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?

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Problem

Mutation analysis is expensive!

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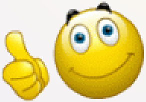
Mutation analysis is expensive!

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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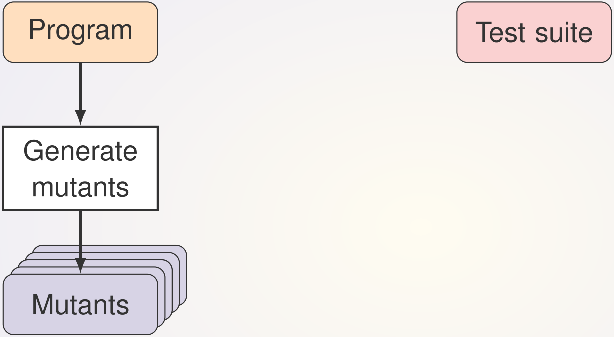
Mutation analysis: systematically seed artificial faults

Mutation analysis overview

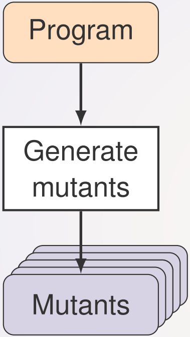
Program

Test suite

Mutation analysis overview



Mutation analysis overview



Program

Generate mutants

Mutants

```
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;
}
```

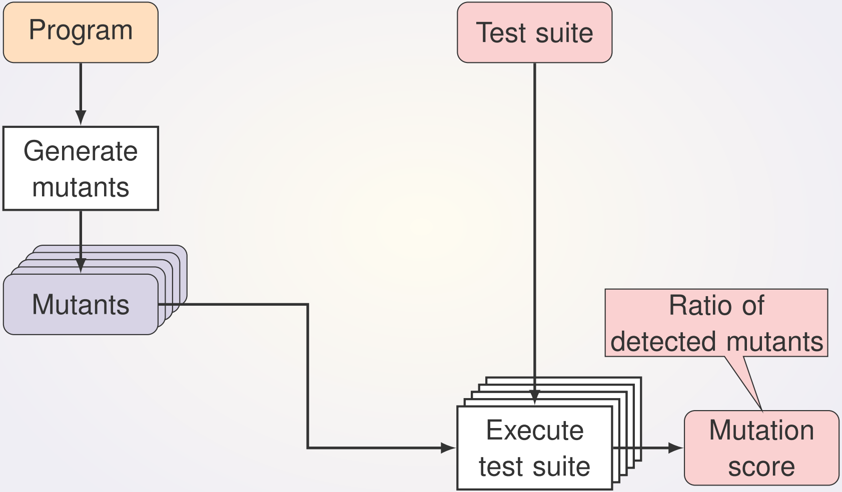
Mutant 1

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

Mutant 2

Each mutant contains a small syntactic change

Mutation analysis overview



Program

Generate mutants

Mutants

Test suite

Execute test suite

Ratio of detected mutants

Mutation score

Where is the catch?

Many mutants can be generated!

```
a > b ?  a :  b
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Many mutants can be generated!

```
a > b ?  a :  b
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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!

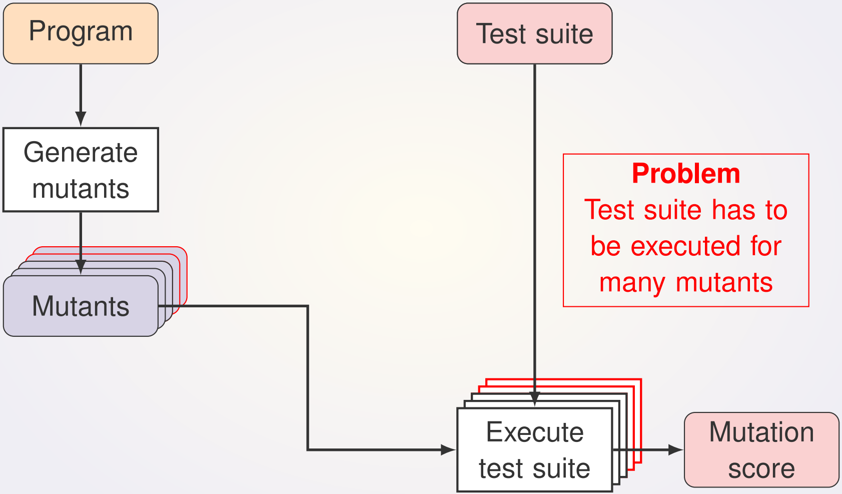
```
a > b ? a : b
```

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

```
0 > b ? a : b
a > 0 ? a : b
a > b ? 0 : b
a > b ? a : 0
0
b > a ? a : b
a > b ? b : a
```

```
-a > b ?  a : b
 a >-b ?  a : b
 a > b ? -a : b
 a > b ?  a :-b
 a > b ?  a :-b
-(a > b ?  a : b)
 a
 b
```

Mutation analysis overview



Problem
Test suite has to be executed for many mutants

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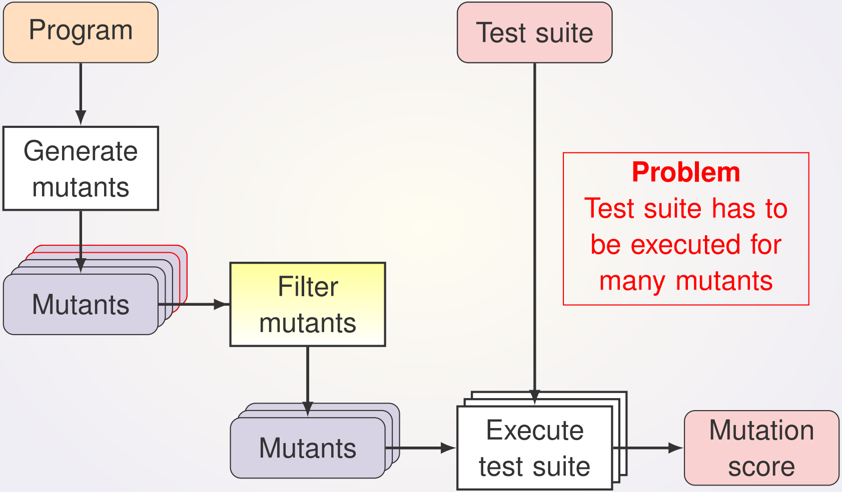

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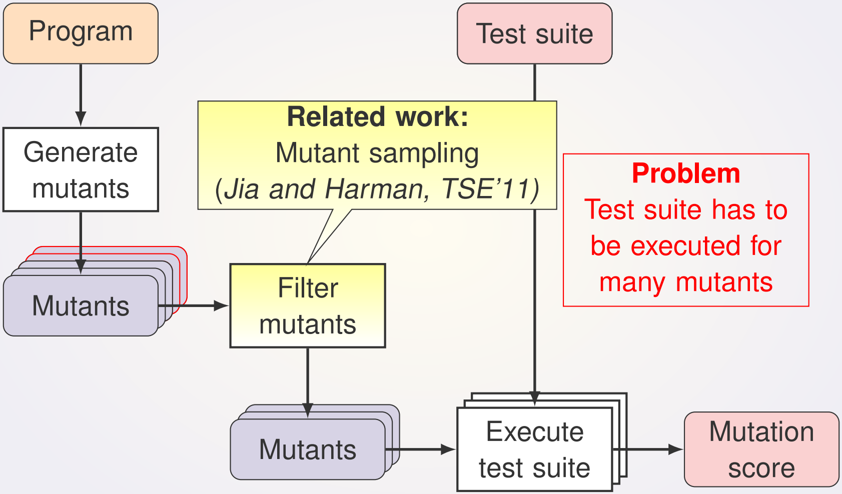

Program

Generate mutants

Mutants

Test suite

Related work:
Mutant sampling
(Jia and Harman, TSE'11)

Filter mutants

Mutants

Execute test suite

Mutation score

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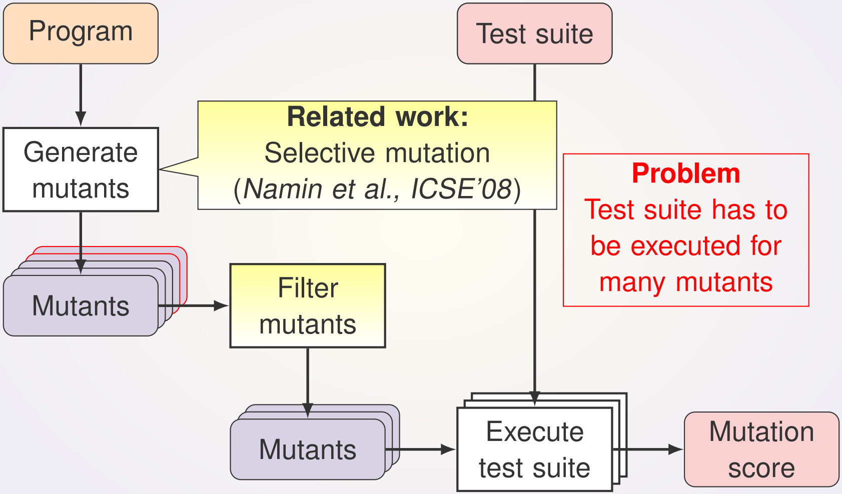

Related work:
Selective mutation
(*Namin et al., ICSE'08*)

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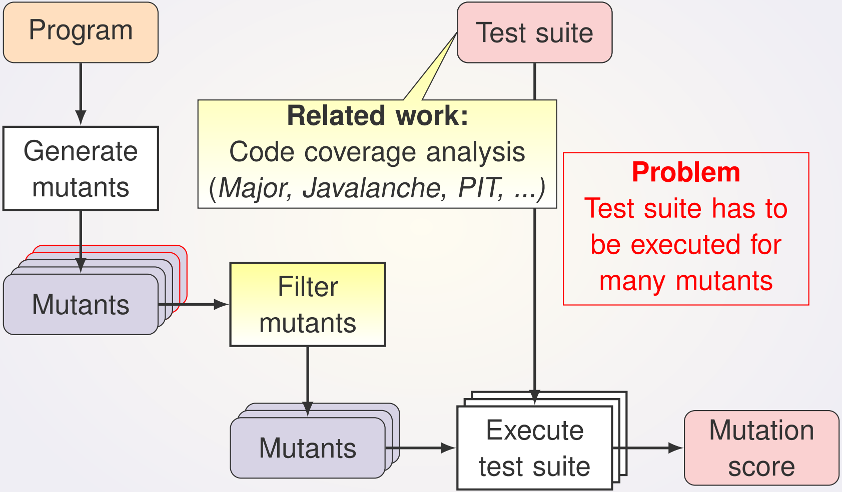

Related work:
Code coverage analysis
(*Major, Javalanche, PIT, ...*)

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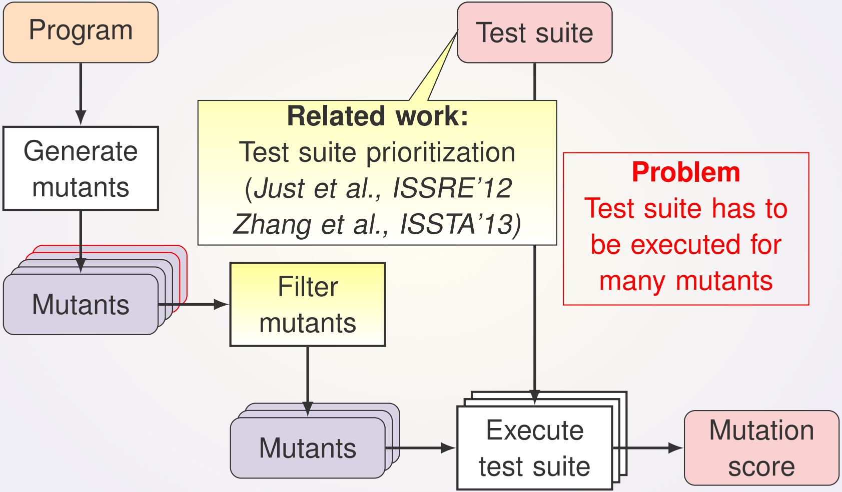

Related work:
Test suite prioritization
(*Just et al., ISSRE'12*
Zhang et al., ISSTA'13)

Problem
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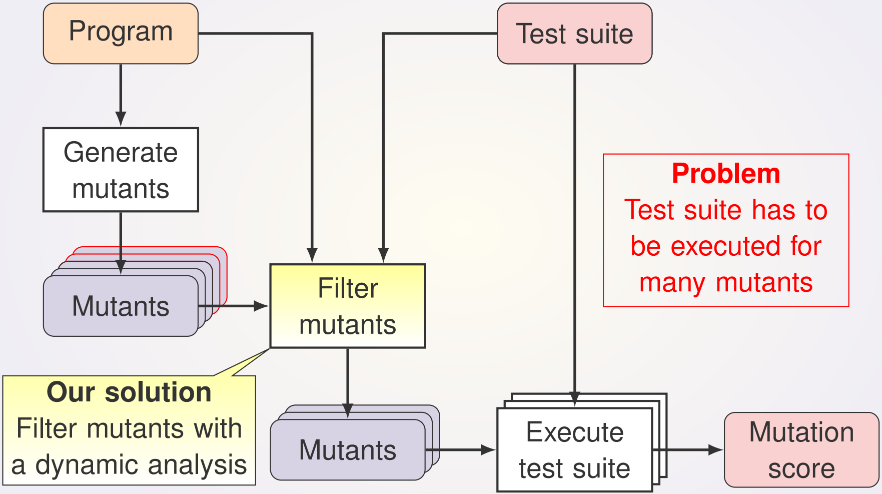
Mutation analysis overview



Problem
Test suite has to be executed for many mutants

Our solution
Filter mutants with a dynamic analysis

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

Wasted effort in mutation analysis

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Mutant 1

Wasted effort in mutation analysis

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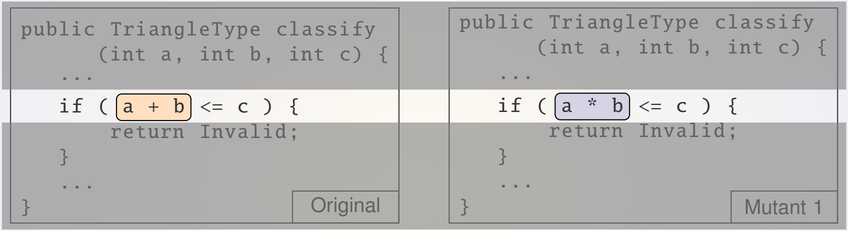

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}
```

Mutant 1

Identical code surrounding mutation

Wasted effort in mutation analysis

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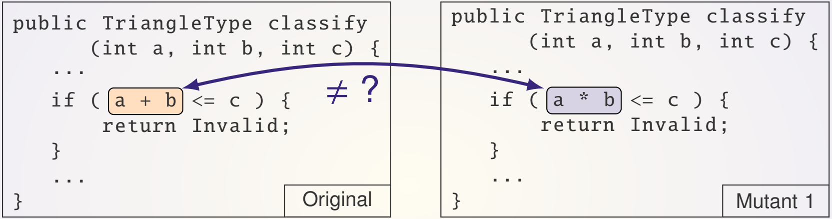

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Optimizations:

- Infection

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Mutant 1

Optimizations:

- Infection
- Propagation

Wasted effort in mutation analysis

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}
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Original

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

Mutant 1

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

Mutant 2

Optimizations:

- Infection
- Propagation

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

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

Mutant 1

= ?

```
public TriangleType classify
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Mutant 2

Optimizations:

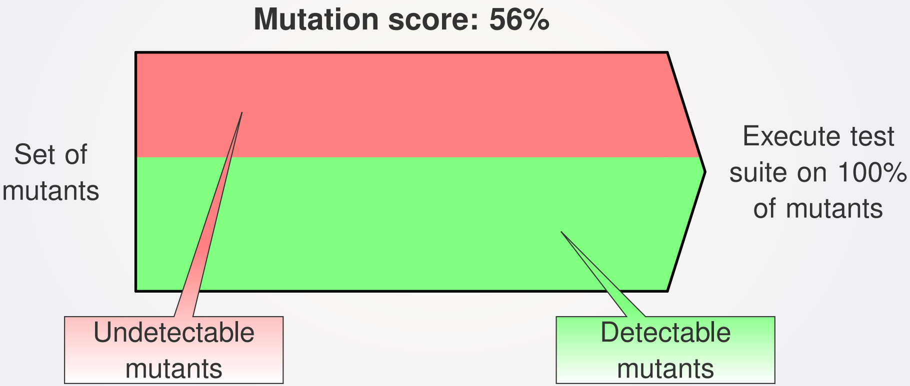
- Infection
- Propagation
- Partitioning

The big picture

Set of mutants

Execute test suite on 100% of mutants

The big picture



Mutation score: 56%

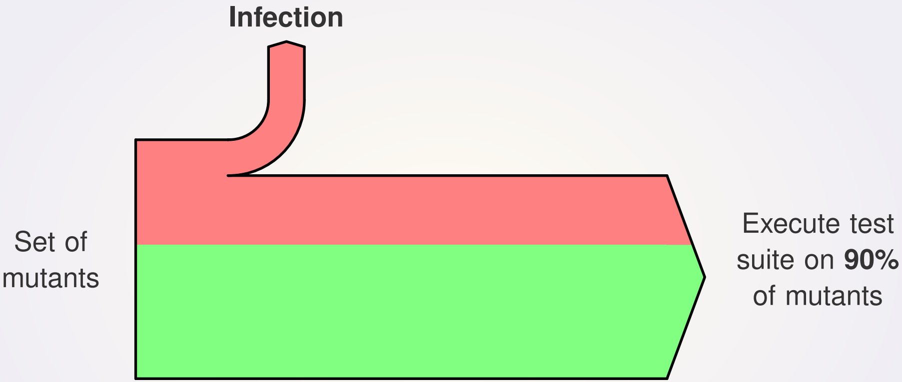
Set of mutants

Execute test suite on 100% of mutants

Undetectable mutants

Detectable mutants

The big picture



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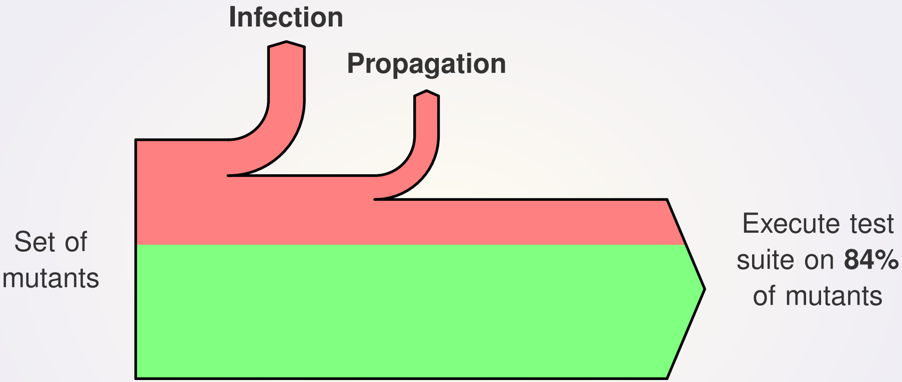

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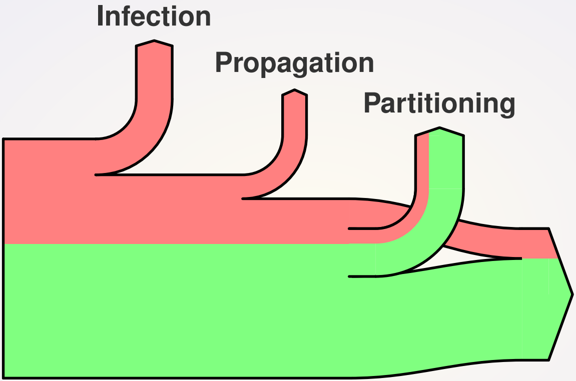
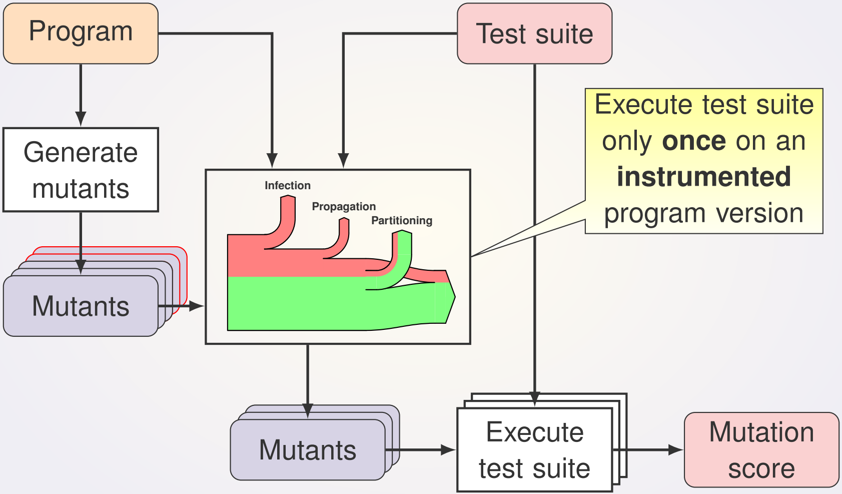


Set of mutants

Execute test suite on **70%** of mutants

Dynamic analysis to filter mutants



Execute test suite only **once** on an **instrumented** program version

Infection

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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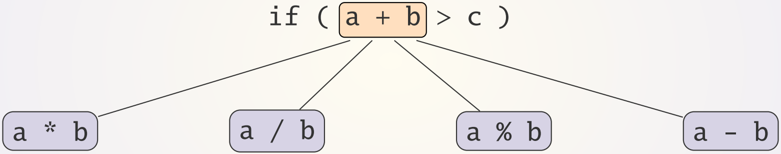

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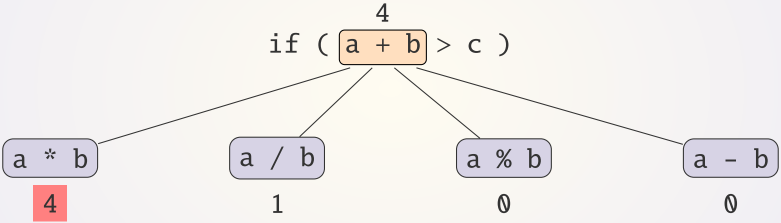

Optimization

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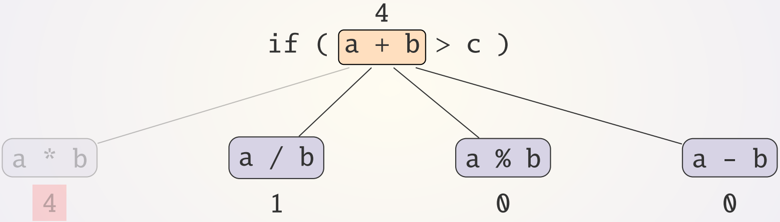

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Propagation

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

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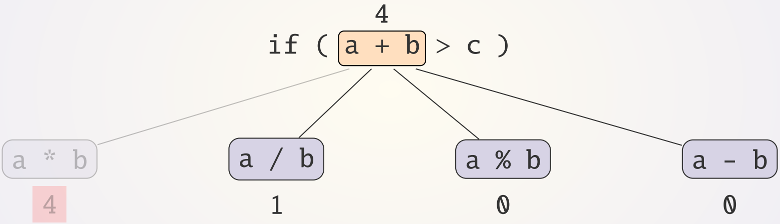

4

`if ( a + b > c )`

`a * b` `a / b` `a % b` `a - b`

4 1 0 0

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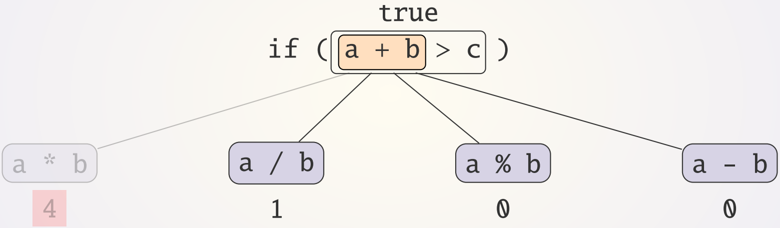

`true`

`if ( a + b > c )`

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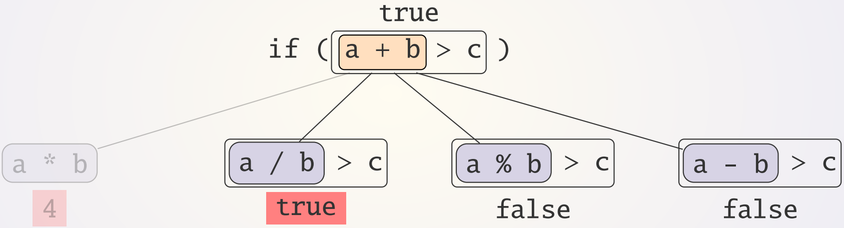

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`a * b`

`4`

`a / b > c`

`true`

`a % b > c`

`false`

`a - b > c`

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Optimization

- Propagate infected execution states in composed expressions
- Filter mutants whose infected state does not propagate

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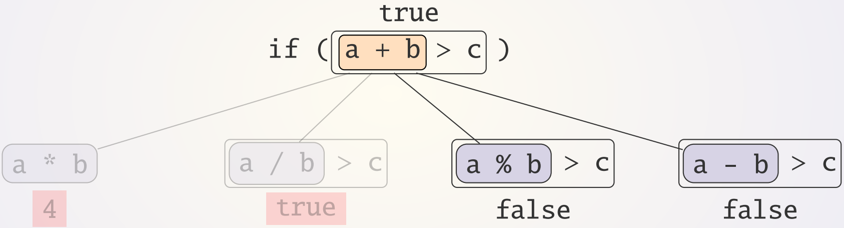

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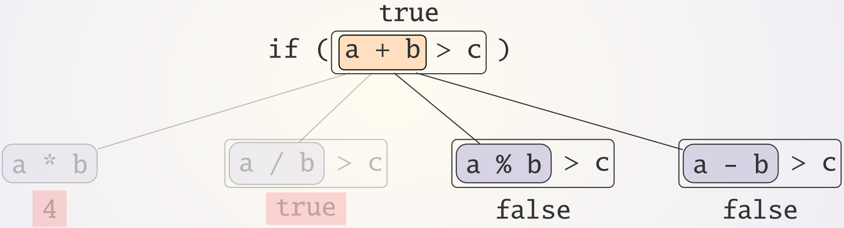
Partitioning

Build partition of identically infected execution states.

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



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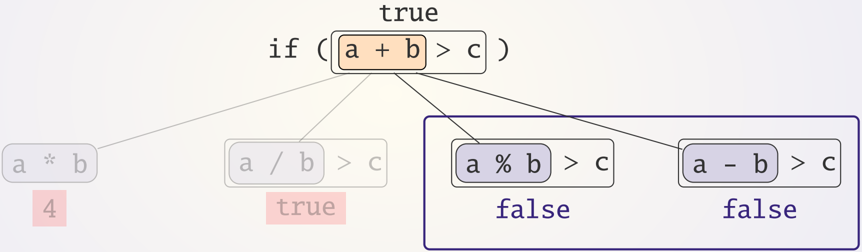

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- **Partition** mutants based on their expression values
- Only execute a test for one mutant per **partition cell**

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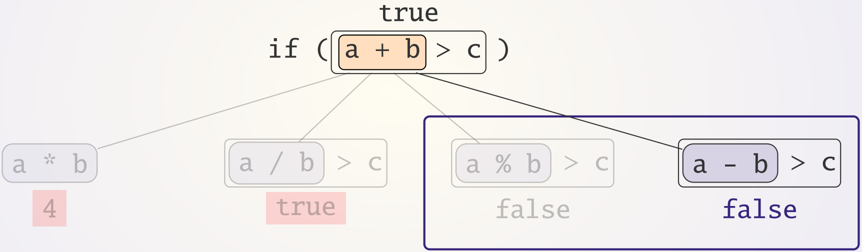

true

`if ( a + b > c )`

`a * b`

4

`a / b > c`

true

`a % b > c`

false

`a - b > c`

false

Optimization

- **Partition** mutants based on their expression values
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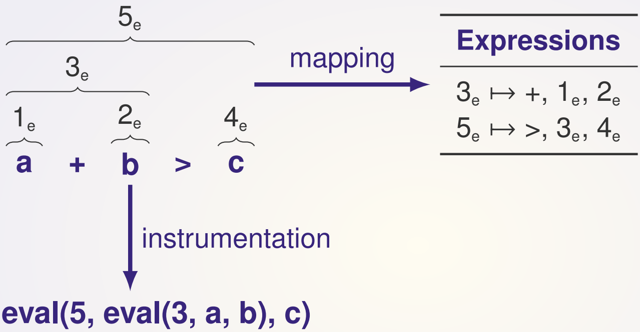
Implementation details

a + b > c

Implementation details

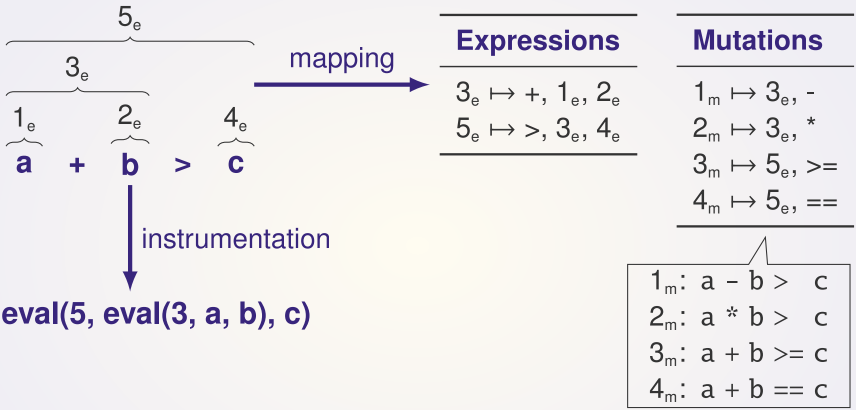


$$\overbrace{\overbrace{\overbrace{\mathbf{a}}^{1_e} + \overbrace{\mathbf{b}}^{2_e}}^{3_e} > \overbrace{\mathbf{c}}^{4_e}}^{5_e} \xrightarrow{\text{mapping}}$$

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

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

Implementation details



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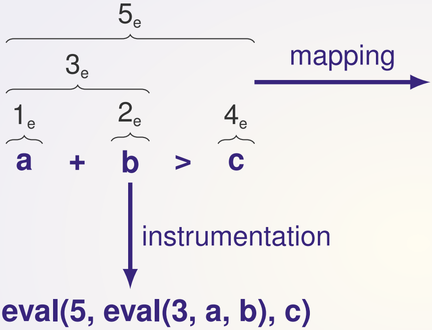
Mutations
$1_m \mapsto 3_e$, -
$2_m \mapsto 3_e$, *
$3_m \mapsto 5_e$, >=
$4_m \mapsto 5_e$, ==

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

Implementation details



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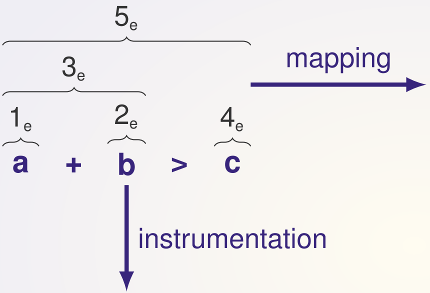
Example: a=2, b=2, c=1

InfectedValues

Implementation details



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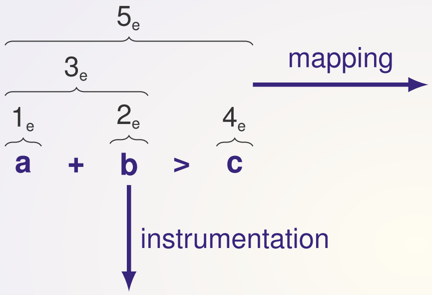
eval(5, eval(3, a, b), c)

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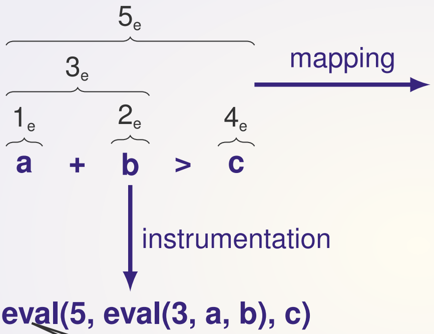
3_e: a + b = 4
1_m: a - b = 0

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

InfectedValues
1_m: 0

Implementation details



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

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

5_e: 4 > c = true

3_m: 4 >= c = true

4_m: 4 == c = false

Expressions

$3_e \mapsto +, 1_e, 2_e$

$5_e \mapsto >, 3_e, 4_e$

Mutations

$1_m \mapsto 3_e$, -

$2_m \mapsto 3_e$, *

$3_m \mapsto 5_e$, >=

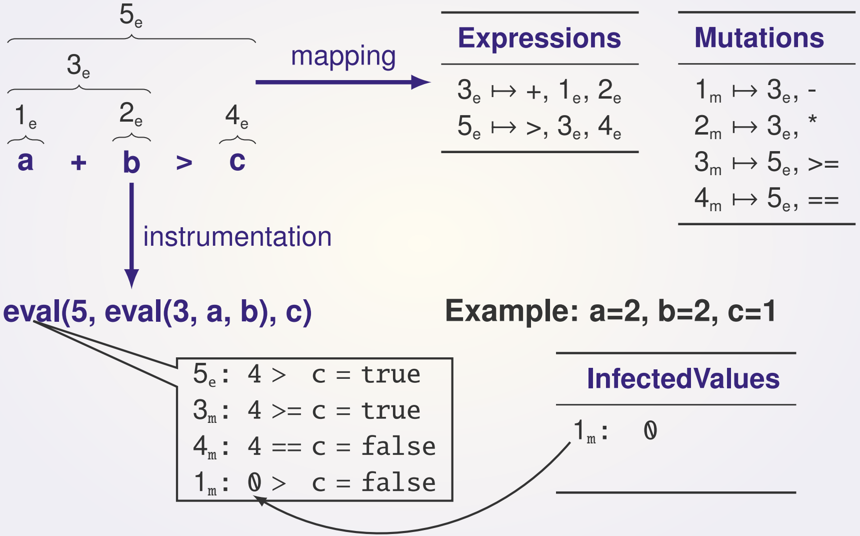
$4_m \mapsto 5_e$, ==

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

InfectedValues

1_m: 0

Implementation details



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mapping

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instrumentation

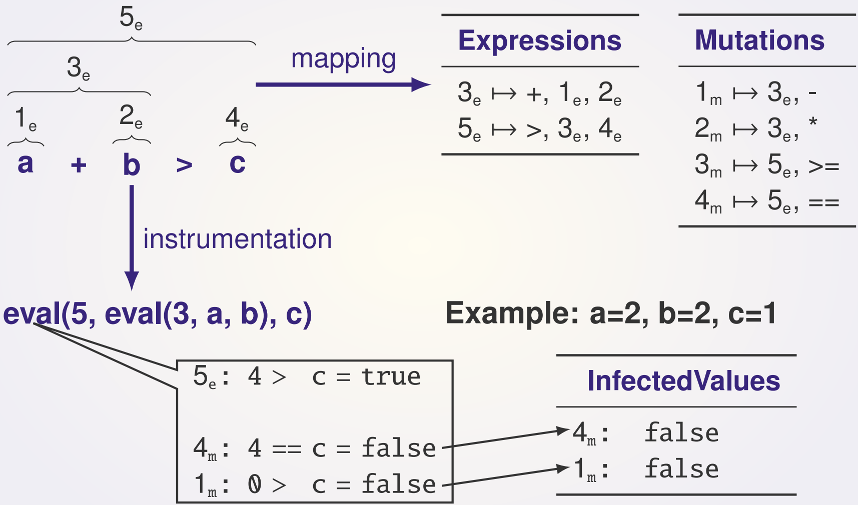
eval(5, eval(3, a, b), c)

```
5e: 4 >  c = true
3m: 4 >= c = true
4m: 4 == c = false
1m: 0 >  c = false
```

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

InfectedValues
`1m:  0`

Implementation details



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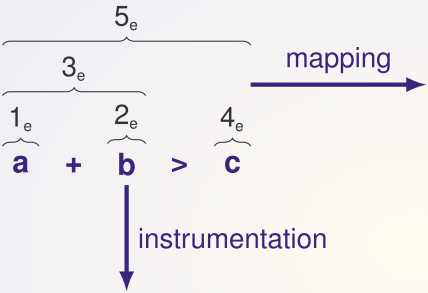
Example: a=2, b=2, c=1

InfectedValues
4_m: false
1_m: false

Implementation details



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

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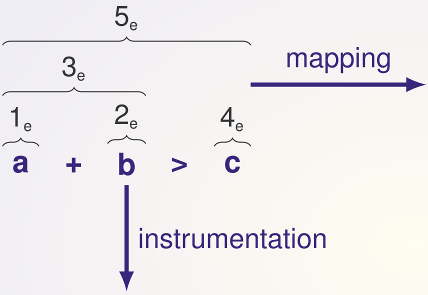
Implementation details



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

InfectedValues
4_m: `false`
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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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  - Weak-mutation
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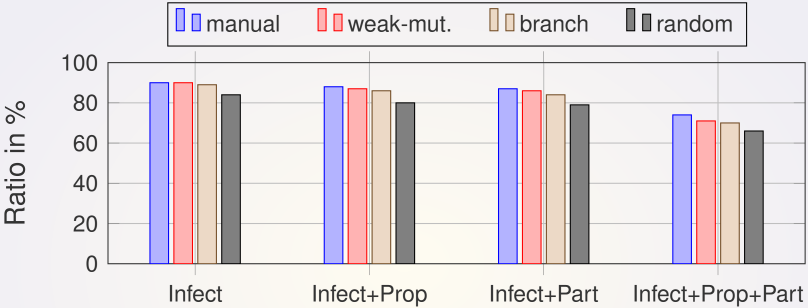
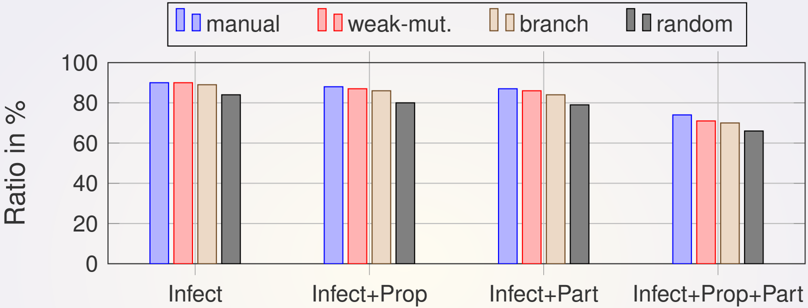
Coverage optimization is baseline

Ratio of analyzed mutants



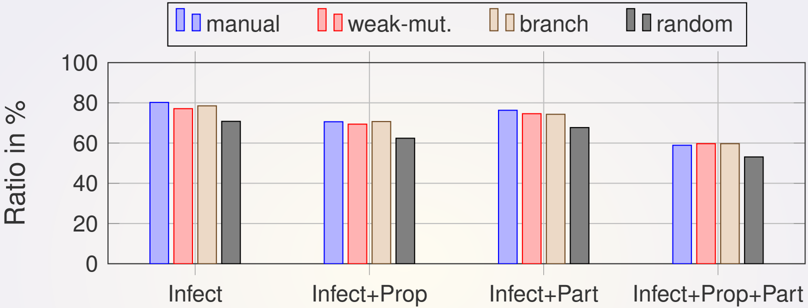
Ratio of analyzed mutants



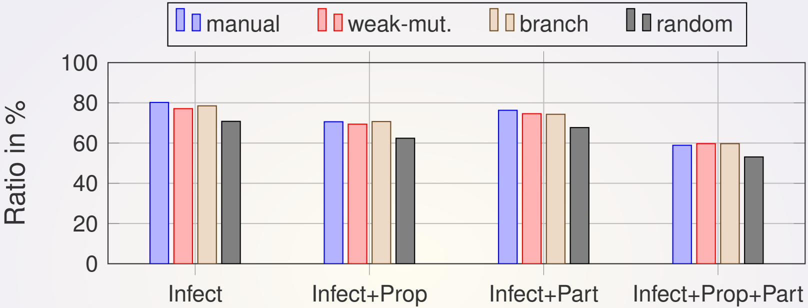
Findings

- 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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Equivalent mutant detection

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

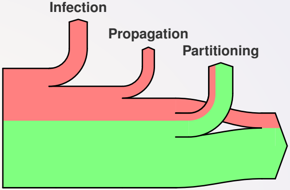
Test generation

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

Contributions

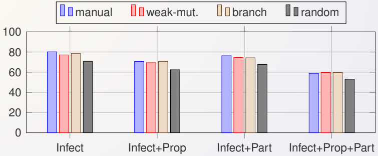
Dynamic prepass analysis

- 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