Practical Techniques for Improving the Efficiency and Usability of Mutation Analysis for Java Programs

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† Joint with René Just and Franz Schweiggert (University of Ulm) and Jonathan Miller Kauffman (Allegheny College)

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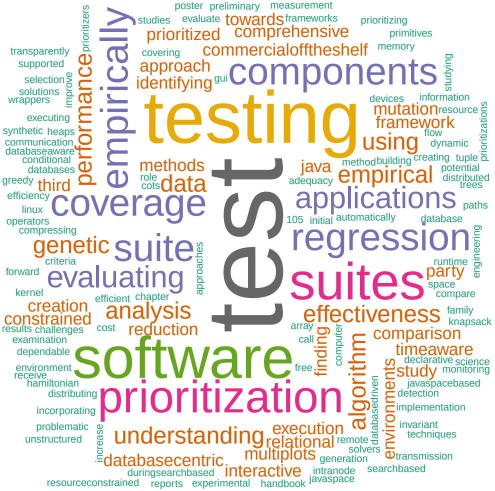
Presenter Introduction: Gregory M. Kapfhammer



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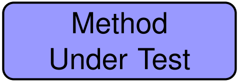

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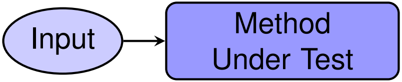

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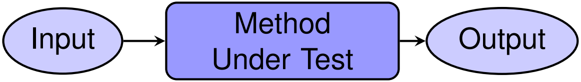

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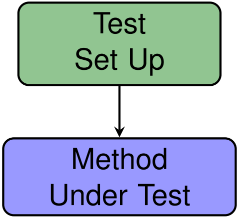

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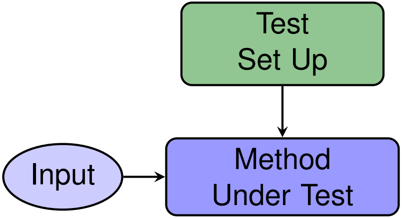

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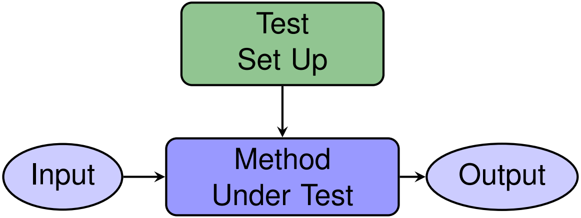

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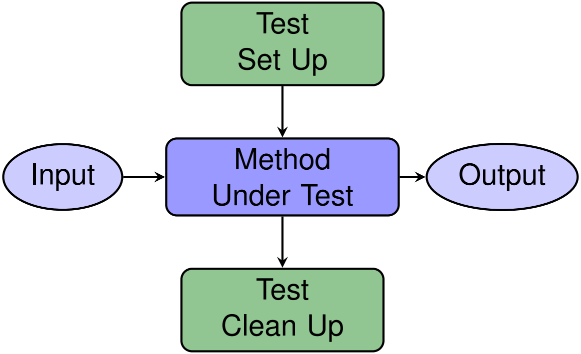

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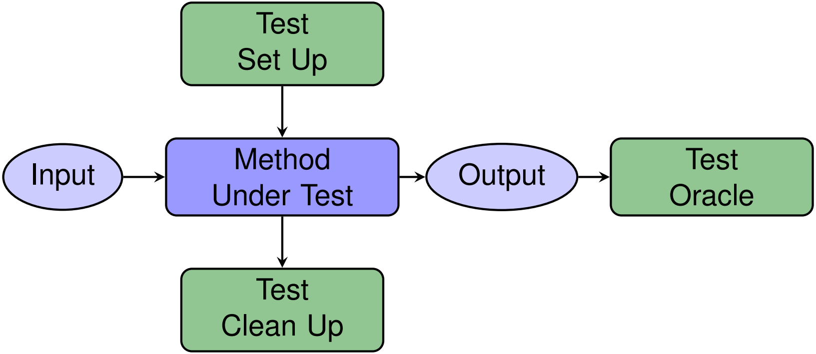

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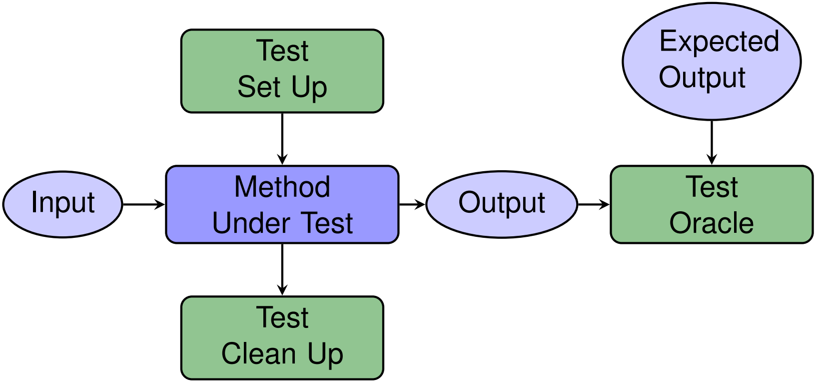

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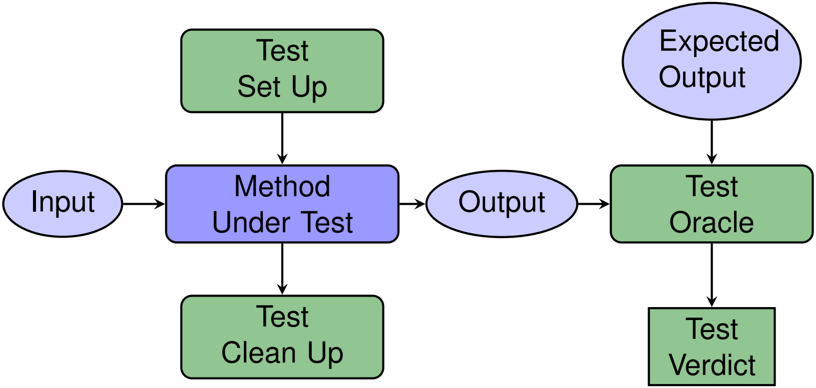

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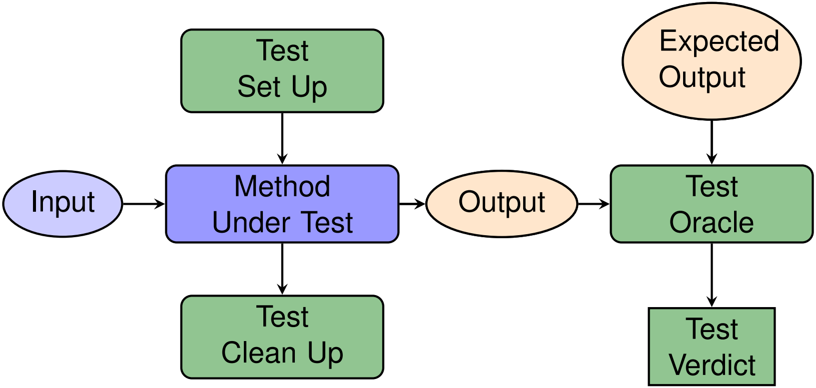

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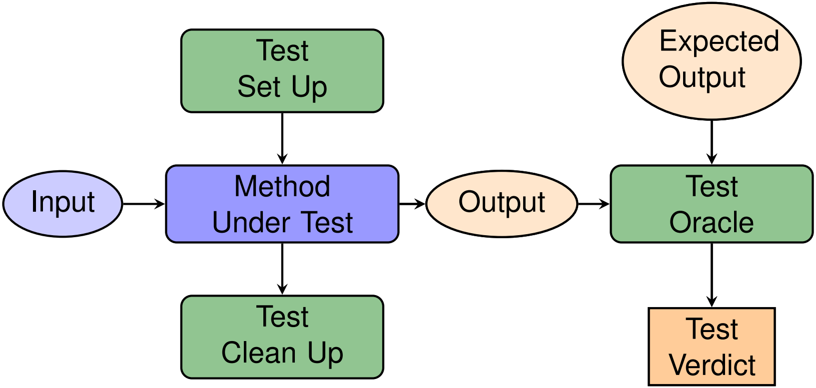

The test case passes and the code is correct!

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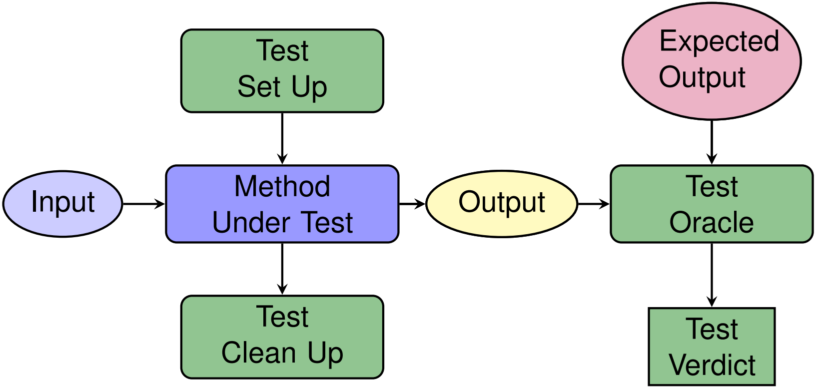

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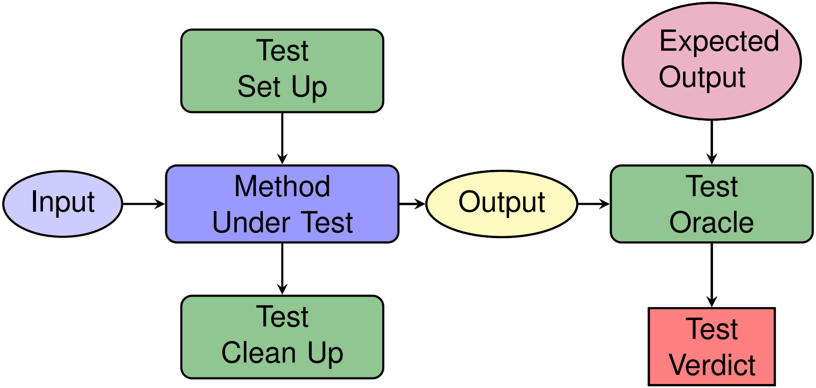

The test case fails and a defect is found!

What is a Test Suite?

T_1 T_2

What is a Test Suite?

T_1 T_2 T_3 T_4

What is a Test Suite?

T_1 T_2 T_3 T_4 T_5 T_6

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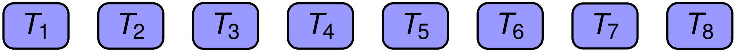

What is a Test Suite?

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

What is a Test Suite?

Test Suite $T = \langle T_1, T_2, \ldots, T_9, T_{10} \rangle$

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Requirements $R = \{R_1, \ldots, R_6\}$, Features $F = \{F_1, \ldots, F_4\}$, Bug Fixes $B = \{B_1, B_2\}$

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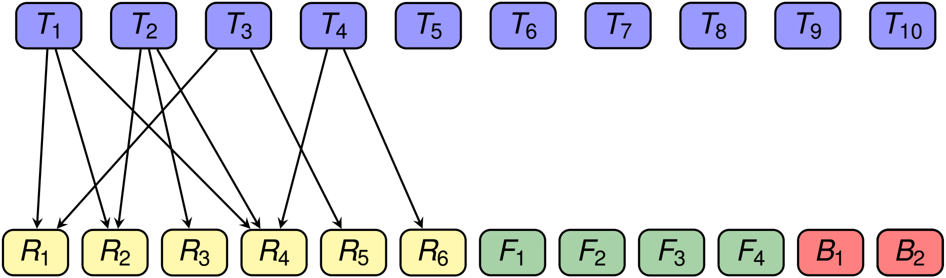

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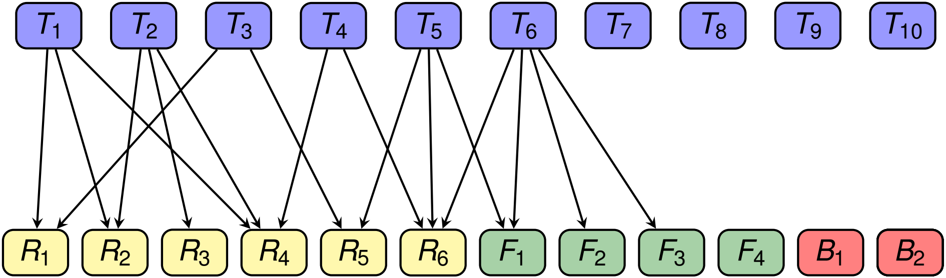

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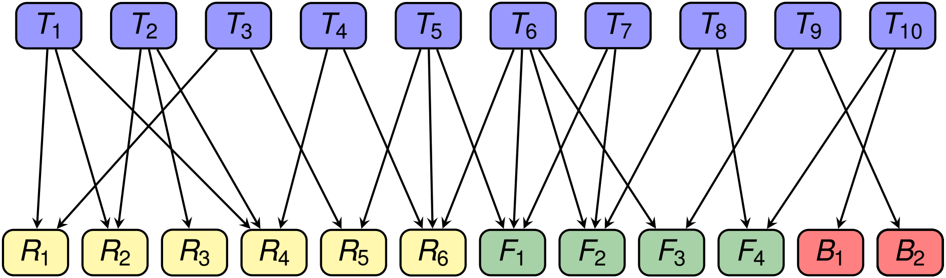

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How Good is Test Suite T?

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How Good is Test Suite T?

Coverage Analysis

R_1 R_2 R_3 R_4 R_5 R_6 F_1 F_2 F_3 F_4 B_1 B_2

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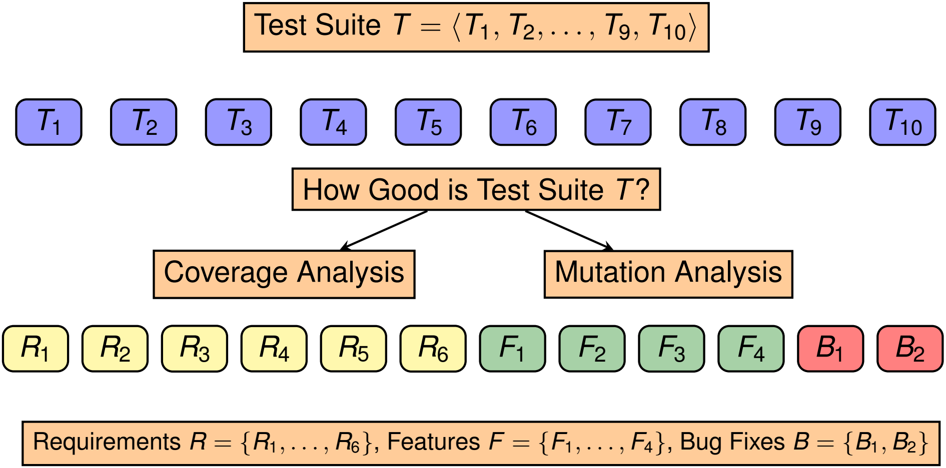

Overview of Mutation Analysis

Mutation Operator

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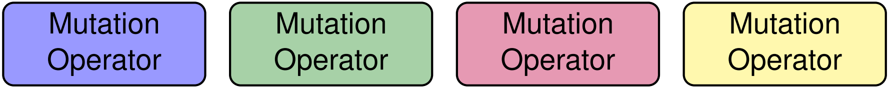

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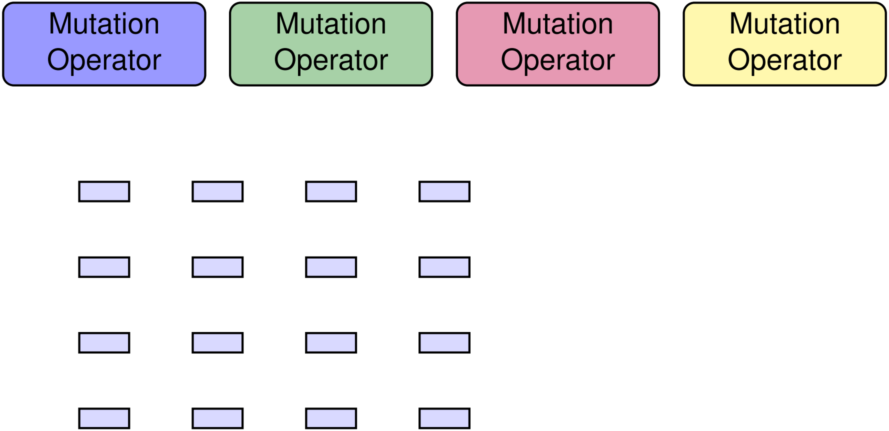

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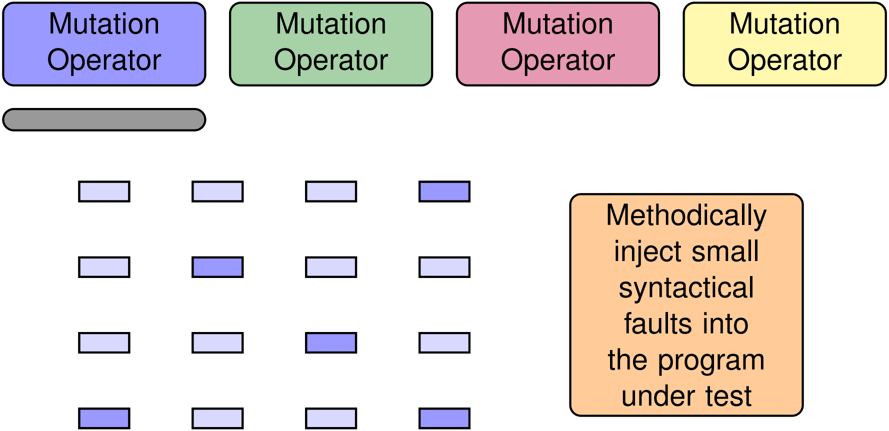

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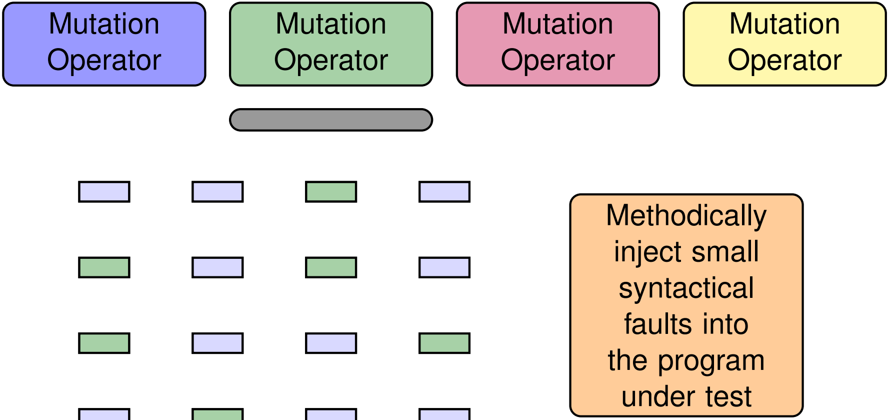

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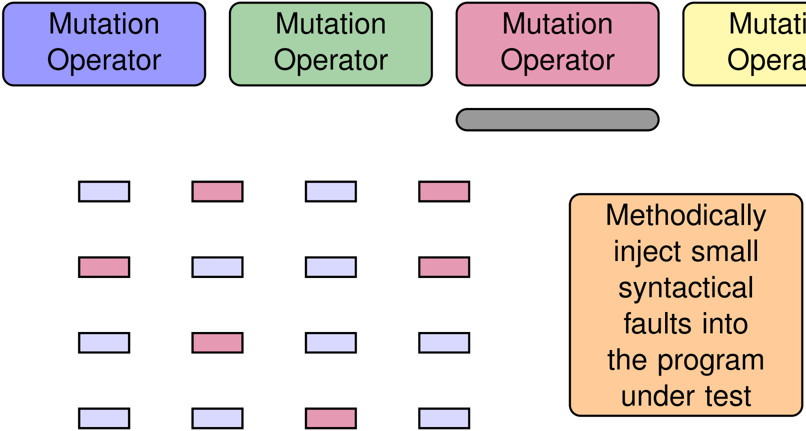

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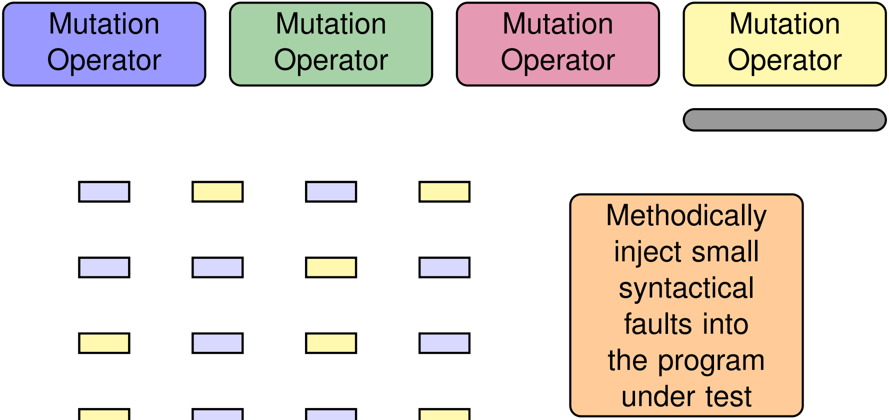

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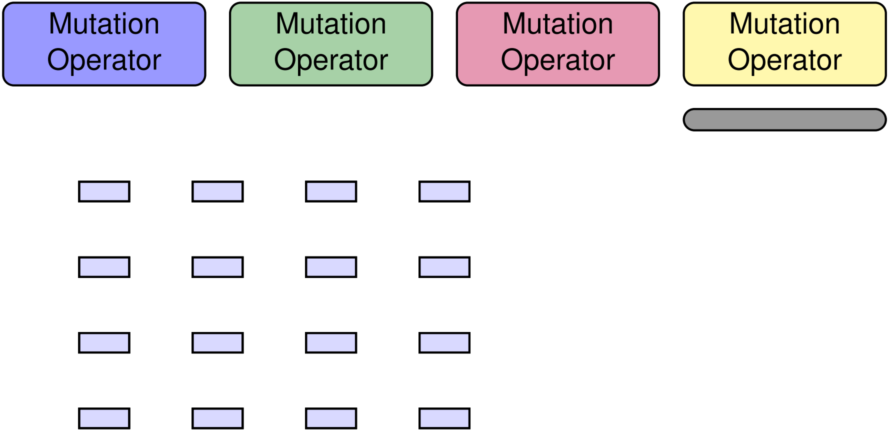

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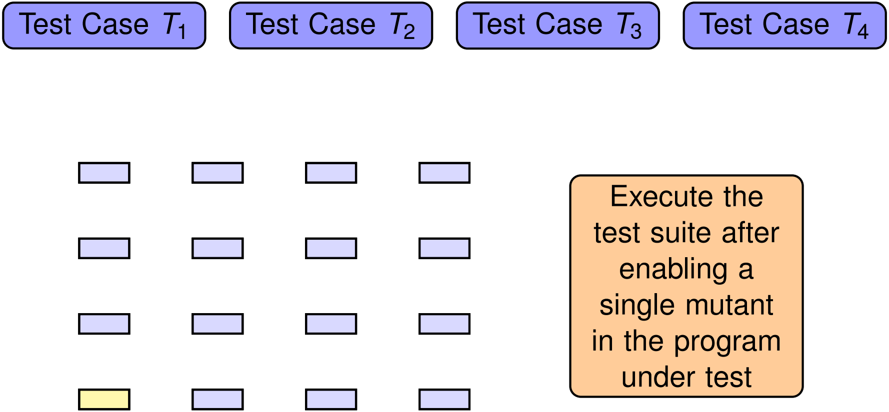
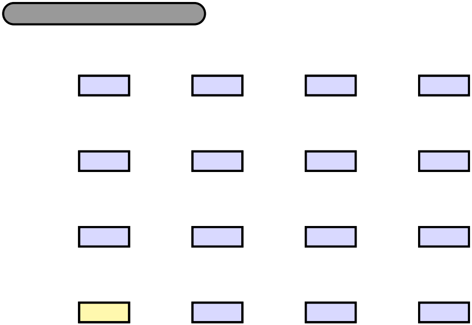


Execute the test suite after enabling a single mutant in the program under test

Overview of Mutation Analysis

Test Case T_1 | Test Case T_2 | Test Case T_3 | Test Case T_4



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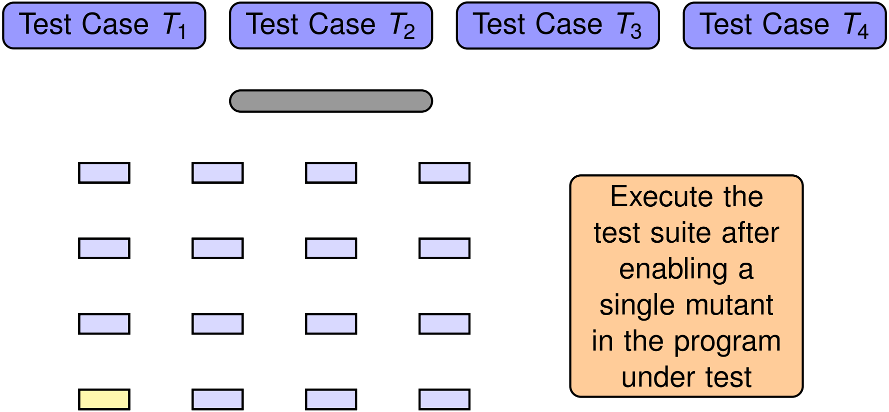

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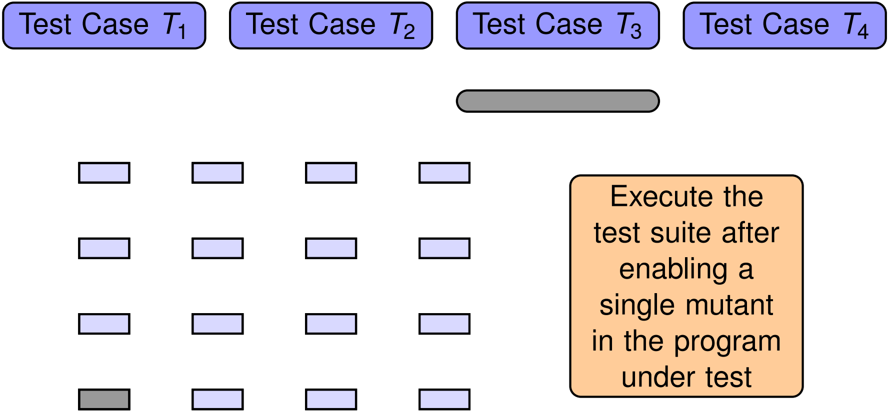

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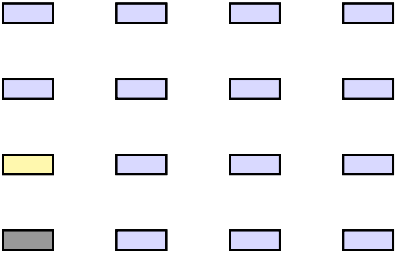

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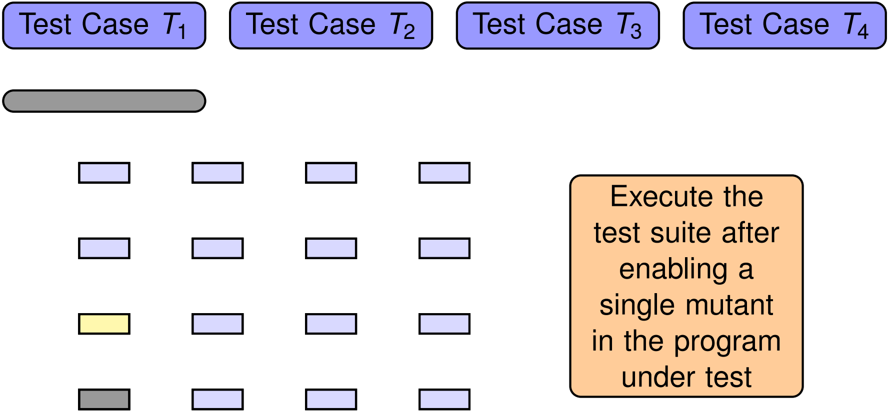

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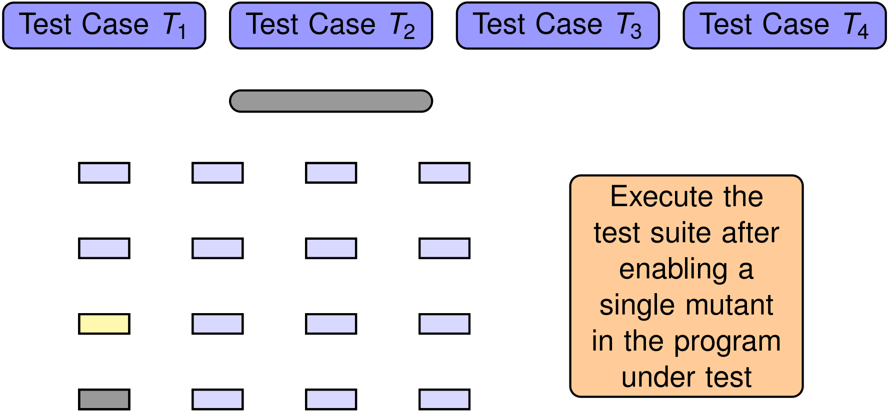

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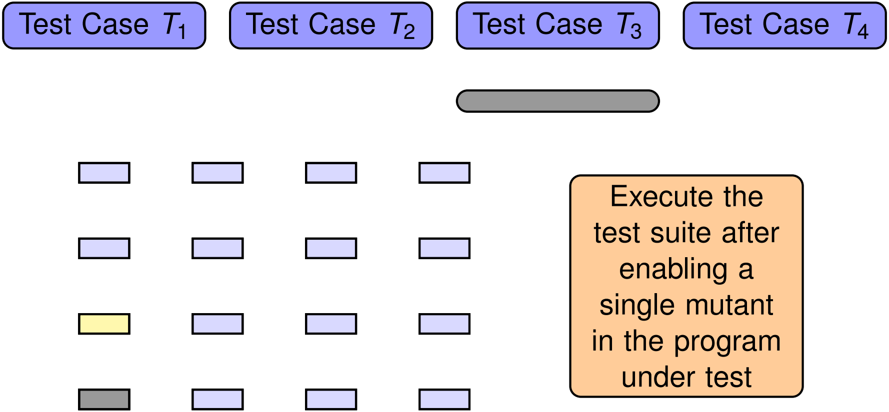

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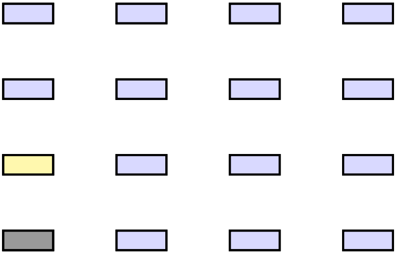

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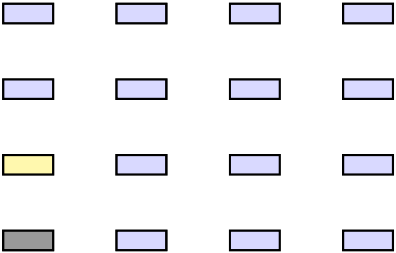

The test suite *cannot* kill the mutant – either a test suite weakness or an equivalent mutant!

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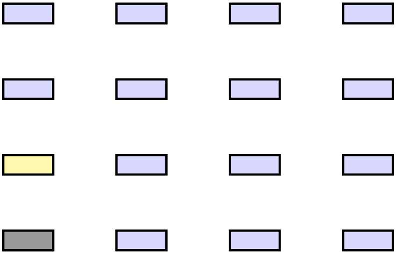

Repeat this process for *all* of the test cases and mutants – calculate mutation score when finished

Contributions of this Presentation

Efficient Mutation Analysis

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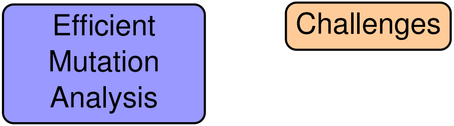

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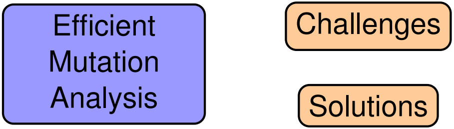

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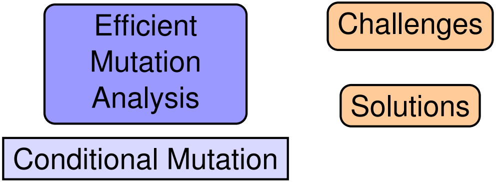

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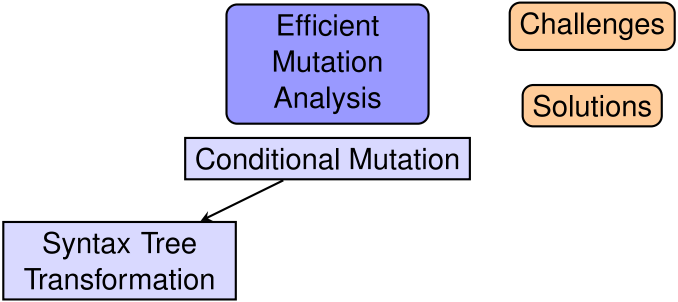

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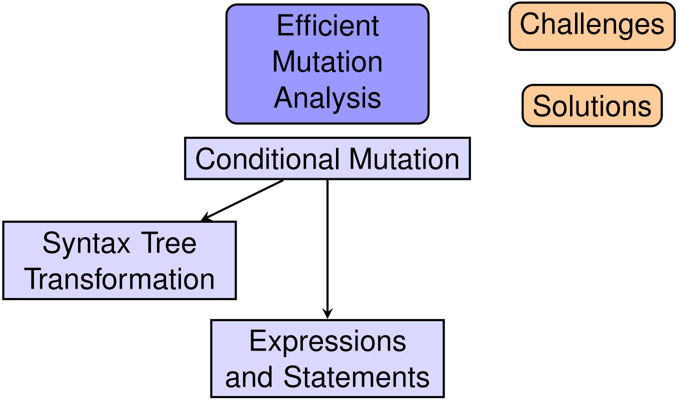

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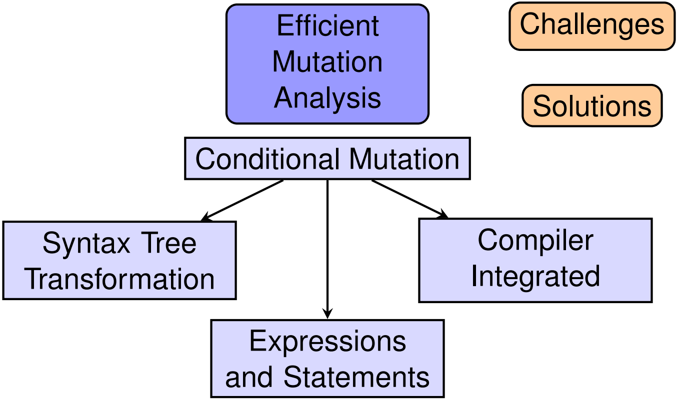

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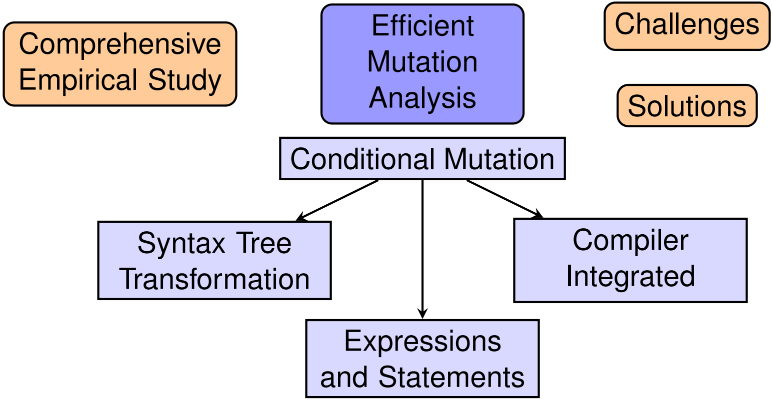

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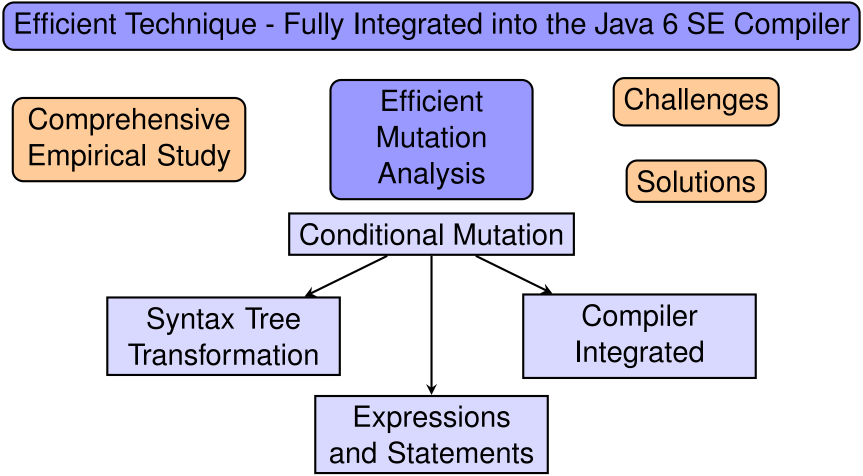

Understanding Mutation Analysis

```
public int eval(int x){
    int a=3, b=1, y;

    y = a * x;

    y += b;
    return y;
}

public int max(int a, int b){
   int max = a;

   if(b>a){
      max=b;
   }

   return max;
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```

Understanding Mutation Analysis

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Methodically inject small syntactical faults into the program under test

Understanding Mutation Analysis

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}
```

⟹

- y = a - x;
- y = a + x;
- y = a / x;

```
public int max(int a, int b){
   int max = a;

   if(b>a){
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   }

   return max;
}
```

⟹

- if(b < a)
- if(b != a)
- if(b == a)

Understanding Mutation Analysis

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Unbiased and powerful method for assessing oracles and input values

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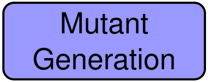
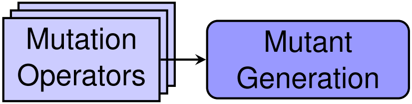
Unbiased and powerful method for assessing oracles and input values

Useful method for fault seeding during the empirical study of testing techniques

Mutation Analysis Challenges



Mutation Analysis Challenges



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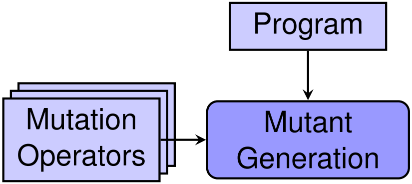

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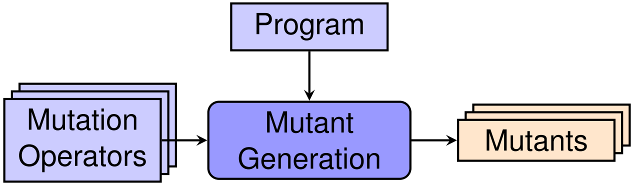

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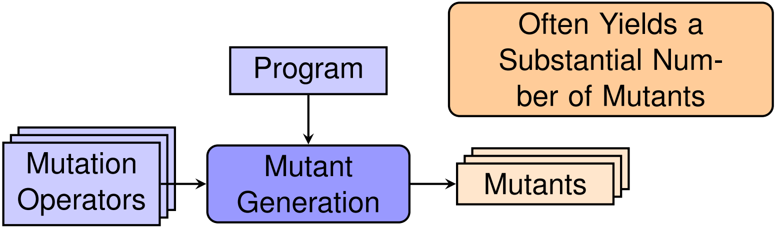

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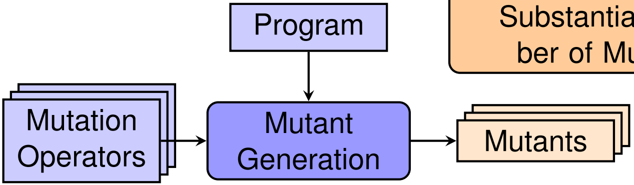
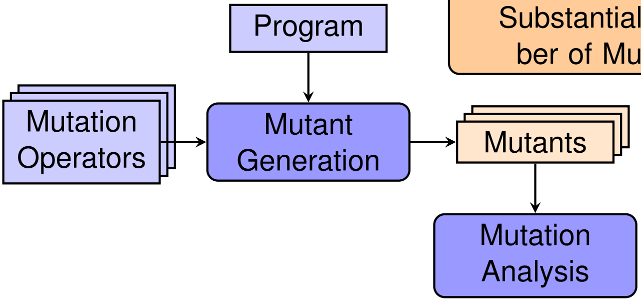


Often Yields a Substantial Number of Mutants

High Time Overhead for Generation

Mutation Analysis Challenges



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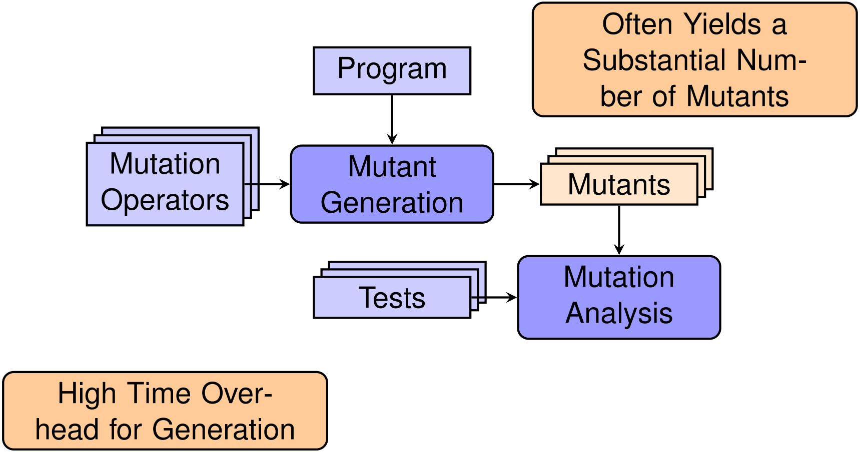

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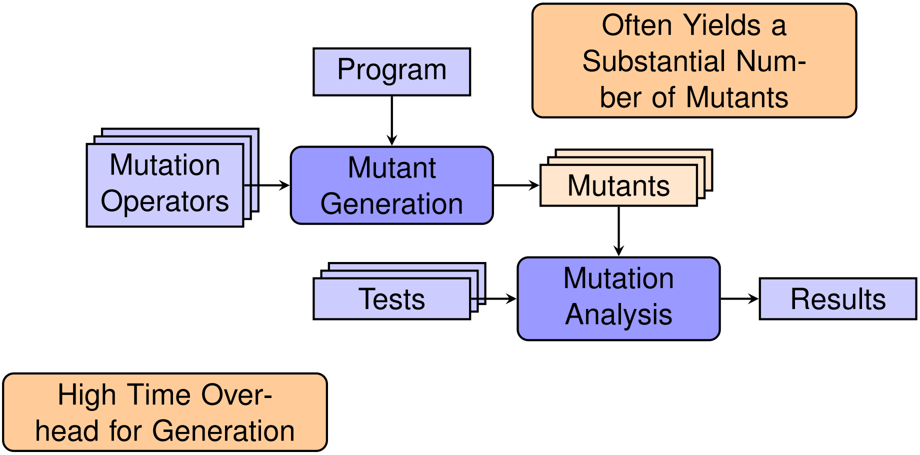

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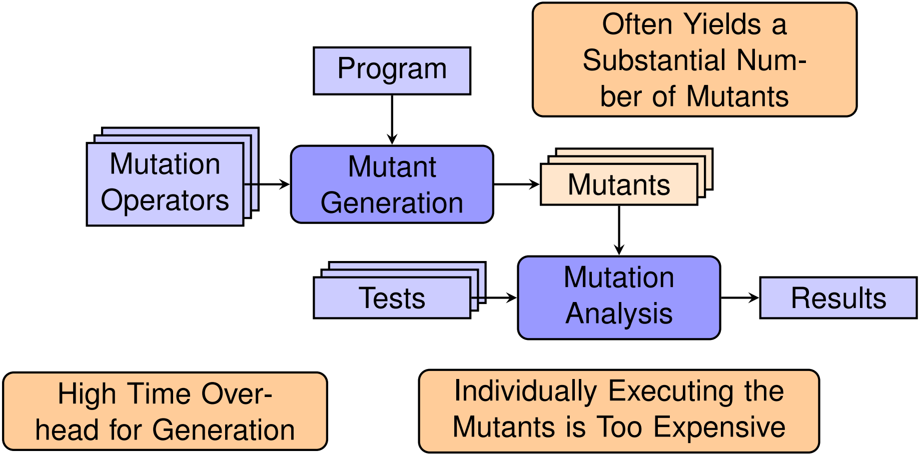

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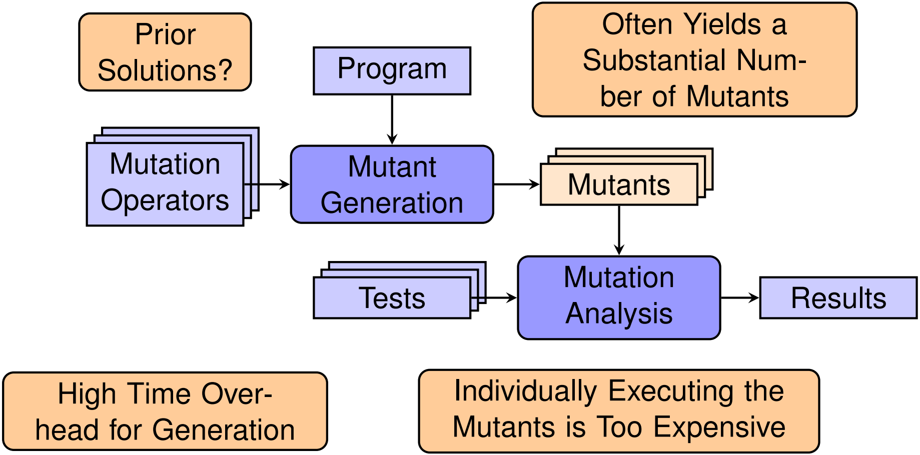


Prior Work in Mutation Analysis

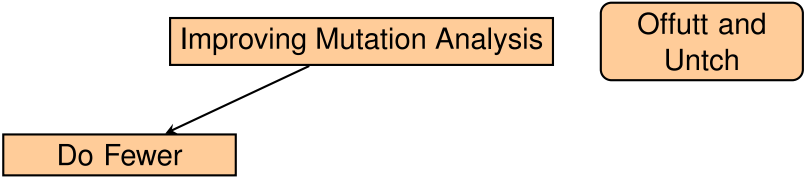
Improving Mutation Analysis

Prior Work in Mutation Analysis

Improving Mutation Analysis

Offutt and Untch

Prior Work in Mutation Analysis



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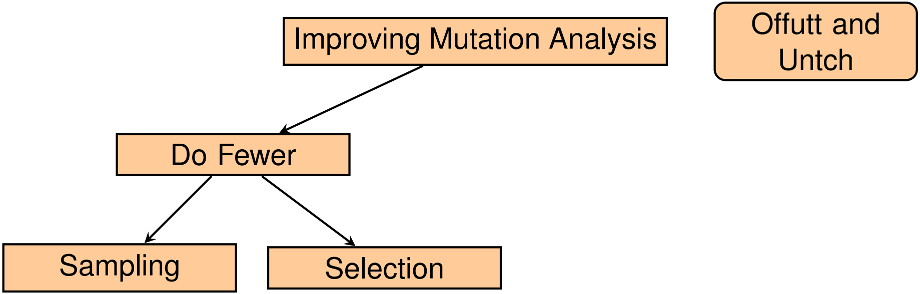

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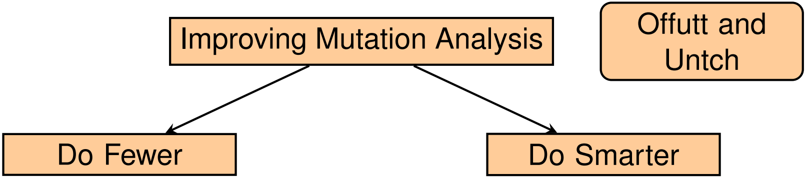

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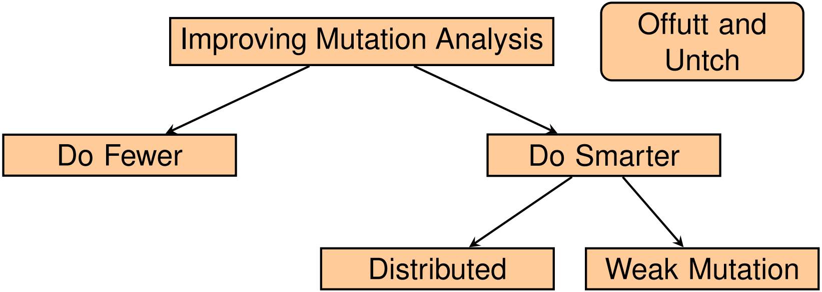

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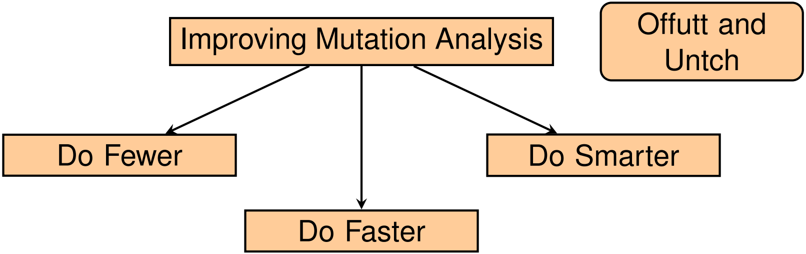

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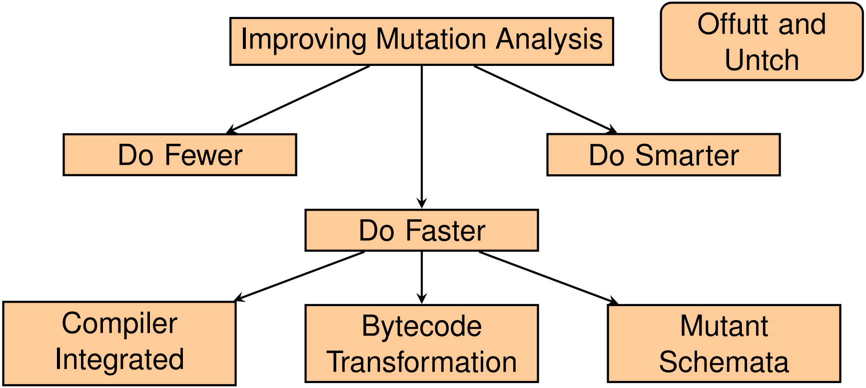

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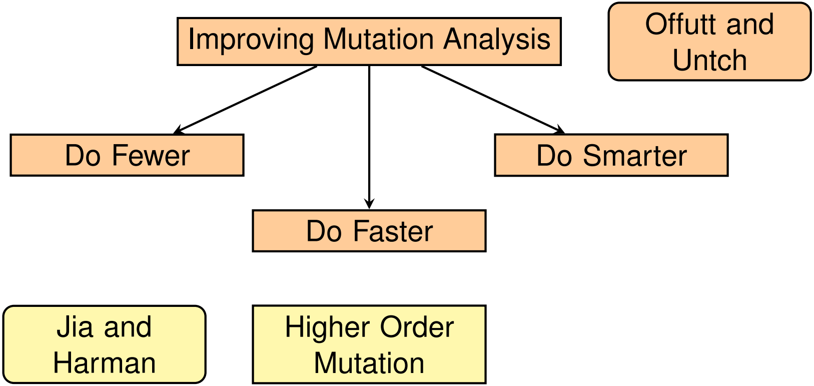

Practical Mutation Analysis

Practical (adjective):

1. Of or concerned with the actual doing or use of something rather than with theory and ideas
2. (of an idea, plan, or method) Likely to succeed or be effective in real circumstances; feasible
3. Suitable for a particular purpose

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What are the practical techniques that MAJOR employs for improving the efficiency and usability of mutation analysis?

Conditional Mutation

Conditional Mutation

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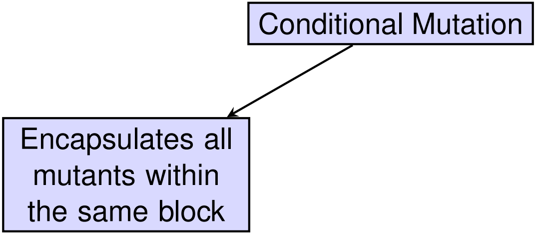

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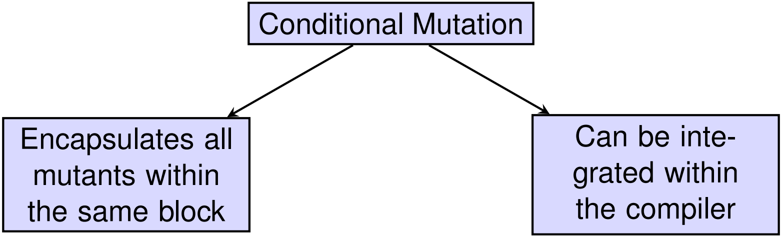

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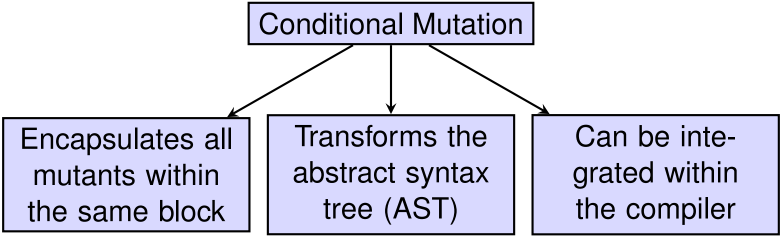

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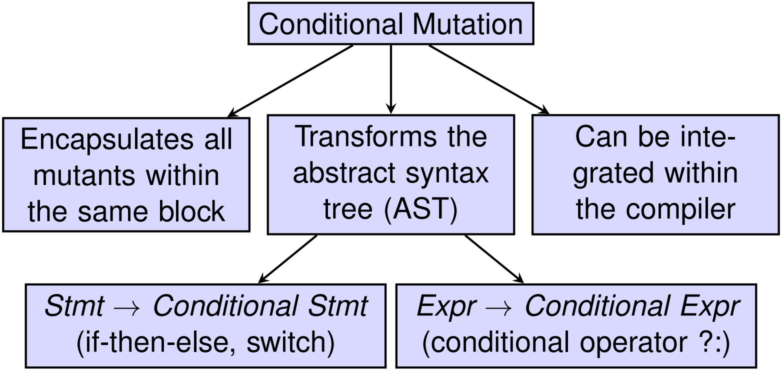

Transforming the AST

```
public int eval(int x){
    int a=3, b=1, y;

    y = a * x;

    y += b;
    return y;
}
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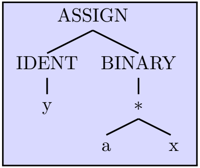

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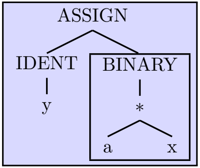

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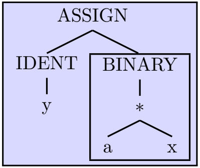

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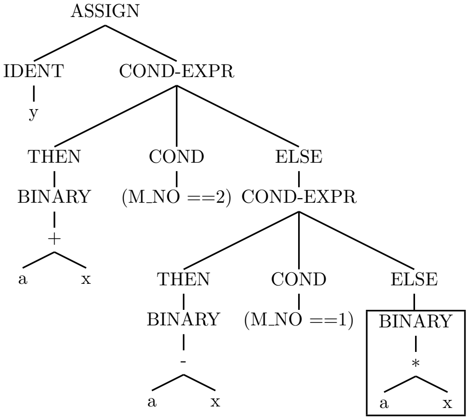

Source Code View of Inserting Mutants

```
public int eval(int x){
    int a=3, b=1, y;


    y = a * x;


    y += b;
    return y;
}
```

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
2. Determine whether current expression or statement is affected by mutation
3. Apply mutation operators

Source Code View of Inserting Mutants

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public int eval(int x){
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Source Code View of Inserting Mutants

```
public int eval(int x){
    int a=3, b=1, y;

    y = [a * x];

    y += b;
    return y;
}
```

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
2. Determine whether current expression or statement is affected by mutation
3. Apply mutation operators

Source Code View of Inserting Mutants

```
public int eval(int x){
    int a=3, b=1, y;

    y = (M_NO==1)? a - x :
                   a * x;

    y += b;
    return y;
}
```

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
2. Determine whether current expression or statement is affected by mutation
3. Apply mutation operators

Source Code View of Inserting Mutants

```
public int eval(int x){
    int a=3, b=1, y;

    y = (M_NO==2)? a + x :
        (M_NO==1)? a - x :
                   a * x;

    y += b;
    return y;
}
```

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
2. Determine whether current expression or statement is affected by mutation
3. Apply mutation operators

Source Code View of Inserting Mutants

```
public int eval(int x){
    int a=3, b=1, y;

    y = (M_NO==3)? a / x :
        (M_NO==2)? a + x :
        (M_NO==1)? a - x :
                   a * x;

    y += b;
    return y;
}
```

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
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Source Code View of Inserting Mutants

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public int eval(int x){
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}
```

Mutants that are not executed cannot be killed

1. Define mutation operators $MOP(x * y) = \{x - y, x + y, x/y\}$
2. Determine whether current expression or statement is affected by mutation
3. Apply mutation operators

Collecting and Using Mutation Coverage

```
public int eval(int x){
    int a=3, b=1, y;

    y = (M_NO==3)? a / x :
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```

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Collecting and Using Mutation Coverage

```
public int eval(int x){
    int a=3, b=1, y;

    y = (M_NO==3)? a / x :
        (M_NO==2)? a + x :
        (M_NO==1)? a - x :
        (M_NO==0 &&
         COVERED(1,3))?
              a * x : a * x;

    y += b;

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```

Mutants that are not executed cannot be killed

Determine covered mutants with additional instrumentation

Collecting and Using Mutation Coverage

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Mutants that are not executed cannot be killed

Determine covered mutants with additional instrumentation

Only execute and investigate the covered mutants

MAJOR's Compiler

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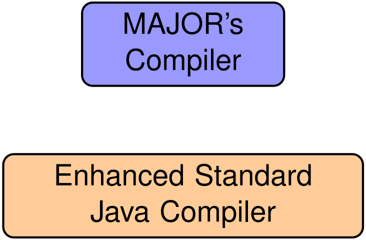
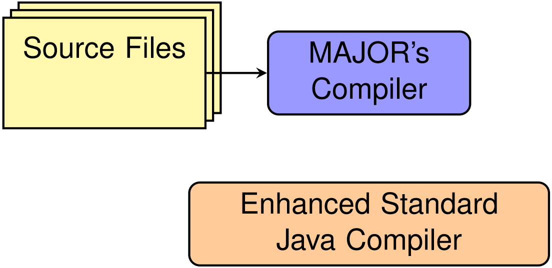


MAJOR's Compiler



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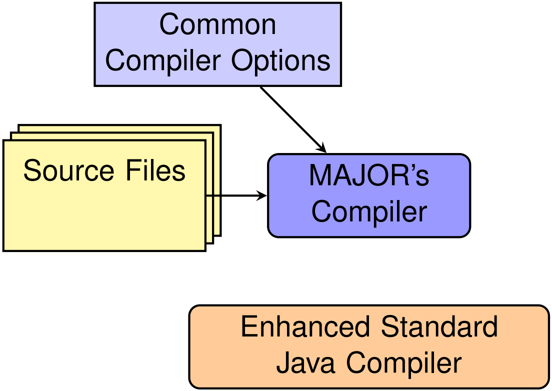

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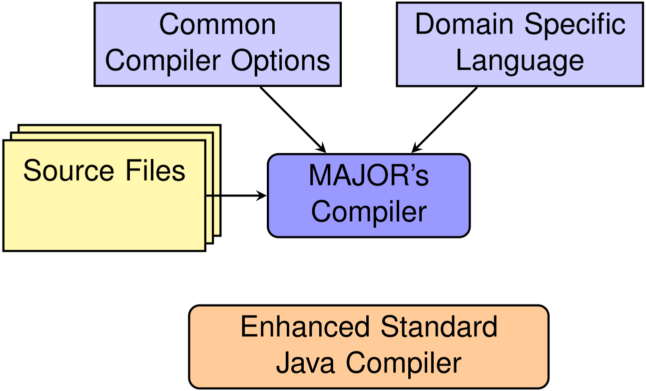

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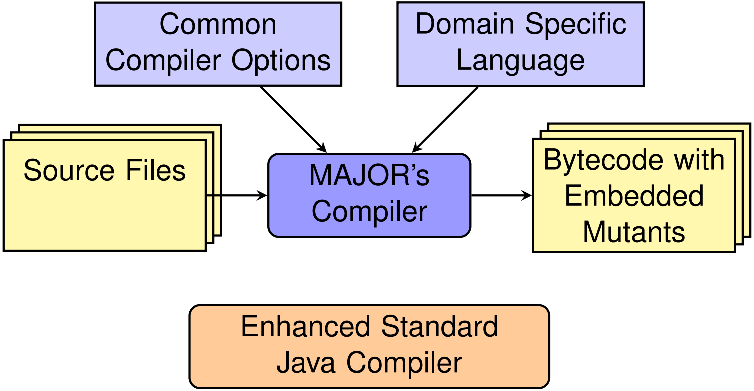
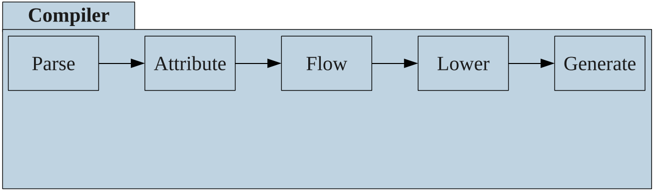


Integration into the Java Compiler



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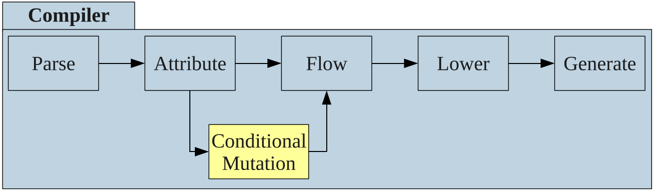

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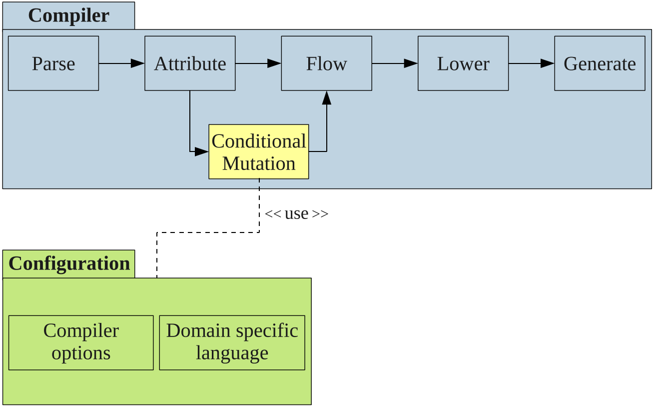

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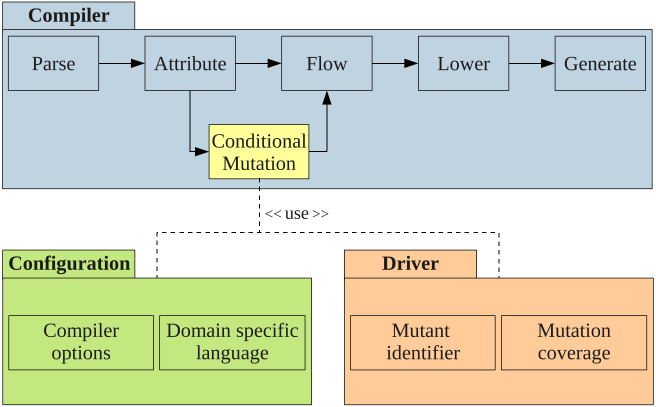

MAJOR's Domain Specific Language

```
// variable declaration
listCOR={&&, ||, ==, !=};
// Define replacement list
BIN(+)<"org"> -> {-,*};
BIN(*)<"org"> -> {/,%};
// Define own operator
myOp{
  BIN(&&) -> listCOR;
  BIN(||) -> listCOR;
  COR;
  LVR;
}
// Enable built-in operator AOR
AOR<"org">;
// Enable operator myOp
myOp<"java.lang.System@println">;
```

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Specify mutation operators in detail

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Specify mutation operators in detail

Define own mutation operator groups

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```
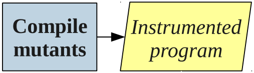

Specify mutation operators in detail

Define own mutation operator groups

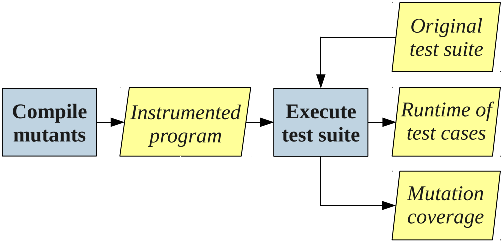
Enable operators for a specific package, class, or method

Optimized Mutation Analysis Process



1. Embed and compile all mutants
2. Run test suite on instrumented program
3. Sort tests according to their runtime
4. Perform mutation analysis with reordered test suite

Optimized Mutation Analysis Process



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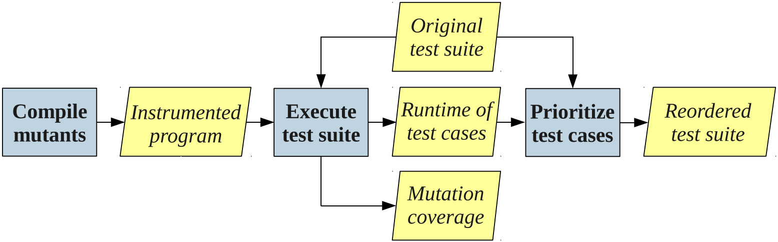

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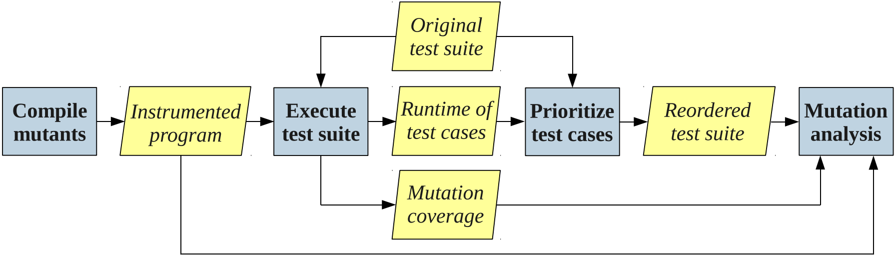

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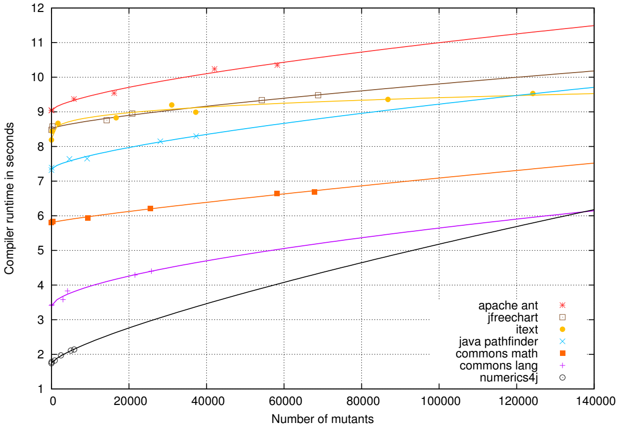
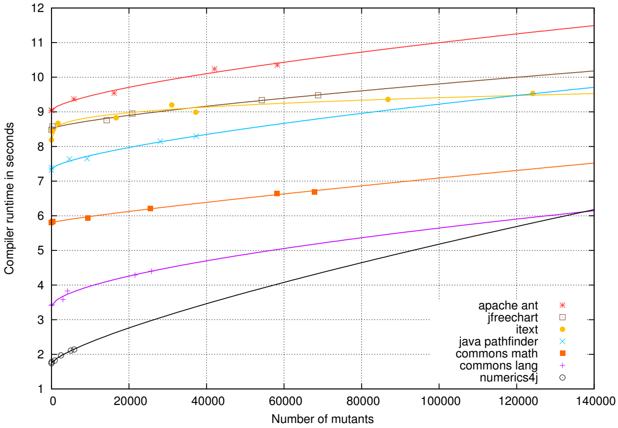
Mutant Generation and Compilation



Overhead for generating and compiling mutants is negligible

Mutant Generation and Compilation



Overhead for generating and compiling mutants is negligible

Time and Space Overhead

Application	***Mutants***	***Runtime of test suite***			***Memory consumption***	
		original	*instrumented*		*original*	*instrumented*
			wcs	*wcs+cov*		
aspectj	406,382	4.3	4.8	5.0	559	813
apache ant	60,258	331.0	335.0	346.0	237	293
jfreechart	68,782	15.0	18.0	23.0	220	303
itext	124,184	5.1	5.6	6.3	217	325
java pathfinder	37,331	17.0	22.0	29.0	182	217
commons math	67,895	67.0	83.0	98.0	153	225
commons lang	25,783	10.3	11.8	14.8	104	149
numerics4j	5,869	1.2	1.3	1.6	73	90

- Runtime overhead is application dependent
  - Larger for CPU-bound applications
  - Small for I/O-bound applications
- Even for large projects, applicable on commodity workstations

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  - Small for I/O-bound applications
- Even for large projects, applicable on commodity workstations

Time and Space Overhead

Application	***Mutants***	***Runtime of test suite***			***Memory consumption***	
		original	*instrumented*		*original*	*instrumented*
			wcs	*wcs+cov*		
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apache ant	60,258	331.0	335.0	346.0	237	293
jfreechart	68,782	15.0	18.0	23.0	220	303
itext	124,184	5.1	5.6	6.3	217	325
java pathfinder	37,331	17.0	22.0	29.0	182	217
commons math	67,895	67.0	83.0	98.0	153	225
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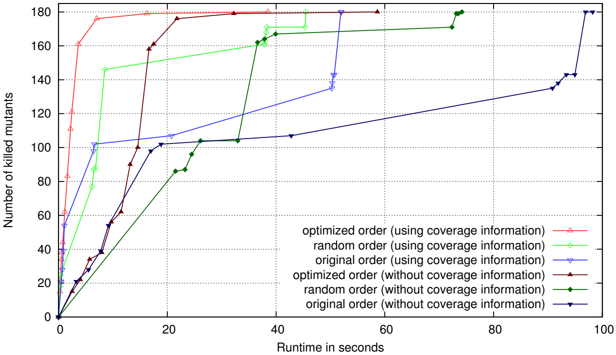
Evaluating and Improving Mutation Analysis



- Mutation analysis is not feasible without coverage information
- Reordering the test suite significantly speeds up the process, especially if runtimes of tests differ by orders of magnitude

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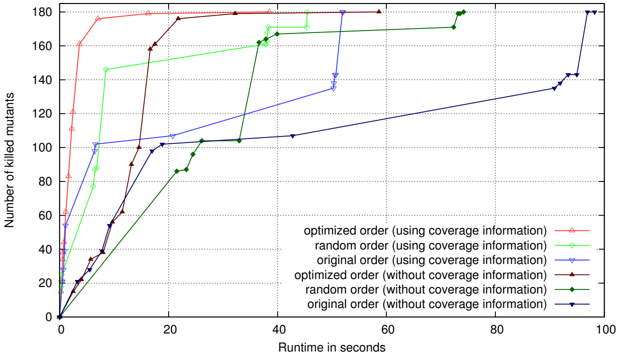

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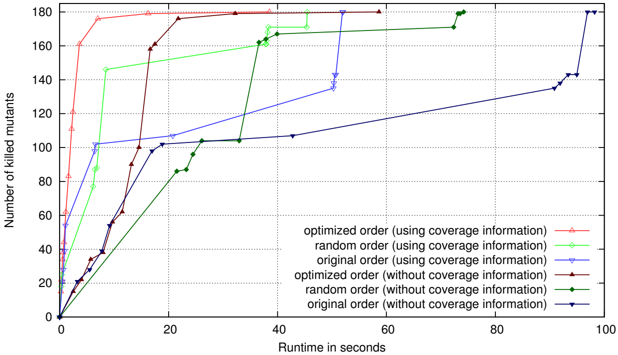

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Revisiting Practical Mutation Analysis

Practical (adjective):

1. Of or concerned with the actual doing or use of something rather than with theory and ideas
2. (of an idea, plan, or method) Likely to succeed or be effective in real circumstances; feasible
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The evidence suggests that MAJOR is “likely to succeed or be effective” in real-world software testing circumstances

Reviewing MAJOR's Contributions

Mutation Analysis

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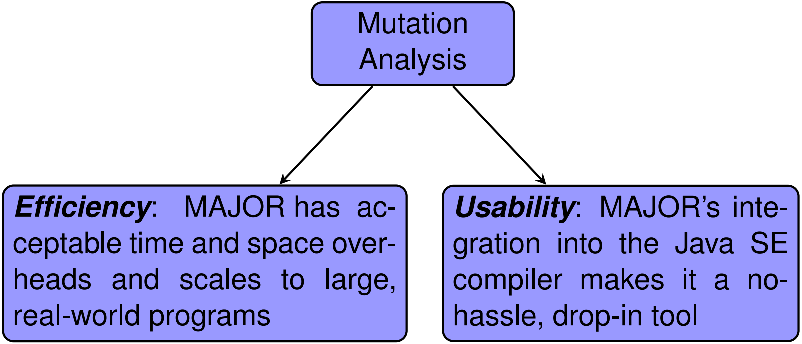
Efficiency: MAJOR has acceptable time and space overheads and scales to large, real-world programs

Reviewing MAJOR’s Contributions



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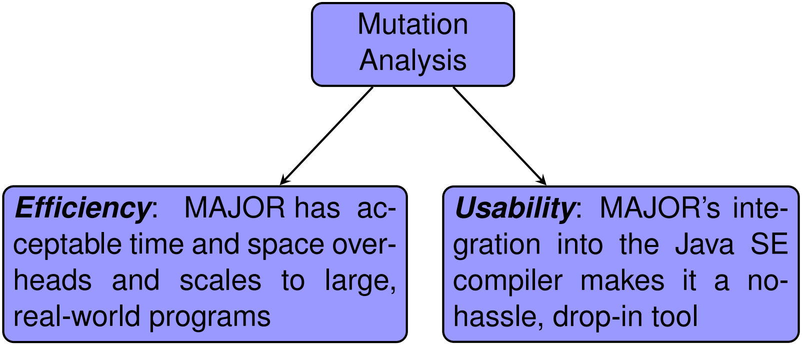

We will release MAJOR as free and open source software

Conclusion

Key Concepts and Features:

- Compiler-integrated solution
- Conditional mutation with the abstract syntax tree
- Furnishes its own domain specific language
- Collects and leverages mutation coverage information

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Characteristics of MAJOR:

- Fast and scalable technique
- Configurable and extensible mutation tool
- Enables an optimized workflow for mutation analysis

Practical Techniques for Improving the Efficiency and Usability of Mutation Analysis for Java Programs

Gregory M. Kapfhammer

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Thank you for your attention!
I welcome your questions and comments.