CSE P 504

Advanced topics in Software Systems

Fall 2022

Mutation-based Testing

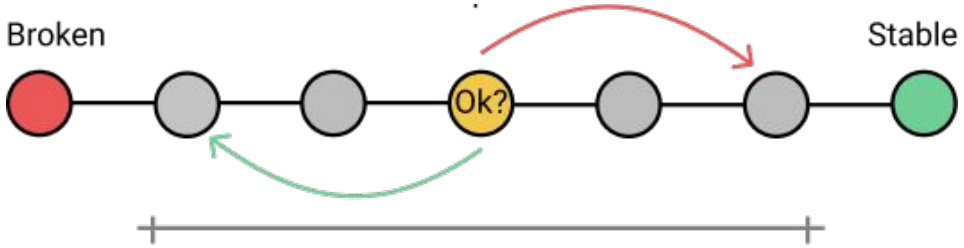
October 24, 2022

Today

- Recap: Git bisect exercise
- Mutation-based testing
  - The basics
  - Productive mutants
  - Mutant subsumption
- Coverage-based vs. mutation-based testing
- In-class exercise 3

Recap: Git bisect

- **Git bisect run-time complexity is always O(log(n))**



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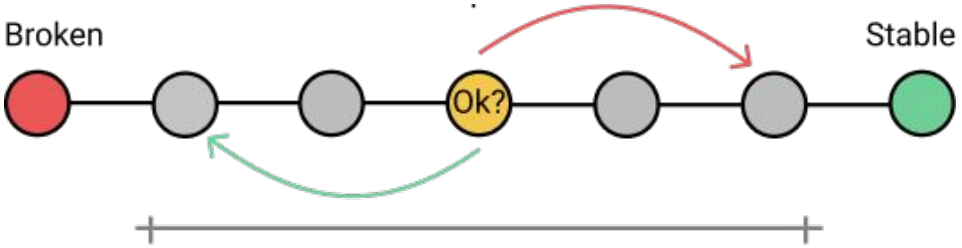
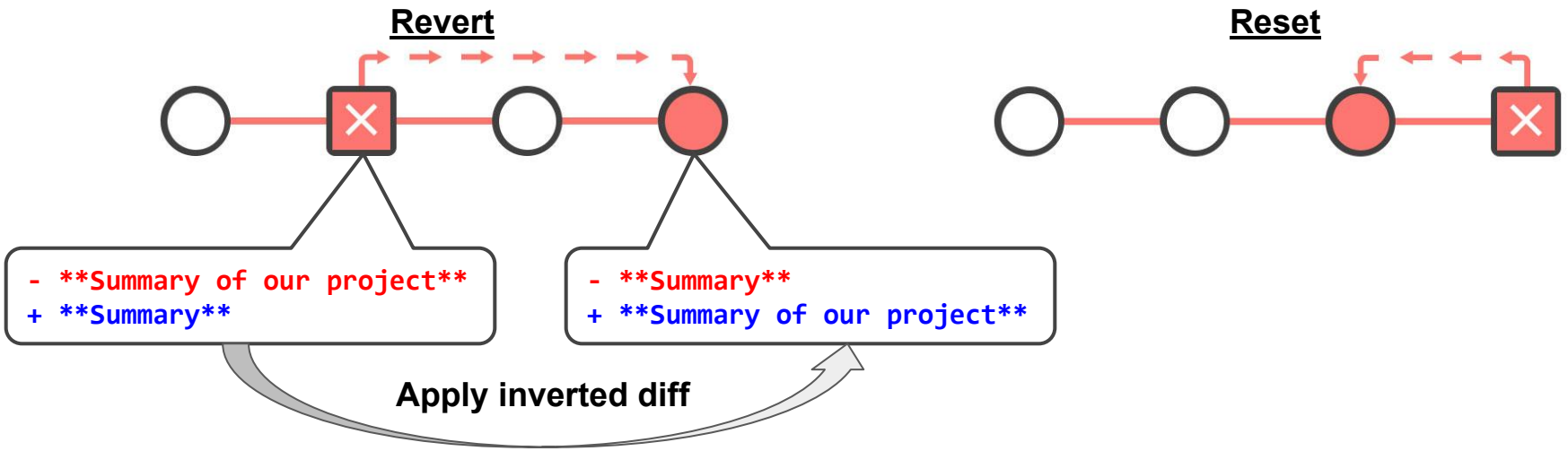


- **Git revert vs. git reset**



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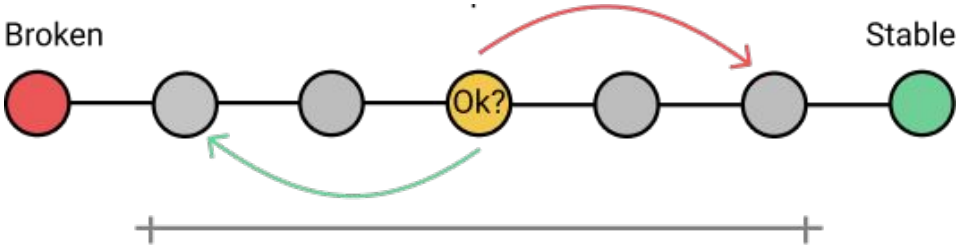

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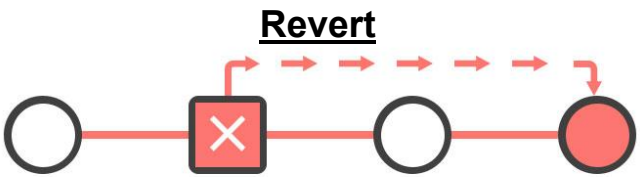
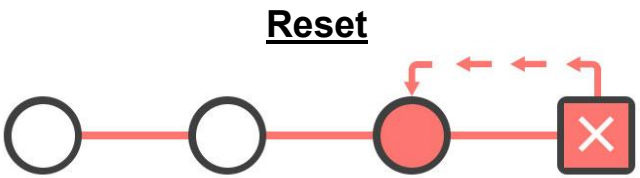
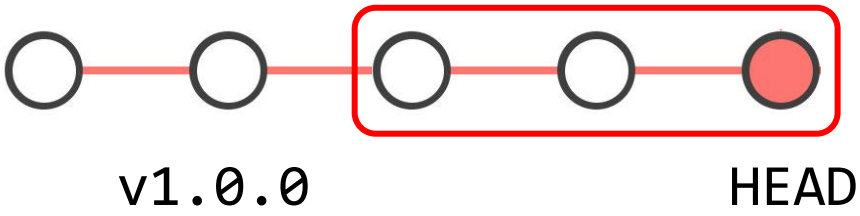


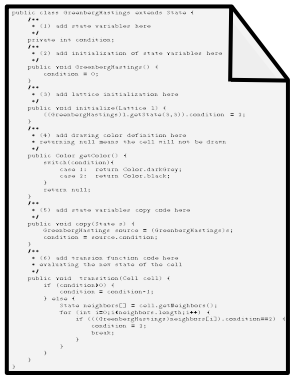


- `git rev-list v1.0.0..HEAD (or HEAD ^v1.0.0)`



Mutation-based testing: the basics

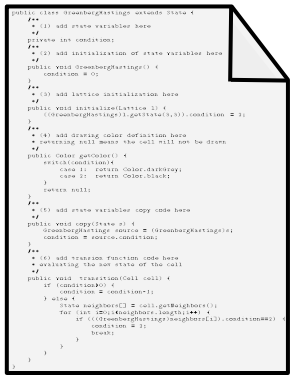
Mutation testing



Program

Mutation testing

Mutation testing: mutant generation



Program

Mutation testing

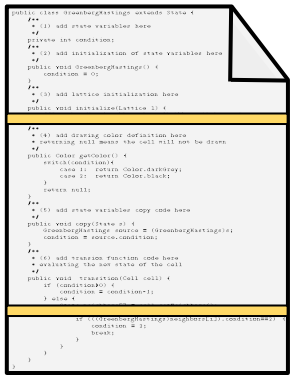
lhs `<` *rhs* ⇒ *lhs* `<=` *rhs*

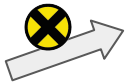
lhs `<` *rhs* ⇒ *lhs* `!=` *rhs*

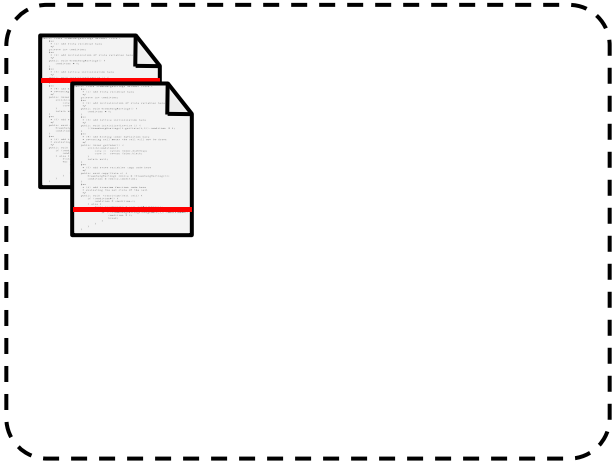
stmt ⇒ *no-op*

Mutation operators

Mutation testing: mutant generation

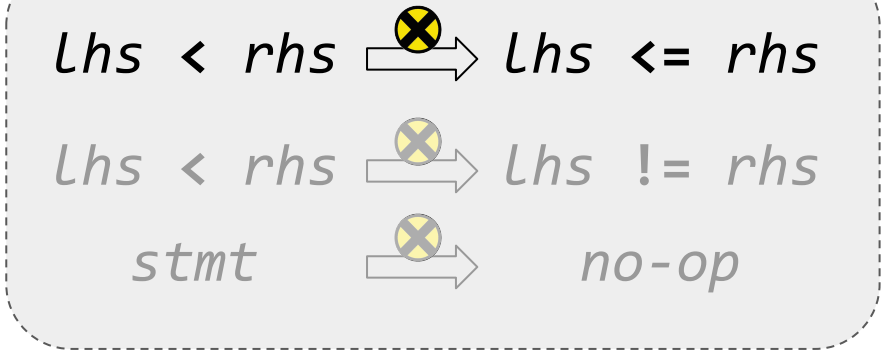






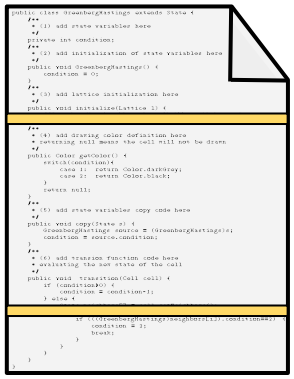
Program

Mutants

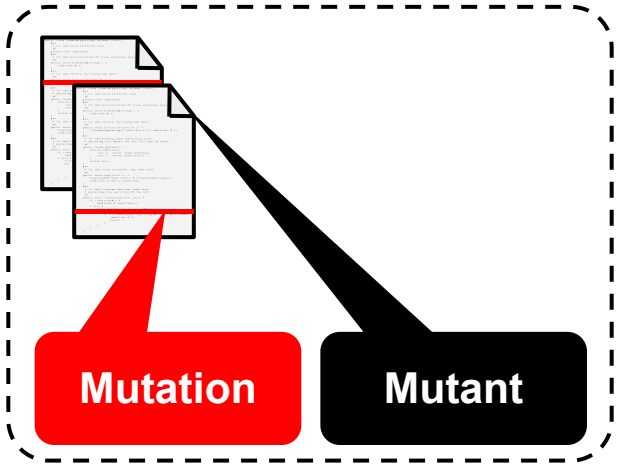


Mutation operators

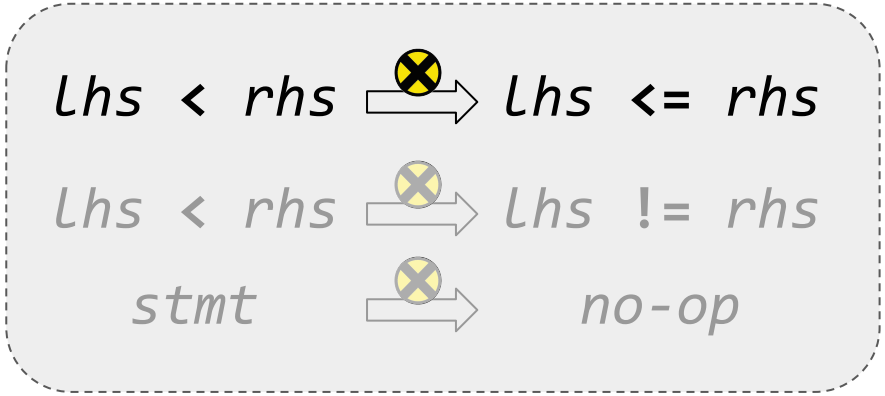
Mutation testing: mutant generation



Program

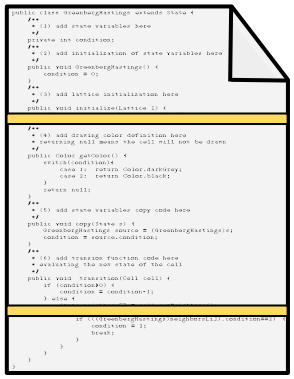


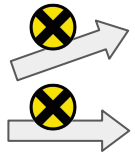
Mutants

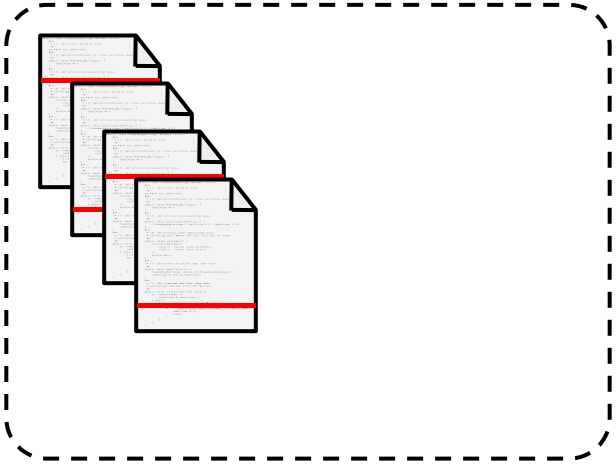


Mutation operators

Mutation testing: mutant generation

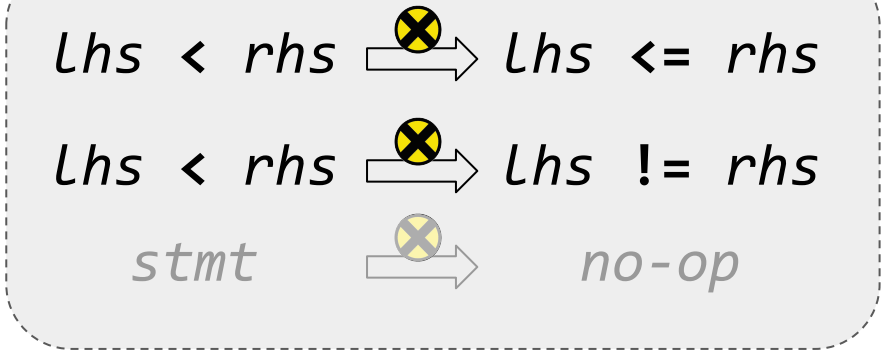






Program

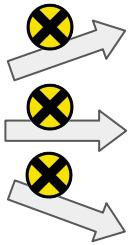
Mutants

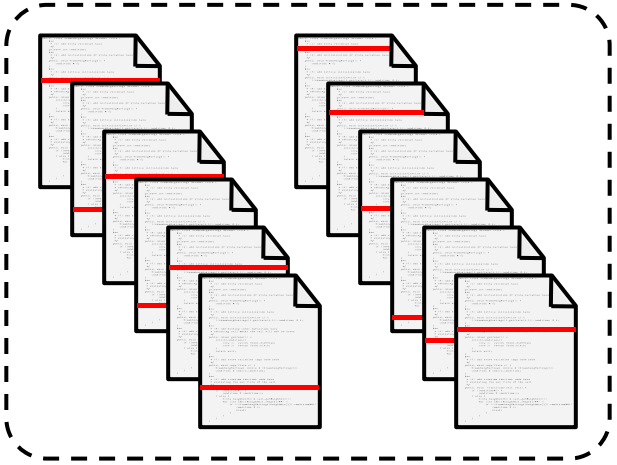


Mutation operators

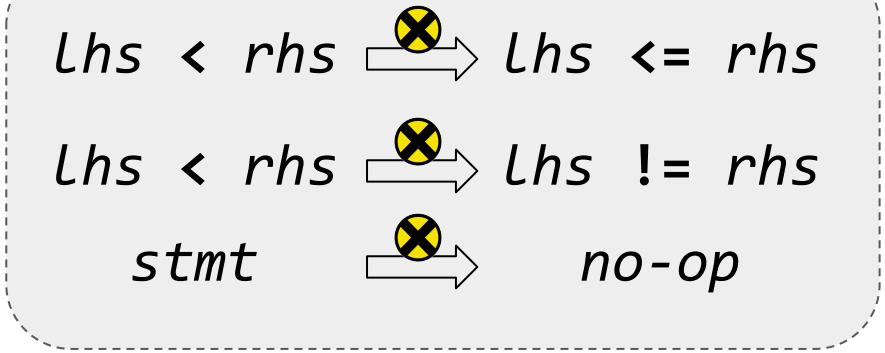
Mutation testing: mutant generation

Program



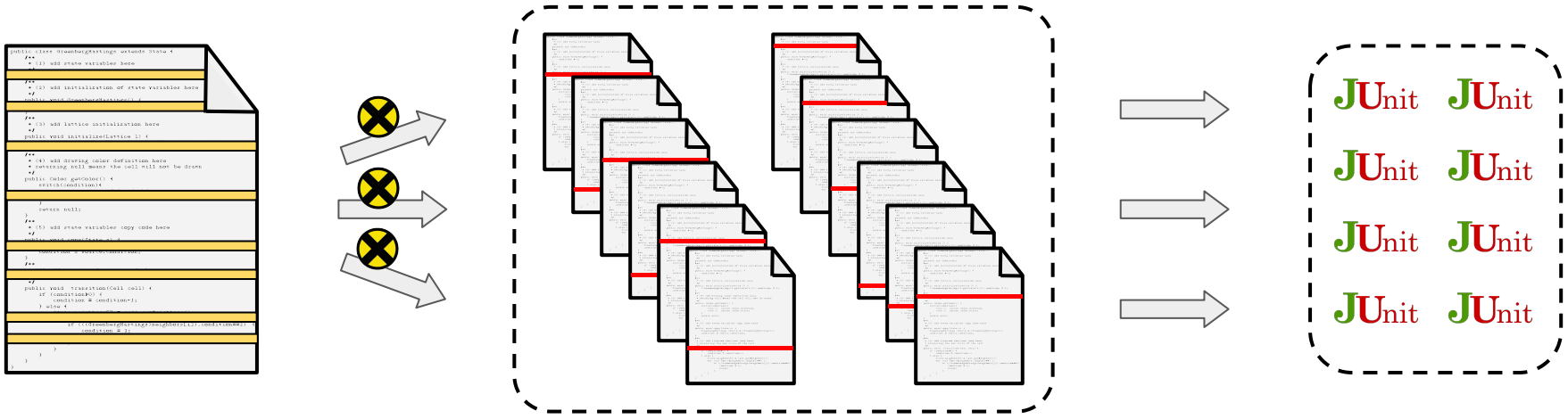


Mutants



Mutation operators

Mutation testing: test creation



Program Mutants Tests

Assumptions

- Mutants are coupled to real faults
- Mutant detection is correlated with real-fault detection

https://homes.cs.washington.edu/~rjust/publ/mutants_real_faults_fse_2014.pdf,
https://homes.cs.washington.edu/~rjust/publ/mutation_testing_practices_icse_2021.pdf

Mutation testing: a concrete example

Original program:

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

Mutant 1:

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

Mutation testing: another 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;
}
```

Mutation testing: yet another 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: last example (I promise)

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: exercise

Original program:

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

Mutants:

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

For each mutant, provide a test case that detects it
(i.e., passes on the original program but fails on the mutant)

Mutation testing: exercise

Original program:

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

Mutants:

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

M4 cannot be detected (equivalent mutant).

a	*b*	Original	M1	M2	M3	M4
1	2	1	1	**2**	**2**	1
1	1	1	1	1	1	1
2	1	1	**2**	1	**2**	1

Mutation testing: exercise

Original program:

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

Mutants:

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

Which mutant(s) should we show to a developer?

a	*b*	Original	M1	M2	M3	M4
1	2	1	1	**2**	**2**	1
1	1	1	1	1	1	1
2	1	1	**2**	1	**2**	1

Mutation testing: summary

Original program:

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

Mutants:

```
M1: return a;
M2: return b;
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```

Redundant

Equivalent

a	*b*	Original	M1	M2	M3	M4
1	2	1	1	**2**	**2**	1
1	1	1	1	1	1	1
2	1	1	**2**	1	**2**	1

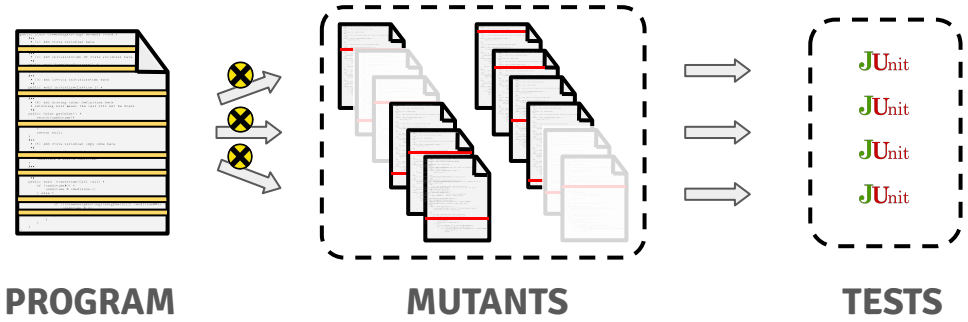
Mutation testing: challenges

- Redundant mutants
  - Inflate the mutant detection ratio
  - Hard to assess progress and remaining effort
- Equivalent mutants
  - Max mutant detection ratio != 100%
  - Waste resources (CPU and human time)

a	***b***	**Original**	**M1**	**M2**	**M3**	**M4**
1	2	1	1	**2**	**2**	1
1	1	1	1	1	1	1
2	1	1	**2**	1	**2**	1

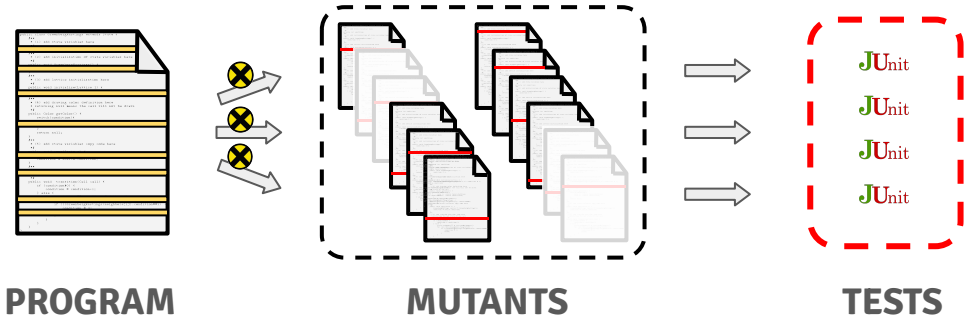
Mutation Testing vs. Mutation Analysis

Mutation Testing



Mutation Testing vs. Mutation Analysis

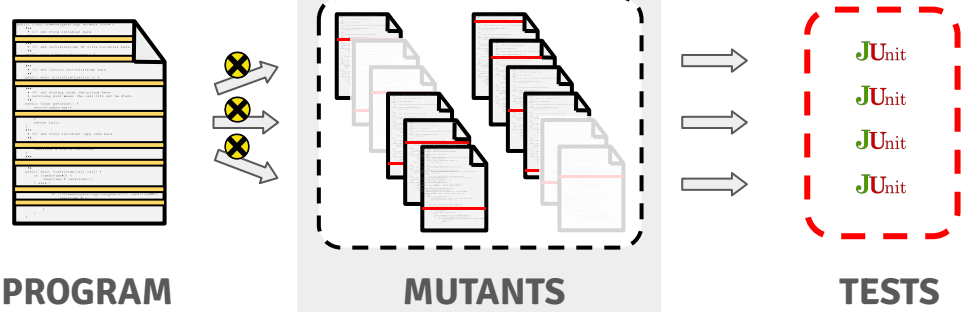
Mutation Testing



Primary output is **new tests**.

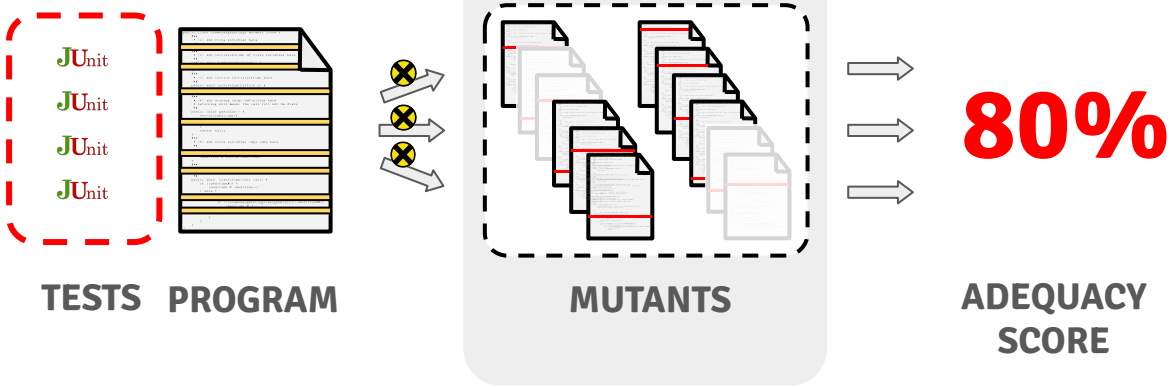
Mutation Testing vs. Mutation Analysis

Mutation Testing



Primary output is **new tests.**

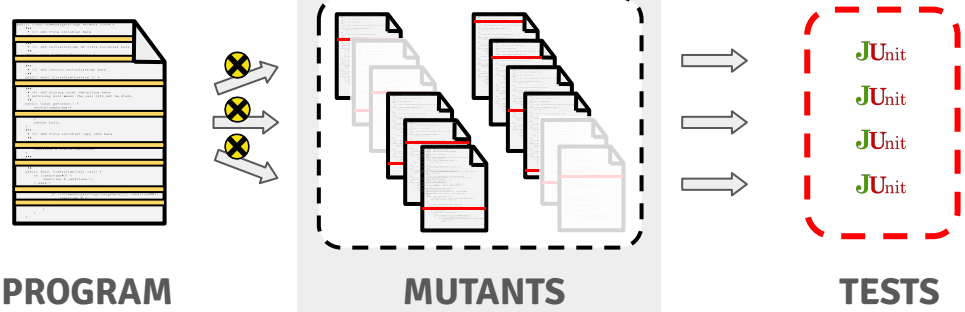
Mutation Analysis



Primary output is **adequacy score** for **existing tests.**

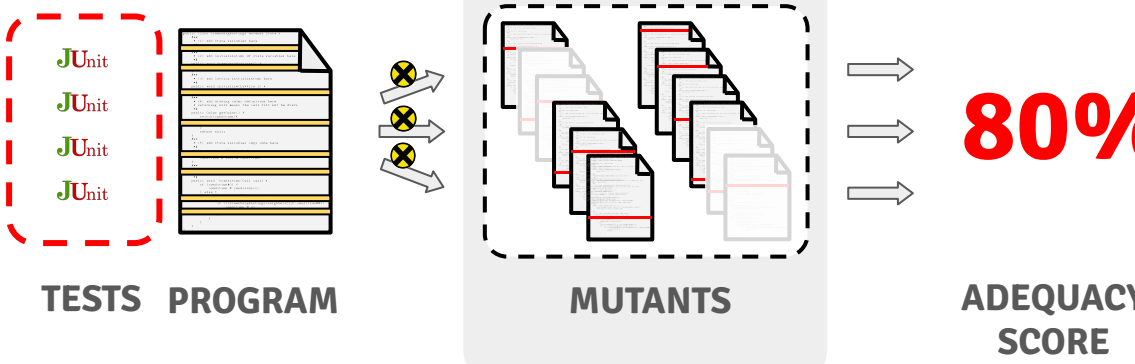
Mutation Testing vs. Mutation Analysis

Mutation Testing



Primary output is **new tests.**

Mutation Analysis



Primary output is **adequacy score** for **existing tests.**

How expensive is mutation testing?

Is the mutation score meaningful?

Mutation-based testing: productive mutants

Detectable vs. productive mutants

Historically

- **Detectable** mutants are **good** ⟹ **tests**
- **Equivalent** mutants are **bad** ⟹ **no tests**

A more nuanced view

- **Detectable vs. equivalent** is **too simplistic**
- **Productive mutants** elicit effective tests, but
  - detectable mutants can be useless, and
  - equivalent mutants can be useful!

The core question here concerns test-goal utility (applies to any adequacy criterion).

Detectable vs. productive mutants

Historically

- **Detectable** mutants are **good** ⟹ **tests**
- **Equivalent** mutants are **bad** ⟹ **no tests**

A more nuanced view

- **Detectable vs. equivalent** is **too simplistic**
- **Productive mutants** elicit effective tests, but
  - detectable mutants can be useless, and
  - equivalent mutants can be useful!

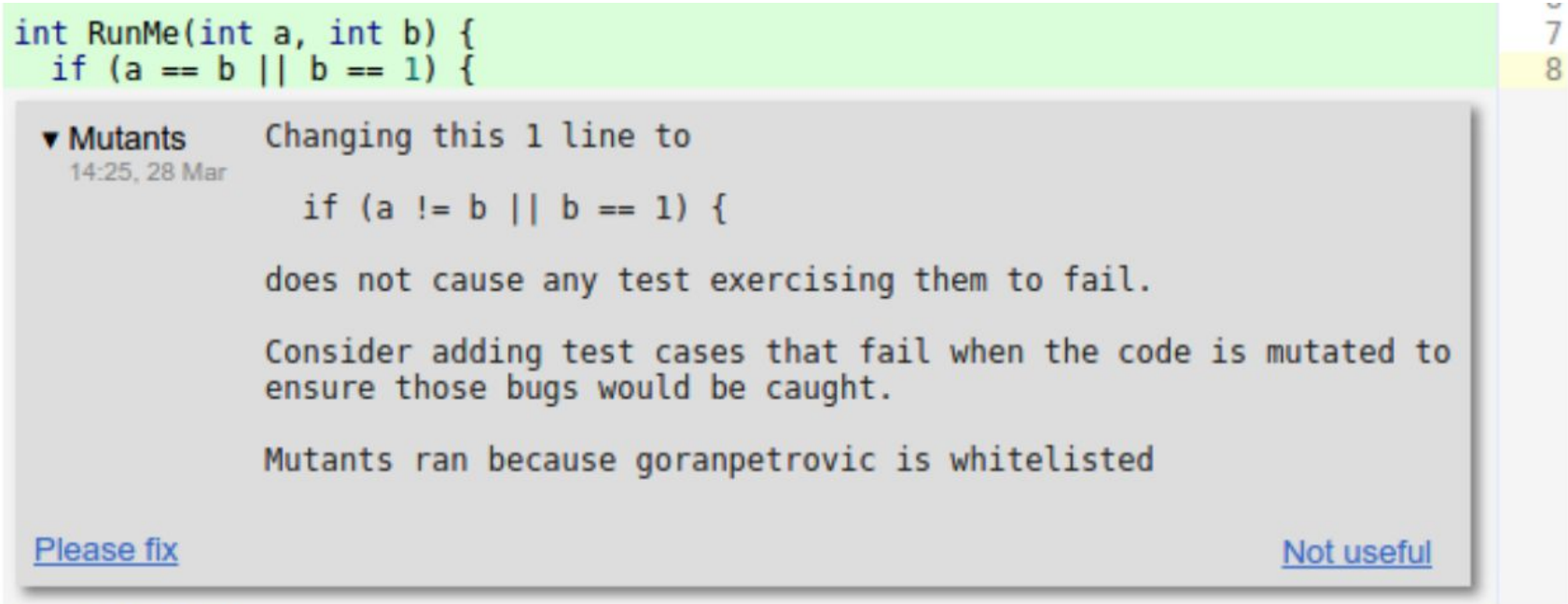
The notion of productive mutants is fuzzy!

A mutant is **productive** if it is

1. **detectable** and **elicits an effective test** or
2. **equivalent** and **advances code quality or knowledge**

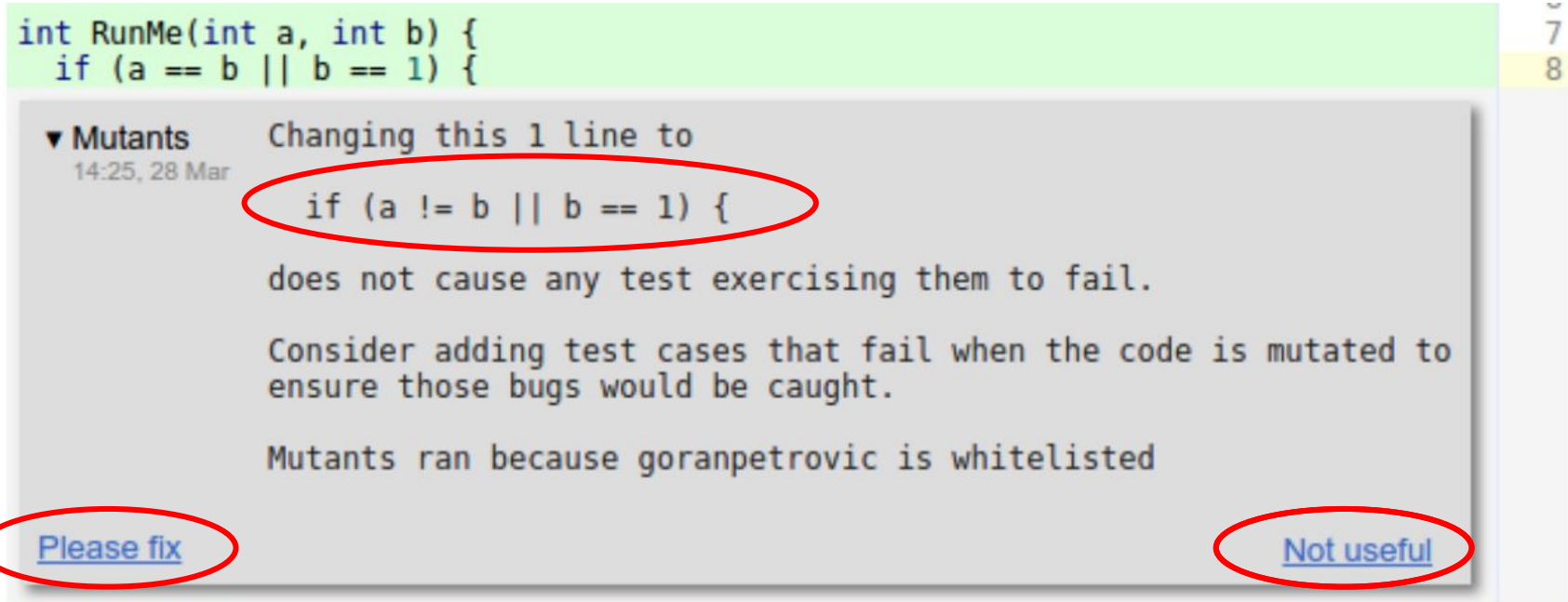
An Industrial Application of Mutation Testing: Lessons, Challenges, and Research Directions (Reading 1)

Productive mutants: mutation testing at Google



Practical Mutation Testing at Scale: A view from Google (Reading 3)

Productive mutants: mutation testing at Google



Practical Mutation Testing at Scale: A view from Google (Reading 3)

Detectable vs. productive mutants (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;
}
```

Mutant

```
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;
}
```

Is the mutant is **detectable?**

Detectable vs. productive mutants (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

```
public double getAvg(double[] nums) {
  double sum = 0;
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  for (int i = 0; i < len; ++i) {
      sum = sum * nums[i];
  }

  return sum / len;
}
```

The mutant is **detectable, but** is it **productive?**

Detectable vs. productive mutants (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;
}
```

Mutant

```
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;
}
```

The mutant is **detectable, but** is it **productive? Yes!**

Detectable vs. productive mutants (2)

Original program

```
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;
}
```

Mutant

```
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 the mutant **detectable?**

Detectable vs. productive mutants (2)

Original program

```
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;
}
```

Mutant

```
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;
}
```

The mutant is **not detectable, but** is it **unproductive?**

Detectable vs. productive mutants (2)

Original program

```
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;
}
```

Mutant

```
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;
}
```

The mutant is **not detectable, but** is it **unproductive? No!**

Detectable vs. productive mutants (3)

Original program

```
...

Set cache = new HashSet(a * b);

...
```

Mutant

```
...

Set cache = new HashSet(a + b);

...
```

Is the mutant **detectable?**

Detectable vs. productive mutants (3)

Original program

```
...

Set cache = new HashSet(a * b);

...
```

Mutant

```
...

Set cache = new HashSet(a + b);

...
```

The mutant is **detectable, but** is it **productive?**

Detectable vs. productive mutants (3)

Original program

```
...

Set cache = new HashSet(a * b);

...
```

Mutant

```
...

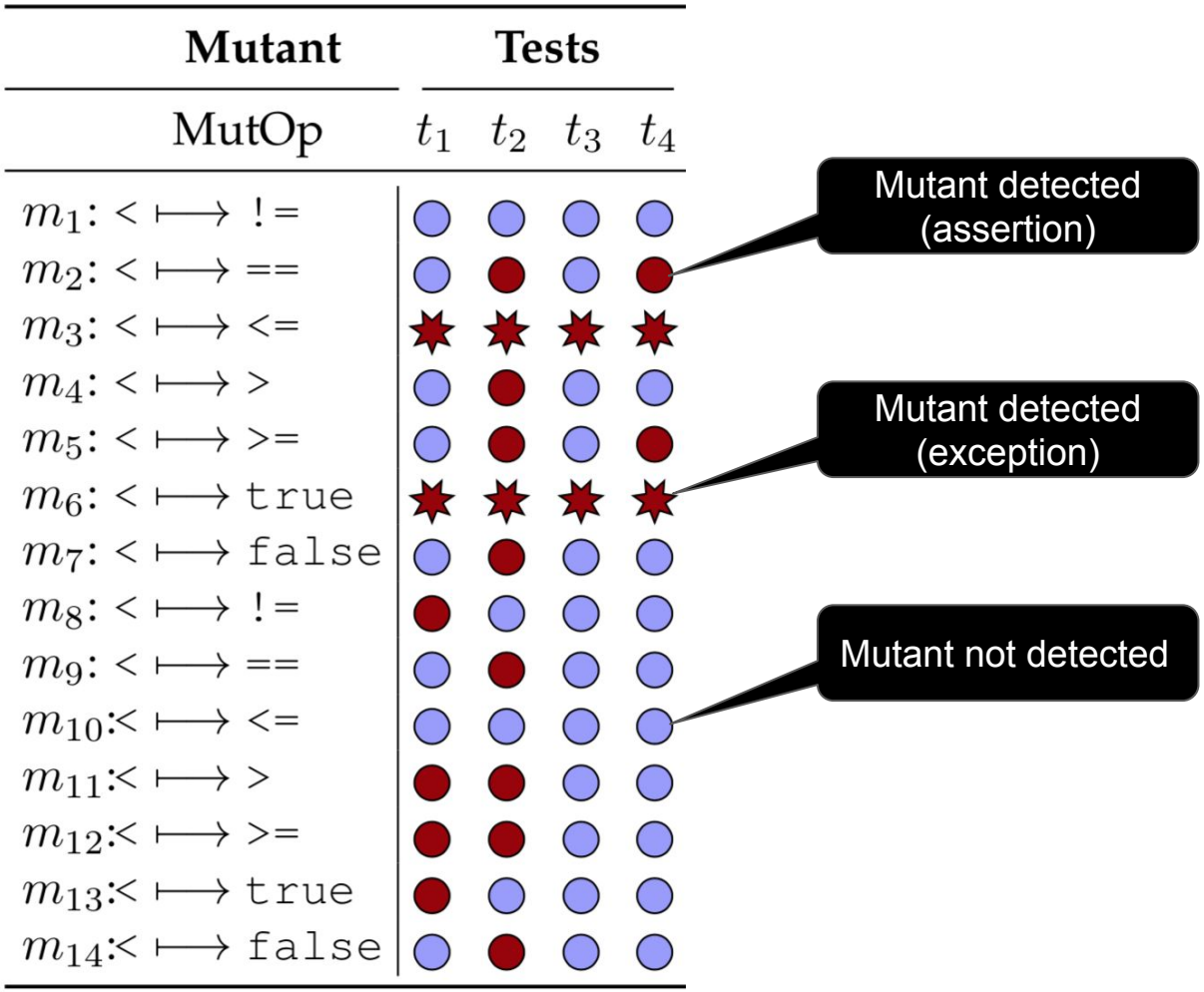
Set cache = new HashSet(a + b);

...
```

The mutant is **detectable, but** is it **productive? No!**

Mutation-based testing: mutant subsumption

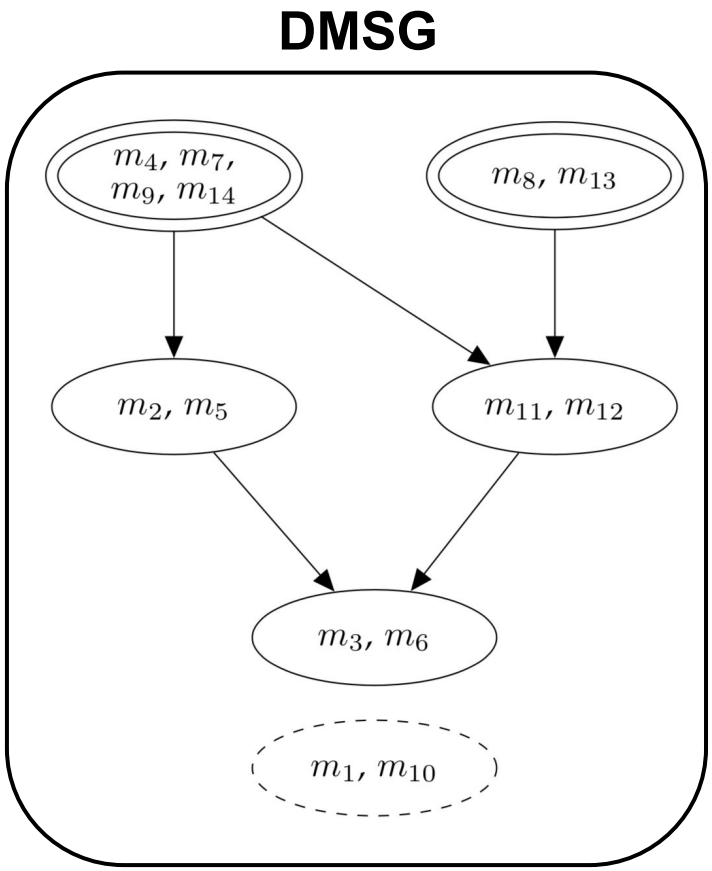
Mutant subsumption



Prioritizing Mutants to Guide Mutation Testing (Reading 2)

DMSG: Dynamic Mutant Subsumption Graph

Mutant	Tests			
MutOp	t_1	t_2	t_3	t_4
m_1: < ⟼ !=	●	●	●	●
m_2: < ⟼ ==	●	●	●	●
m_3: < ⟼ <=	✸	✸	✸	✸
m_4: < ⟼ >	●	●	●	●
m_5: < ⟼ >=	●	●	●	●
m_6: < ⟼ true	✸	✸	✸	✸
m_7: < ⟼ false	●	●	●	●
m_8: < ⟼ !=	●	●	●	●
m_9: < ⟼ ==	●	●	●	●
m_{10}:< ⟼ <=	●	●	●	●
m_{11}:< ⟼ >	●	●	●	●
m_{12}:< ⟼ >=	●	●	●	●
m_{13}:< ⟼ true	●	●	●	●
m_{14}:< ⟼ false	●	●	●	●



Prioritizing Mutants to Guide Mutation Testing (Reading 2)

Coverage-based vs. mutation-based testing

See dedicated Slides (4 pages).