CSE 403

Software Engineering

Mutation-based Testing

This week: more on test adequacy

- Mutation-based testing
- In-class exercise: hands-on mutation testing

Recap: structural code coverage

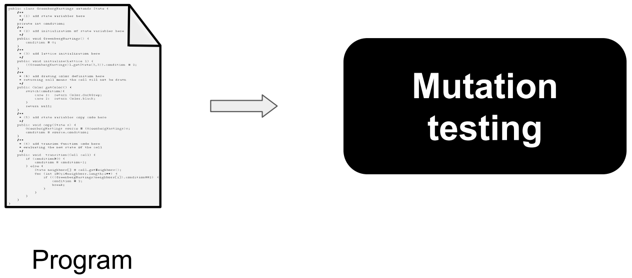
Classes in this File	Line Coverage		Branch Coverage		Complexity
Avg	100%	10/10	100%	8/8	6

```java
package avg;

public class Avg {

    /*
     * Compute the average of the absolute values of an array of doubles
     */
    public double avgAbs(double ... numbers) {
        // We expect the array to be non-null and non-empty
        if (numbers == null || numbers.length == 0) {
            throw new IllegalArgumentException("Array numbers must not be null or empty!");
        }

        double sum = 0;
        for (int i=0; i<numbers.length; ++i) {
            double d = numbers[i];
            if (d < 0) {
                sum -= d;
            } else {
                sum += d;
            }
        }
        return sum/numbers.length;
    }
}
```

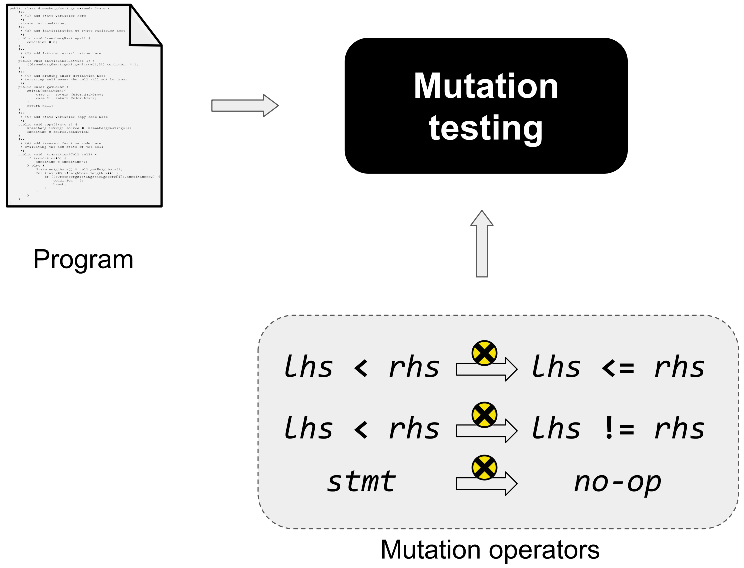
- Code coverage is easy to compute.
- Code coverage has an intuitive interpretation.
- Code coverage in industry: Code coverage at Google
- Code coverage itself is not sufficient!

Mutation-based testing: the basics

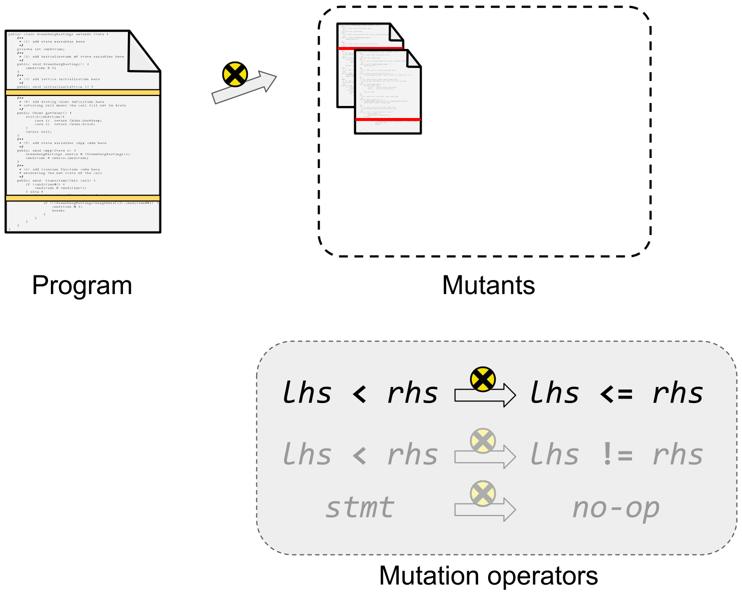
Mutation testing



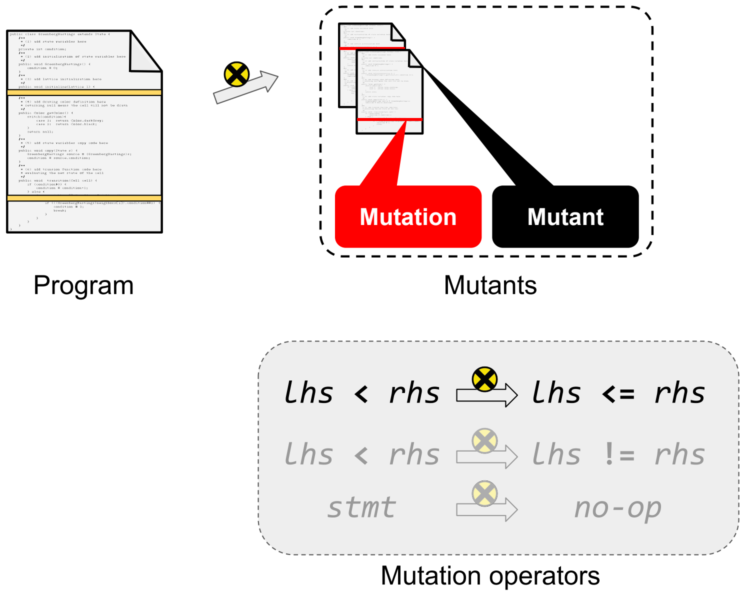
Mutation testing: mutant generation



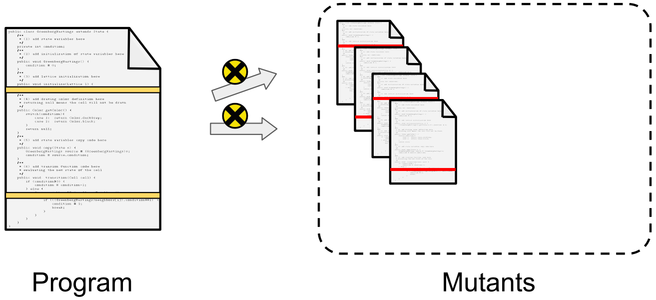
Mutation testing: mutant generation



Mutation testing: mutant generation



Mutation testing: mutant generation



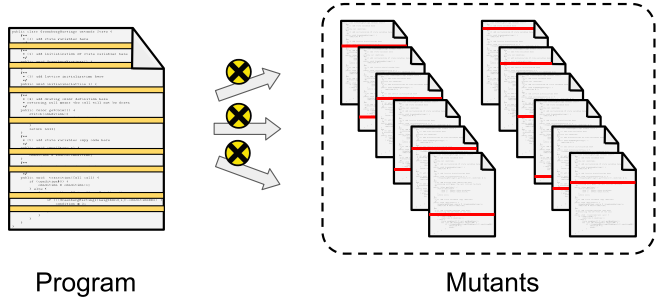
lhs < *rhs* → *lhs* <= *rhs*

lhs < *rhs* → *lhs* != *rhs*

stmt → *no-op*

Mutation operators

Mutation testing: mutant generation



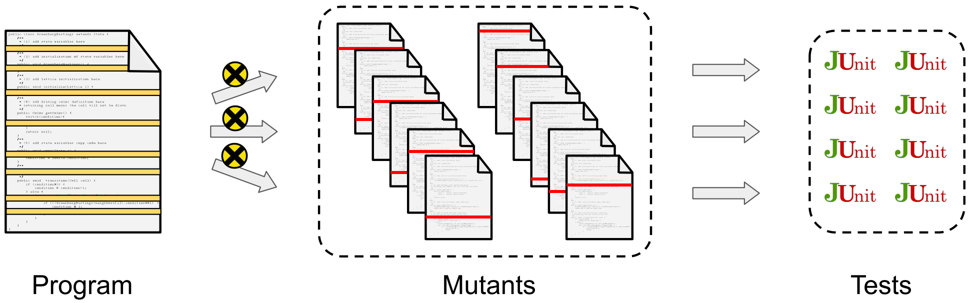
lhs < *rhs* → *lhs* <= *rhs*

lhs < *rhs* → *lhs* != *rhs*

stmt → *no-op*

Mutation operators

Mutation testing: test creation



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)

https://forms.gle/ADTR1nDzewgqRXaD9

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

Redundant **Equivalent**

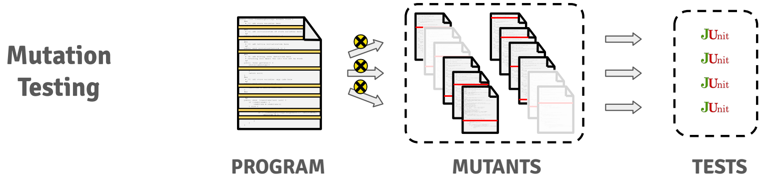
a	*b*	Original	M1	M2	M3	M4
1	2	1	1	**2**	**2**	1
1	1	1	1	1	1	1
2	1	1	**2**	1	**2**	1

Mutation testing: challenges

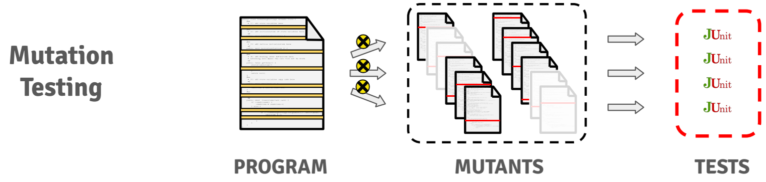
- Redundant mutants
  - Inflate the mutant detection ratio
  - Hard to assess progress and remaining effort
- Equivalent mutants
  - Max mutant detection ratio != 100%
  - Waste resources (CPU and human time)

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

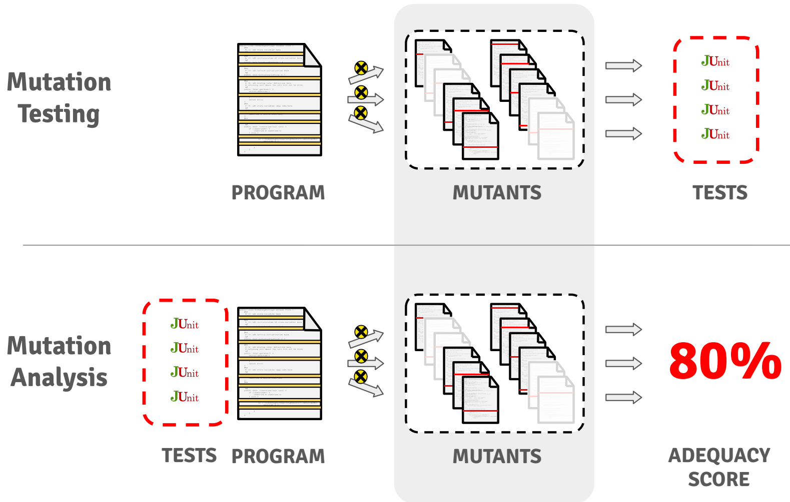


Mutation Testing vs. Mutation Analysis



Primary output is **new tests.**

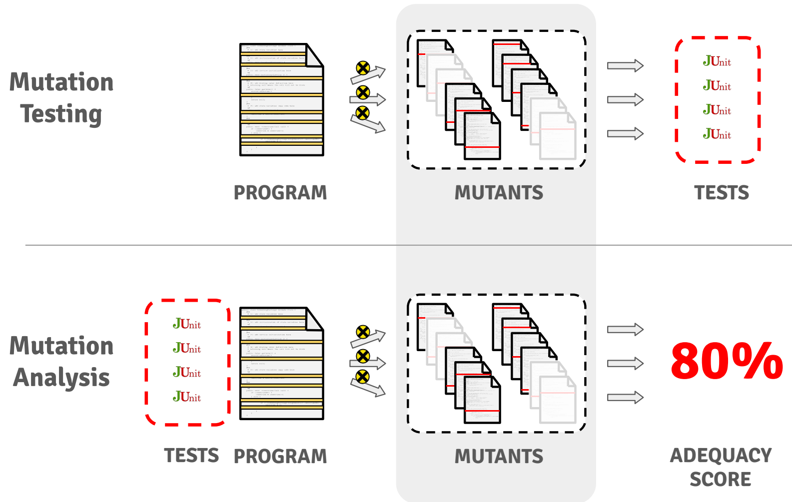
Mutation Testing vs. Mutation Analysis



Primary output is **new tests.**

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

Mutation Testing vs. Mutation Analysis



Primary output is **new tests.**

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).

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

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!

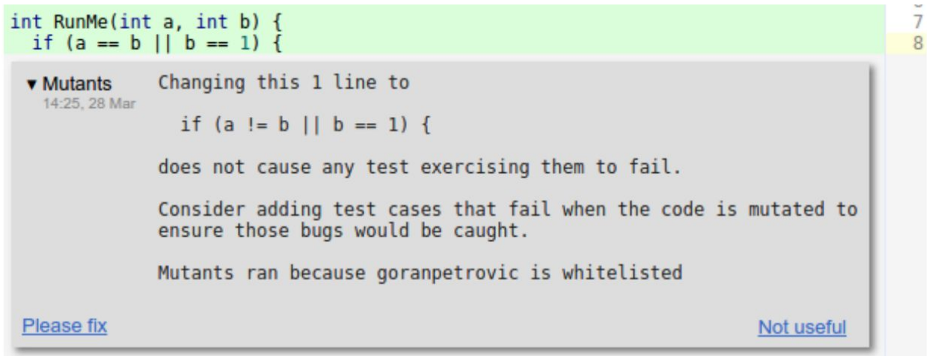
The notion of productive mutants is fuzzy!

A mutant is **productive** if it is

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

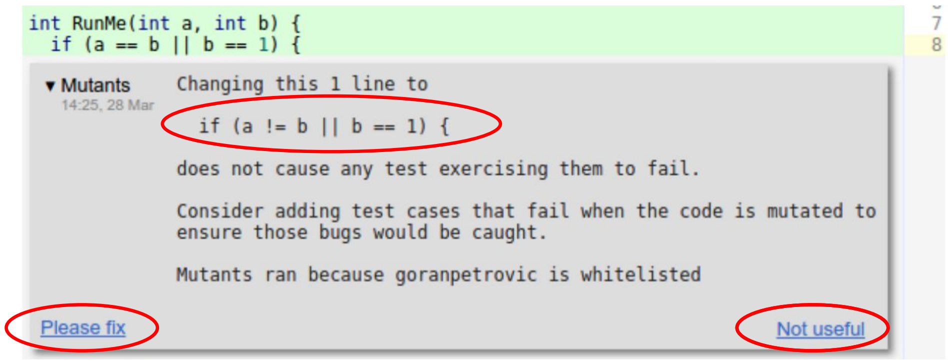
An Industrial Application of Mutation Testing: Lessons, Challenges, and Research Directions (Reading)

Productive mutants: mutation testing at Google



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

Productive mutants: mutation testing at Google



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

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;
}
```

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?**

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);
...
```

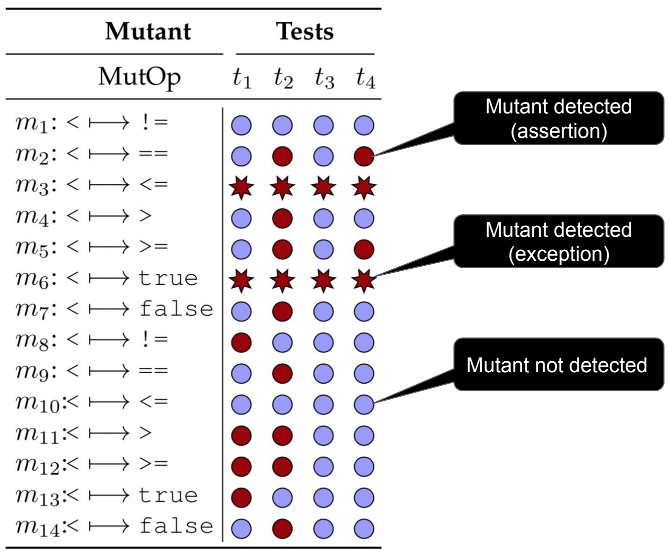
Mutant

```
...
Set cache = new HashSet(a + b);
...
```

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

Mutation-based testing: mutant subsumption

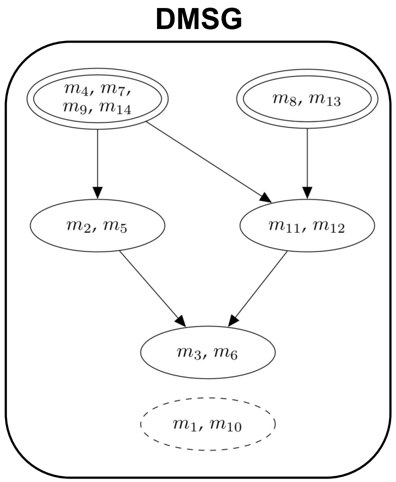
Mutant subsumption



Prioritizing Mutants to Guide Mutation Testing (*Reading*)

DMSG: Dynamic Mutant Subsumption Graph

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



Prioritizing Mutants to Guide Mutation Testing (Reading)