

Lecture 7 – Mutation Testing

AAA705: Software Testing and Quality Assurance

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2026 Fall

- Regression Fault – a change breaks what used to work
- Test Suite Minimization
 - Drop redundant tests – set cover, greedy with cost or score
- Test Case Selection
 - Rerun only the tests that reach the change – safe or predictive
- Test Case Prioritization
 - A surrogate for fault detection – coverage, clusters, failure history
- In practice: at CI scale, prioritize the **commits**

How Good Is a Test Suite?

```
def abs(x: Int): Int = if (x < 0) -x else x

def test(): Unit = { abs(-3); abs(0); abs(3) }
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- It also checks **nothing**. Replace $-x$ by x and the test still passes. Coverage says the line was **run**, not that it was **tested**.

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- It also checks **nothing**. Replace `-x` by `x` and the test still passes. Coverage says the line was **run**, not that it was **tested**.
- **Today**: break the program on purpose, and ask whether the suite **notices**.

1. Mutation Testing

- Fundamental Hypotheses

- Overall Process

- Mutation Generation

- Kill vs Alive

- Equivalent Mutants

- How to Kill A Mutant

- Scalability

- Higher Order Mutants

- Tools

2. Test Flakiness

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- Fundamental Hypotheses

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2. Test Flakiness

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- **Mutation testing** is a white-box and fault-based testing technique.
- **Inverts** the testing adequacy criterion: the goal is to **assess** the effectiveness of the existing test suite in terms of its **fault detection capabilities**.
 - **Test suites** test **programs**
 - **Mutants** test **test suites**
- The most widely used adequacy score is **mutation score**: it measures the quality of the given test suite as **the percentage of injected faults that you can detect**.

Mutation testing publications per year – the idea is from **1978**, the tools are recent.¹

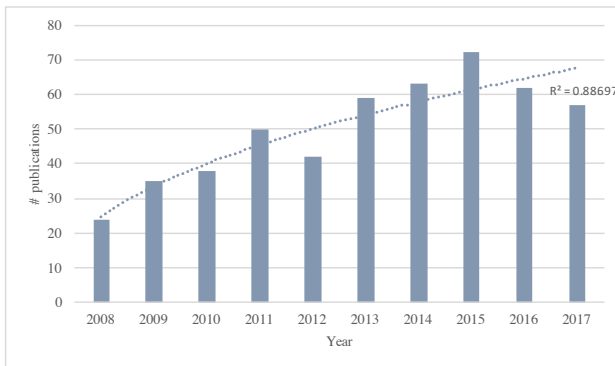


Figure 1: Number of mutation testing publications per year (years: 2008-2017).

¹[Adv. Comput.'19] M. Papadakis, M. Kintis, J. Zhang, Y. Jia, Y. Le Traon, M. Harman. "Mutation Testing Advances: An Analysis and Survey."

Which environment is better test environment for car? **Why?**



Let's **sabotage** the car! In the **bendy road**, the car will **crash**!

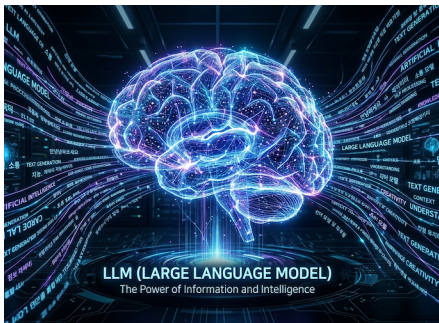


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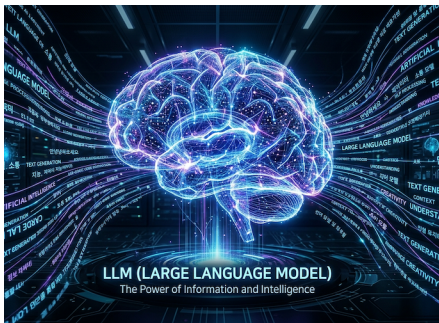
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- **Mutation testing:** the **quality** of a test suite can be indirectly measured by **artificially injecting faults** and **checking how well the test suite can detect them**.
 - **Seed** the original program with small faults – each seeded version is a **mutant**.
 - **Execute** the given test suite on every mutant.
 - If the results **differ** from the original, the fault was detected: the mutant is **killed**. Otherwise it is still **alive**.

(1) Competent Programmer Hypothesis



What do **programmers** and **LLMs** have in common when they write code?

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What do **programmers** and **LLMs** have in common when they write code?

They both write **almost correct** code.

(1) Competent Programmer Hypothesis



On average, programmers are **competent** (they write **almost correct** programs). A **faulty program** source code is different from the correct one **only in a few**, minor detail.

(2) Coupling Effect Hypothesis

- If a **test suite** detects **all small syntactic faults**, it will also detect **larger, semantic faults** that are **coupled with** them.²

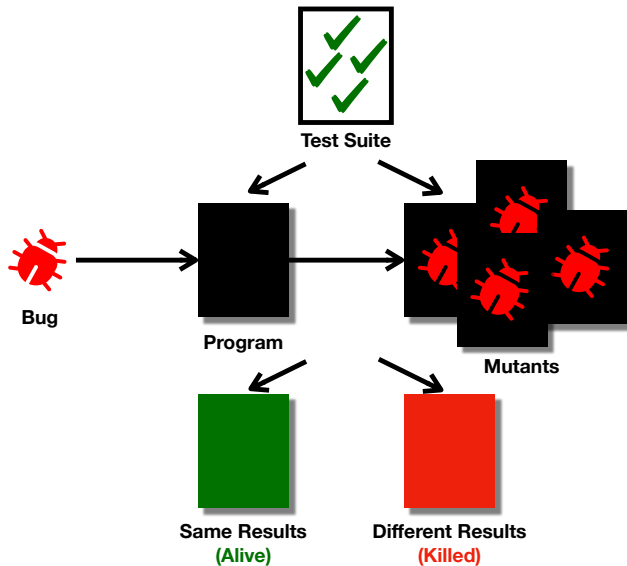
²[Computer'78] R. A. DeMillo, R. J. Lipton, F. G. Sayward. "*Hints on Test Data Selection: Help for the Practicing Programmer.*" [TOSEM'92] A. J. Offutt. "*Investigations of the Software Testing Coupling Effect.*"

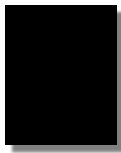
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- If a **test suite** detects **all small syntactic faults**, it will also detect **larger, semantic faults** that are **coupled with** them.²
- **Big** faults and **small** mutants tend to fail on the **same inputs**. A test that kills the small one catches the big one too.
- This is an **empirical** claim, not a theorem. Offutt tested it and found it holds for the operators we use.

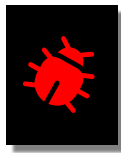
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- **Mutation testing** is based on two **fundamental hypotheses**:
 - ① **Competent Programmer Hypothesis**: programmers are likely to make simple faults.
 - ② **Coupling Effect Hypothesis**: if we catch all the simple faults, we will be able to catch more complicated faults.
- Let's artificially **inject simple faults**!



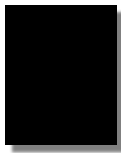


Program P

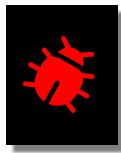


Mutant P'

- P' differs from P by a **simple mutation**.



Program P



Mutant P'

- P' differs from P by a **simple mutation**.
- **Mutation**: a typical simple error programmers are likely to make – off-by-one errors, typo, mistaken identity, etc.

A **mutation operator** is an atomic syntactic rule. One rule applied at one place gives one mutant.

ROR: Relational Operator Replacement

```
if (x >= y)
```



```
if (x > y)  
if (x == y)  
if (x < y)  
if (x != y)
```

One line, **four** mutants. This is where the numbers come from.

The operators of **Mothra**, the Fortran system that set the standard.³

	Rule	Original	Mutant
ABS	Absolute value insertion	<code>x = 4 * y;</code>	<code>x = 4 * abs(y);</code>
AOR	Arithmetic operator replacement	<code>x = y + z;</code>	<code>x = y * z;</code>
ROR	Relational operator replacement	<code>if (x >= y)</code>	<code>if (x > y)</code>
COR	Conditional operator replacement	<code>if (x && y)</code>	<code>if (x y)</code>
SDL	Statement deletion	<code>y = x + 5;</code>	<i>(deleted)</i>

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ABS also has `-abs(y)` and `failOnZero(y)`: the point of ABS is to force a test at **zero** and at a **negative** value.

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- For **Spreadsheets**
 - R. Abraham and M. Erwig. Mutation operators for spreadsheets. IEEE Transactions on Software Engineering, 35(1):94–108, 2009.

Object-oriented languages need operators that break **inheritance** and **dispatch**, not just arithmetic.⁴

Group	Example operator	What it breaks
Access control (1)	AMC – change public to private	Information hiding
Inheritance (7)	IHD – delete a hiding field	Which size you read
Polymorphism (4)	Change a declared type to its parent	Which override runs
Overloading (4)	Delete one overloaded method	Which signature is chosen
Java-specific (4)	Delete this , static, an initializer	Default values

⁴[ISSRE'02] Y.-S. Ma, Y.-R. Kwon, J. Offutt. "Inter-Class Mutation Operators for Java."

IOP – **o**verridden method calling **p**osition change: move the **super** call, which invokes the parent's (overridden) method.

```
class Stack extends List {  
    void setEnv() {  
        super.setEnv();  
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- The parent sets `size = 5`. Before the swap the child wins (10); after it, the parent wins (5).
- A test only kills this mutant if it **reads** `size` **afterwards**. Merely constructing a `Stack` is not enough.

```
x = y + z;  
print(x);
```



```
x = y * z;  
print(x);
```

program P

mutant P' (AOR)

test	P	P'	
$(y, z) = (2, 2)$	4	4	Alive
$(y, z) = (3, 1)$	4	3	Kill

The same mutant, two verdicts. **The input decides**, not the mutant.

```
x = y + y;  
print(x);
```



```
x = y * 2;  
print(x);
```

program P

mutant P'

test	P	P'	
$y = 2$	4	4	Alive
$y = 3$	6	6	Alive

No input can tell them apart. That is the next slide.

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- What if a **mutant** has the same **behavior** as the original program?
- For example, consider the following program and its mutant:



- Checking whether an arbitrary mutant is equivalent or not is **undecidable**.
- This is one of the **major obstacles** to the mainstream adoption of mutation testing.
 - My **mutation score** is 70%. Is my test suite bad, or are there too many equivalent mutants?

$$MS = \frac{(\# \text{ of killed mutants})}{(\# \text{ of non-equivalent mutants})}$$

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what tools report – an **underestimate**

A score never reaches 100%, and two projects' scores are not comparable.

Use it on **one suite, before and after**.

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We categorize the kill conditions into two types: **weak** and **strong**.

- **(Weak Kill) = Reachability + Infection**
(i.e., we stop after confirming infection, do not check the propagation to the outside world)
- **(Strong Kill) = Reachability + Infection + Propagation**
(i.e., the kill can be observed from the outside world)

```
if (x < y) {  
    if (z < y) {  
//if (z < y + 1) {  
        if (x < z) {  
            result = z;  
        } else {  
            result = x;  
        }  
    } else {  
        result = y;  
    }  
} else {  
    result = 0;  
}
```

- **Reachability:** $x < y$

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The **same value**.

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The **same value**.
- **Strong kill:** $(x < y) \wedge (z = y) \wedge (y \neq z)$
– **unsatisfiable**.

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- This is why **weak** mutation is attractive – it needs no propagation and stops at the infected state – and also why it is **optimistic**: it reports a kill where the outside world sees nothing.
- The conditions also say what a **test generator** must solve. Reachability is a **path condition** – the same formula symbolic execution collects – and infection and propagation are two more constraints on top of it.

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- We tend to get a large number of mutants:
 - No prior knowledge of **which mutation** operator is the **most effective** (w.r.t. improving the test suite quality): the default is to apply everything
 - **Programs are large!**

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 - **Static subsumption** is defined with results of static analysis.
- **Selective Mutation** – apply only a **subset** of **operators**. Five operators reproduce most of the full set's power.

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- **Weak mutation testing** – **relax the kill criterion to weak kills** (requires instrumentation for the embedded oracle).
- **Parallel/distributed mutation testing** – obvious.

- **Trivial Compiler Equivalence (TCE)⁵** – a mutant is **trivially equivalent** if the binary code of the mutant is **same** as the binary code of the original program after the compilation (thanks to the **compiler optimization**).

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- A large scale empirical study showed that TCE can detect **7% of the mutants to be equivalent**; more importantly, **21% of all mutants were duplicates** (i.e., not equivalent to the original program, but identical to another non-equivalent mutant).

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- **Incremental** – mutate only the **lines in the diff**, during **code review**. No score for the code base, no whole-program run.

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- **Incremental** – mutate only the **lines in the diff**, during **code review**. No score for the code base, no whole-program run.
- **Filtered** – drop **arid** mutants, the ones no reasonable test would ever be written for (logging, timeouts, performance knobs). At most **one** surviving mutant is shown per line.

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- **Filtered** – drop **arid** mutants, the ones no reasonable test would ever be written for (logging, timeouts, performance knobs). At most **one** surviving mutant is shown per line.
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- The output is not a number but a **review comment**: “this line survives this change – is a test missing?” Developers act on it.

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- One empirical question: **does killing mutants predict catching real faults?**

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mutant detection vs. real fault detection	correlated
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- A **better proxy** than coverage, whose correlation fades once suite **size** is controlled.⁸ Still a proxy – and the 10% is why new operators keep coming, lately from a language model.⁹

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- One such HOM stands in for its FOMs: **fewer** mutants, **harder** ones.

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Diverse **mutation testing tools** are available:

- **Fortran** – **Mothra** (a long-lasting impact on the mutation testing)
- **C/C++** – Proteum, MiLU, MUSIC
- **Java** – muJava, Major, Javalanche, PIT
- **JavaScript** – Stryker
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In practice **PIT** and **Stryker** are the ones you are most likely to meet in a CI pipeline.

1. Mutation Testing

Fundamental Hypotheses

Overall Process

Mutation Generation

Kill vs Alive

Equivalent Mutants

How to Kill A Mutant

Scalability

Higher Order Mutants

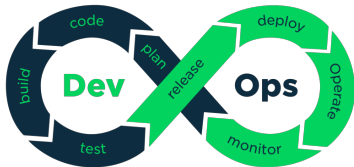
Tools

2. Test Flakiness

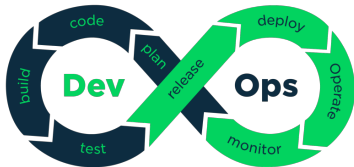
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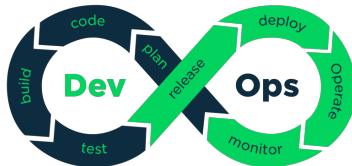
- Everything so far judged a mutant by one rule: **run the suite, see whether the results differ**.
- A **flaky** test gives a different result on the **same** code. Then the rule reports a kill where nothing was killed – and the same rule is what told us a regression had appeared last time.
- So before trusting any of it: how bad is this, and what can we do?



- A **DevOps** concept popularized by Google, more commonly and also known as: **Continuous Integration and Deployment (CI/CD)**



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- A **DevOps** concept popularized by Google, more commonly and also known as: **Continuous Integration and Deployment (CI/CD)**
- Newest version of software is automatically deployed whenever all tests pass.
- Test results are critical
 - **False Negative** (i.e., test passes even though there is a bug): you end up releasing a buggy software
 - **False Positive** (i.e., test fails even though there is no bug): slows down the development process

“Making *Push On Green* a Reality” – what it takes to deploy on a green test run, from Google.¹¹

Making Push On Green a Reality

Daniel V. Klein, Google

¹¹[LISA'14] D. V. Klein, D. M. Betser, M. G. Monroe. “*Making “Push On Green” a Reality.*” USENIX LISA.

“Making *Push On Green* a Reality” – what it takes to deploy on a green test run, from Google.¹¹

Making Push On Green a Reality

Daniel V. Klein, Google

Every mechanism we saw last time – selection, prioritization, parallel runs – exists to make that green light **arrive sooner**. It is worth nothing if the light is **wrong**.

¹¹[LISA'14] D. V. Klein, D. M. Betser, M. G. Monroe. “Making “Push On Green” a Reality.” USENIX LISA.

- We call a test case to be **flaky** if it changes outcome against the same codebase.

- We call a test case to be **flaky** if it changes outcome against the same codebase.
- This creates a **huge problem** for the Push on Green philosophy: when a test transitions from pass to fail, is it flaky or is it actually a real problem?

Analysis of Test Results at Google

- Analysis of a large sample of tests (1 month) showed:
 - 84% of transitions from Pass -> Fail are from "flaky" tests
 - Only 1.23% of tests ever found a breakage
 - Frequently changed files more likely to cause a breakage
 - 3 or more developers changing a file is more likely to cause a breakage
 - Changes "closer" in the dependency graph more likely to cause a breakage
 - Certain people / automation more likely to cause breakages (oops!)
 - Certain languages more likely to cause breakages (sorry)



Google

See: prior [deck](#) about Google CI System, See this [paper](#) about piper and CLs

From Google's continuous integration.¹²

¹²[ICST'17 keynote] J. Micco. "The State of Continuous Integration Testing at Google."

Flaky Tests

- Test [Flakiness](#) is a huge problem
- Flakiness is a test that is observed to both Pass and Fail with the same code
- Almost 16% of our 4.2M tests have some level of flakiness
- Flaky failures frequently block and delay releases
- Developers ignore flaky tests when submitting - sometimes incorrectly
- We spend between 2 and 16% of our compute resources re-running flaky tests

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Almost every line above is **concurrency** or **randomness**. It is the same non-determinism that forced repeated runs when we compared fuzzers.

- Better synchronization

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- Fixed seed for random number generation

- A talk given by Alister Scott (Automattic) at GTAC 2015 (GTAC – Google Test Automation Conference)
 - <https://www.youtube.com/watch?v=hmk1h40shaE>
 - Here is the [slide](#)
- “That test is flaky” **is not** a get out of jail free card
- A re-run culture is **toxic**

- **Detection** – is this test failure real, or a result of flakiness?

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- **Prediction** – how likely is this test case to be flaky?
- **Repair** – automatically remove flakiness? (Most ambitious goal)

- A test fails. How do you determine whether it is flaky or not?

¹⁴[ICSE'18] J. Bell, O. Legunsen, M. Hilton, L. Eloussi, T. Yung, D. Marinov. "*DeFlaker: Automatically Detecting Flaky Tests.*"

- A test fails. How do you determine whether it is flaky or not?
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- A test fails. How do you determine whether it is flaky or not?
- A test case that transitions from pass to fail but does not cover any of the changed part is likely to be flaky! (because the changed behavior is caused by the changed code)
- **DeFlaker** does exactly that: it computes the coverage of the **changed** code from the diff, and calls a new failure **flaky** when the test touches none of it – with no reruns.¹⁴

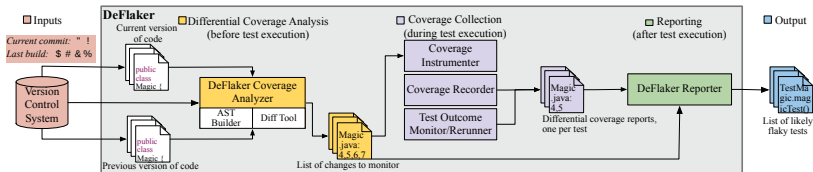


Figure 1: High-level architecture of DeFLAKER, with three phases: before, during and after test execution.

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4,846 flaky tests found in 26 open-source projects – and the reruns that the same study needed for comparison took **hours** per project.

Table 1: Number of flaky tests found by re-running 5,966 builds of 26 open-source projects. We consider only new test failures where a test passed on the previous commit, and report flakes reported by each phase of our RERUN strategies. DEFILER found more flaky tests than the Surefire or Fork rerun strategies: only the very costly Reboot strategy found more flaky tests than DEFILER.

Project	#SHAs	Test Methods in Project		Total New Failures	Confirmed flaky by RERUN strategy			DEFILER labeled as:			
		Total	Failing		Surefire	+Fork	++Reboot	Flaky		Not Flaky	
								Confirmed	Unconf.	Confirmed	Unconf.
achilles	227	337	77	242	13	14	230	225	4	5	8
ambari	500	896	7	75	52	71	74	74	0	0	1
assertj-core	29	6,261	2	3	2	2	2	2	0	0	1
checkstyle	500	1,787	1	1	0	0	0	0	0	0	1
cloudera.oryx	332	275	23	29	5	5	5	5	20	0	4
commons-exec	70	89	2	22	22	22	22	21	0	1	0
dropwizard	298	428	1	60	60	60	60	55	0	5	0
hadoop	298	2,361	365	1,081	284	865	1,054	1,028	25	26	2
handlebars	27	712	7	9	3	7	7	6	2	1	0
hbase	127	431	106	406	62	242	390	383	12	7	4
hector	159	142	12	87	0	74	79	72	4	7	4
httpcore	34	712	2	2	2	2	2	1	0	1	0
jackrabbit-oak	500	4,035	26	34	10	33	34	32	0	2	0
jimfs	164	628	7	21	21	21	21	15	0	6	0
logback	50	964	11	18	18	18	18	18	0	0	0
ninja	317	307	37	122	37	77	110	94	2	16	10
okhttp	500	1,778	129	333	296	305	310	231	0	79	23
oozie	113	1,025	1,065	2,246	42	2,032	2,244	2,234	0	10	2
orbit	227	86	9	86	84	85	85	73	0	12	1
oryx	212	200	38	46	14	14	46	14	0	32	0
spring-boot	111	2,002	67	140	73	107	135	135	3	0	2
tachyon	500	470	4	5	3	5	5	5	0	0	0
togglez	140	227	21	28	5	14	28	28	0	0	0
undertow	7	340	0	0	0	0	0	0	0	0	0
wro4j	306	1,160	114	217	39	96	99	80	8	19	110
zxing	218	415	2	15	15	15	15	15	0	0	0
26 Total	5,966	28,068	2,135	5,328	1,162	4,186	5,075	4,846	80	229	173

- Can we build a predictive model that can tell us whether a test case is likely to be flaky?

¹⁵[ICSE'21] A. Alshammari, C. Morris, M. Hilton, J. Bell. "*FlakeFlagger: Predicting Flakiness Without Rerunning Tests.*"

- Can we build a predictive model that can tell us whether a test case is likely to be flaky?
- **FlakeFlagger**: collect features of known flaky tests, and train a classifier on them.¹⁵

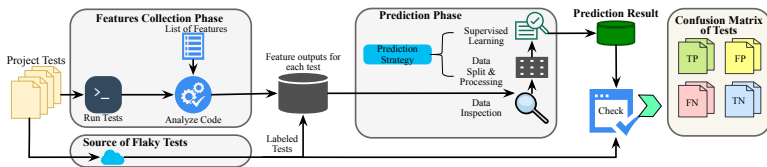


Fig. 1: Overview of FlakeFlagger's approach to predict likely flaky tests given a set of known flaky tests.

¹⁵[ICSE'21] A. Alshammari, C. Morris, M. Hilton, J. Bell. "FlakeFlagger: Predicting Flakiness Without Rerunning Tests."

It utilizes the following features for supervised learning:

	Feature	Description
Test Smells	Indirect Testing	True if the test interacts with the object under test via an intermediary [24]
	Eager Testing	True if the test exercises more than one method of the tested object [24]
	Test Run War	True if the test allocates a file or resource which might be used by other tests [24]
	Conditional Logic	True if the test has a conditional if-statement within the test method body [25]
	Fire and Forget	True if the test launches background threads or tasks. [26]
	Mystery Guest	True if the test accesses external resources [24]
	Assertion Roulette	True if the test has multiple assertions [24]
Numeric Features	Resources Optimism	True if the test accesses external resources without checking their availability [24]
	Test Lines of Code	Number of lines of code in the test method body
	Number of Assertions	Number of assertions checked by the test
	Execution Time	Running time for the test execution
	Source Covered Lines	Number of lines covered by each test, counting only production code
	Covered Lines	Total number of lines of code covered by the test
	Source Covered Classes	Total number of production classes covered by each test
	External Libraries	Number of external libraries used by the test
	Covered Lines Churn	h -index capturing churn of covered lines in past 5, 10, 25, 50, 75, 100, 500, and 10,000 commits. Each value h indicates that at least h lines were modified at least h times in that period.

Prediction of Flaky Tests

It has 86% prediction accuracy for flaky tests on 23 projects

Project	Flaky by		FlakeFlagger							Vocabulary-Based Approach [12]							Combined Approach						
	Tests	Reruns	TP	FN	FP	TN	Pr	R	F	TP	FN	FP	TN	Pr	R	F	TP	FN	FP	TN	Pr	R	F
spring-boot	2,108	160	139	21	15	1,933	90%	87%	89%	134	26	703	1,245	16%	84%	27%	143	17	18	1,930	89%	89%	89%
hbase	431	145	129	16	32	254	80%	89%	84%	89	56	152	134	37%	61%	46%	130	15	33	253	80%	90%	84%
alluxio	187	116	116	0	0	71	100%	100%	100%	108	8	11	60	91%	93%	92%	116	0	0	71	100%	100%	100%
okhttp	810	100	52	48	159	551	25%	52%	33%	79	21	444	266	15%	79%	25%	46	54	104	606	31%	46%	37%
ambari	324	52	47	5	3	269	94%	90%	92%	36	16	121	151	23%	69%	34%	47	5	3	269	94%	90%	92%
hector	142	33	30	3	8	101	79%	91%	85%	13	20	23	86	36%	39%	38%	25	8	11	98	69%	76%	72%
activiti	2,043	32	10	22	43	1,968	19%	31%	24%	12	20	531	1,480	2%	38%	4%	7	25	34	1,977	17%	22%	19%
java-websocket	145	23	19	4	1	121	95%	83%	88%	23	0	74	48	24%	100%	38%	19	4	4	118	83%	83%	83%
wildfly	1,023	23	11	12	27	973	29%	48%	36%	20	3	554	446	3%	87%	7%	17	6	24	976	41%	74%	53%
httpcore	712	22	14	8	23	667	38%	64%	47%	16	6	375	315	4%	73%	8%	15	7	24	666	38%	68%	49%
logback	805	22	3	19	17	766	15%	14%	14%	10	12	259	524	4%	45%	7%	5	17	11	772	31%	23%	26%
incubator-dubbo	2,174	19	8	11	35	2,120	19%	42%	26%	11	8	813	1,342	1%	58%	3%	13	6	23	2,132	36%	68%	47%
http-request	163	18	12	6	6	139	67%	67%	67%	16	2	84	61	16%	89%	27%	12	6	6	139	67%	67%	67%
wro4j	1,135	16	4	12	2	1,117	67%	25%	36%	2	14	101	1,018	2%	12%	3%	0	16	1	1,118	0%	0%	0%
orbit	86	7	1	6	8	71	11%	14%	12%	6	1	32	47	16%	86%	27%	1	6	7	72	12%	14%	13%
undertow	183	7	2	5	8	168	20%	29%	24%	6	1	63	113	9%	86%	16%	3	4	8	168	27%	43%	33%
achilles	1,317	4	2	2	3	1,310	40%	50%	44%	0	4	0	1,313	0%	0%	0%	0	4	0	1,313	0%	0%	0%
elastic-job-lite	558	3	0	3	0	555	0%	0%	0%	0	3	34	521	0%	0%	0%	1	2	0	555	100%	33%	50%
zxing	345	2	0	2	2	341	0%	0%	0%	1	1	144	199	1%	50%	1%	0	2	2	341	0%	0%	0%
assertj-core	6,261	1	0	1	5	6,255	0%	0%	0%	0	1	6	6,254	0%	0%	0%	0	1	0	6,260	0%	0%	0%
commons-exec	55	1	0	1	1	53	0%	0%	0%	1	0	18	36	5%	100%	10%	0	1	1	53	0%	0%	0%
handlebars.java	420	1	0	1	5	414	0%	0%	0%	0	1	91	328	0%	0%	0%	0	1	0	419	0%	0%	0%
ninja	307	1	0	1	3	303	0%	0%	0%	0	1	50	256	0%	0%	0%	0	1	0	306	0%	0%	0%
Total	21,734	808	599	209	406	20,520	60%	74%	66%	583	225	4,683	16,243	11%	72%	19%	600	208	314	20,612	66%	74%	86%
AUC (Average per fold)			86%							75%							86%						

- Another way to statically predict flakiness is to use **lexical analysis** on the test case to extract specific **lexical patterns** on flaky tests for limited domain (network related latency, external resources not ready, file I/O, etc.)

¹⁶[\[MSR'20\]](#) G. Pinto, B. Miranda, S. Dissanayake, M. d'Amorim, C. Treude, A. Bertolino. "What Is the Vocabulary of Flaky Tests?"

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- Static flaky test prediction essentially becomes **text classification**

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The most telling tokens are the ones you would guess: job, wait, sleep, async, poll, retry, random.

```
@Test
public void testCodingEmptySrcBuffer() throws Exception {
    final WritableByteChannelMock channel = new WritableByteChannelMock(64);
    final SessionOutputBuffer outbuf = new SessionOutputBufferImpl(1024, 128);
    final BasicHttpTransportMetrics metrics = new BasicHttpTransportMetrics();
    final IdentityEncoder encoder = new IdentityEncoder(channel, outbuf, metrics);
    encoder.write(CodecTestUtils.wrap("stuff"));
    final ByteBuffer empty = ByteBuffer.allocate(100);
    empty.flip();
    encoder.write(empty);
    encoder.write(null);
    encoder.complete();
    outbuf.flush(channel);
    final String s = channel.dump(StandardCharsets.US_ASCII);
    Assert.assertTrue(encoder.isCompleted());
    Assert.assertEquals("stuff", s);
}
```



pty src buffer codec test utils standard charsets
channel assert equals encoder byte buffer empty test
coding empty assert allocate flush outbuf metrics
dump complete wrap write flip stuff completed

The most telling tokens are the ones you would guess: job, wait, sleep, async, poll, retry, random.

```
@Test
public void testCodingEmptySrcBuffer() throws Exception {
    final WritableByteChannelMock channel = new WritableByteChannelMock(64);
    final SessionOutputBuffer outbuf = new SessionOutputBufferImpl(1024, 128);
    final BasicHttpTransportMetrics metrics = new BasicHttpTransportMetrics();
    final IdentityEncoder encoder = new IdentityEncoder(channel, outbuf, metrics);
    encoder.write(CodecTestUtils.wrap("stuff"));
    final ByteBuffer empty = ByteBuffer.allocate(100);
    empty.flip();
    encoder.write(empty);
    encoder.write(null);
    encoder.complete();
    outbuf.flush(channel);
    final String s = channel.dump(StandardCharsets.US_ASCII);
    Assert.assertTrue(encoder.isCompleted());
    Assert.assertEquals("stuff", s);
}
```



pty src buffer codec test utils standard charsets
channel assert equals encoder byte buffer empty test
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Flakiness has a **vocabulary** because its causes are few: waiting, ordering, and randomness.

It achieves an F-measure of 0.95 for the prediction of flaky tests.

Table 3: Classifier performance

algorithm	precision	recall	F_1	MCC	AUC
Random Forest	0.99	0.91	0.95	0.90	0.98
Decision Tree	0.89	0.88	0.89	0.77	0.91
Naive Bayes	0.93	0.80	0.86	0.74	0.93
Support Vector	0.93	0.92	0.93	0.85	0.93
Nearest Neighbour	0.97	0.88	0.92	0.85	0.93

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- Both halves of today rest on the same move: **compare two runs** and call a difference a signal. Flakiness is what happens when the comparison itself is unreliable.
- **Next**: what if there is nothing to compare against – no expected output at all?

1. Mutation Testing

- Fundamental Hypotheses

- Overall Process

- Mutation Generation

- Kill vs Alive

- Equivalent Mutants

- How to Kill A Mutant

- Scalability

- Higher Order Mutants

- Tools

2. Test Flakiness

- Implement the **mutation operators** for a small subset of **JavaScript**, measure the **mutation score** of a test suite, and write a suite that **kills every mutant**.
- Please see this document on GitHub:

<https://github.com/ku-plrg-classroom/js-mutest>

- The due date is **23:59 on October 5 (Mon.)**, and please submit it to [LMS](#).

- Testing Oracles

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