Mutation Testing

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Reading Quiz: mutation testing

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- **B.** when the developer runs the tests locally
- **C.** at code review time
- **D.** after the code is deployed

Q2: Write a one-line snippet of code that is obviously **arid**, as defined by the paper.

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Agenda: mutation testing

- **motivation and definitions**
- assumptions and implications
- practicality

Mutation testing: motivation

- ***“Quis custodes ipsos custodiet?”***

Mutation testing: motivation

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- what does this have to do with **testing**?

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- usually translated into English as “***who watches the watchers?***”
  - this question is **recursive**: whatever the answer, we can ask the same question about the it!
- what does this have to do with **testing**?
  - a key question that we need to ask ourselves is “how do we test that our tests are actually good?”
    - after all, tests are programs, too, and we only need to test because we know that most programs contain bugs…

Mutation testing: what tests the tests?

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  - coverage is at best a **rough guideline** to the actual quality of a test suite
- our question for today: **how can we do better**?
  - **key question**: can a test suite quality metric naturally consider both **input quality** and **oracle quality**?

Mutation testing: quis custodes ipsos custodiet

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- there is a **general technique** for solving “who watches the watchers”-style problems: intentionally introduce a small number of known-in-advance problems into the system
    - and then see whether the “watchers” **actually detect** the known problems!
        - this general technique can be applied recursively:
            - add some fake “known problems”…
        - but it’s generally **very expensive**: more “watchers of watchers of watchers …” are always being added

Mutation testing: quis custodes ipsos custodiet

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  - in the analogy, **known problems** are **fake bugs**
    - that is, we intentionally introduce some changes to the program that ***we expect to cause the tests to fail***
      - this idea is the essense of mutation testing!

Mutation testing

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- Informally: “You claim your test suite is really great at finding security bugs? Well, I'll just **intentionally add a bug** to my source code and see if your test suite finds it!”
  - recall the **truffle-sniffing pig analogy** from a few weeks ago:
    - to evaluate truffle-sniffing pigs, hide some truffles
    - the best pig is the one that finds the most truffles!

Mutation testing: verisimilitude

- In the truffle-pig analogy from a few weeks ago, if every truffle I hide in my backyard is next to a smelly red flower, a pig that finds them all may not actually do well in the real world

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  - The truffle placements I made up were **not indicative** of real-world truffles
- Similarly, if I add a bunch of defects to my software that are not the sort of defects real humans would make, then mutation testing is uninformative
  - **Implication**: mutation testing requires us to know what real bugs look like

Mutation testing: defect seeding

Definition: ***Defect seeding*** is the process of intentionally introducing a defect into a program.

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Definition: ***Defect seeding*** is the process of intentionally introducing a defect into a program.

- The defect introduced is typically intentionally similar to defects introduced by real developers.
- The seeding is typically done by changing the source code.
- For mutation testing, defect seeding is typically done automatically (given a model of what human bugs look like)
    - however, you can do "lightweight" mutation testing yourself!
        - e.g., regression testing and TDD can both be viewed as forms of **manual** mutation testing

Mutation testing: mutation operators

Definition: A ***mutation operator*** systematically changes a program point. In mutation testing, the mutation operators are modeled on historical human defects.

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- Example mutations:
  - `if (a < b)` → `if (a <= b)`
  - `if (a == b)` → `if (a != b)`
  - `a = b + c` → `a = b - c`
  - `f(); g();` → `g(); f();`
  - `x = y` → `x = z`

Mutation testing: mu

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  - `if (a < b)` →
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TABLE 3
The First Set of Mutation Operators: The 22 “Mothra” Fortran Mutation Operators (Adapted from [131])

Mutation Operator	Description
AAR	array reference for array reference replacement
ABS	absolute value insertion
ACR	array reference for constant replacement
AOR	arithmetic operator replacement
ASR	array reference for scalar variable replacement
CAR	constant for array reference replacement
CNR	comparable array name replacement
CRP	constant replacement
CSR	constant for scalar variable replacement
DER	DO statement alterations
DSA	DATA statement alterations
GLR	GOTO label replacement
LCR	logical connector replacement
ROR	relational operator replacement
RSR	RETURN statement replacement
SAN	statement analysis
SAR	scalar variable for array reference replacement
SCR	scalar for constant replacement
SDL	statement deletion
SRC	source constant replacement
SVR	scalar variable replacement
UOI	unary operator insertion

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- Example
  - if
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  - a =
  - f();
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UOI	unary operator insertion

Key questions in mutation testing are ***what operators to use*** and ***how often to use each operator***.

- I'm intentionally not giving you a ton of advice on the answers to these questions - I want you to figure it out yourselves in HW6

Mutation testing: mutants

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```
// original                         // 2nd-order mutant
if (a < b):                     if (a <= b):
x = a + b          →                x = a - b
print(x)                        print(x)
```

Mutation testing: killing mutants

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    - A test suite with a **higher score is better**.
- (Sorry for all of the vocabulary!)

Agenda: mutation testing

- motivation and definitions
- **assumptions and implications**
- practicality

Mutation testing: comparing scores

Suppose that I have two programs, each with its own test suite:

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Which program has a better test suite? **A** or **B**?

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- **Program A**'s test suite has an **80%** mutation score.
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Which program has a better test suite? **A** or **B**?

Answer: we don't know!

- Mutation scores are **not comparable** across different programs!
  - standard setting: **same program, different test suites**
    - in this case, higher mutation score test suite is better

Mutation testing: assumptions

- Modern mutation testing relies on two important assumptions:
  - the ***competent programmer hypothesis***
  - the ***coupling effect hypothesis***

Mutation testing: assumptions

- Modern mutation testing relies on two important assumptions:
  - the ***competent programmer hypothesis***
  - the ***coupling effect hypothesis***
- Let’s look at each in detail next.
  - Hint: a common style of test question that I like to ask is “consider some assumption that we discussed that a particular technique makes. How would that technique behave if the assumption wasn’t true?”

Mutation testing: competent programmers

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  - Programmers write programs that are largely correct. Thus small mutants simulate the likely effect of real faults.
  - Therefore, **if the test suite is good at catching the artificial mutants, it will also be good at catching the unknown but real faults** in the program.

Mutation testing: competent programmers

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Is the competent programmer hypothesis true?

- Yes and no.
- It is true that humans often make simple typos (e.g., + vs -).
- But it is also true that some bugs are much more complex than that.

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- But it is also true that some bugs are much **more complex** than that!

Mutation testing: coupling effect

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- Is this true?

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- Is this true?
  - Tests that detect simple mutants were also able to detect **over 99%** of second- and third-order mutants historically

[A. J. Offutt. Investigations of the software testing coupling effect. ACM Trans. Softw. Eng. Methodol., 1(1):5–20, Jan. 1992.]

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    - are higher-order mutants a **good proxy** for real complex bugs?

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- Is this true?
  - Tests that detect simple mutants were also able to detect **over 99%** of second- and third-order mutants historically
    - are higher-order mutants a **good proxy** for real complex bugs? The jury is still out.

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Mutation testing: concrete example

Original program:

```
public int min(int a, int b) {
    return a < b ? a : b;
}
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public int min(int a, int b) {
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```

Mutant 1:

```
public int min(int a, int b)
{
    return a; < b ? a : b;
}
```

Mutation testing: concrete example

Original program:

```
public int min(int a, int b) {
    return a < b ? a : b;
}
```

Mutant 2:

`public int min(int a, int b)`
`{`
    `return b;` ~~< b ? a : b;~~
`}`

Mutation testing: concrete example

Original program:

```
public int min(int a, int b) {
    return a < b ? a : b;
}
```

Mutant 3:

```
public int min(int a, int b)
{
    return a >= b ? a : b;
}
```

Mutation testing: concrete example

Original program:

```
public int min(int a, int b) {
    return a < b ? a : b;
}
```

Mutant 4:

```
public int min(int a, int b)
{
    return a <= b ? a : b;
}
```

Mutation testing: concrete example

Original program:

```
public int min(int a, int b) {
    return a < b ? a : b;
}
```

Four mutants:

```
M1: return a;
M2: return b;
M3: return a >= b ? a : b;
M4: return a <= b ? a : b;
```

Mutation testing: concrete example

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```

In-class exercise: For each mutant, provide a test case that detects it (i.e., passes on the original program but fails on the mutant) (5 mins)

Mutation testing: concrete example

Original program:

```
publ
    r
}
```

a	b	original	M1	M2	M3	M4

Four

M1: **return a;**

M2: **return b;**

M3: **return a >= b ? a : b;**

M4: **return a <= b ? a : b;**

(i.e., passes on the original program but fails on the mutant) (5 mins)

Mutation testing: concrete example

Original program:

```
publ
    r
}
```

a	b	original	M1	M2	M3	M4
1	1					

Four

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}
```

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1	1	1	1	1	1	1

Four

```
M1:
M2: return b;
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Mutation testing: concrete example

Original program:

```
publ
    r
}
```

a	b	original	M1	M2	M3	M4
1	1	1	1	1	1	1
1	2					

Four

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M1: return a;
M2: return b;
M3: return a >= b ? a : b;
M4: return a <= b ? a : b;
```

(i.e., passes on the original program but fails on the mutant) (5 mins)

Mutation testing: concrete example

Original program:

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```

a	b	original	M1	M2	M3	M4
1	1	1	1	1	1	1
1	2	1	1	2	2	1

Four

```
M1: return a;
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1	1	1	1	1	1	1
1	2	1	1	2	2	1
2	1					

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M1: return a;
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```

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1	2	1	1	2	2	1
2	1	1	2	1	2	1

Four

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M1: return a;
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}
```

a	b	origin				
1	1	1				
1	2	1	1	2	2	1
2	1	1	2	1	2	1

Did anyone find a test case that can detect M4? Does such a test case even exist?

Four

```
M1:
M2: return b;
M3: return a >= b ? a : b;
M4: return a <= b ? a : b;
```

(i.e., passes on the original program but fails on the mutant) (5 mins)

Mutation testing: equivalent mutant problem

- Suppose you have "`x = a + b; y = c + d;`" and you swap those two statements.

Mutation testing: equivalent mutant problem

- Suppose you have "`x = a + b; y = c + d;`" and you swap those two statements.
- The resulting program is a mutant, but it is **semantically equivalent** to the original.

Mutation testing: equivalent mutant problem

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Remember when I mentioned **reductions** earlier? Now is a good time to do one!

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- It is **undecidable**! (= there is no algorithm for it that can always give the correct answer)
  - by direct reduction to the **Halting Problem** (or by **Rice's theorem**)

```
def foo():              # foo halts if and only if
if p1() == p2():        # p1 is equivalent to p2
    return 0
foo()
```

Mutation testing: equivalent mutant problem

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- There have been **many attempts** to detect equivalent mutants
  - this is a theme in SE/PL: undecidable problems attract researchers who try to find **good approximations**
- We'll discuss two, to give you a sense of the options:
  - a rough approximation that is cheap to compute: ***trivial compiler equivalence*** (***TCE***)
  - a more precise approximation that is more expensive to compute: **reduction to SMT**

Mutation testing: equivalent mutants: TCE

Definition: ***trivial compiler equivalence*** (***TCE***) is an equivalent mutant detection that shows that two programs are equivalent if an optimizing compiler produces the same result when compiling both

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  - detects redundant mutants, too (we'll come back to this soon)

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- Alternative strategy: prove that mutants are equivalent by **reduction to SMT**

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    - e.g., what if the mutant modifies the heap?

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  - **applicability**: it’s difficult to reduce some mutations to SMT
    - e.g., what if the mutant modifies the heap?
  - **efficiency**: SMT solvers can be slow! Caching can help, though.

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Mutation testing: concrete example

Original program:

a	b	original	M1	M2	M3	~~M4~~
1	1	1	1	1	1	~~1~~
1	2	1	1	2	2	~~1~~
2	1	1	2	1	2	~~1~~

```
publ
    r
}
```

Four

```
M1: return a;
M2: return b;
M3: return a >= b ? a : b;
M4: return a <= b ? a : b;
```

(i.e., passes on the original program but fails on the mutant) (5 mins)

Mutation te

Do we need **all** of M1, M2, and M3? In other words, is it possible to **predict** if any of these mutants will be killed based on whether the others are killed?

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Can we **formalize** this notion? (Hint: we can, or I wouldn't be asking.)

Mutation testing: subsumption

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Definition: A mutant M1 ***subsumes*** another mutant M2 iff:

- some test kills M1
- all tests that kill M1 also kill M2

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    - this set is infinite, usually
    - so checking "true" subsumption is undecidable

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What do we do when we face undecidable problems?

Approximate!

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Mutation testing: dynamic subsumption

Definition: Given a finite set of tests T, mutant M1 ***dynamically subsumes*** another mutant M2 with respect to T iff:

- some test **in T** kills M1
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Note that dynamic subsumption is true subsumption iff T contains all possible tests (which can only occur if you're testing **exhaustively**).

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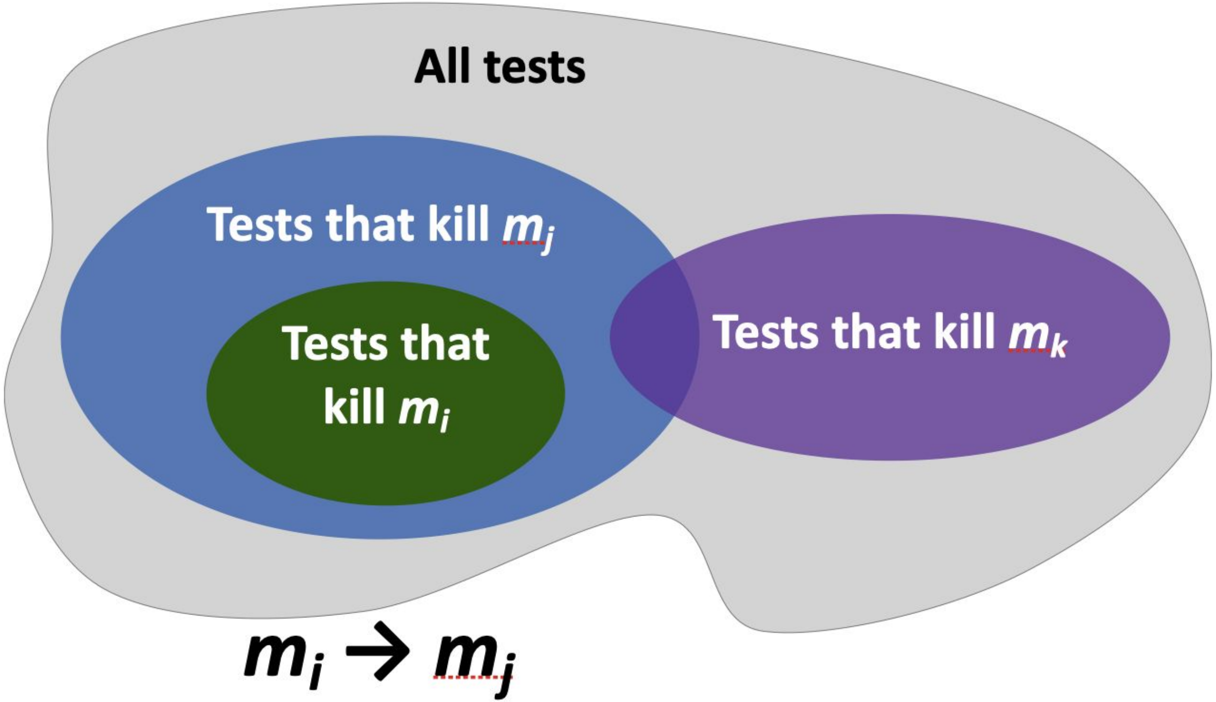
Mutation testing: dynamic subsumption



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Mutation testing: mutant subsumption graph

We can model mutant subsumption with a graph:

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- **nodes** represent a maximal set of ***indistinguished*** mutants

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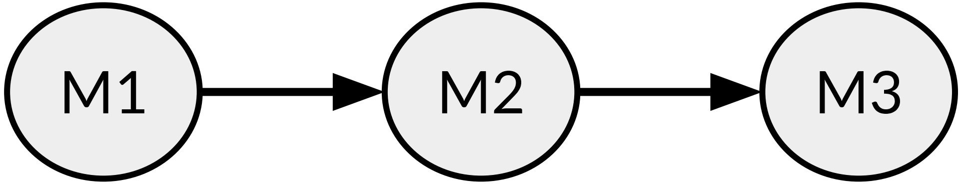
E.g., if M1 subsumes M2, which subsumes M3, we could represent that using this graph:



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Mutation testing: DMSG

A mutation testing tool can then maintain a ***dynamic mutant subsumption graph*** (***DMSG***) that keeps track of which mutants are actually subsumed or indistinguished.

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A mutation testing tool can then maintain a ***dynamic mutant subsumption graph*** (***DMSG***) that keeps track of which mutants are actually subsumed or indistinguished.

- subsumed mutants occupy a node with **in-degree > 0**
- indistinguished mutants occupy **the same** node

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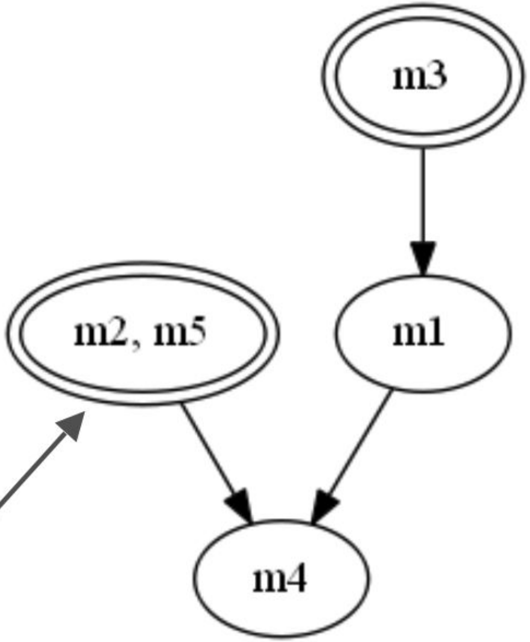
Mutation testing: DMSG example

	m_1	m_2	m_3	m_4	m_5
t_1	✓	✓		✓	✓
t_2	✓		✓	✓	
t_3				✓	
t_4		✓		✓	✓



"Indistinguished" mutants

$T = \{ t_1, t_2, t_3, t_4 \}$

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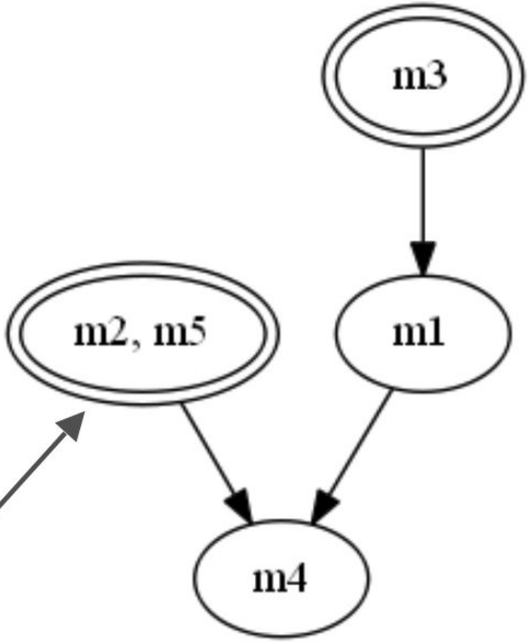

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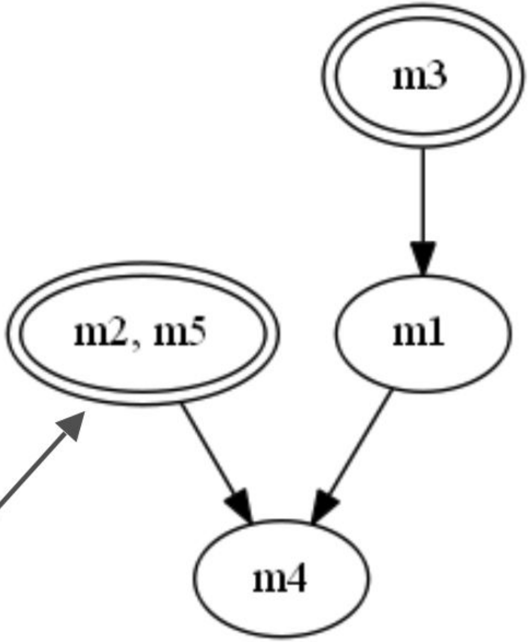

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- all others are redundant!

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Agenda: mutation testing

- motivation and definitions
- assumptions and implications
- **practicality**

Mutation testing: detectable vs productive

- Historically:
  - detectable mutants are **good** (we can create tests)
  - equivalent mutants are **bad** (we can’t create tests)

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The core question here concerns **test-goal utility** and applies to any adequacy criterion.

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Mutation testing: detectable vs productive (1)

Original program

```
public double getAvg(double[] nums) {
  double sum = 0;
  int len = nums.length;

  for (int i = 0; i < len; ++i) {
      sum = sum + nums[i];
  }

  return sum / len;
}
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Mutant

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Is this mutant **detectable**? Yes.

Is it **productive**? **Also yes!**

Mutation testing: detectable vs productive (2)

Original program

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public double getAvg(double[] nums) {
  int len = nums.length;
  double sum = 0;
  double avg = 0;

  for (int i = 0; i < len; ++i) {
      avg = avg + (nums[i] / len);
      sum = sum + nums[i];
  }

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Mutant

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Mutant

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public double getAvg(double[] nums) {
  int len = nums.length;
  double sum = 0;
  double avg = 0;

  for (int i = 0; i < len; ++i) {
      avg = avg * (nums[i] / len);
      sum = sum + nums[i];
  }

  return sum / len;
```

Is this mutant **detectable**? No.

Mutation testing: detectable vs productive (2)

Original program

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Is this mutant **detectable**? No.

But is it **productive**? **Actually yes**!

Mutation testing: detectable vs productive (3)

Original program

```
...

Set cache = new HashSet(a * b);

...
```

Mutant

```
...

Set cache = new HashSet(a + b);

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Is this mutant **detectable**?

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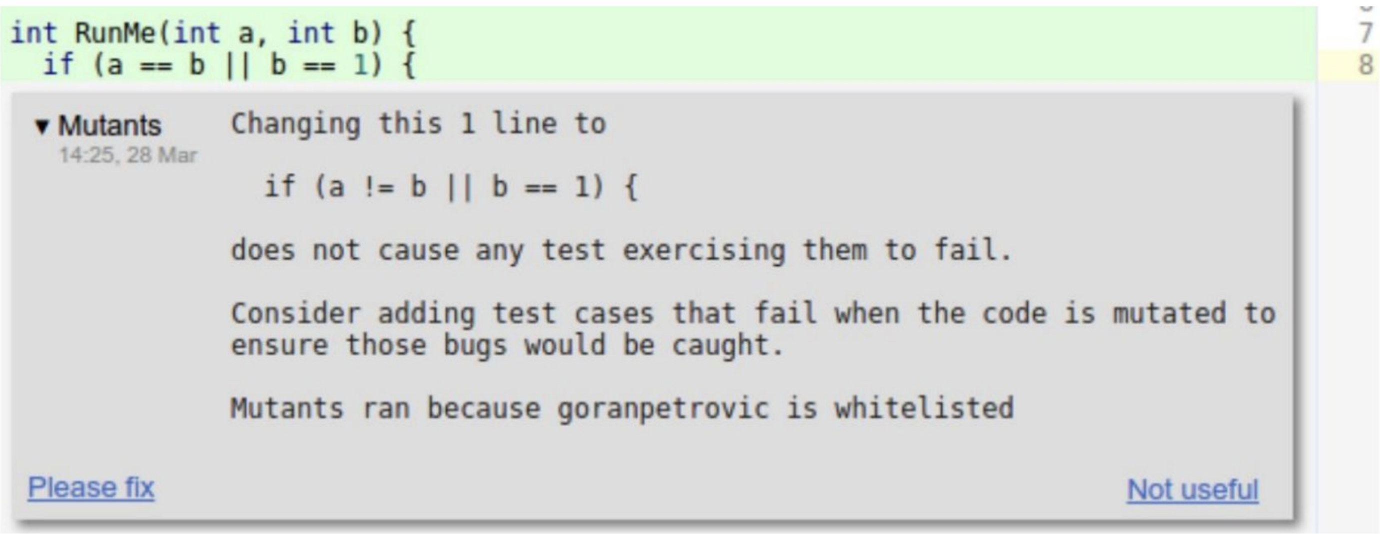
Mutation testing: productive mutants

E.g., @ Google:



[*Practical Mutation Testing at Scale: A view from Google.* Petrović, Ivanković, Fraser, Just. TSE 2022.]

Mutation testing: productive mutants

E.g., @ Google:

```
int RunMe(int a, int b) {
  if (a == b || b == 1) {
```

7
8

▾ Mutants
14:25, 28 Mar

Changing this 1 line to

```
if (a != b || b == 1) {
```

mutant

does not cause any test exercising them to fail.

Consider adding test cases that fail when the code is mutated to ensure those bugs would be caught.

Mutants ran because goranpetrovic is whitelisted

Please fix

Not useful

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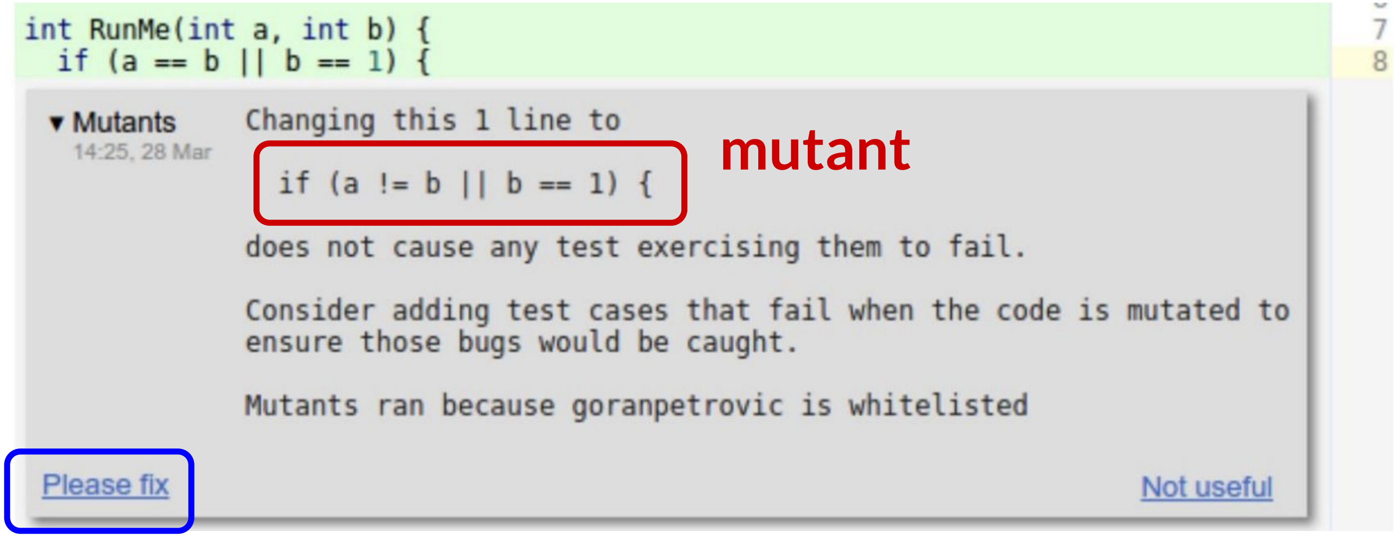

feedback to dev whose code is under review

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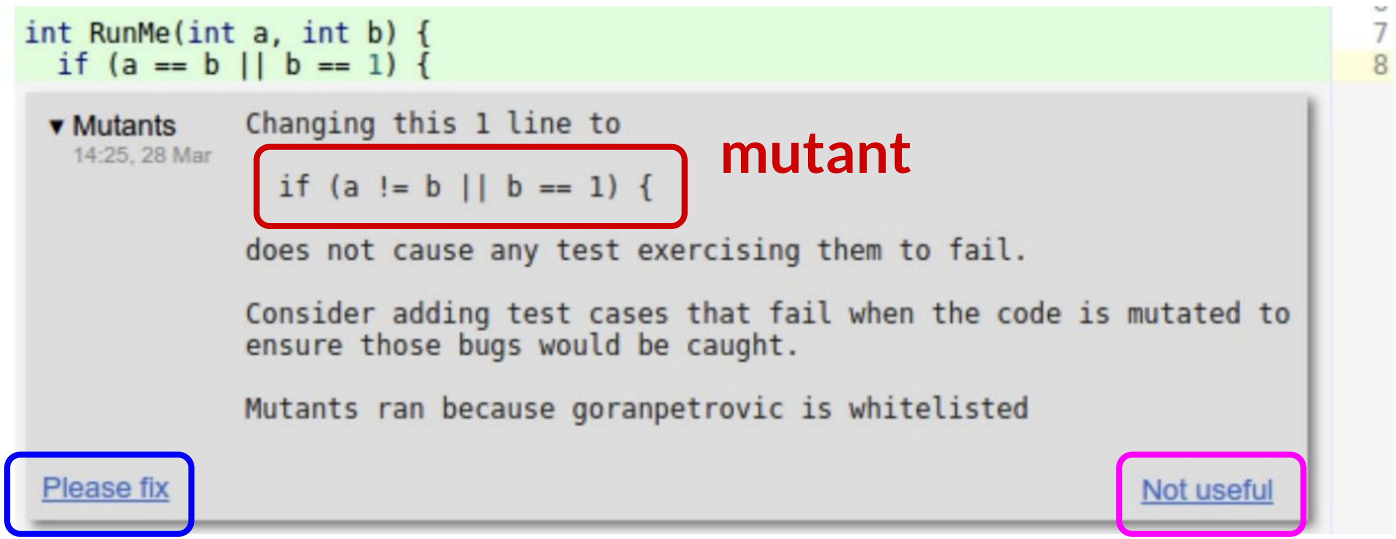

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feedback to mutation testing tool developers

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    - **No**! These are always unproductive.

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- Google keeps a list of all known-arid kinds of statements, which **avoids creating** these unproductive mutants in the first place

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- **Difficult** to do well:
  - Which mutation operators do you use?
  - Where do you apply them? How often do you apply them?
    - Typically done at random, but how?
- It is **very expensive**. If you make 1,000 mutants, you must now run your test suite 1,000 times!

Announcements & HW6

- Recall there is an exam during the first class after spring break
    - Note that you will be permitted to bring one letter-sized piece of paper with **handwritten** notes (double-sided)
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- Kazi's OH this week will be slightly shorter (3:30-4:30)