Luxembourg National Research Fund

Killing Stubborn Mutants with Symbolic Execution

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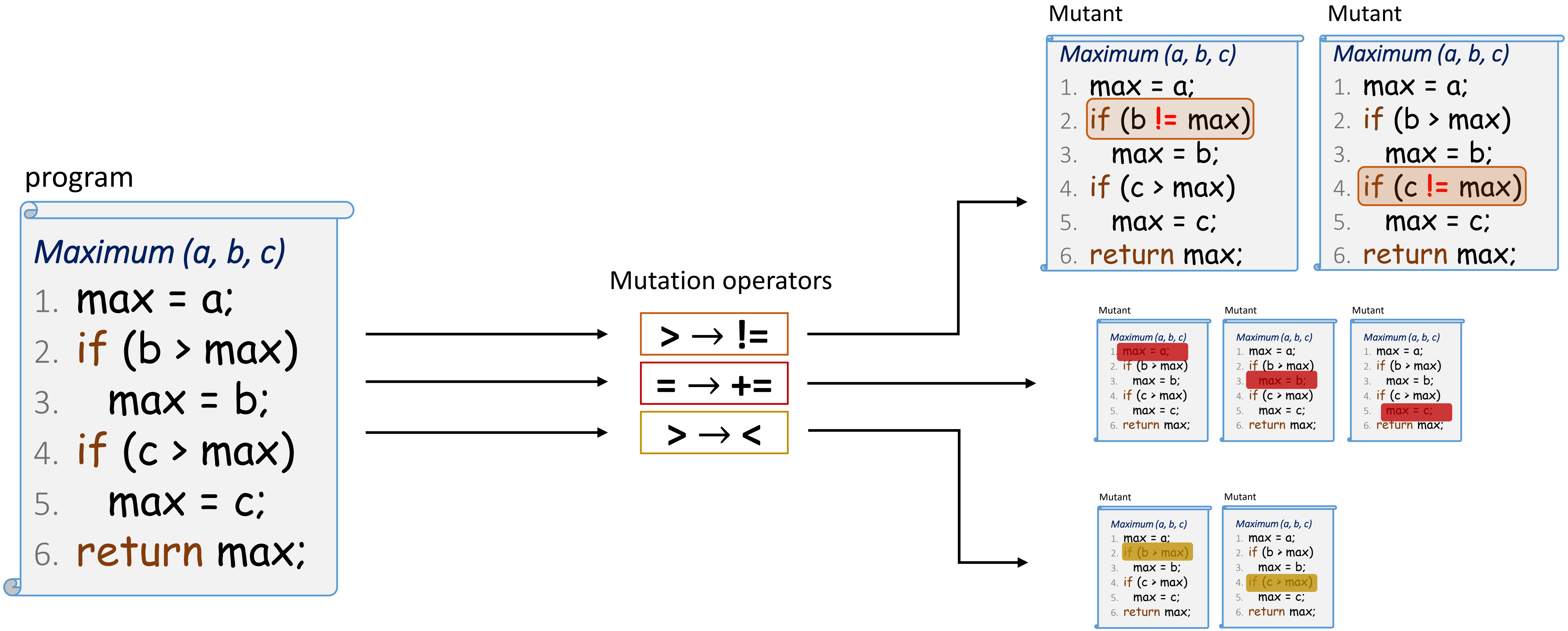
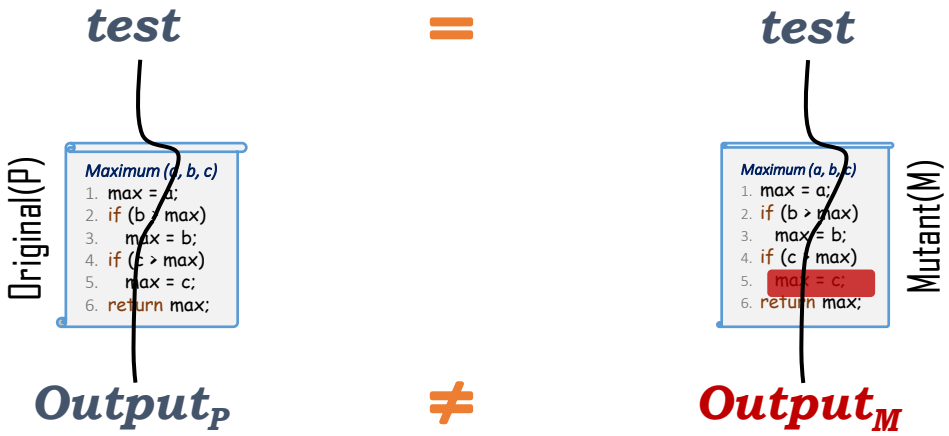
KLEE Workshop 2021

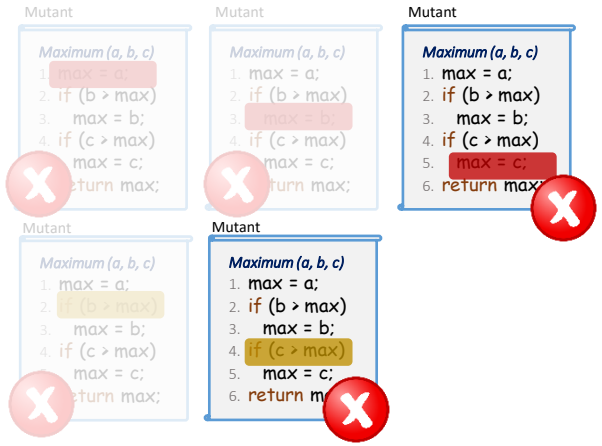
Mutation


program
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;
Mutation operators
> → !=
= → +=
> → <
Mutant
Maximum (a, b, c)
1. max = a;
2. if (b != max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;
Mutant
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c != max)
5. max = c;
6. return max;
Mutant
Mutant
Mutant
Mutant
Mutant

Mutation


test
=
test
Original(P)
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;
Mutant(M)
Output_P
≠
Output_M


Existing
Test suite
Generated
tests


Mutant
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;
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Maximum (a, b, c)
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4. if (c > max)
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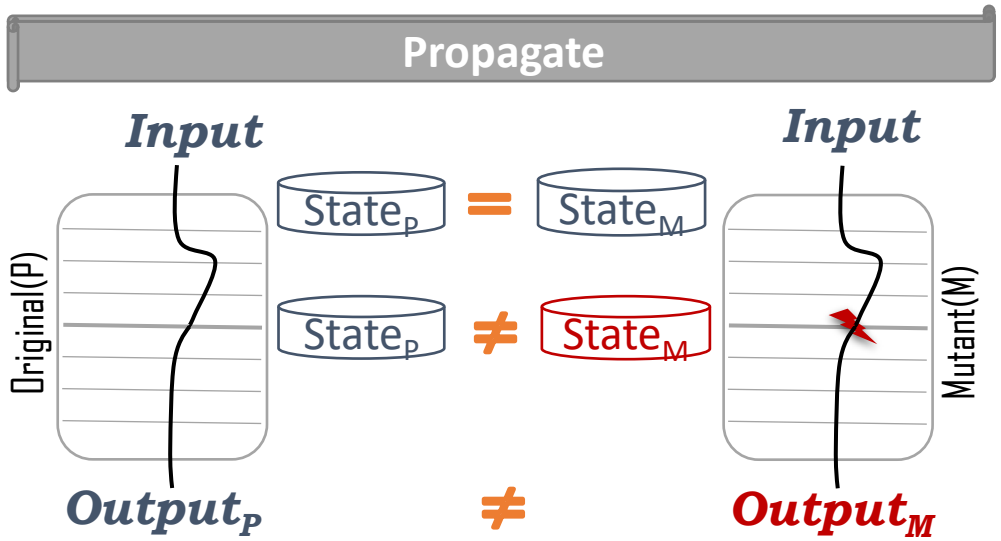
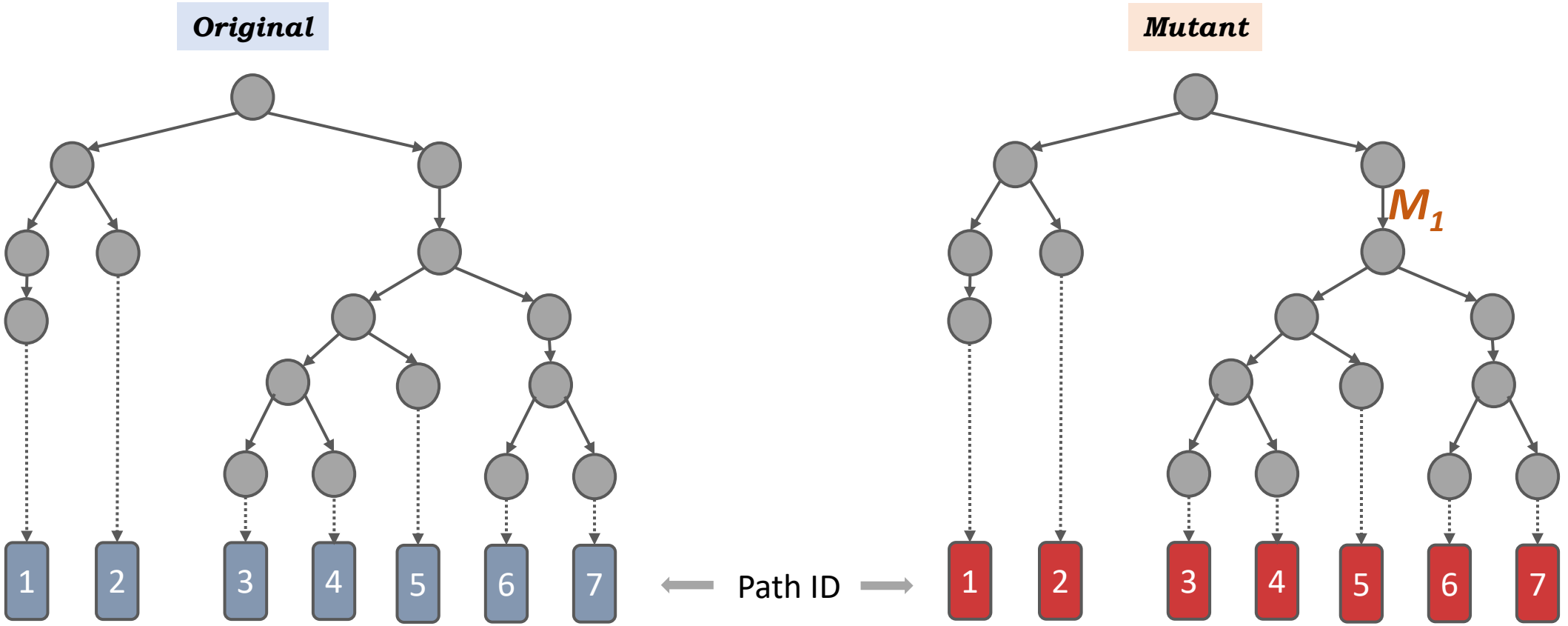
Mutant
Maximum (a, b, c)
1. max = a;
2. if (b > max)
3. max = b;
4. if (c > max)
5. max = c;
6. return max;

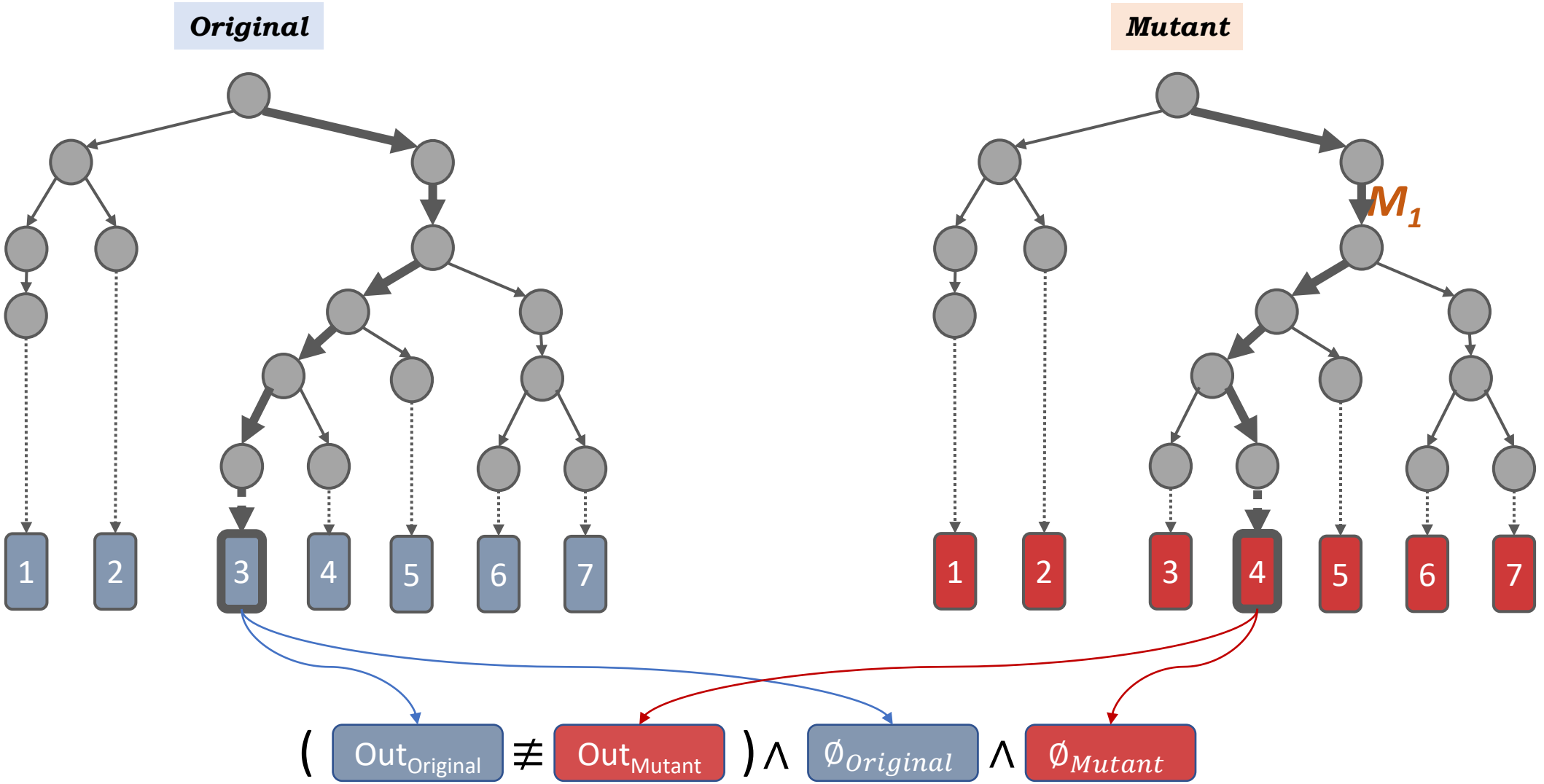
Mutant Killing



Symbolic Mutant Test Generation

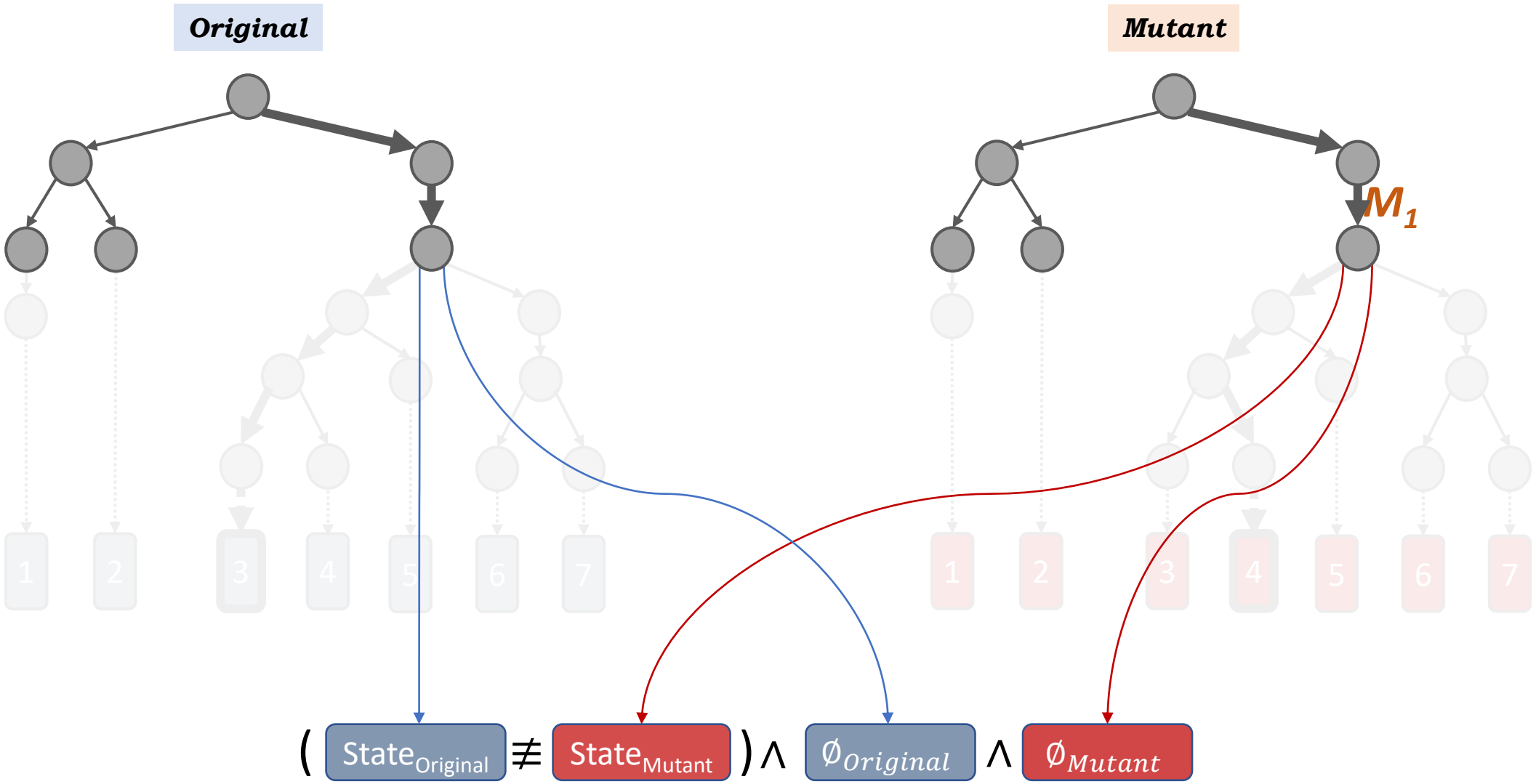


Symbolic Mutant Test Generation



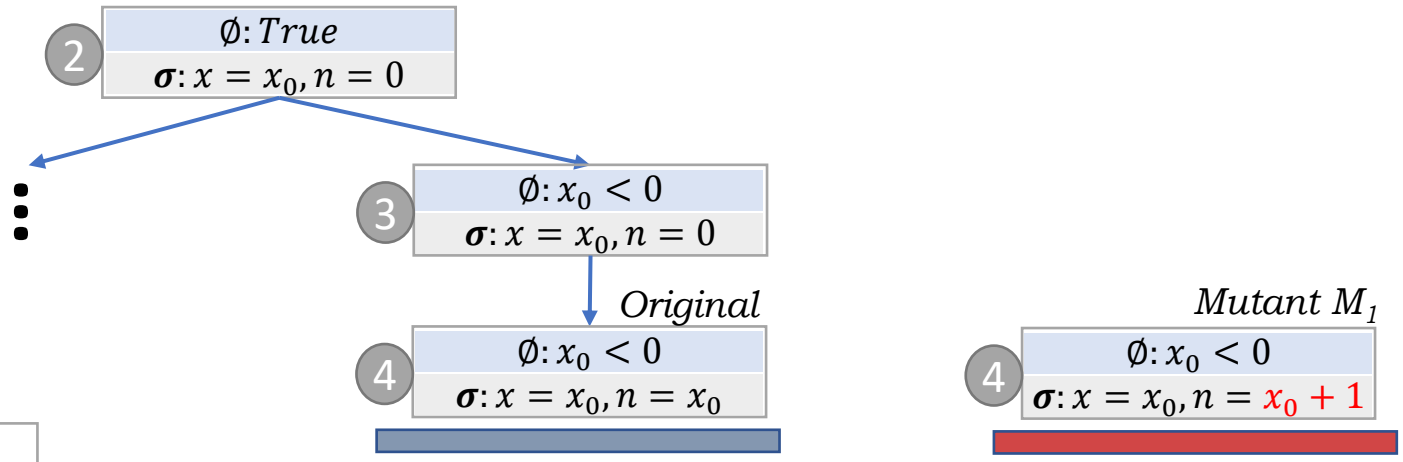
Symbolic Mutant Test Generation

Infect-only



Symbolic Mutant Test Generation

Infect-only



Program

```
int func (int x) {
1.   int n = 0;
2.   if (x < 0) {
3.       n = x; // M1 (n = x + 1;)
4.       if (n)
5.           n++;
     }
7.   return n;
}
```

The mutant M_1 is **not** killed by the test

$$(\ State_{Original} \not\equiv State_{Mutant}\ ) \wedge \emptyset_{Original} \wedge \emptyset_{Mutant}$$

$$(\ x_0 \neq x_0 + 1\ ) \wedge x_0 < 0 \wedge x_0 < 0$$

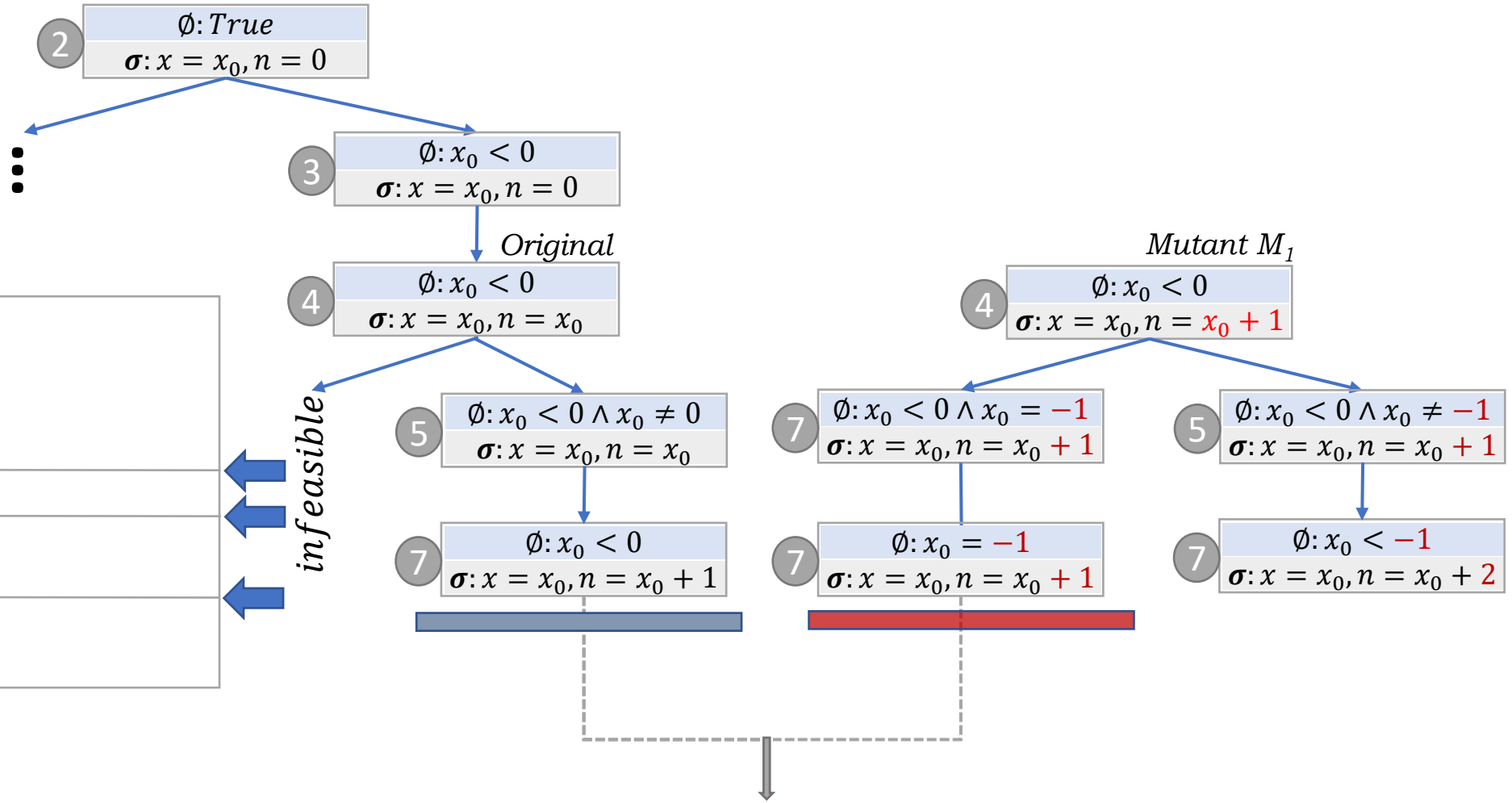
Z3 solver

$$x_0 = -1$$

$$Out_{Original} = 0$$
$$Out_{Mutant} = 0$$

Symbolic Mutant Test Generation

SEMu



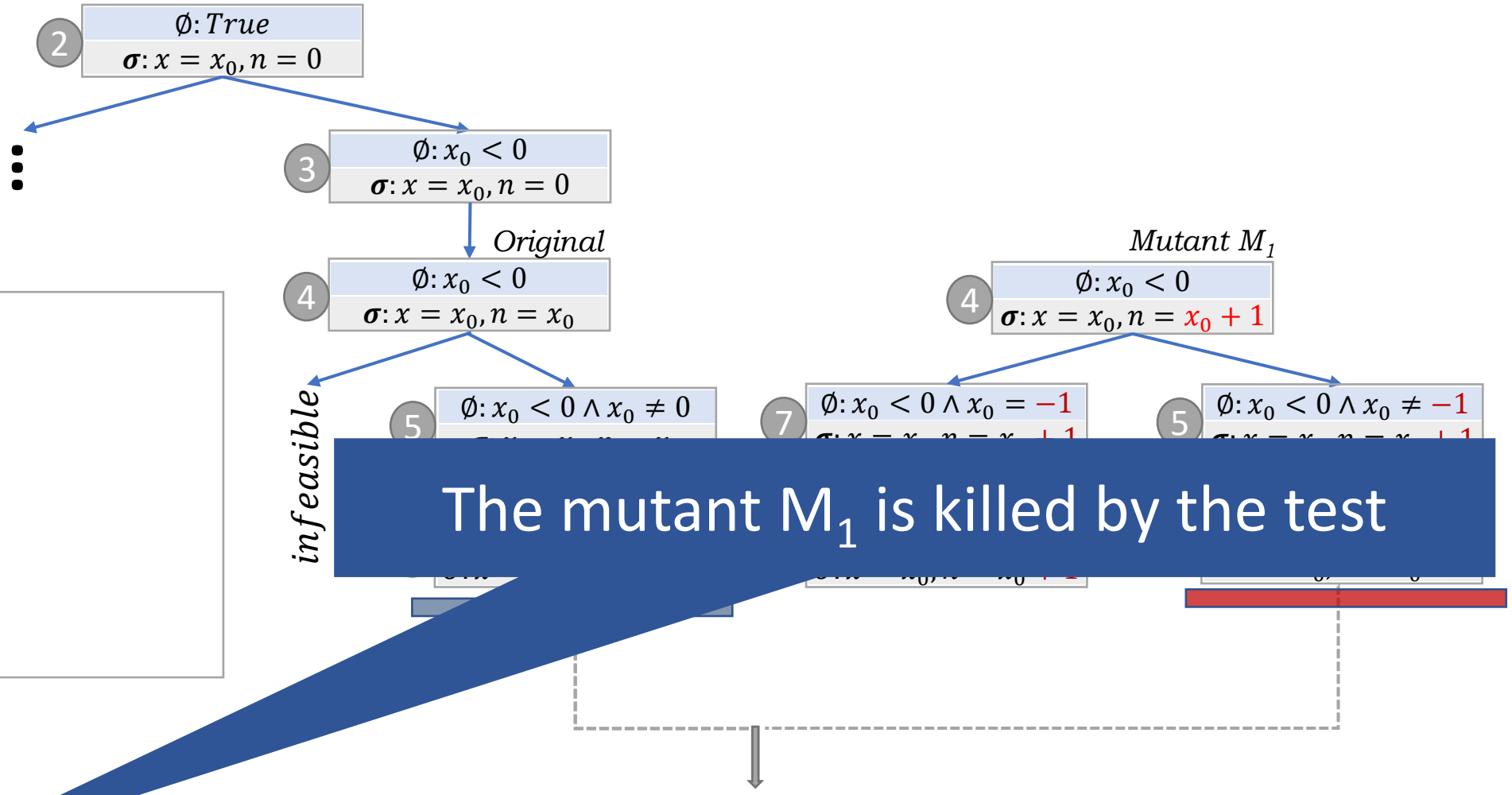
Program

```
int func (int x) {
1.   int n = 0;
2.   if (x < 0) {
3.       n = x; // M1 (n = x + 1;)
4.       if (n)
5.           n++;
     }
7.   return n;
}
```

$Infeasible$ ← *Z3 solver* $(x_0 + 1 \neq x_0 + 1) \wedge x_0 < 0 \wedge x_0 = -1$

Symbolic Mutant Test Generation

SEMu



Program

```
int func (int x) {
1.   int n = 0;
2.   if (x < 0) {
3.       n = x; // M1 (n = x + 1;)
4.       if (n)
5.           n++;
     }
7.   return n;
}
```

The mutant M_1 is killed by the test

$Out_{Original} = -1$
$Out_{Mutant} = 0$

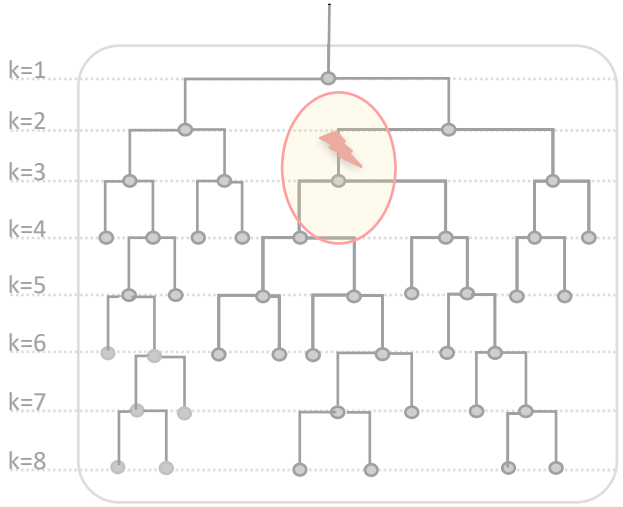
$x_0 = -2$ ← *Z3 solver*

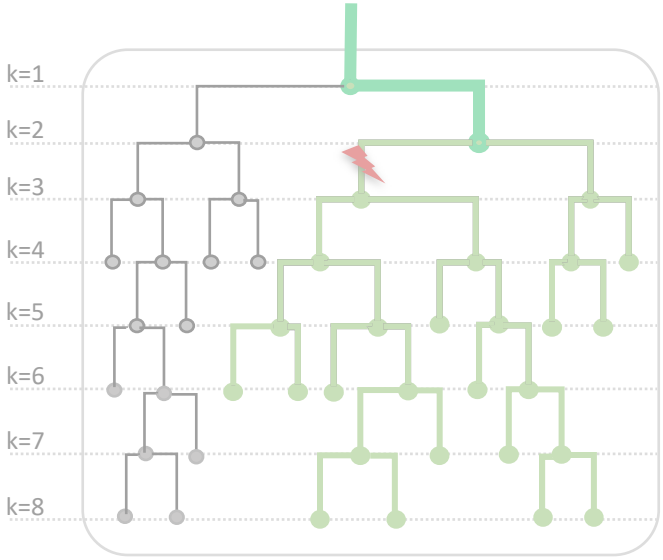
$(\ x_0 + 1 \neq x_0 + 2\ ) \wedge x_0 < 0 \wedge x_0 < -1$

SEMu

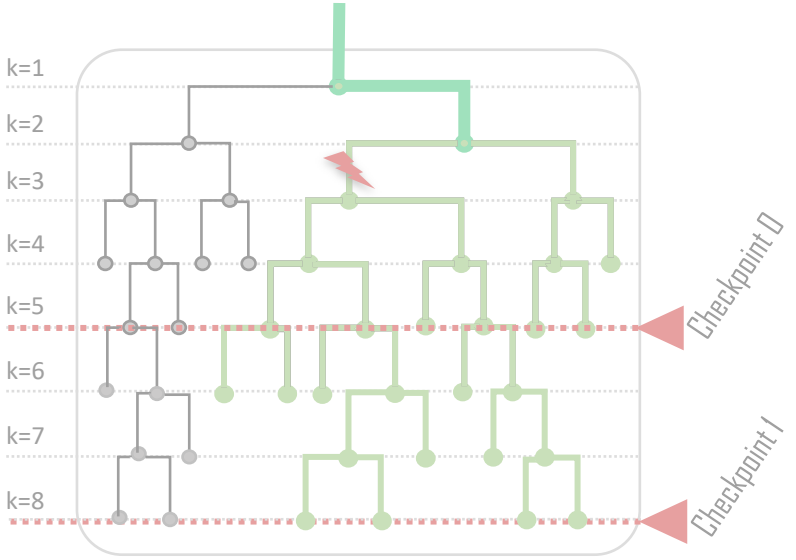
***SEMu* implements heuristics that enable scalable and deeper mutant-error propagation**

SEMu Cost-control Heuristics

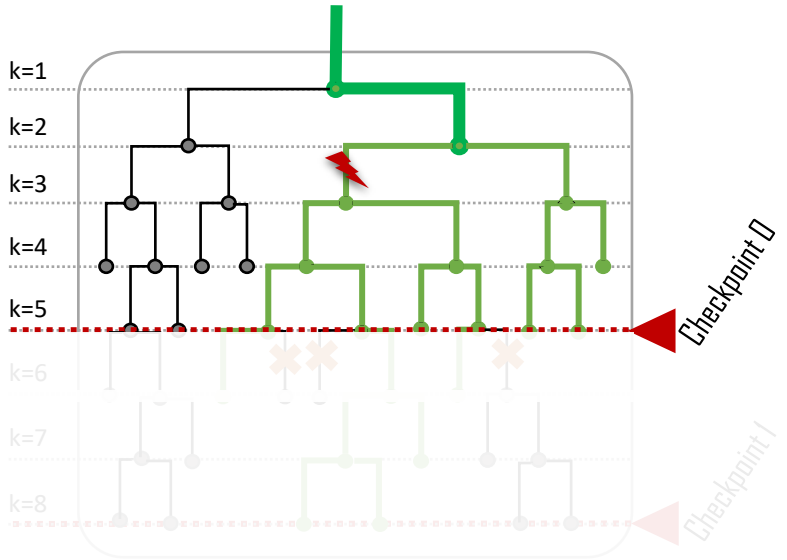




(a)



(b)

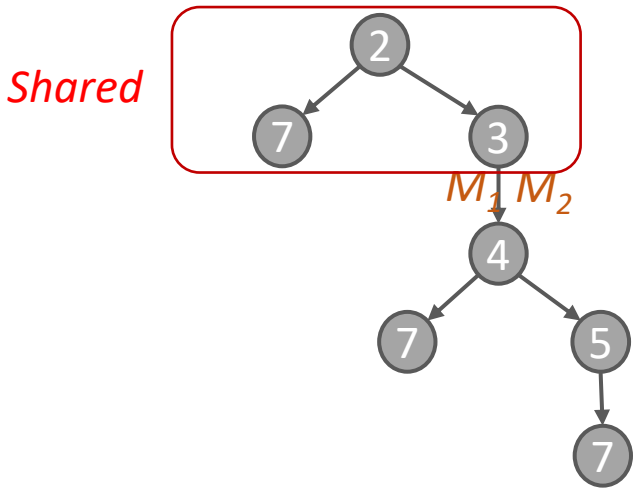


(c)

Completeness Preserving Optimizations

Program

```
int func (int x) {
1.   int n = 0;
2.   if (x < 0) {
3.       n = x; // M1 (n = x + 1;) M2 (n += x;)
4.       if (n)
5.           n++;
     }
7.   return n;
}
```



Meta-mutant Program

```
unsigned MUTANT_ID;
int func (int x) {
1.   int n = 0;
2.   if (x < 0) {
3.       switch(MUTANT_ID){
           case 1: n = x + 1; break;
           case 2: n += x; break;
           default: n = x;
         }
4.       if (n)
5.           n++;
     }
7.   return n;
}
```

Implementation

SEMu **is implemented on KLEE**

Our implementation added/modified more than 8,000 lines of code.

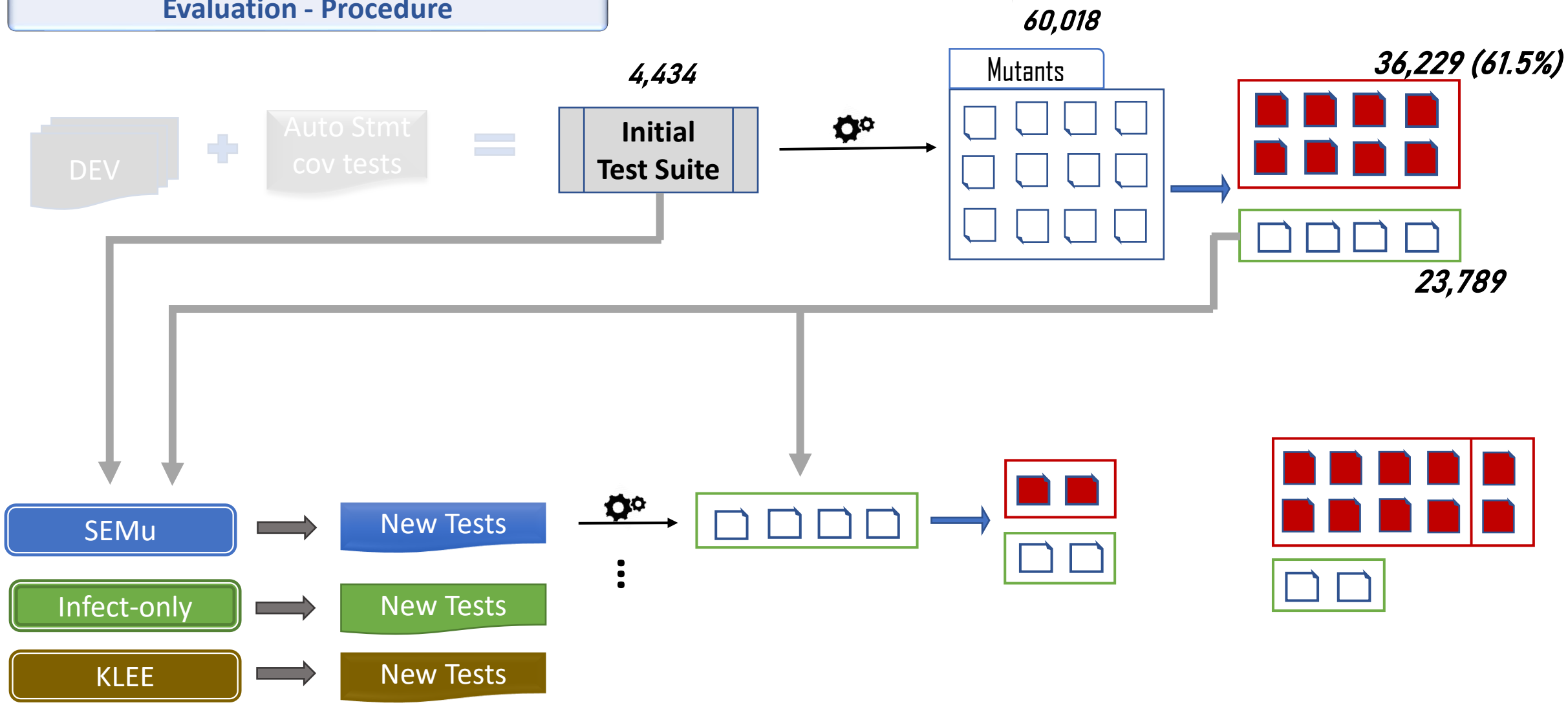
https://github.com/thierry-tct/KLEE-SEMu

Evaluation

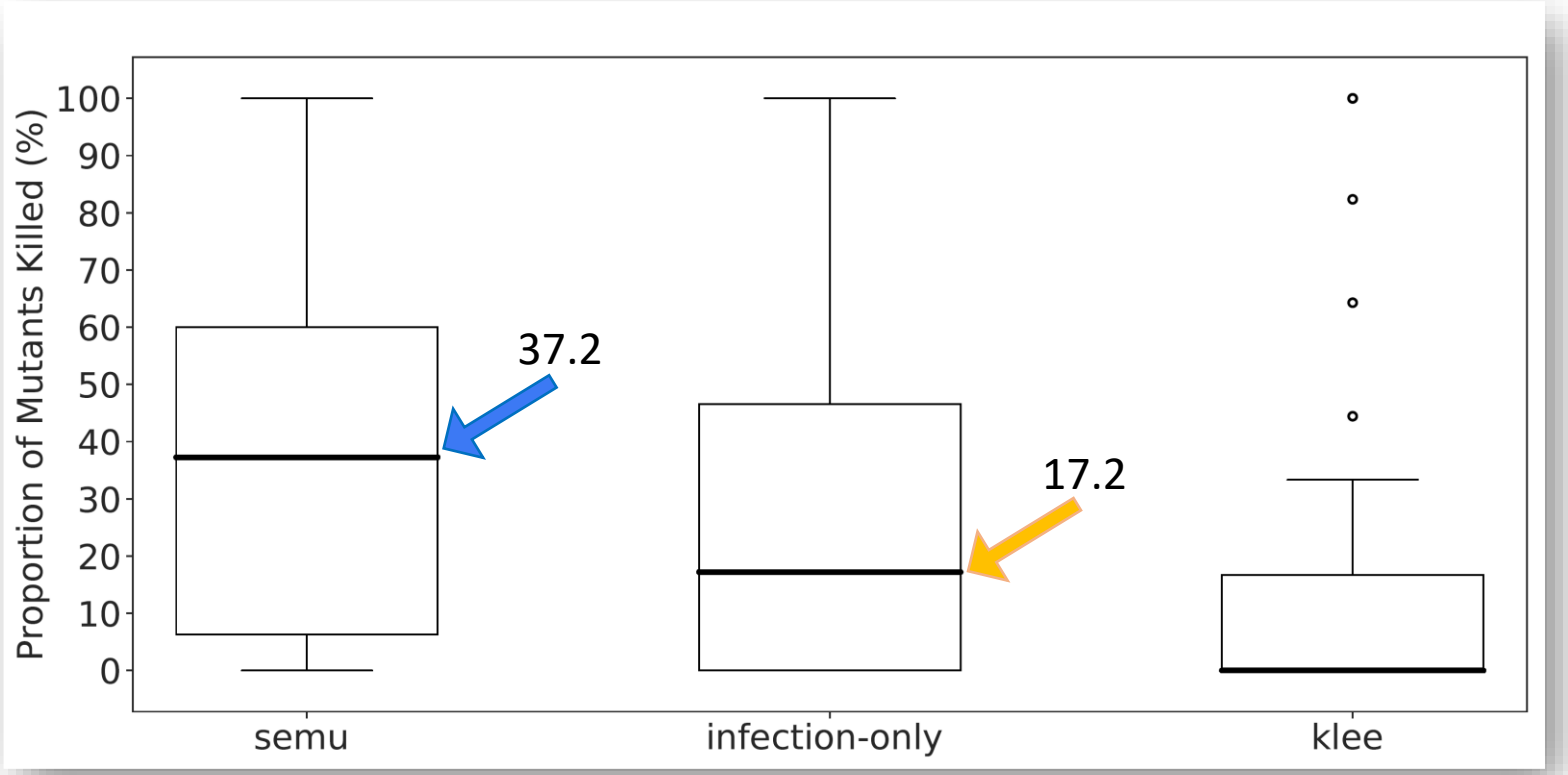
We evaluate *SEMu* and compare with KLEE and the state-of-the-art-approach (*infect-only*)

Subjects: **36** Programs from GNU Coreutils

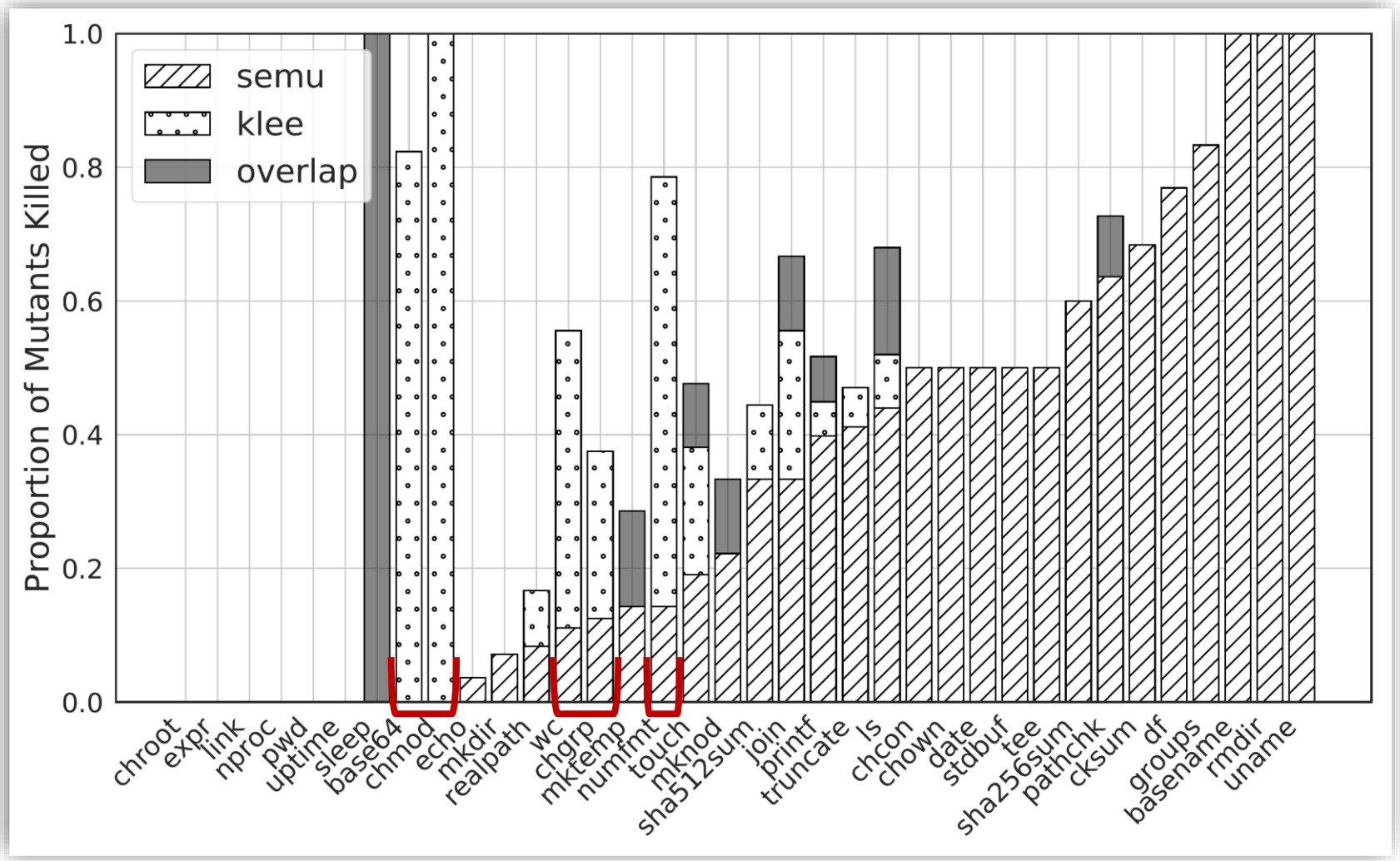
Evaluation - Procedure



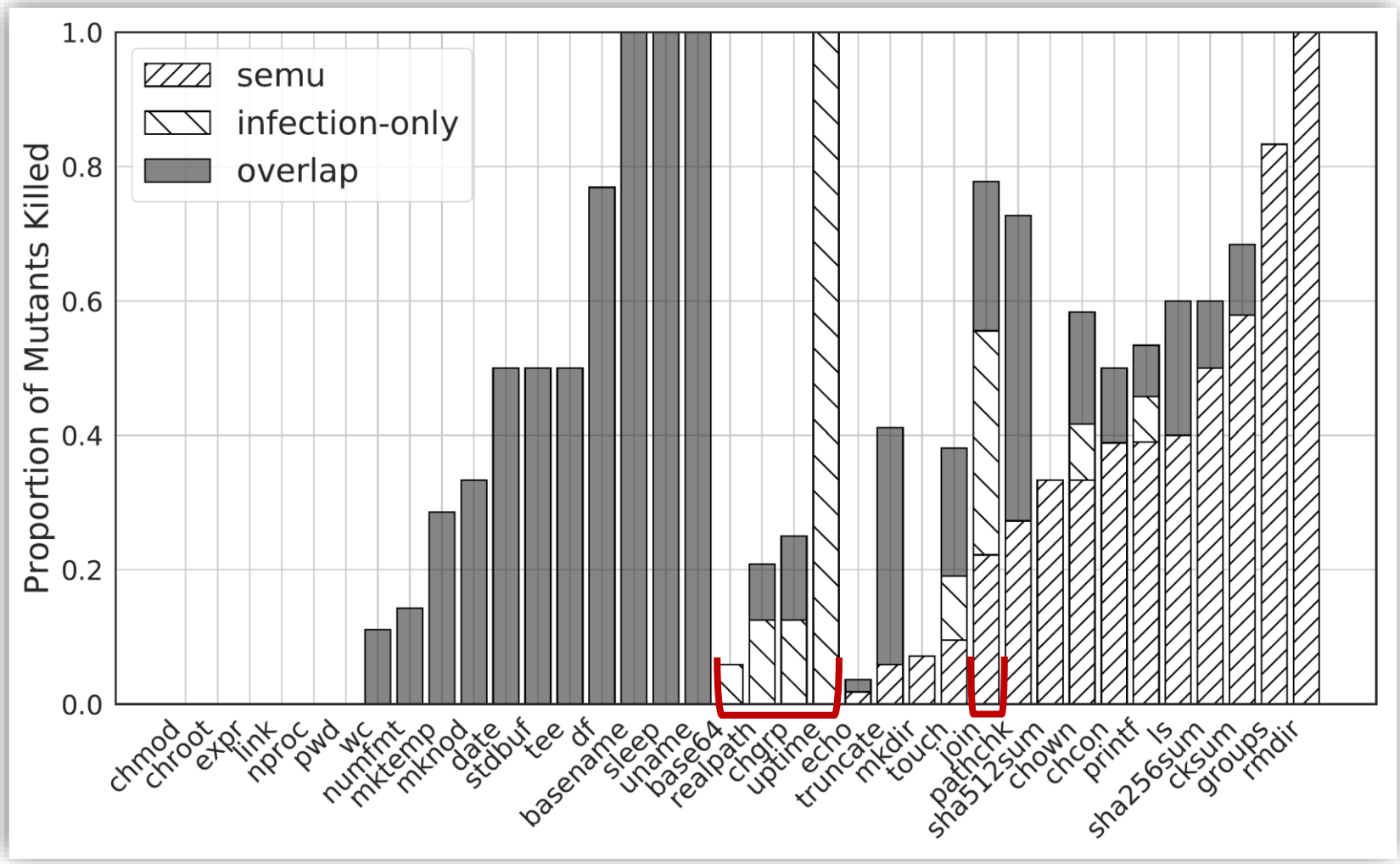
Evaluation - Results



Evaluation - Results



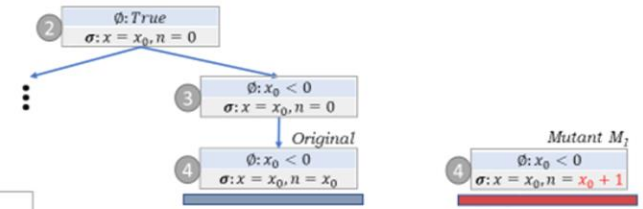
Evaluation - Results



Mutation

Symbolic Mutant Test Generation

Infect-only



Program

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2.  if (x < 0) {
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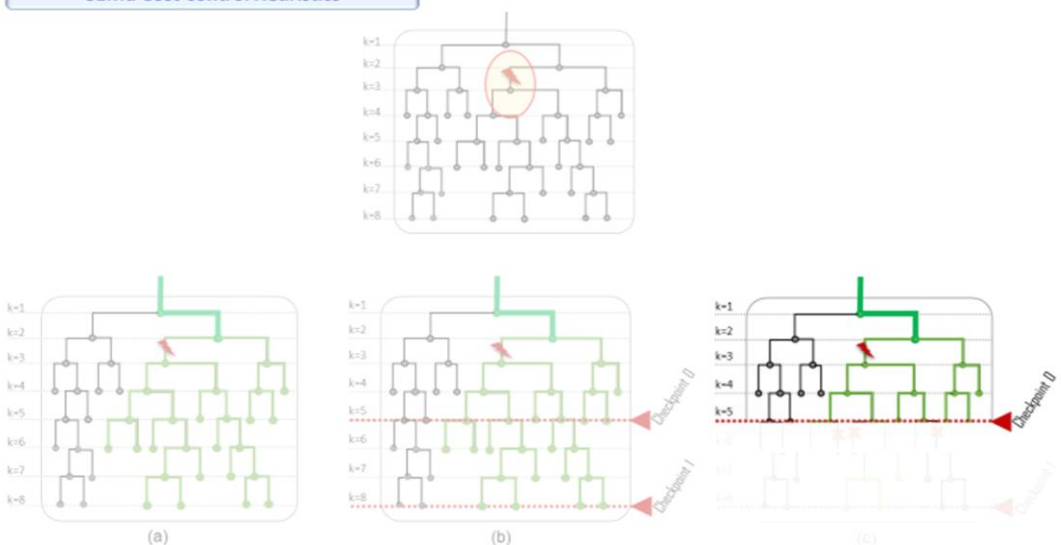
4.      if (n)
5.          n++;
    }
7.  return n;
}
```

The mutant M_1 is **not** killed by the test

$$(State_{Original} \not\equiv State_{Mutant}) \wedge \emptyset_{Original} \wedge \emptyset_{Mutant}$$

$$Out_{Original} = 0 \quad Out_{Mutant} = 0 \quad x_0 = -1 \quad \text{Z3 solver} \quad (x_0 \neq x_0 + 1) \wedge x_0 < 0 \wedge x_0 < 0$$

SEMu Cost-control Heuristics



Evaluation - Results