CMPT 473
Software Quality Assurance

Mutation Analysis & Testing

Nick Sumner
With material from Ammann & Offutt, Patrick Lam, Gordon Fraser

How Else Can We Judge Adequacy?

- Input & graph based techniques provide requirements that measure quality.

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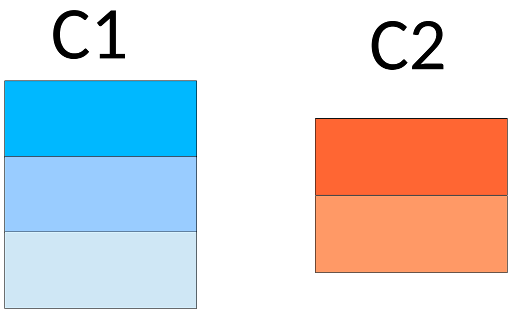

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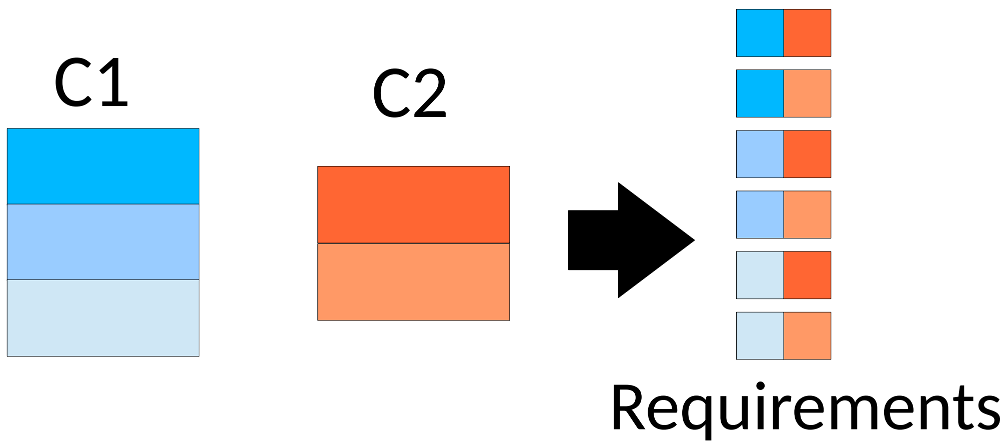

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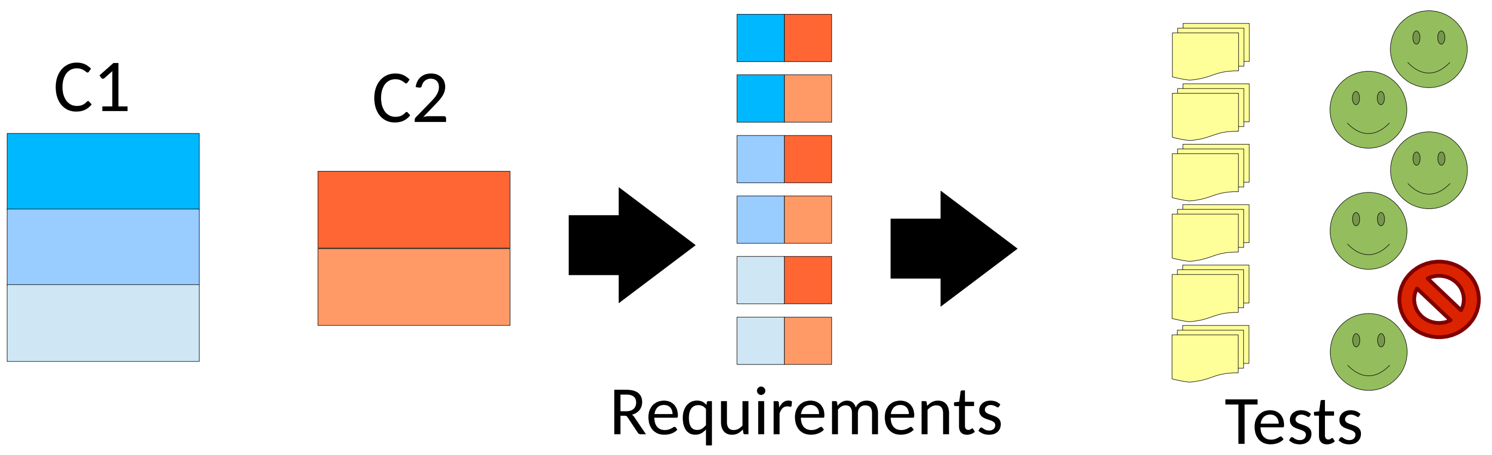

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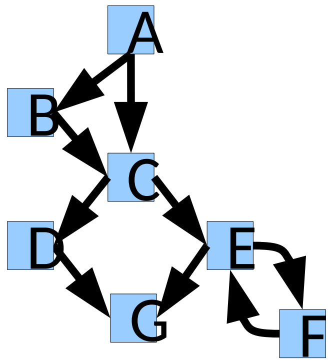

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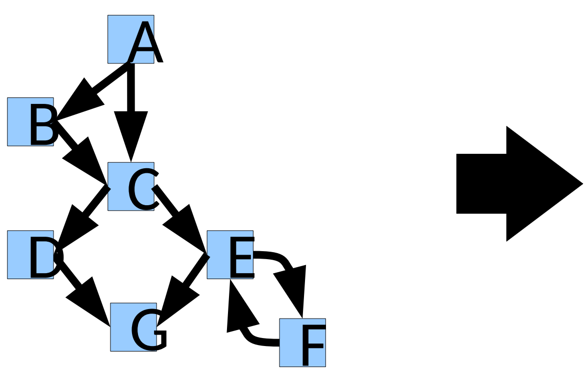

ABCDG
ACDG
ABCEG
ACEG
ACEF
FEG
EFE
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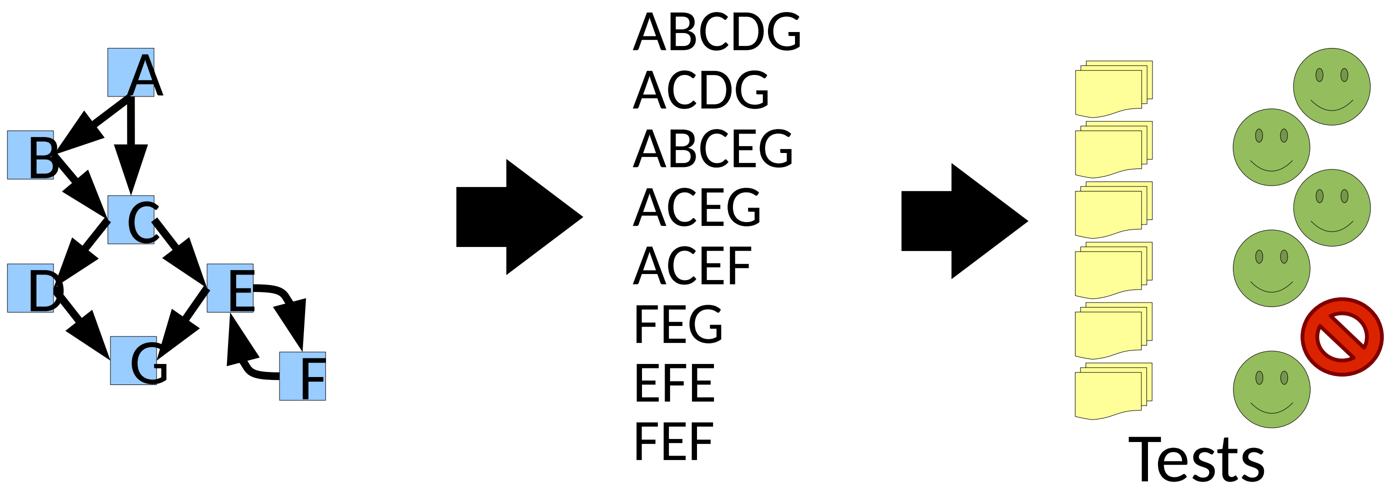

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- Input & graph based techniques provide requirements that measure quality.
  - But they still have difficulties finding bugs!
  - Can we try to measure that directly?

How might you go about this?

Fault Seeding

- Insert or ***seed*** representative/typical faults

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- Why might this fail?

Fault Seeding

- Insert or ***seed*** representative/typical faults
- Measure how many are found or ***killed*** by the test suite
  - Effectiveness = # killed / # seeded
  - Directly measures bug finding ability
- Why might this fail?
  - What are representative faults?
  - Are there enough faults to be meaningful?
  - Did you forget to remove faults afterward?

Mutation Analysis & Testing

- Mutant
  - A valid program that behaves differently than the original

Mutation Analysis & Testing

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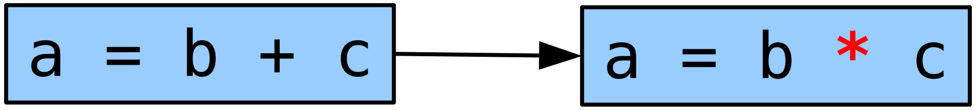
  - Consider small, local changes to programs



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What does this mean?

Mutation Analysis & Testing

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  - Consider small, local changes to programs
  - A test t kills a mutant m if t produces a different outcome on m than the original program
- Systematically generate mutants separately from original program

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  - **Mutation Analysis** – Measure bug finding ability

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- Mutant
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  - Consider small, local changes to programs
  - A test t kills a mutant m if t produces a different outcome on m than the original program
- Systematically generate mutants separately from original program
- The goal is to:
  - **Mutation Analysis** – Measure bug finding ability
  - **Mutation Testing** – create a test suite that kills a representative set of mutants

Mutation

- What are possible mutants?

```
int foo(int x, int y) {
  if (x > 5) {return x + y;}
  else {return x;}
}
```

Mutation

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- Some are not generally useful:

Why might they not be useful?

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  - (*Equivalent*) Indistinguishable from original program

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- Some are not generally useful:
  - Not compilable
  - (*Trivial*) Killed by most test cases
  - (*Equivalent*) Indistinguishable from original program
  - (*Redundant*) Indistinguishable from other mutants

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
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int min(int a, int b) {
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  }
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```
int min(int a, int b) {
  int minVal;
  minVal = a;
Mutant 1: minVal = b;
  if (b < a) {


    minVal = b;




  }
  return minVal;
}
```

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Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
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  }
  return minVal;
}
```

```
int min(int a, int b) {
  int minVal;
  minVal = a;
Mutant 1: minVal = b;
  if (b < a) {
Mutant 2: if (b > a) {
    minVal = b;
  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
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Mutant 1: minVal = b;
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Mutant 3: if (b < minVal) {
    minVal = b;
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  return minVal;
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Mutant 1: minVal = b;
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Mutant 2: if (b > a) {
Mutant 3: if (b < minVal) {
    minVal = b;
Mutant 4:   BOMB();
  }
  return minVal;
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Mutant 5:   minVal = a;

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Mutant 4:   BOMB();
Mutant 5:   minVal = a;
Mutant 6:   minVal = failOnZero(b);
  }
  return minVal;
}
```

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Mutation

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Mutant 1: minVal = b;
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What mimics statement coverage?

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

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  }
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```

What mimics input classes?

- Mimic mistakes
- Encode knowledge from other techniques

Mutation Analysis

Mutants

`Mutant 1`

`Mutant 2`

`Mutant 3`

`Mutant 4`

`Mutant 5`

`Mutant 6`

Mutation Analysis

Mutants

- Mutant 1
- Mutant 2
- Mutant 3
- Mutant 4
- Mutant 5
- Mutant 6

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Mutation Analysis

Mutants

```
Mutant 1
Mutant 2
Mutant 3
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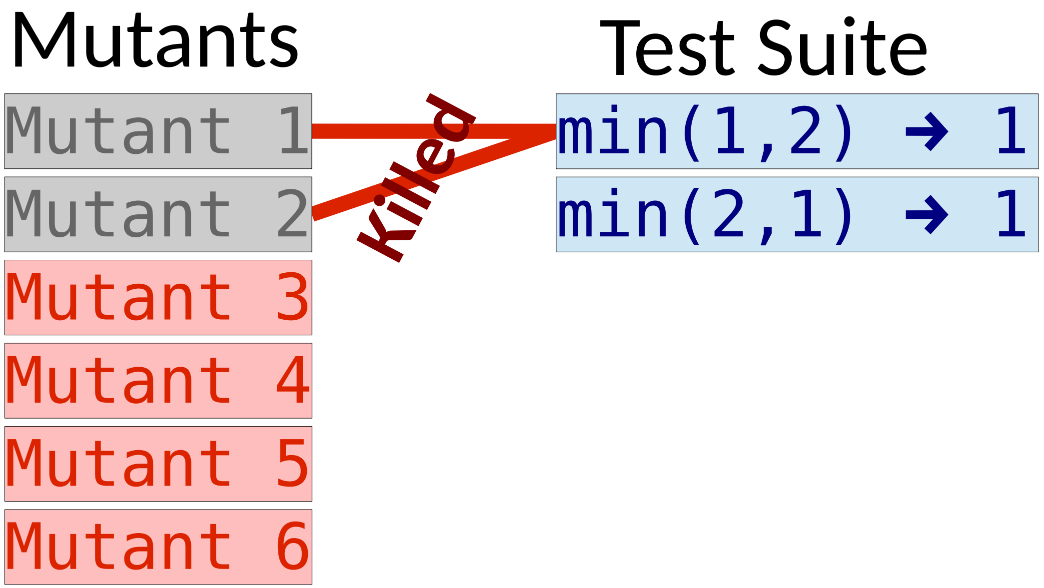
Mutant 5
Mutant 6
```

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Try every mutant on test 1.

Mutation Analysis



Mutation Analysis

Mutants

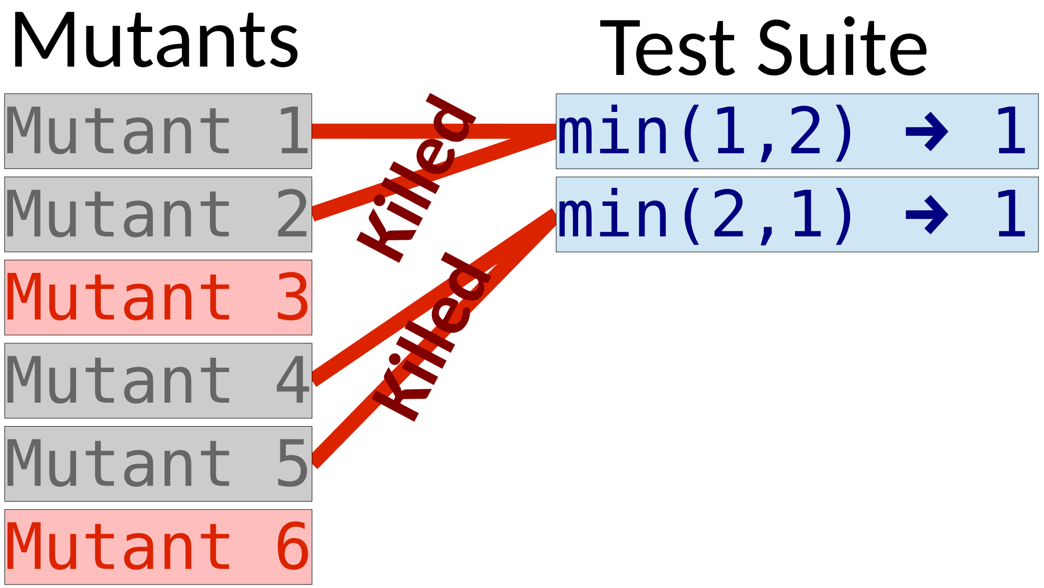
Test Suite

```
Mutant 1    min(1,2) → 1
Mutant 2    min(2,1) → 1
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

Killed

Try every ***live*** mutant on test 2.

Mutation Analysis



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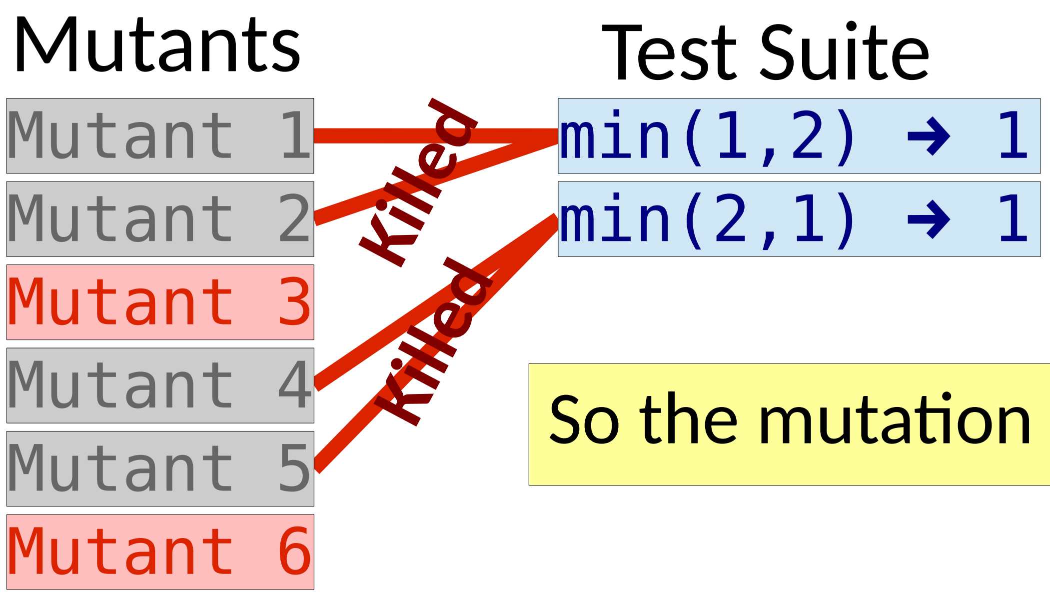
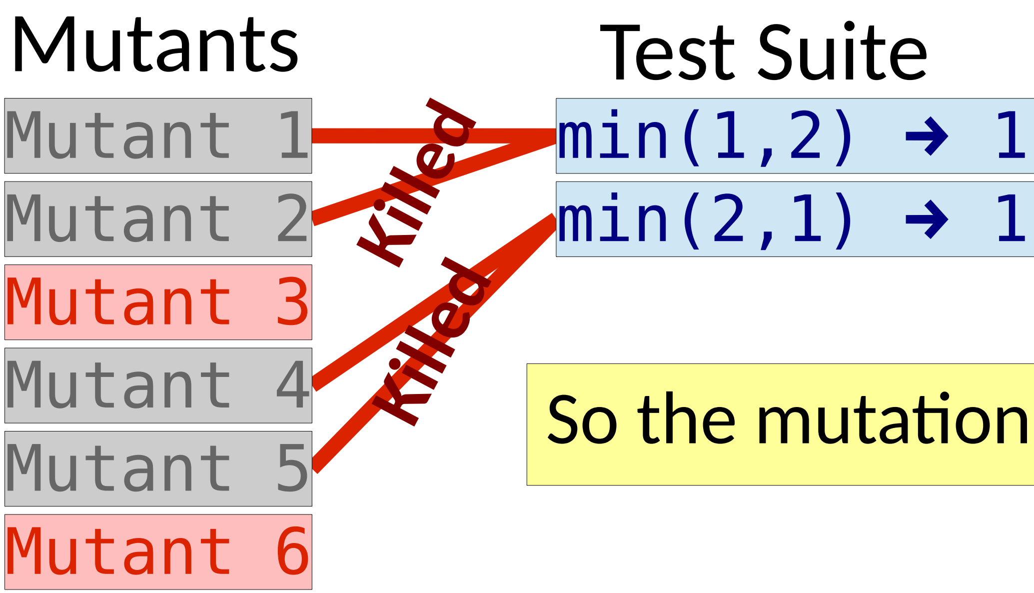


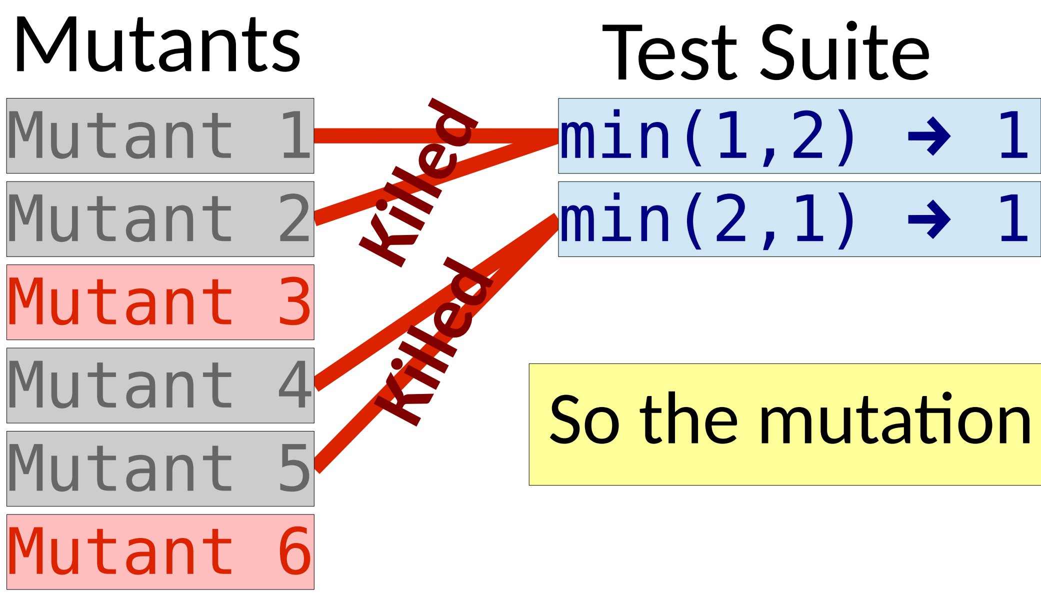
So the mutation score is…

Mutation Analysis



So the mutation score is… **4/5**. *Why?*

Mutation Analysis



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```
min3(int a, int b):
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  minVal = a;
  if (b < minVal)
    minVal = b;
  return minVal;
```

```
min6(int a, int b):
  int minVal;
  minVal = a;
  if (b < a)
    minVal = failOnZero(b);
  return minVal;
```

Mutation Analysis

Mutants

- Mutant 1
- Mutant 2
- Mutant 3
- Mutant 4
- Mutant 5
- Mutant 6

Test Suite

- `min(1,2) → 1`
- `min(2,1) → 1`

Killed

Killed

So the mutation score is… **4/5**. *Why?*

Equivalent to the original!
There is no injected bug.

```
min3(int a, int b):
  int minVal;
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  if (b < minVal)
    minVal = b;
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$$\frac{\#Killed}{\#Mutants}$$

Start with the score from fault seeding

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted
- New Mutation Score:

$$\frac{\#\,\text{Killed}}{\#\,\text{Mutants} - \#\,\text{Equivalent}}$$

Traditional mutation score from literature

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted
- New Mutation Score:

$$\frac{\#\text{Killed} - \#\text{Killed Duplicates}}{\#\text{Mutants} - \#\text{Equivalent} - \#\text{Duplicates}}$$

Updated for modern handling of duplicate & equivalent mutants

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Reachability **I**nfection **P**ropagation

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More on this later....

Reachability ? **I**nfection ? **P**ropagation

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```
min3(int a, int b):
  int minVal;
  minVal = a;
  if (b < minVal)
    minVal = b;
  return minVal;
```

Requires reasoning about why the result was the same.

Mutation Testing

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Mutation Testing

- Given an unkilled mutant, how can we improve the test suite?

```
min3(int a, int b):
  int minVal;
  minVal = a;
  if (b < a)
    minVal = failOnZero(b);
  return minVal;
```

New Test: `min(2,0) → 0`

New Score: 5/5

Mutation Operators

- The mutants should guide the tester toward an effective test suite

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  - Systematic changes that may be applied to produce mutants

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Why might they be language dependent?

Some Mutation Operators – in Java

- Absolute Value Insertion
  - Each arithmetic (sub)expression is wrapped with `abs()`, `-abs()`, and `failOnZero()`

```
w = x + y + z
```

Just for `abs()`?

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Just for `abs()`?

```
w = abs(x) + y + z
```

```
w = abs(x + y) + z
```

```
w = x + abs(y) + z
```

```
w = x + abs(y + z)
```

```
w = x + y + abs(z)
```

```
w = abs(x + y + z)
```

Just for `abs()`!

Some Mutation Operators – in Java

- Absolute Value Insertion
  - Each arithmetic (sub)expression is wrapped with `abs()`, `-abs()`, and `failOnZero()`
- Arithmetic Operator Replacement
  - Each operator (+,-,*,/,%,...) is replaced with each other operator and LEFTOP and RIGHTOP (returning the named operand).

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```
w = x + y + z
```

```
w = x + y * z
```

```
w = x + y
```

...

Some Mutation Operators – in Java

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  - Each arithmetic (sub)expression is wrapped with `abs()`, `-abs()`, and `failOnZero()`
- Arithmetic Operator Replacement
  - Each operator (+,-,*,/,%,…) is replaced with each other operator and LEFTOP and RIGHTOP (returning the named operand).
- Relational Operator Replacement
  - Each operator (=,!=,<,<=,>,>=) is replaced with each other and TRUEOP and FALSEOP

Some Mutation Operators – in Java

- Conditional Operator Replacement
  - Replace operators (&&, ||, &, |, ^) with each other and LEFTOP, RIGHTOP, TRUEOP, FALSEOP

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Could these be used to mimic edge coverage?

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- Scalar Variable Replacement
  - Replace each variable use with another compatible variable in scope

What does compatible mean? Is it necessary?

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  - Assignme … on

How does the BOMB() operator mimic statement coverage?

- Scalar Variable Replacement
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  - …
- And more…
  - Interface Mutation, Object Oriented Mutation, …

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- These are all ***intra***procedural (within one method)
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  - …
- And more…
- Often just the simplest are used

Mutation Operators

- Are the mutants representative of all bugs?
- Do we expect the mutation score to be meaningful?

Ideas? Why? Why not?

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Ideas? Why? Why not?

2 Key ideas are missing….

Competent Programmer Hypothesis

Programmers *tend* to write code that is *almost* correct

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- So *most* of the time simple mutations should reflect the real bugs.

Coupling Effect

Tests that cover so much behavior that even simple errors are detected should also be sensitive enough to detect more complex errors

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Tests that cover so much behavior that even simple errors are detected should also be sensitive enough to detect more complex errors

- By casting a fine enough net, we'll catch the big fish, too
  (sorry dolphins)

What Problems Remain?

- Scale (there are a lot of tests)

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  - Testing mutants simultaneously

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- Scale may be attacked in many ways
  - Coverage filters
  - Short circuiting tests
  - Testing mutants simultaneously
- Can also modify *mutation criteria* to help with *both…*

Mutation Criteria

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What does it mean if a mutant was killed?

What does it mean if a mutant was ***not*** killed?

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How might this happen?

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int min(int a, int b) {
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They always behave the same way!

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Leading to…

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How might weak coverage help with equivalence?

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How might weak coverage help with scalability?

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How might weak coverage help with equivalence?

How might weak coverage help with scalability?

Is there any reason to prefer strong coverage?

Mutation Testing

- Considered one of the strongest criteria

Why?

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  - Mimics some input specifications
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Mutation Testing

- Considered one of the strongest criteria
  - Mimics some input specifications
  - Mimics some graph coverage (node, edge, …)
- Massive number of criteria.
- Still not always the most tests.

Why?

Traditional Coverage vs Mutation

- Statement & branch based coverage are the most popular adequacy measures in practice.

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What if you change |T|?

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    → You cannot assume that better coverage increases defect finding ability!

Then does coverage serve a purpose?

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  - It just cannot fully measure defect finding capability.

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- Mutation analysis/testing correlates with defect finding independent of code coverage! [Just 2014]

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So is that it?
Can we just do mutation testing & be done?

A Summary of Test Adequacy

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- ***Mutation testing*** is the strongest known single approach we presently have, but it comes at a price.
- Even combining all adequacy measures, there will still be bugs.
  - And they have consequences http://arstechnica.com/security/2016/02/extremely-severe-bug-leaves-dizzying-number-of-apps-and-devices-vulnerable/