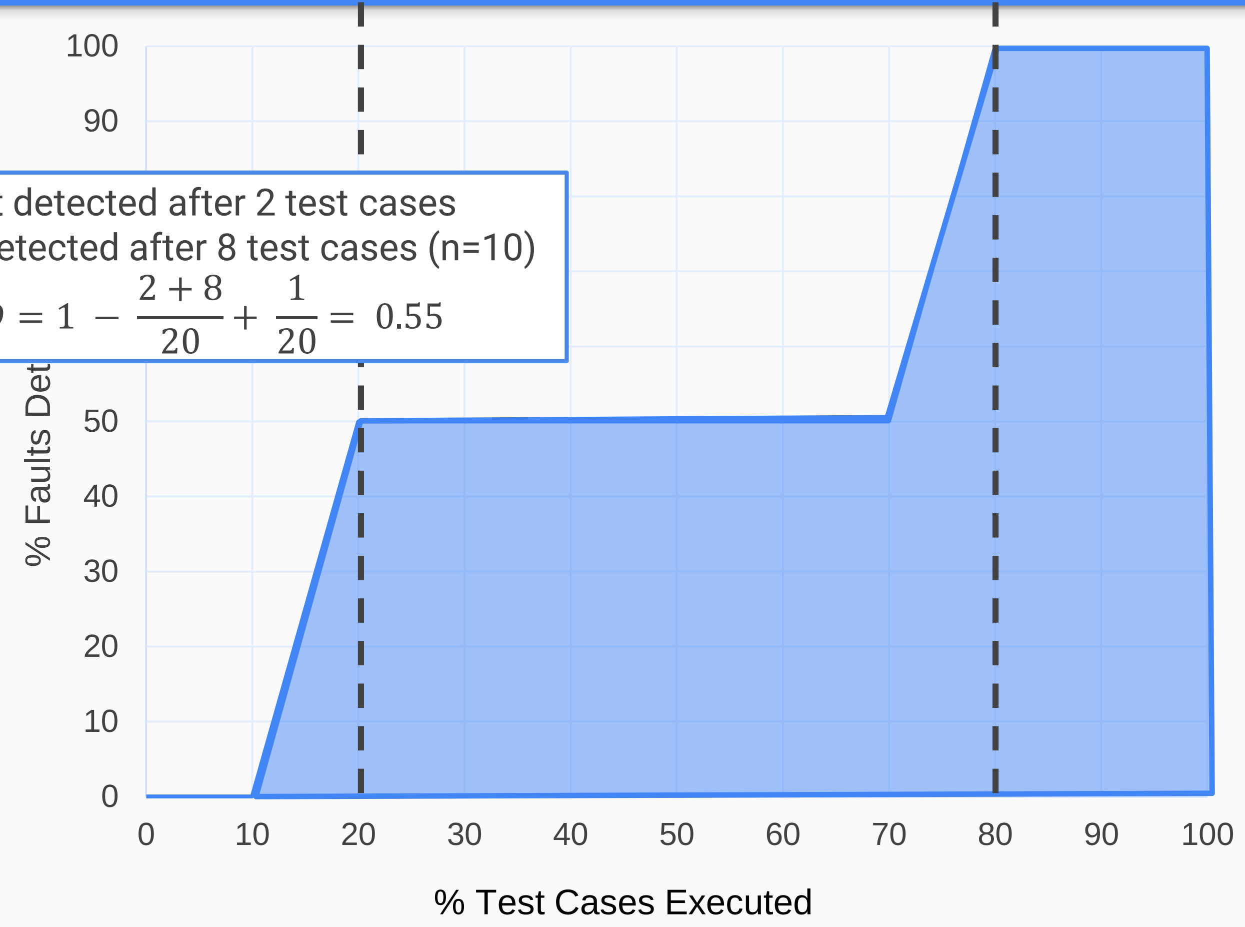
Evaluating Test Prioritization



1 fault detected after 1 test cases (n=20)

$$APFD = 1 - \frac{1}{20} + \frac{1}{40} = 0.975$$

Evaluating Test Prioritization



1 fault detected after 2 test cases
2nd fault detected after 8 test cases (n=10)

$$APFD = 1 - \frac{2+8}{20} + \frac{1}{20} = 0.55$$

Test Case Prioritization

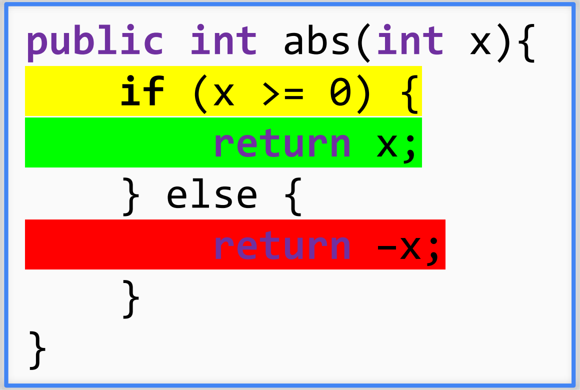
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	APFD
Version 1	☑	✗	☑	☑	☑	☑	☑	☑	☑	☑	-
Version 2	☑	✗	☑	☑	☑	☑	✗	☑	☑	☑	0.55
Version 3	☑	✗	☑	✗	☑	✗	☑	☑	☑	☑	0.45

Test Case Prioritization

	t_1	t_8	t_4	t_5	t_7	t_9	t_2	t_{10}	t_6	t_3	APFD
Version 1	☑	☑	☑	☑	☑	☑	✗	☑	☑	☑	-
Version 2	☑	☑	☑	☑	✗	☑	✗	☑	☑	☑	0.85
Version 3	☑	☑	✗	☑	☑	☑	✗	☑	✗	☑	0.8

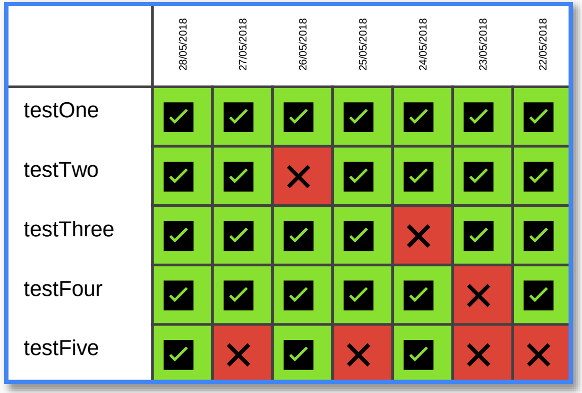
Techniques

Coverage-Based



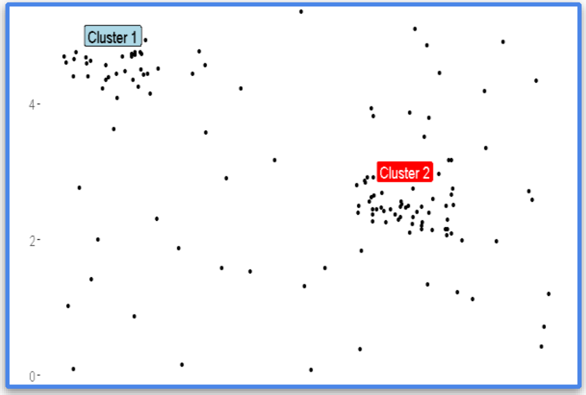
```
public int abs(int x){
    if (x >= 0) {
        return x;
    } else {
        return -x;
    }
}
```

History-Based



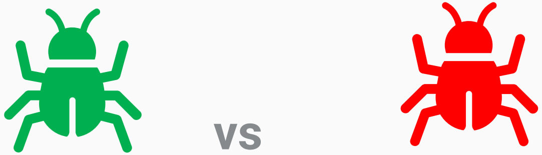
	28/05/2018	27/05/2018	26/05/2018	25/05/2018	24/05/2018	23/05/2018	22/05/2018
testOne	✓	✓	✓	✓	✓	✓	✓
testTwo	✓	✓	✗	✓	✓	✓	✓
testThree	✓	✓	✓	✓	✗	✓	✓
testFour	✓	✓	✓	✓	✓	✗	✓
testFive	✓	✗	✓	✗	✓	✗	✗

Cluster-Based



Evaluation

RQ1: How does the effectiveness of test case prioritization compare between a single real fault and a single mutant?



vs

RQ2: How does the effectiveness of test case prioritization compare between single faults and multiple faults?

vs

vs

Subjects

- **Defects4J**: Large repository containing 357 real faults from 5 open-source repositories [1]

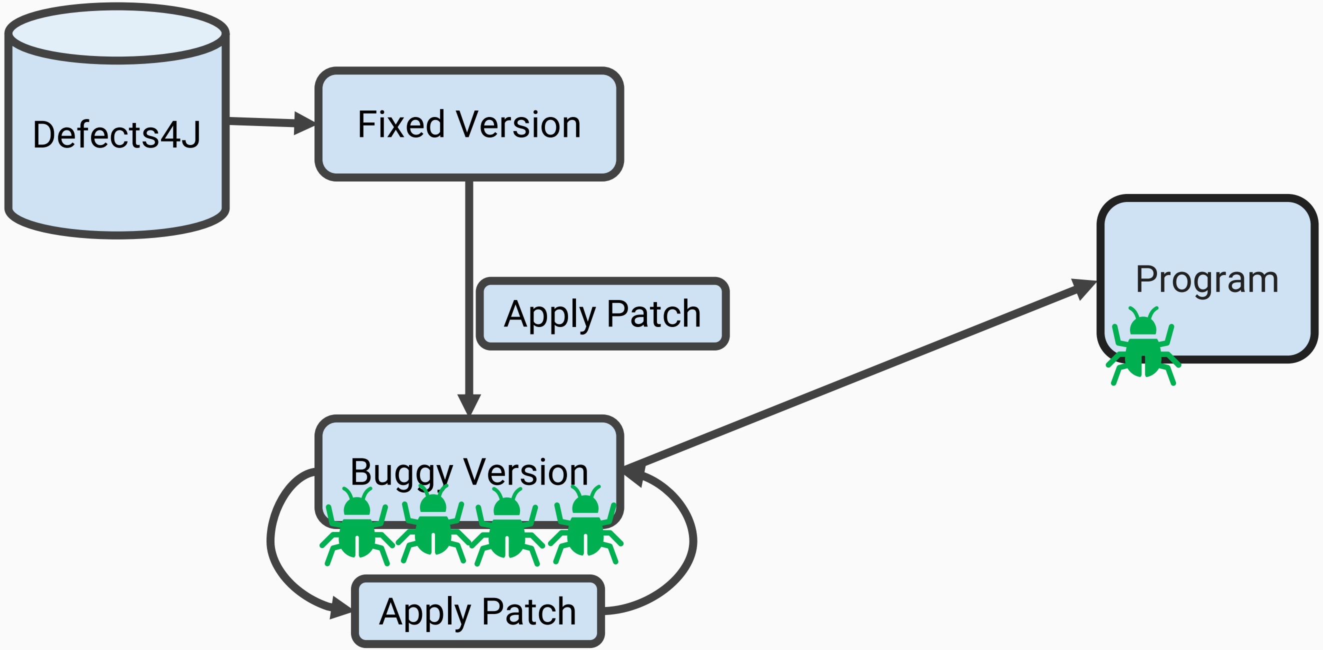
Project	GitHub	Number of Bugs	KLOC	Tests
JFreeChart	https://github.com/jfree/jfreechart	26	96	2,205
Closure Compiler	https://github.com/google/closure-compiler	133	90	7,927
Apache Commons Lang	https://github.com/apache/commons-lang	65	85	3,602
Apache Commons Math	https://github.com/apache/commons-math	106	28	4,130
Joda Time	https://github.com/JodaOrg/joda-time	27	22	2,245

- Contains developer written test suites

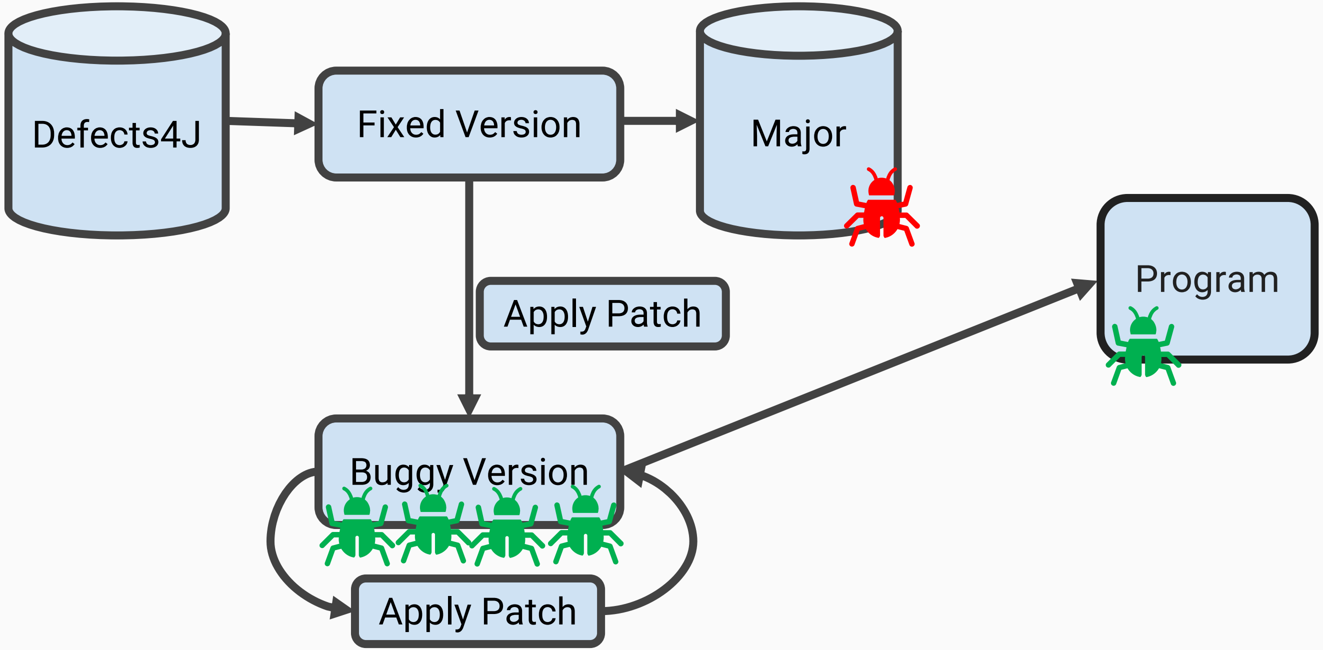
- Provides 2 versions of every subject – one buggy and one fixed

[1] https://github.com/rjust/defects4
[2] https://homes.cs.washington.edu/~mernst/pubs/bug-database-issta2014.pdfj

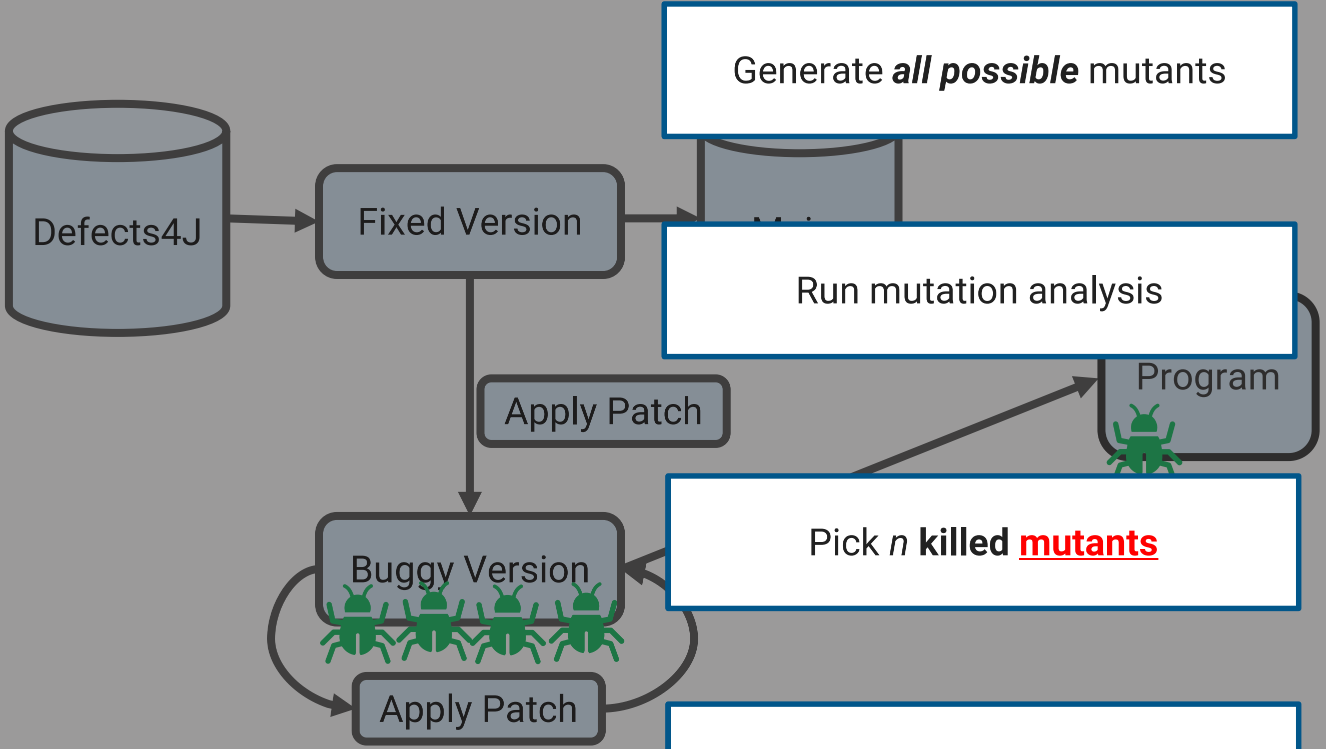
Experimental Process



Experimental Process



Experimental Process



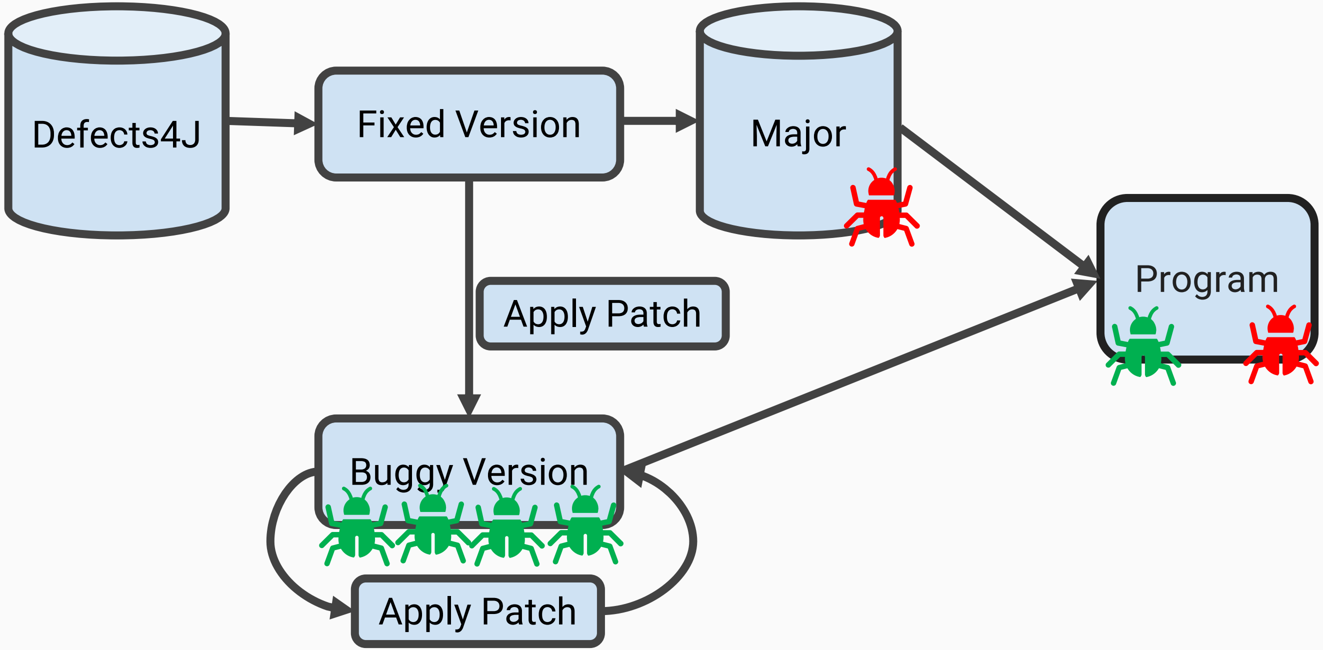
Generate ***all possible*** mutants

Run mutation analysis

Pick *n* **killed** **mutants**

Identify ***trigger tests***

Experimental Process



Defects4J

Fixed Version

Major

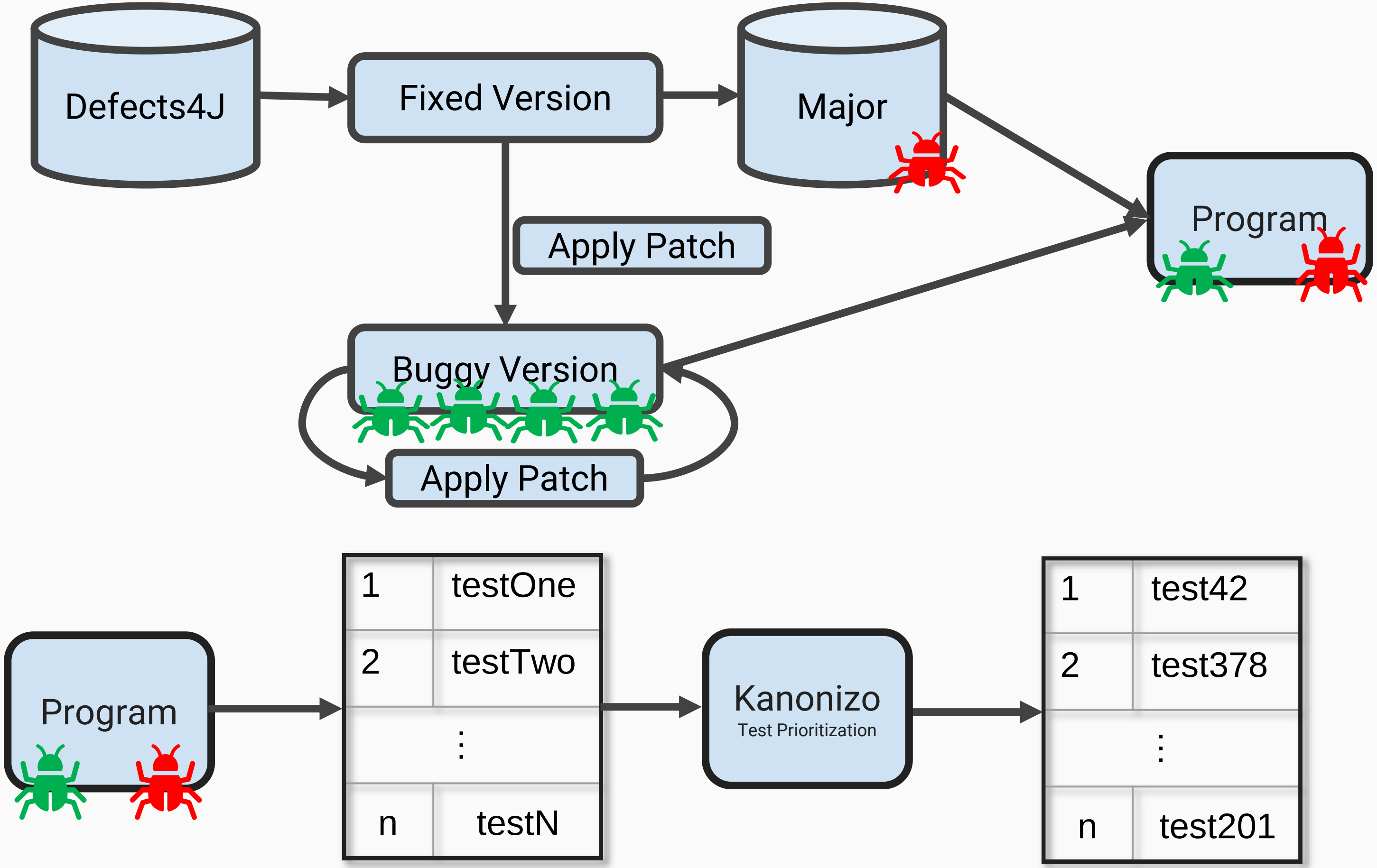
Apply Patch

Program

Buggy Version

Apply Patch

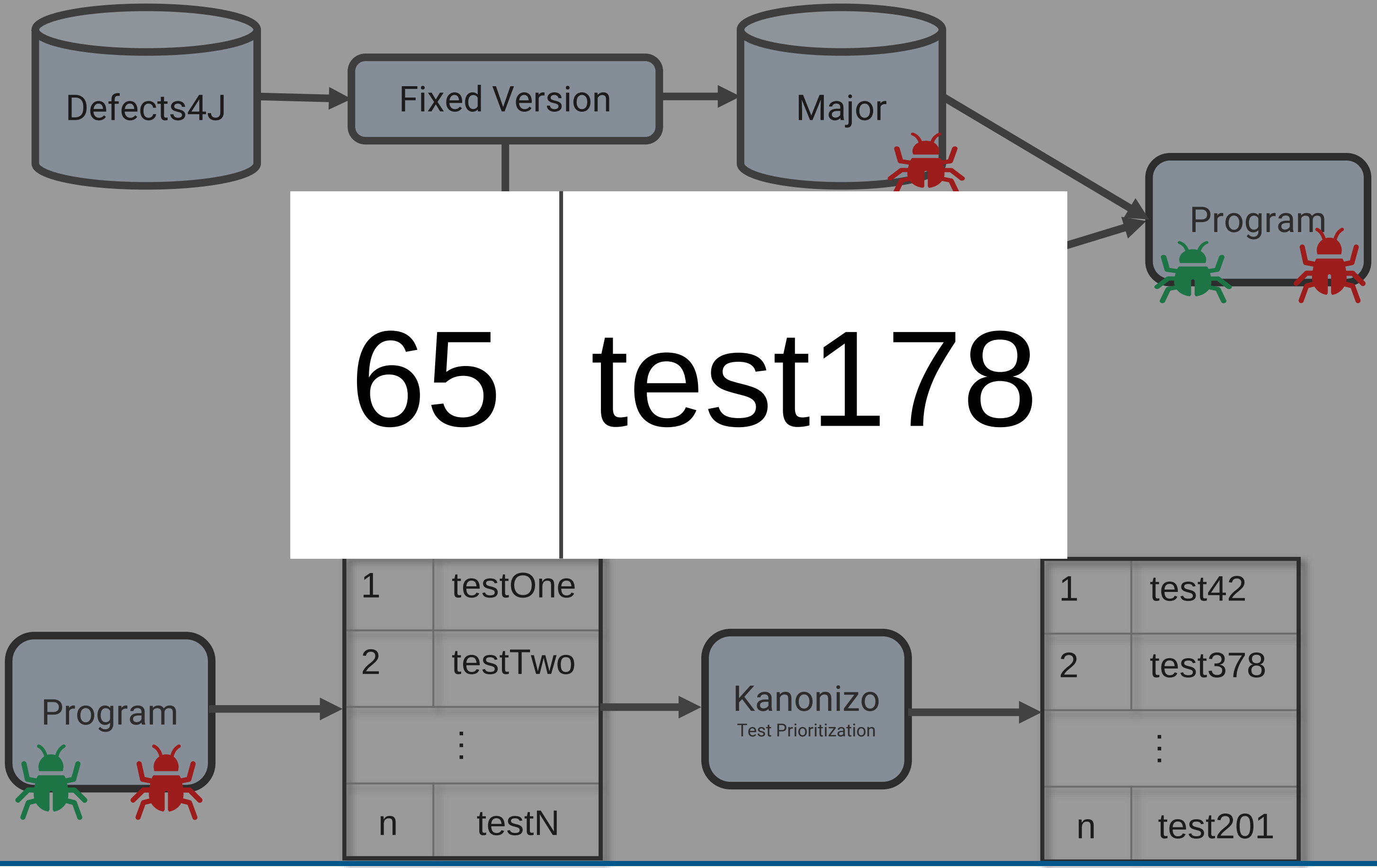
Experimental Process



1	testOne
2	testTwo
	⋮
n	testN

1	test42
2	test378
	⋮
n	test201

Experimental Process



65	test178

1	testOne
2	testTwo
	⋮
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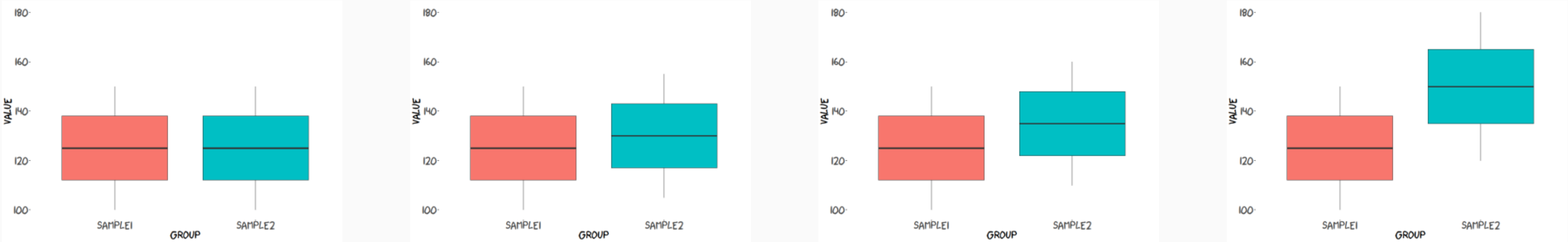
1	test42
2	test378
	⋮
n	test201

Metrics

- **Wilcoxon U-Test** measures likelihood that 2 samples originate from the same distribution p
  - Significant differences occur often when samples are large

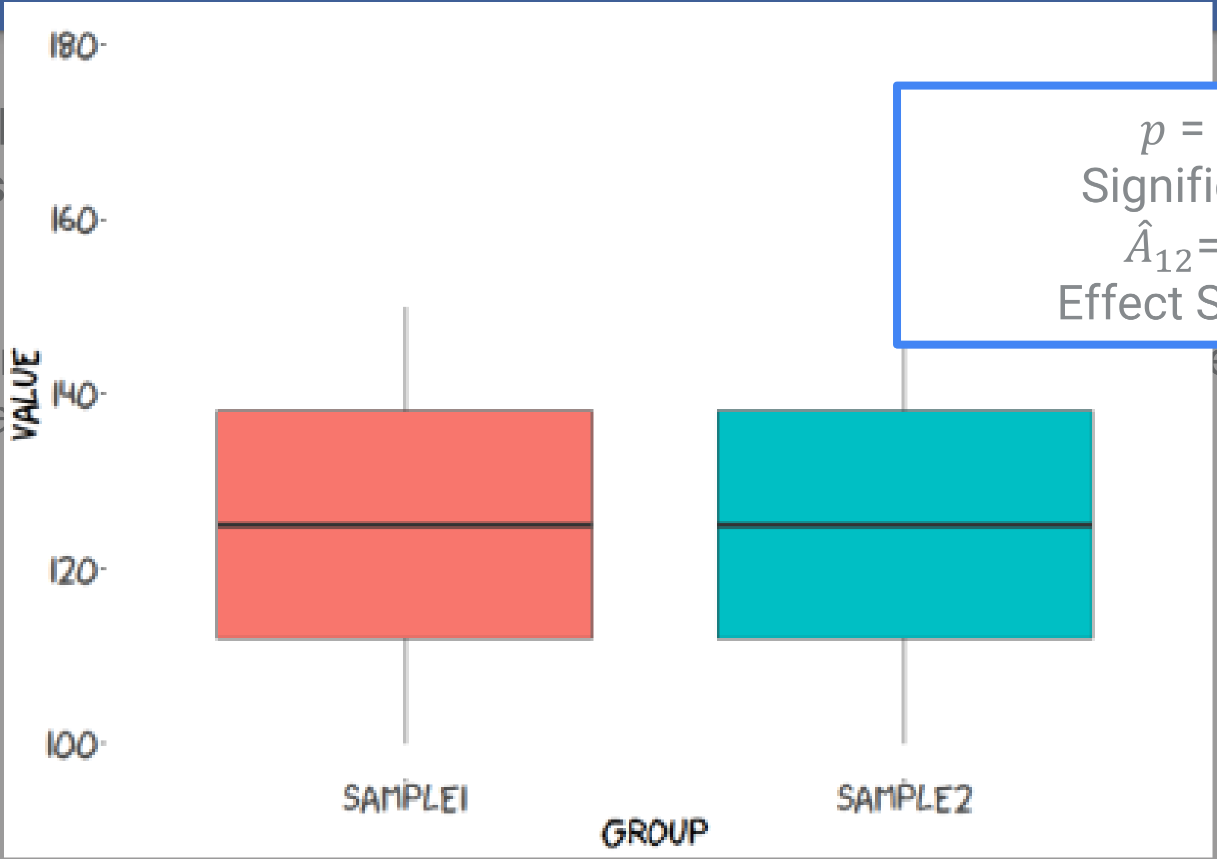
- **Vargha-Delaney** effect size calculates the *magnitude* of differences $\hat{A}_{12}$ – the practical difference between two samples



Metrics

- **Wi**
  dis

- **Va** erences – the
  pra

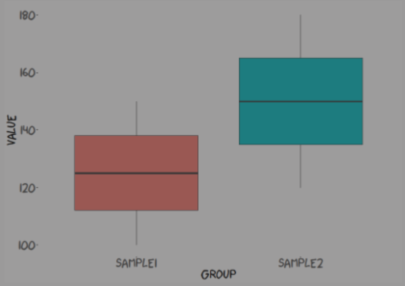


p = 0.5544

Significant = ✗

$\hat{A}_{12}$= 0.5007

Effect Size = None



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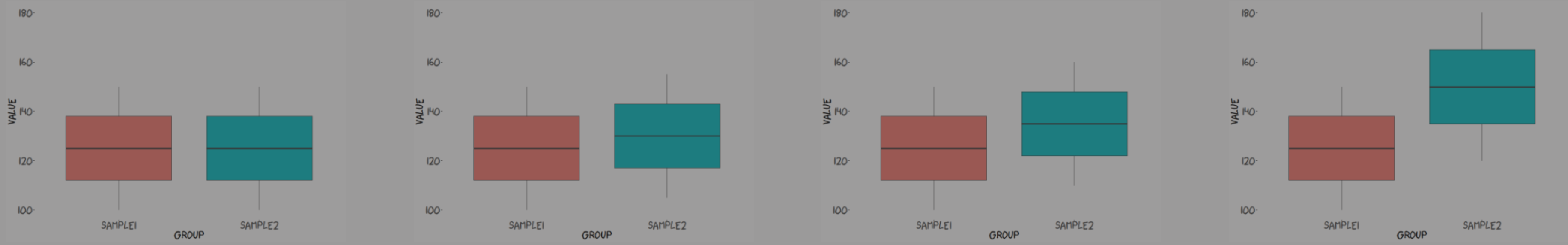

Metrics

- **Wilcox**
  distribu
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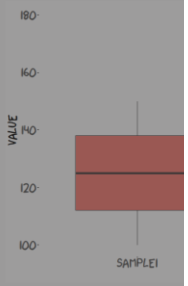
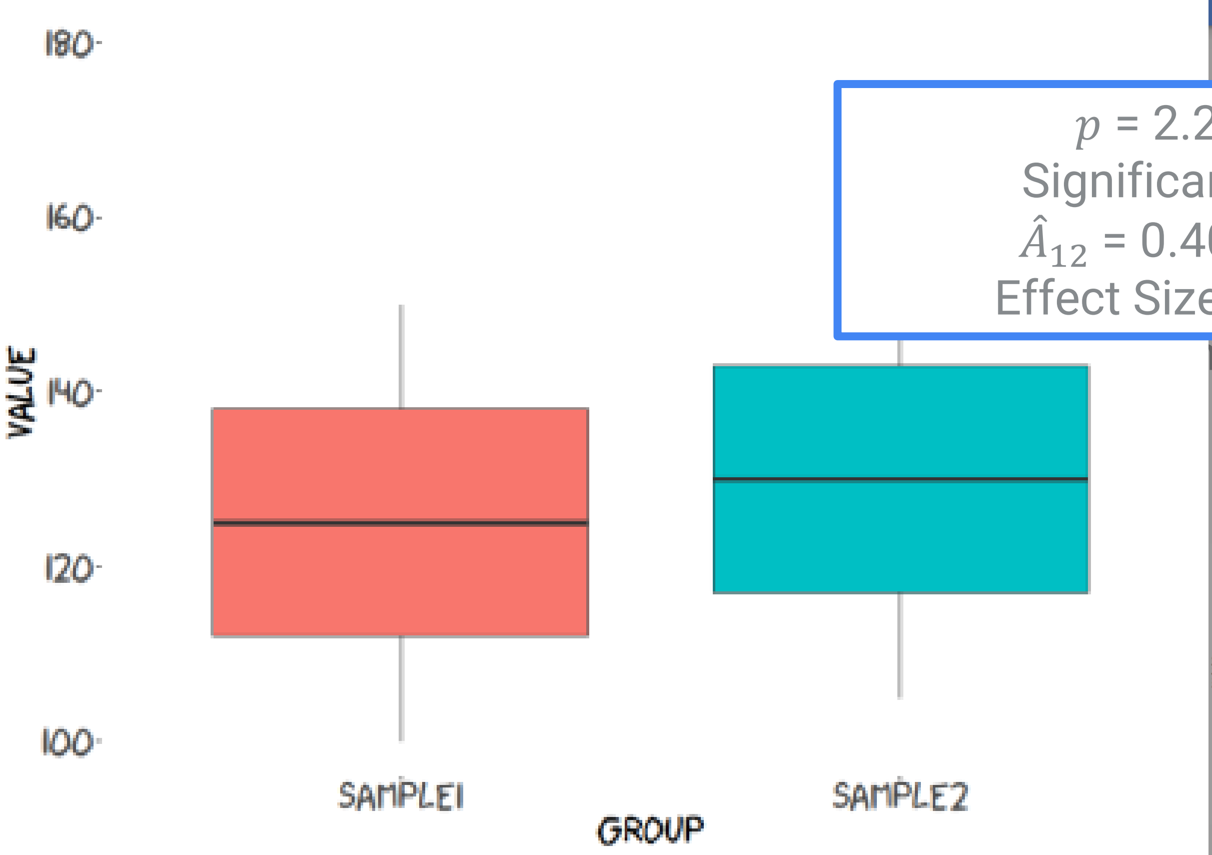
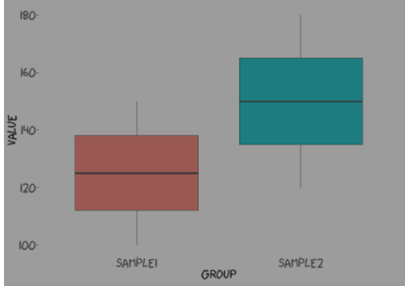




p = 2.2e-16
Significant = ✓
$\hat{A}_{12}$ = 0.4075059
Effect Size = Small



Metrics

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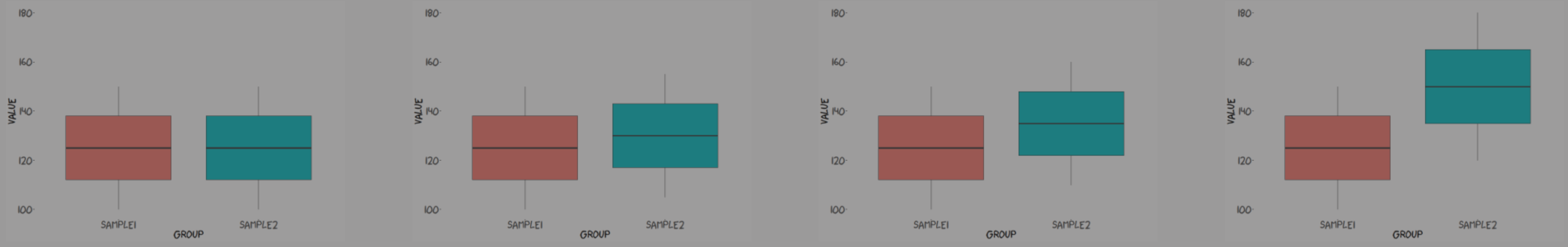
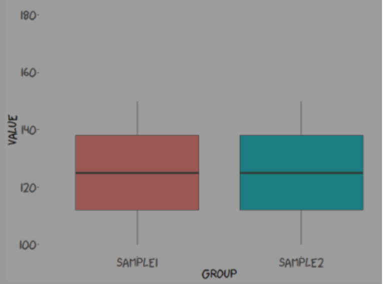
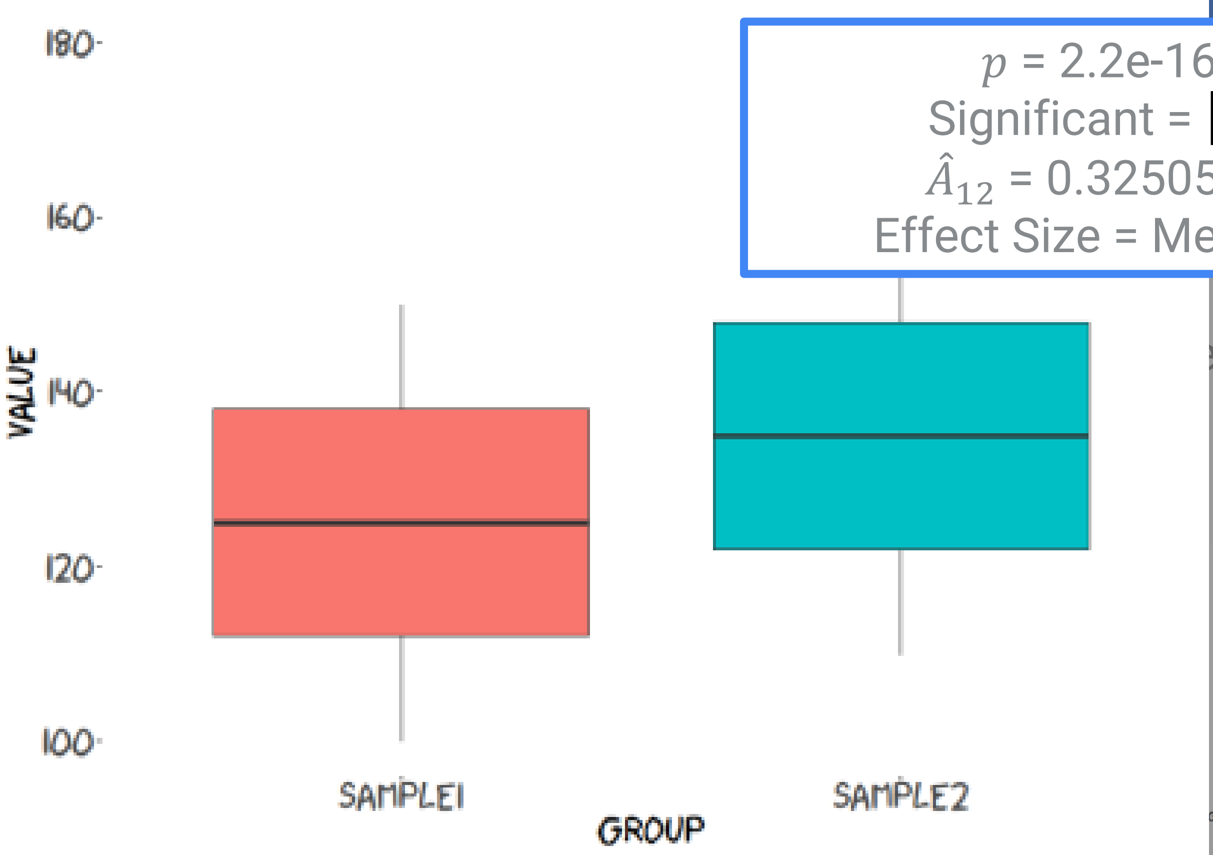


Metrics

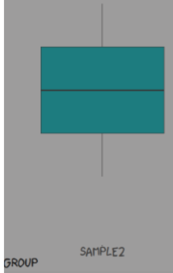
- **Wilcoxon U-Tes**
  distribution
  - Significa

- **Vargha-Delaney** e
  practical differe





p = 2.2e-16
Significant = ✓
$\hat{A}_{12}$ = 0.3250598
Effect Size = Medium



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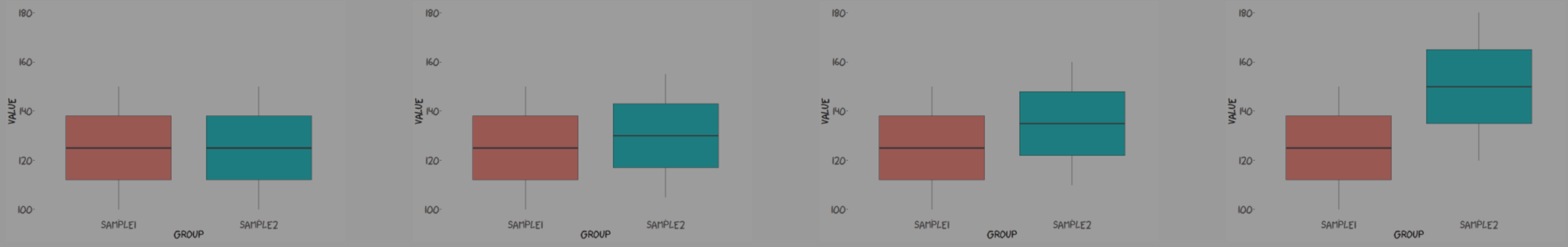


Metrics

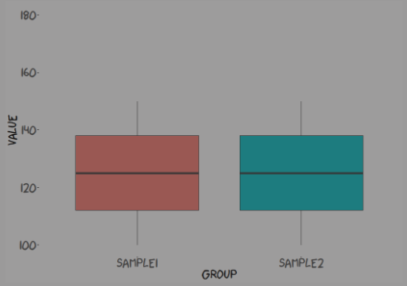
- **Wilc** distr
- **Vargha-Delaney** effect practical difference be

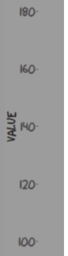
p = 2.2e-16

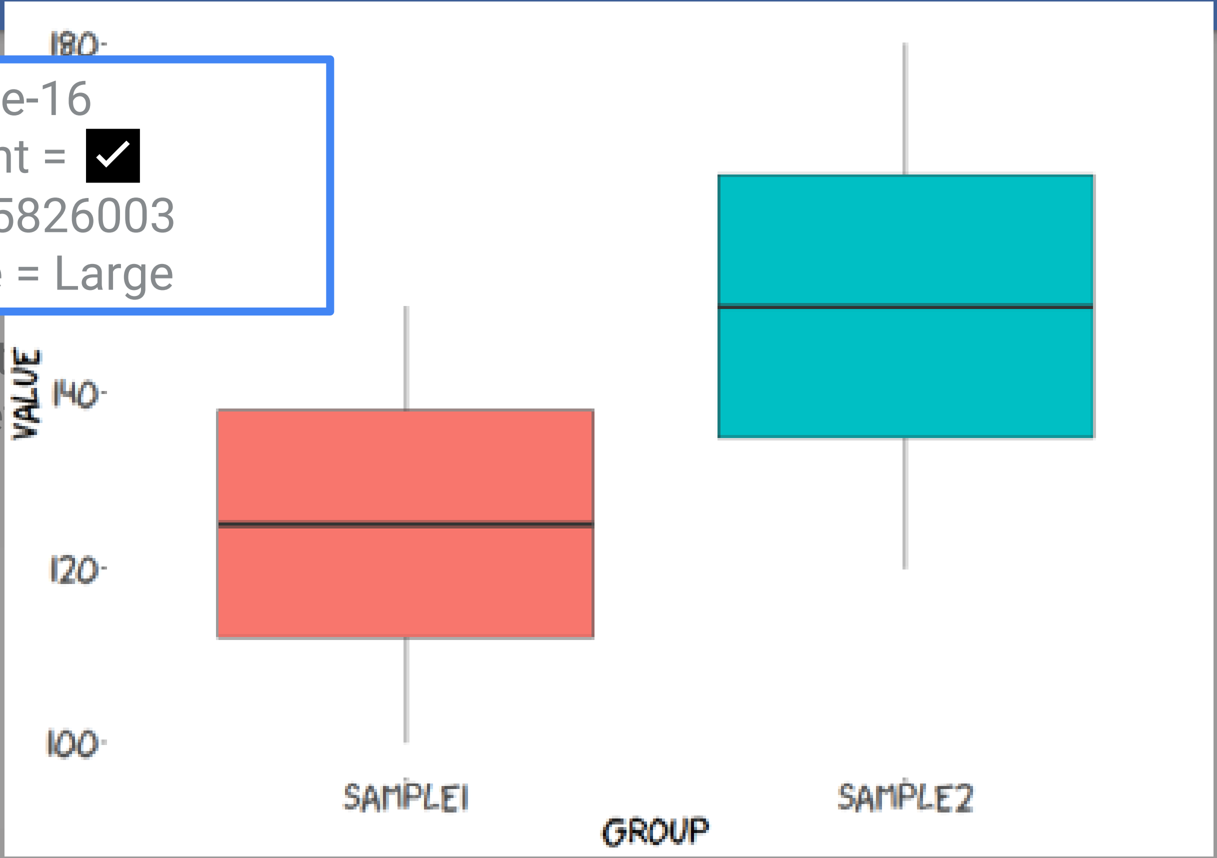
Significant = ☑

$\hat{A}_{12}$ = 0.005826003

Effect Size = Large







Comparisons

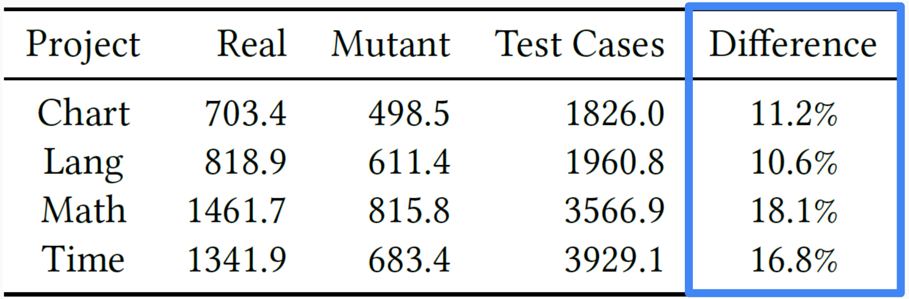
RQ1				RQ2				
Strategy 1	Strategy 2	Fault Type 1	Fault Type 2	Strategy 1	Strategy 2	Faults 1	Faults 2	Faults 3
A	A	**Real**	**Mutant**	A	A	1	5	10
A	B	**Real**	**Real**	A	B	1	5	10
A	B	**Mutant**	**Mutant**					

Results

RQ1: Real Faults vs Mutants

- APFD is **significantly higher** for **mutants** than **real faults** in all but one case

- On average, over **10% additional** test cases were required to find the **real faults**



Project	Real	Mutant	Test Cases	Difference
Chart	703.4	498.5	1826.0	11.2%
Lang	818.9	611.4	1960.8	10.6%
Math	1461.7	815.8	3566.9	18.1%
Time	1341.9	683.4	3929.1	16.8%

- For **real faults**, **3 out of 16** project/strategy combinations significantly improve over the baseline, compared to **10 out of 16** improvements for **mutants**

Results

RQ1: Real Faults vs Mutants

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Time	1341.0	683.4	2020.1	16.8%

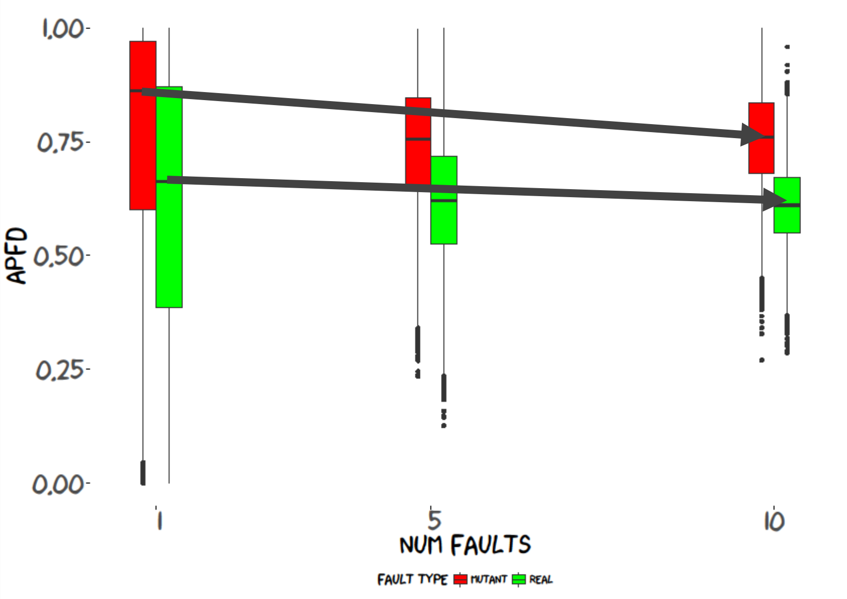
Test Case Prioritization is much more effective for mutants than real faults

- For **real faul** rove over the
  baseline, co

Results

RQ2: Single faults vs Multiple Faults

- Variance in APFD scores **<u>significantly</u>** reduces as more faults are introduced



- In **<u>37/40</u>** cases, median APFD *decreased* as more faults are introduced

  - APFD punishes test suites that are not able to find **<u>all</u>** faults

Results

RQ2: Single faults vs Multiple Faults

- However, **real faults** and **mutants** still disagree on the effectiveness of TCP techniques

- For **real faults**, there is very rarely any practical difference when including more faults
  - 17 of 40 comparisons are significant, of which 3 are **M**edium or **L**arge effect size

- For **mutants**, increasing the number of faults makes the results clearer
  - 35 of 40 comparisons are significant, of which 16 are **M**edium or **L**arge effect size
  - Effect size increases in **all but one** case for more faults

Results

RQ2: Single faults vs Multiple Faults

- However, **real faults** and **mutants** still disagree on the effectiveness of TCP techniques

- For **real faults**, there is very rarely any practical difference when including more faults

  - 17 of 40 comparisons are significant, of which 3 are Medium or Large effect size

- For **mutants**, increasing the number of faults makes the results clearer

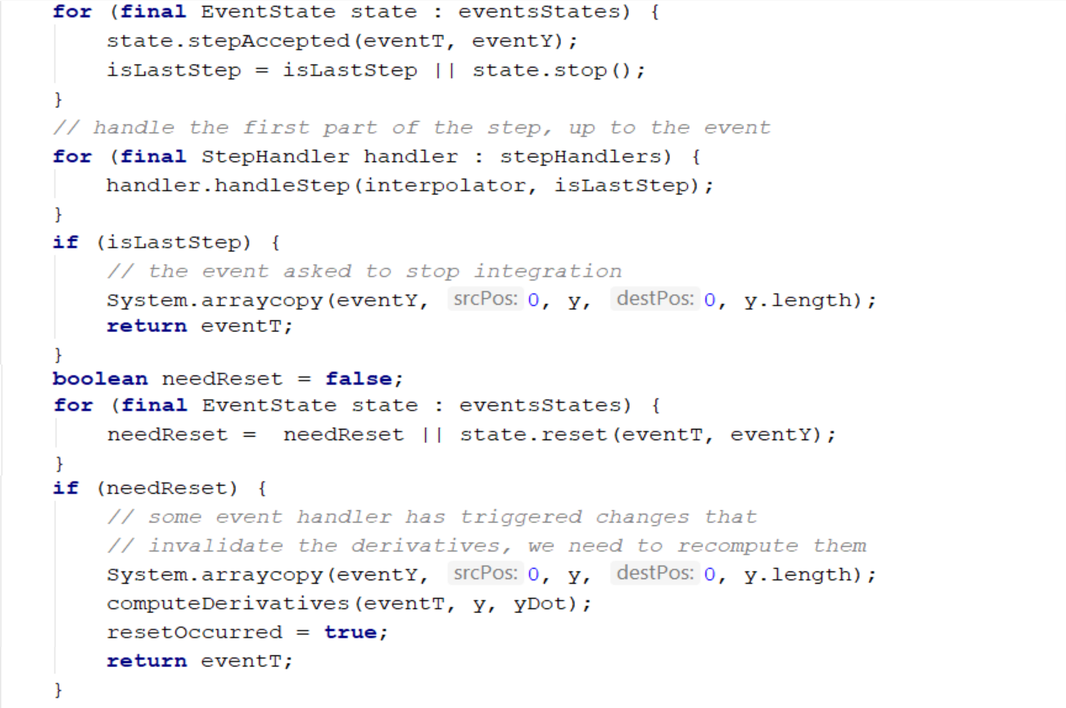
  - 35 of ge effect size

  - Effect

Using more faults lessens the effect of randomness, but still does not make mutants and real faults consistent

Real Faults vs Mutants

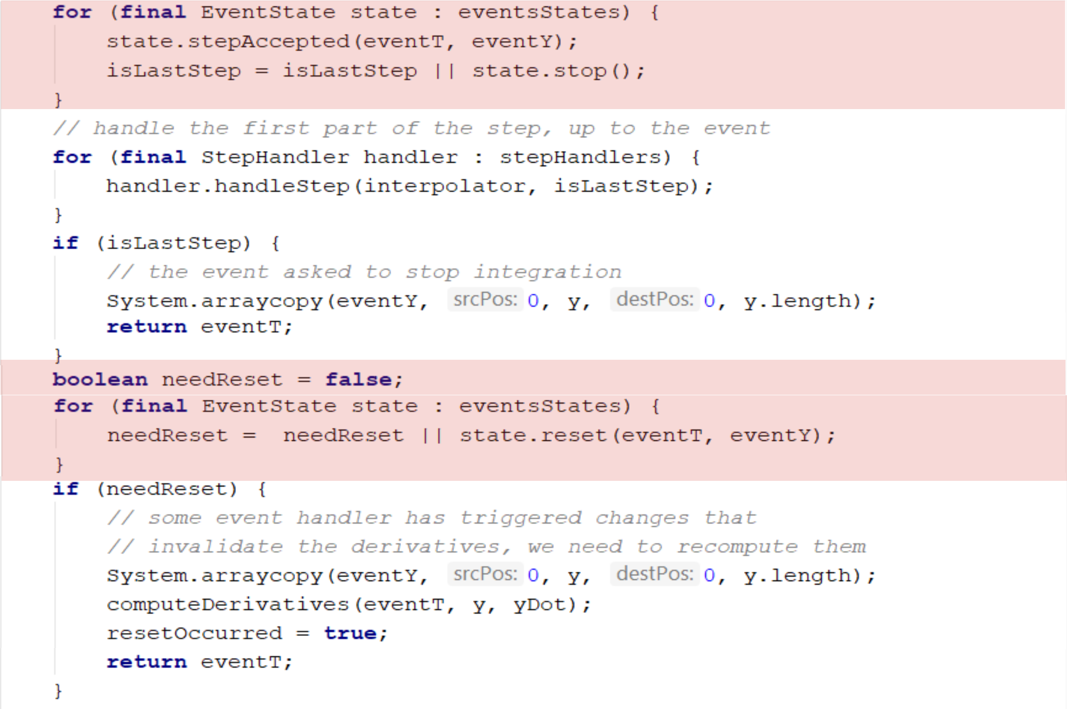
- Real faults are much more complex than mutants



```java
for (final EventState state : eventsStates) {
    state.stepAccepted(eventT, eventY);
    isLastStep = isLastStep || state.stop();
}
// handle the first part of the step, up to the event
for (final StepHandler handler : stepHandlers) {
    handler.handleStep(interpolator, isLastStep);
}
if (isLastStep) {
    // the event asked to stop integration
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    return eventT;
}
boolean needReset = false;
for (final EventState state : eventsStates) {
    needReset =  needReset || state.reset(eventT, eventY);
}
if (needReset) {
    // some event handler has triggered changes that
    // invalidate the derivatives, we need to recompute them
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    computeDerivatives(eventT, y, yDot);
    resetOccurred = true;
    return eventT;
}
```

Real Faults vs Mutants

- Real faults are much more complex than mutants



```
for (final EventState state : eventsStates) {
    state.stepAccepted(eventT, eventY);
    isLastStep = isLastStep || state.stop();
}
// handle the first part of the step, up to the event
for (final StepHandler handler : stepHandlers) {
    handler.handleStep(interpolator, isLastStep);
}
if (isLastStep) {
    // the event asked to stop integration
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    return eventT;
}
boolean needReset = false;
for (final EventState state : eventsStates) {
    needReset =  needReset || state.reset(eventT, eventY);
}
if (needReset) {
    // some event handler has triggered changes that
    // invalidate the derivatives, we need to recompute them
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    computeDerivatives(eventT, y, yDot);
    resetOccurred = true;
    return eventT;
}
```

Real Faults vs Mutants

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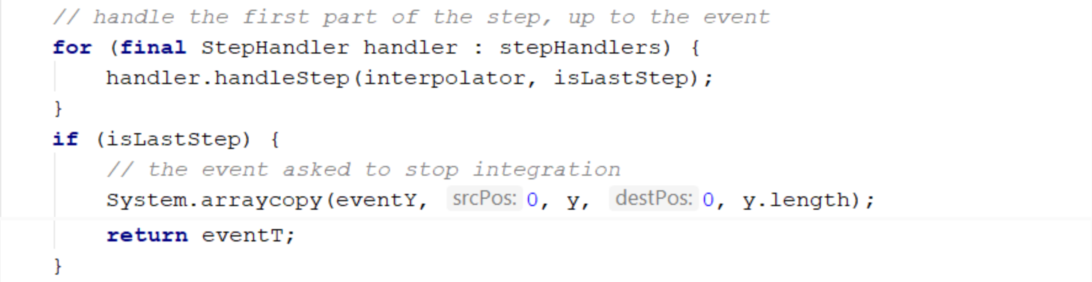
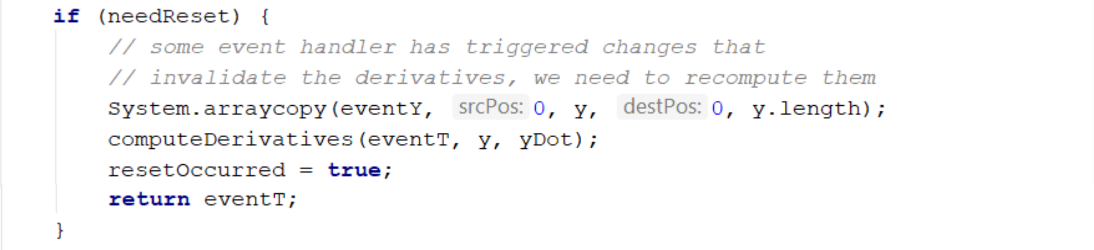


```
// handle the first part of the step, up to the event
for (final StepHandler handler : stepHandlers) {
    handler.handleStep(interpolator, isLastStep);
}
if (isLastStep) {
    // the event asked to stop integration
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    return eventT;
}
```



```
if (needReset) {
    // some event handler has triggered changes that
    // invalidate the derivatives, we need to recompute them
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    computeDerivatives(eventT, y, yDot);
    resetOccurred = true;
    return eventT;
}
```

Real Faults vs Mutants

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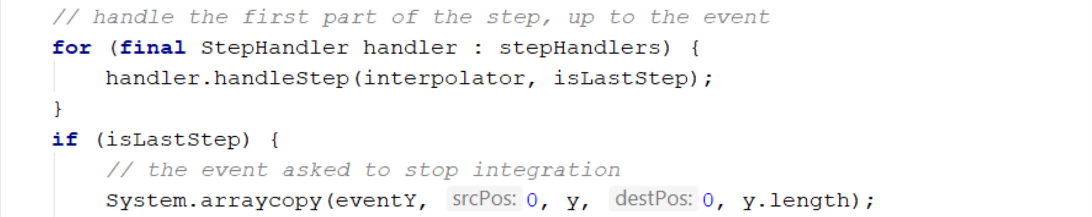
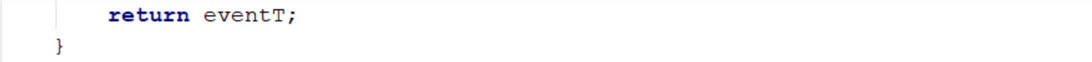
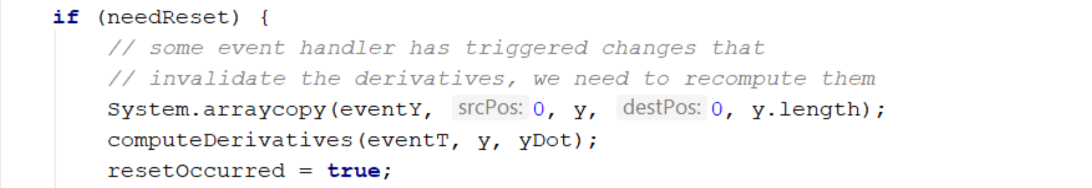


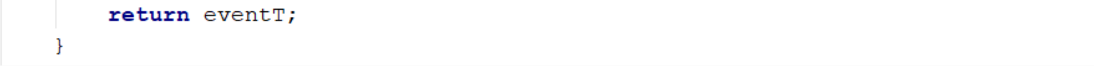
```
// handle the first part of the step, up to the event
for (final StepHandler handler : stepHandlers) {
    handler.handleStep(interpolator, isLastStep);
}
if (isLastStep) {
    // the event asked to stop integration
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
```



```
    return eventT;
}
```



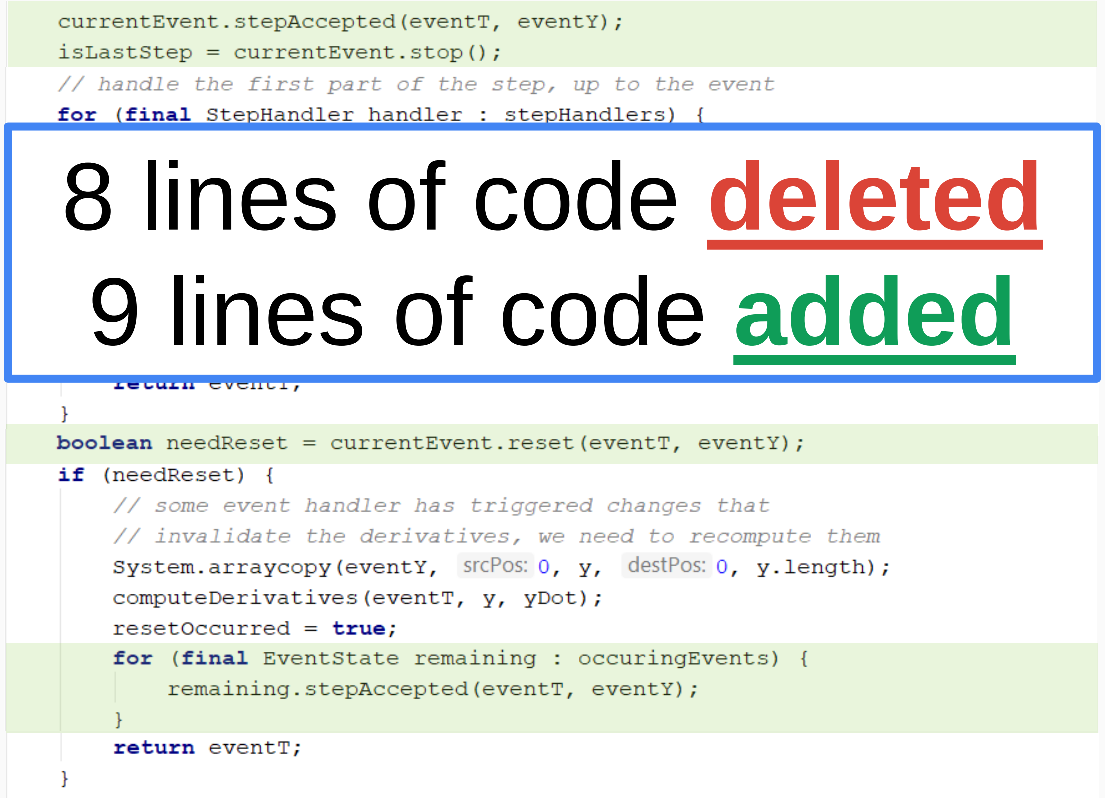
```
if (needReset) {
    // some event handler has triggered changes that
    // invalidate the derivatives, we need to recompute them
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    computeDerivatives(eventT, y, yDot);
    resetOccurred = true;
```



```
    return eventT;
}
```

Real Faults vs Mutants

- Real faults are much more complex than mutants



```
currentEvent.stepAccepted(eventT, eventY);
isLastStep = currentEvent.stop();
// handle the first part of the step, up to the event
for (final StepHandler handler : stepHandlers) {
    return eventT;
}
boolean needReset = currentEvent.reset(eventT, eventY);
if (needReset) {
    // some event handler has triggered changes that
    // invalidate the derivatives, we need to recompute them
    System.arraycopy(eventY, srcPos: 0, y, destPos: 0, y.length);
    computeDerivatives(eventT, y, yDot);
    resetOccurred = true;
    for (final EventState remaining : occuringEvents) {
        remaining.stepAccepted(eventT, eventY);
    }
    return eventT;
}
```

8 lines of code <u>deleted</u>

9 lines of code <u>added</u>

Real Faults vs Mutants

- Real faults are much more complex than mutants
  - On average, fixing a **real fault** added 1.98 lines and removed 7.2
  - Fixing a **mutant** is always **max** +/- 1 line

```
boolean needsReset = true;
```

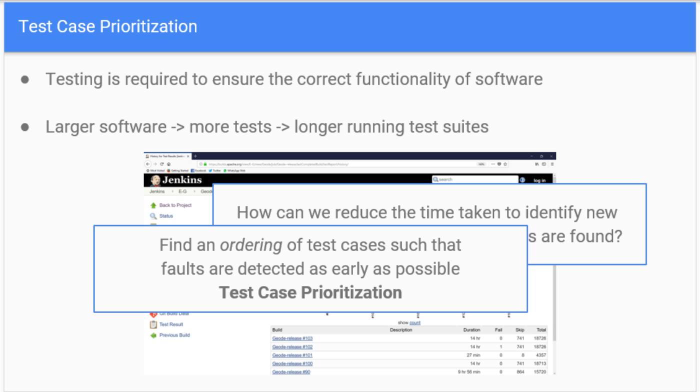
Real Faults vs Mutants

- Real faults are much more complex than mutants
  - On average, fixing a **real fault** added 1.98 lines and removed 7.2
  - Fixing a **mutant** is always **max** +/- 1 line

```
boolean needsReset = false;
```

- This results in **more** test cases detecting **mutants**
  - On average, 3.18 test cases detected single **real faults**
  - Meanwhile, 57.38 test cases detected single **mutants**

Summary



Test Case Prioritization

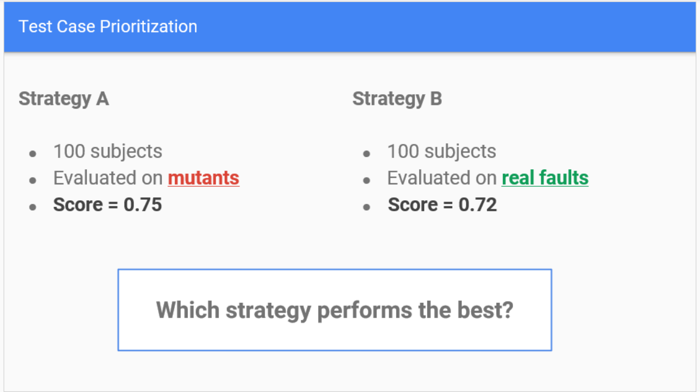
- Testing is required to ensure the correct functionality of software
- Larger software -> more tests -> longer running test suites

How can we reduce the time taken to identify new

s are found?

Find an *ordering* of test cases such that faults are detected as early as possible

Test Case Prioritization



Test Case Prioritization

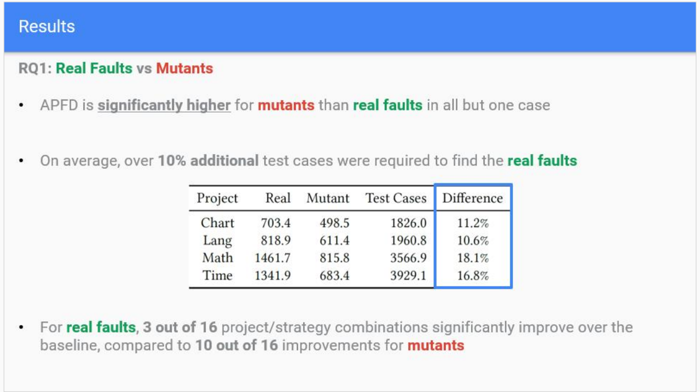
Strategy A

- 100 subjects
- Evaluated on **mutants**
- **Score = 0.75**

Strategy B

- 100 subjects
- Evaluated on **real faults**
- **Score = 0.72**

Which strategy performs the best?



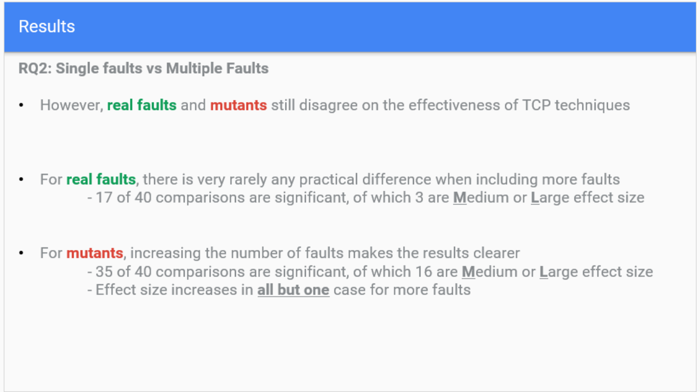
Results

RQ1: Real Faults vs Mutants

- APFD is **significantly higher** for **mutants** than **real faults** in all but one case
- On average, over **10% additional** test cases were required to find the **real faults**

Project	Real	Mutant	Test Cases	Difference
Chart	703.4	498.5	1826.0	11.2%
Lang	818.9	611.4	1960.8	10.6%
Math	1461.7	815.8	3566.9	18.1%
Time	1341.9	683.4	3929.1	16.8%

- For **real faults**, **3 out of 16** project/strategy combinations significantly improve over the baseline, compared to **10 out of 16** improvements for **mutants**



Results

RQ2: Single faults vs Multiple Faults

- However, **real faults** and **mutants** still disagree on the effectiveness of TCP techniques
- For **real faults**, there is very rarely any practical difference when including more faults
  - 17 of 40 comparisons are significant, of which 3 are Medium or Large effect size
- For **mutants**, increasing the number of faults makes the results clearer
  - 35 of 40 comparisons are significant, of which 16 are Medium or Large effect size
  - Effect size increases in **all but one** case for more faults

Tool:
https://github.com/kanonizo/kanonizo

Data:
https://bitbucket.org/djpaterson/ast2018_data