Efficient Mutation Analysis by Propagating and Partitioning Infected Execution States

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A rough outline

Motivation

What is mutation analysis — is it useful?

A rough outline

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Problem

Mutation analysis is expensive!

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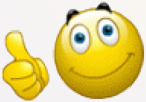
Solution



Dynamic prepass analysis to make mutation practical!

Test suite quality

Why assess test suite quality?

- Selection: Given two test suites, which is better?
- Minimization: Are there redundant tests in a test suite?
- Prioritization: Which tests of a test suite should run first?

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Mutation analysis: systematically seed artificial faults

Mutation analysis overview

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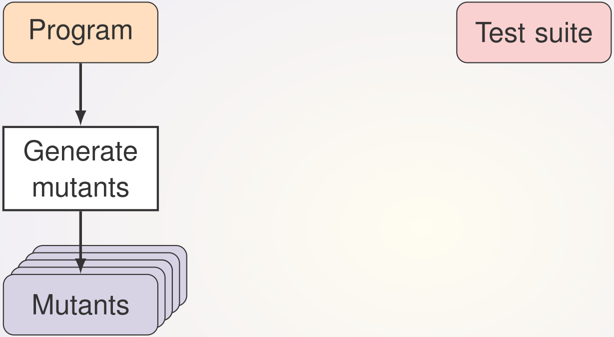
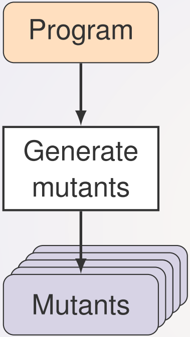


Mutation analysis overview



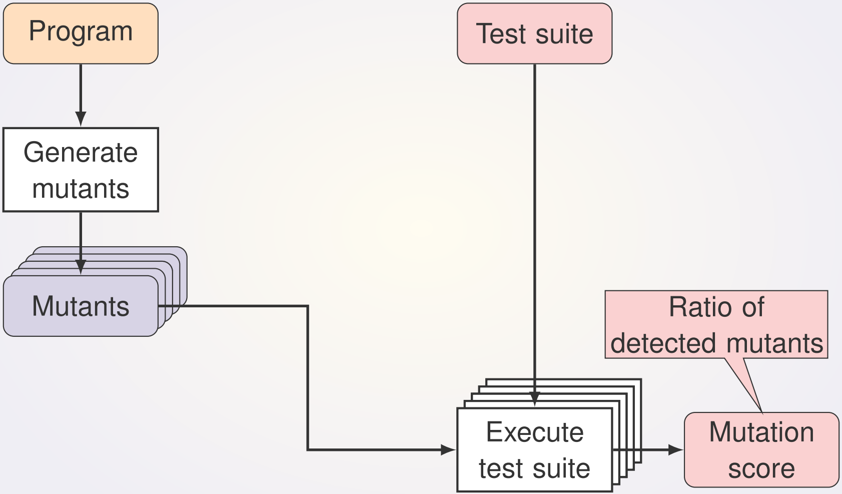

```
public int max(int a, int b){
   return (a > b) ? a : b;
}
```
Original

```
public int max(int a, int b){
   return (a >= b) ? a : b;
}
```
Mutant 1

```
public int max(int a, int b){
   return (a != b) ? a : b;
}
```
Mutant 2

Each mutant contains a small syntactic change

Mutation analysis overview



Where is the catch?

Many mutants can be generated!

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```
  a >= b ? a : b
  a <  b ? a : b
  a <= b ? a : b
  a != b ? a : b
  a == b ? a : b
!(a > b) ? a : b
  true   ? a : b
  false  ? a : b
```

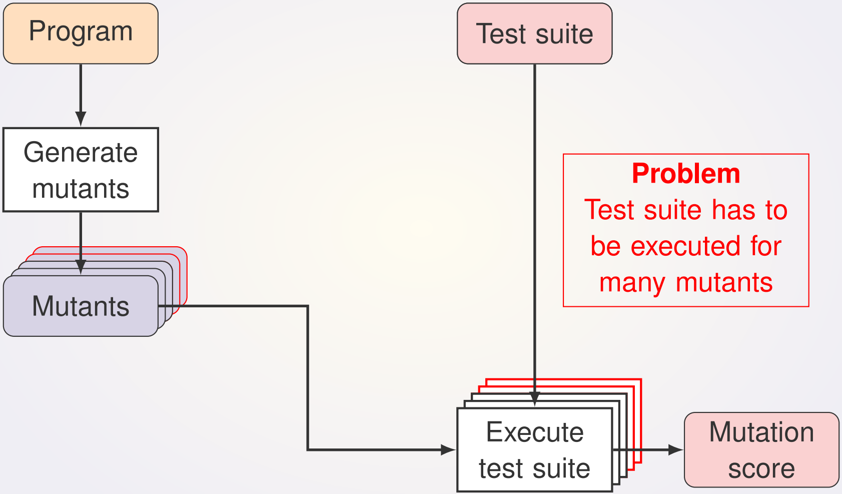
Where is the catch?

Many mutants can be generated!

```
a > b ?  a :  b
```

```
a >= b ? a : b        0 > b ? a : b       -a > b ?  a : b
a <  b ? a : b        a > 0 ? a : b        a >-b ?  a : b
a <= b ? a : b        a > b ? 0 : b        a > b ? -a : b
a != b ? a : b        a > b ? a : 0        a > b ?  a :-b
a == b ? a : b        0                    a > b ?  a :-b
!(a > b) ? a : b      b > a ? a : b       -(a > b ?  a : b)
true  ? a : b         a > b ? b : a        a
false ? a : b                              b
```

Mutation analysis overview



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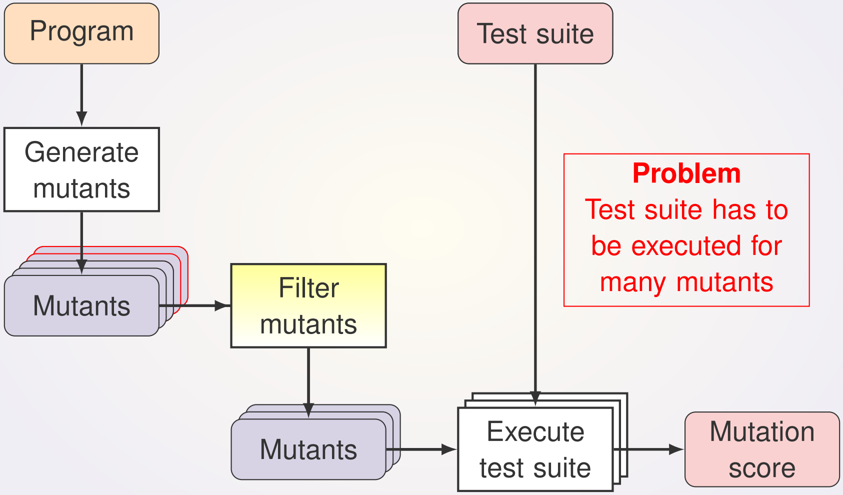

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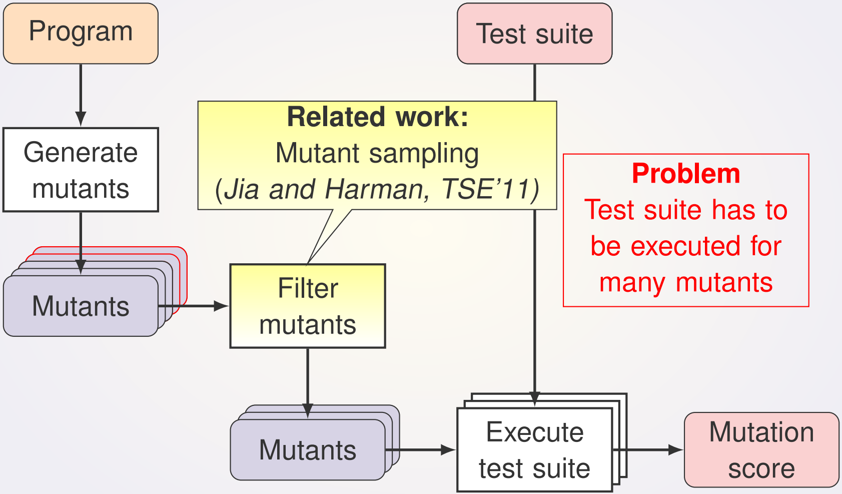

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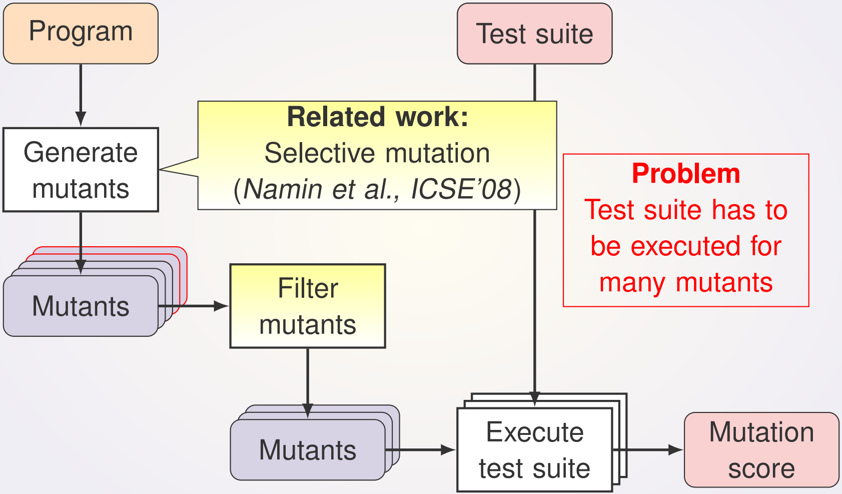

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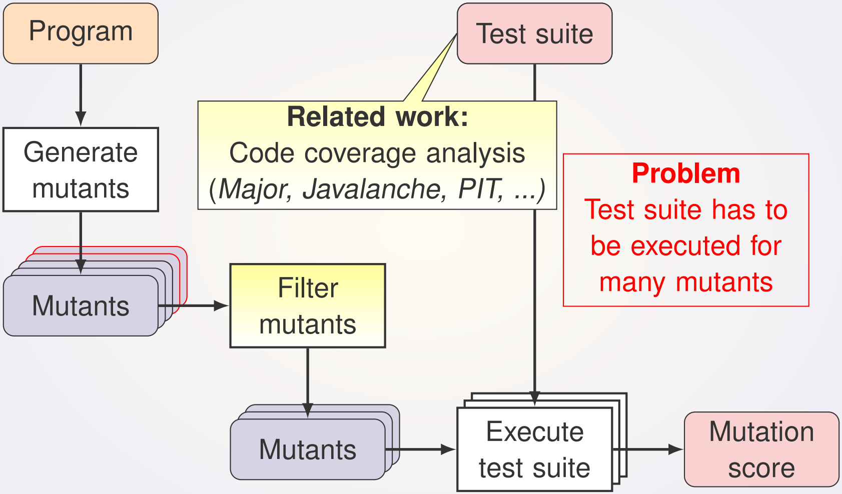

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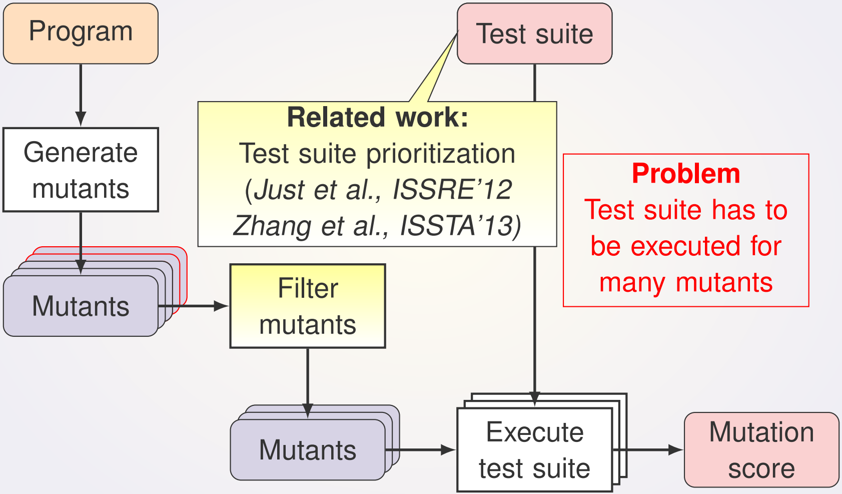

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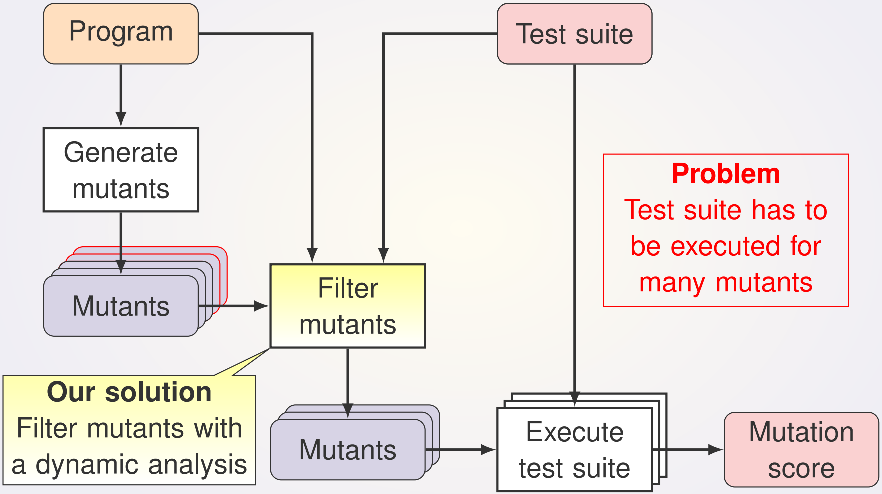

Wasted effort in mutation analysis

Example: testing triangle classification

```
public TriangleType classify
      (int a, int b, int c) {
   ...
   if ( a + b <= c ) {
       return Invalid;
   }
   ...
}
```

Original

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Mutant 1

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Mutant 1

Identical code surrounding mutation

Wasted effort in mutation analysis

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Optimizations:

- Infection

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Mutant 1

```
public TriangleType classify
      (int a, int b, int c) {
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        return Invalid;
   }
   ...
}
```
Mutant 2

Optimizations:

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Wasted effort in mutation analysis

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Mutant 2

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- Propagation
- Partitioning

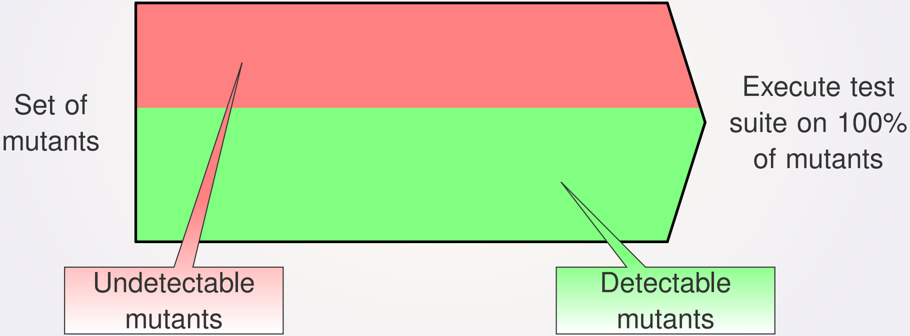
The big picture

Set of mutants

Execute test suite on 100% of mutants

The big picture

Mutation score: 56%



The big picture

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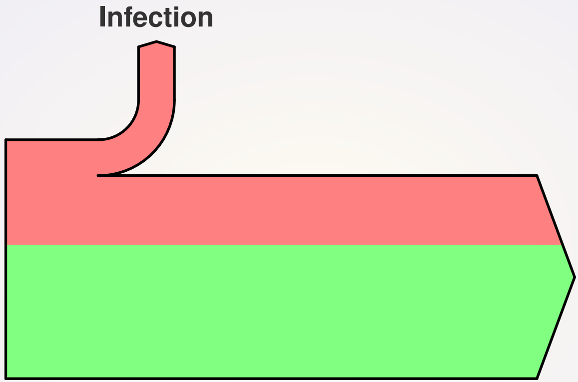
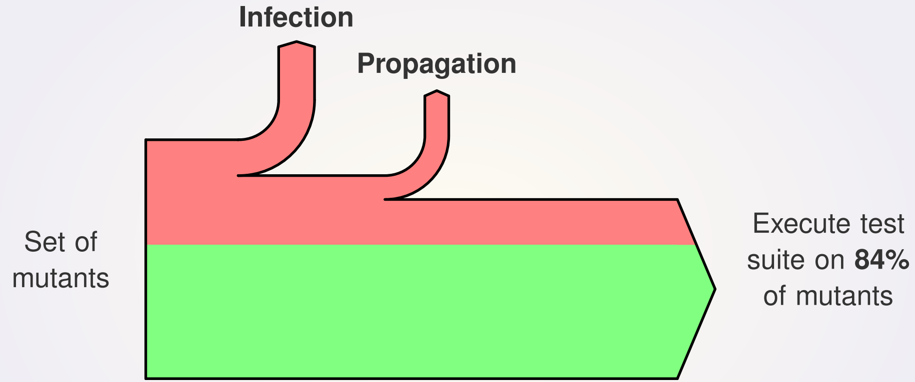


Execute test suite on **90%** of mutants

The big picture



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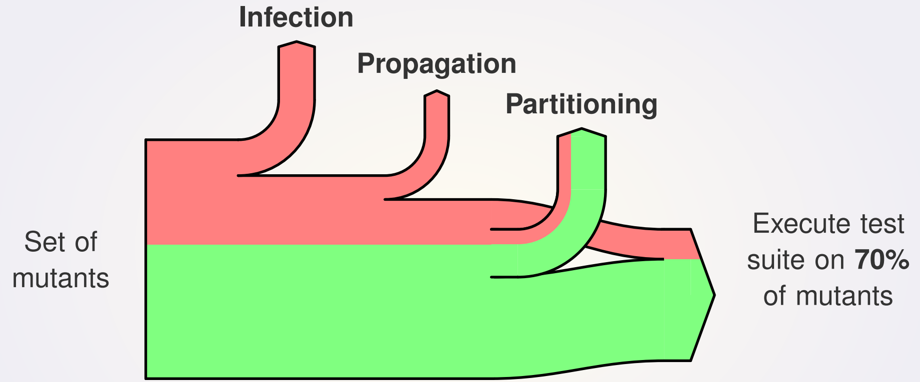
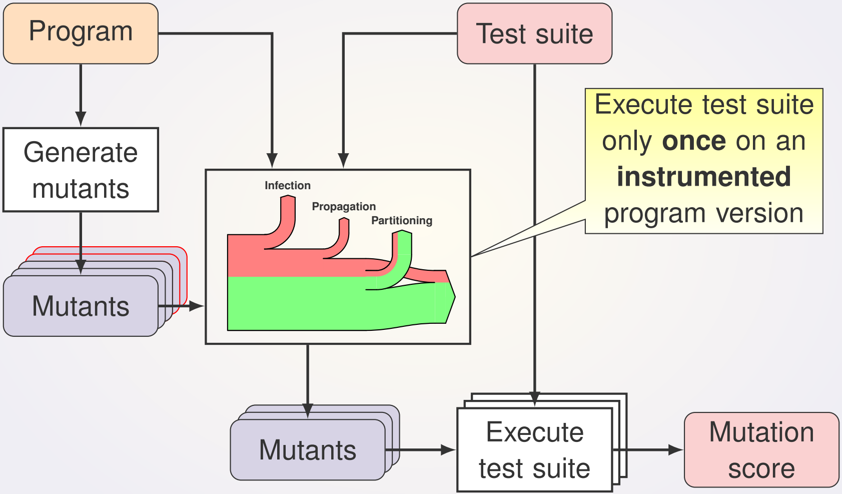


Dynamic analysis to filter mutants



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A test infects the execution state of a mutant if the expression values of the mutation and the original version differ.

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Example: `a=2, b=2, c=0`

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if ( a + b > c )
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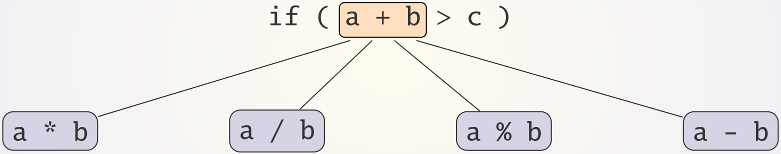

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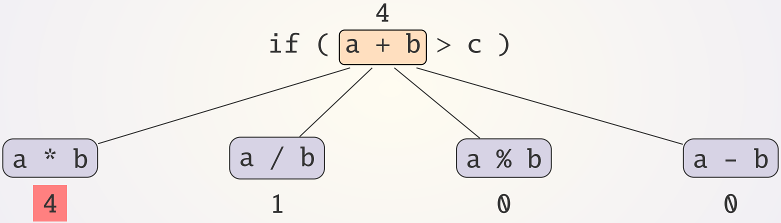

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- Execute mutations and monitor infected execution states
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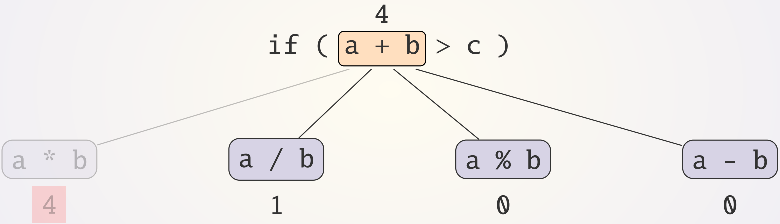

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An infected execution state propagates if it leads to an infected execution state of a lexically enclosing expression.

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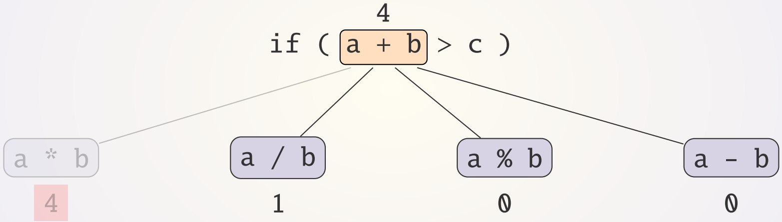

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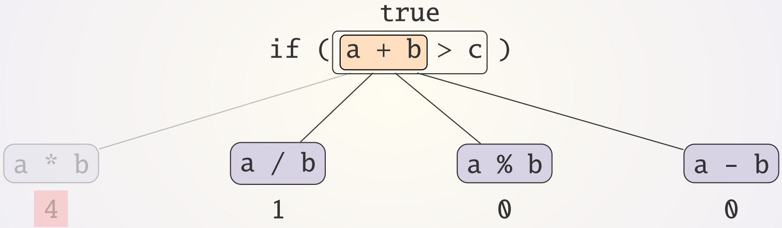

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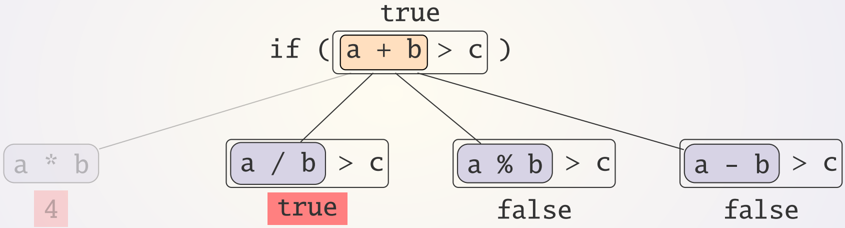

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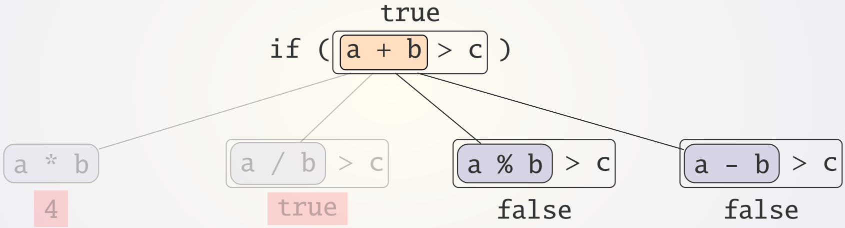

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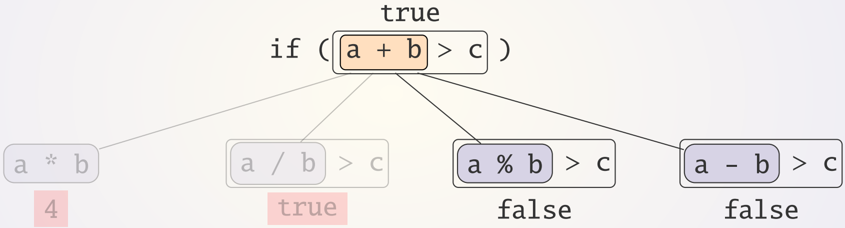
Partitioning

Build partition of identically infected execution states.

Example: `a=2, b=2, c=0`



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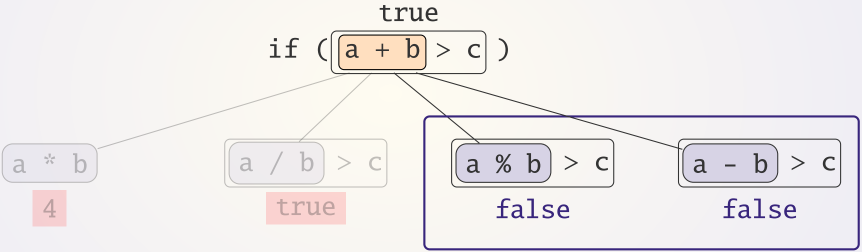

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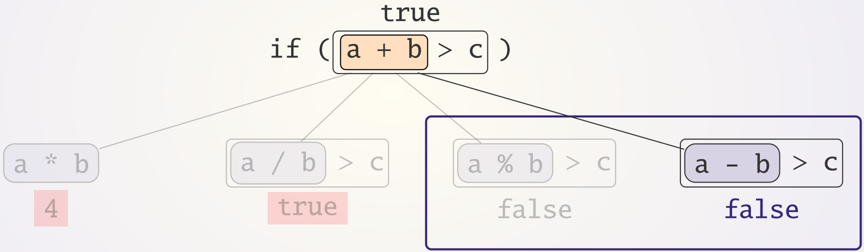

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Implementation details

a + b > c

Implementation details

$$\overbrace{\overbrace{\overbrace{a}^{1_e} + \overbrace{b}^{2_e}}^{3_e} > \overbrace{c}^{4_e}}^{5_e} \xrightarrow{\text{mapping}}$$

Expressions
$3_e \mapsto +, 1_e, 2_e$
$5_e \mapsto >, 3_e, 4_e$

$$\Big\downarrow \text{instrumentation}$$

eval(5, eval(3, a, b), c)

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Mutations
$1_m \mapsto 3_e$, -
$2_m \mapsto 3_e$, *
$3_m \mapsto 5_e$, >=
$4_m \mapsto 5_e$, ==

1_m: a - b > c
2_m: a * b > c
3_m: a + b >= c
4_m: a + b == c

$\downarrow$ instrumentation

eval(5, eval(3, a, b), c)

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Example: a=2, b=2, c=1

InfectedValues

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instrumentation

eval(5, eval(3, a, b), c)

3_e: a + b = 4
1_m: a - b = 0
2_m: a * b = 4

Example: a=2, b=2, c=1

InfectedValues

Implementation details

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5_e: 4 > c = true
3_m: 4 >= c = true
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InfectedValues
1_m: 0

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InfectedValues
1_m: 0

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instrumentation

eval(5, eval(3, a, b), c)

```
5e: 4 >  c = true

4m: 4 == c = false
1m: 0 >  c = false
```

Example: a=2, b=2, c=1

InfectedValues	
4_m:	false
1_m:	false

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Example: a=2, b=2, c=1

InfectedValues	
4_m:	false
1_m:	false

Implemented in Major

- Compact instrumentation
- Soundly handles side effects and short-circuit operators

Experimental setup

14 subject programs

- Open-source programs from different application domains
- 670,000 lines of code
- 540,000 generated mutants

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4 test suites for each program

- 1 developer-written test suite (released with program)
- 3 generated test suites (EvoSuite)
  - Weak-mutation
  - Branch coverage
  - Random

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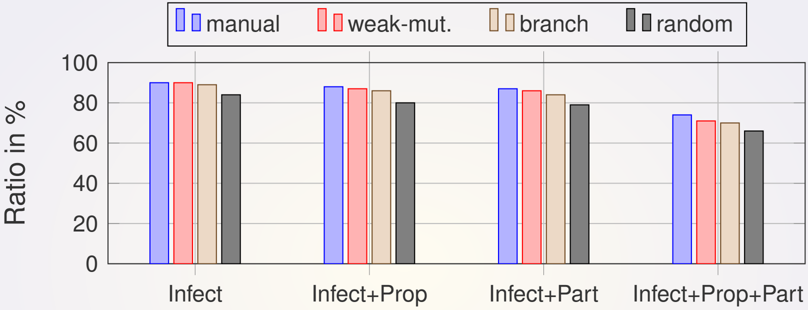
4 test suites for each program

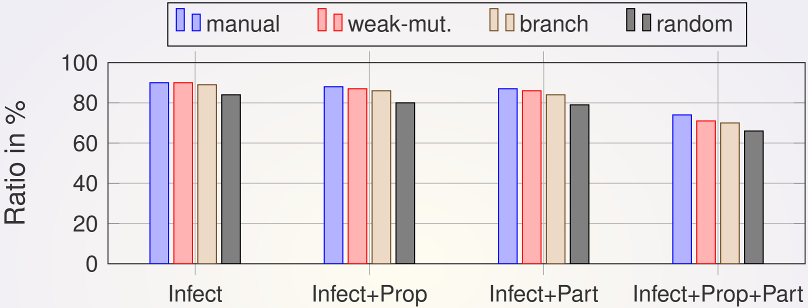
- 1 developer-written test suite (released with program)
- 3 generated test suites (EvoSuite)
    - Weak-mutation
    - Branch coverage
    - Random

Coverage optimization is baseline

Ratio of analyzed mutants



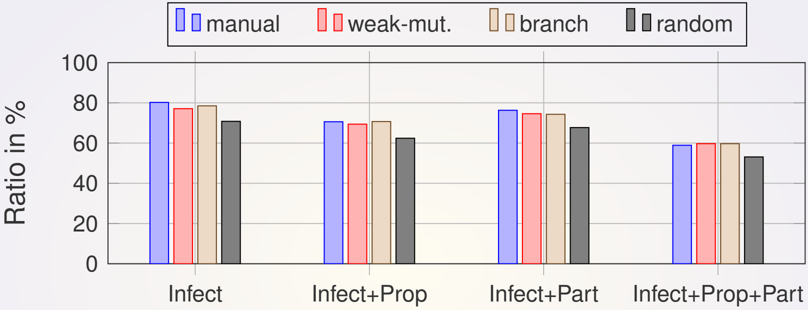
Ratio of analyzed mutants



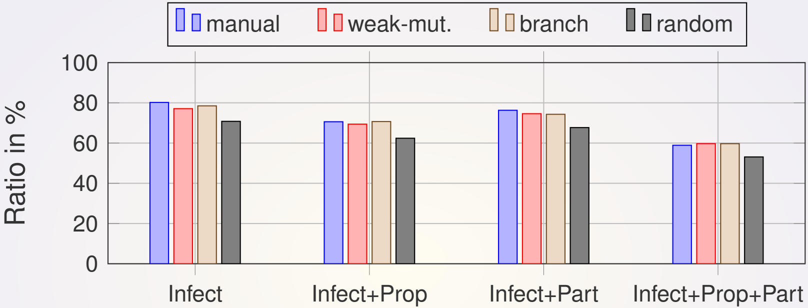
Findings

- Only 70% of covered mutants need to be analyzed
- Similar ratio for Propagation and Partitioning
- Partitioning is (most) effective after Propagation
- Lower ratio for weaker test suites (e.g., Random)

Ratio of total runtime



Ratio of total runtime



Findings

- Total run time reduced by 40%
- Filtering costs are almost negligible
- Partitioning is (most) effective after Propagation
- Run-time improvements similar for all test suites

Future work

Equivalent mutant detection

- Can propagation predict equivalent mutants?
- Solve constraints necessary to achieve propagation

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- Can propagation predict equivalent mutants?
- Solve constraints necessary to achieve propagation

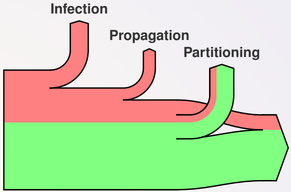
Test generation

- Generate tests that achieve propagation
- Improve mutation-driven test generation
  (Zhang et al., ICSM'10, Fraser and Zeller, TSE'12)

Contributions

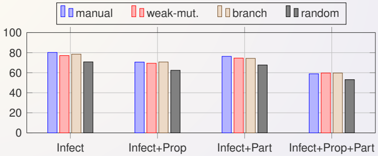
Dynamic prepass analysis

- Three new optimizations that significantly improve efficiency
- Filter mutants with single test execution on instrumented program



Empirical evaluation

- 14 programs and 540,000 mutants
- Total run time reduced by 40%
- Propagation and Partitioning should be combined



http://www.mutation-testing.org