Efficient and Effective Mutation Testing: Supporting the Implementation of Quality Software by Purposefully Inserting Defects

Gregory M. Kapfhammer[†]

Department of Computer Science
Allegheny College
http://www.cs.allegheny.edu/~gkapfham/

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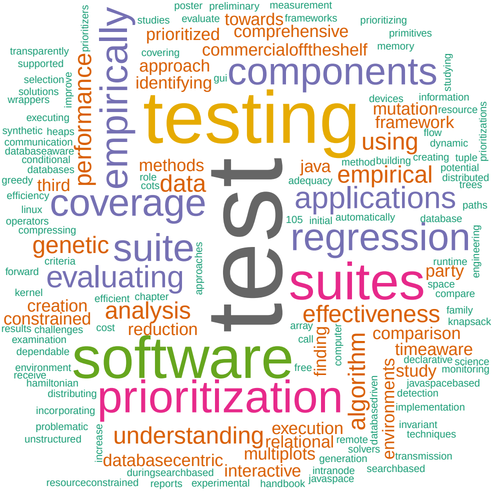
[†] Joint with René Just and Franz Schweiggert (University of Ulm) and Jonathan Miller Kauffman (Allegheny College)

Presenter Introduction: Gregory M. Kapfhammer



Inspiration and Motivation

> The magic of myth and legend has come true in our time. One types the correct incantation on a keyboard, and a display screen comes to life, showing things that never were nor could be.

Frederick P. Brooks, Jr.

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In reference to *software*!

Inspiration and Motivation

> *I believe the hard part of building software to be the specification, design, and testing of this conceptual construct*, not the labor of representing it and testing the fidelity of the representation.

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What happens if the “incantation” is incorrect?

Inspiration and Motivation

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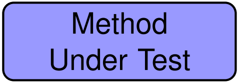
Frederick P. Brooks, Jr.

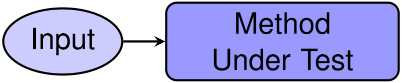
How do we efficiently and effectively test software?

What is a Test Case?



Method
Under Test

What is a Test Case?



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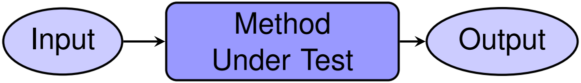

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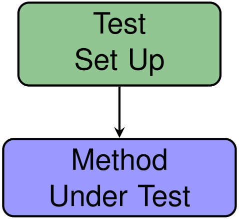

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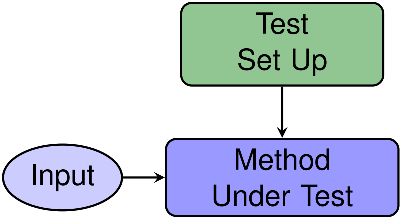

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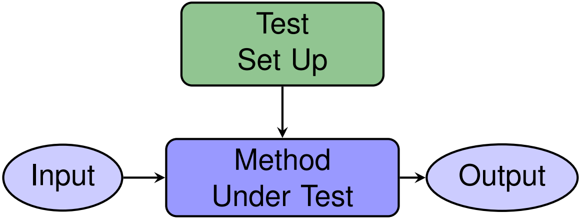

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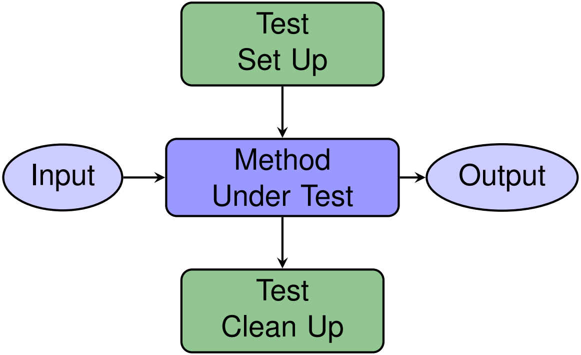

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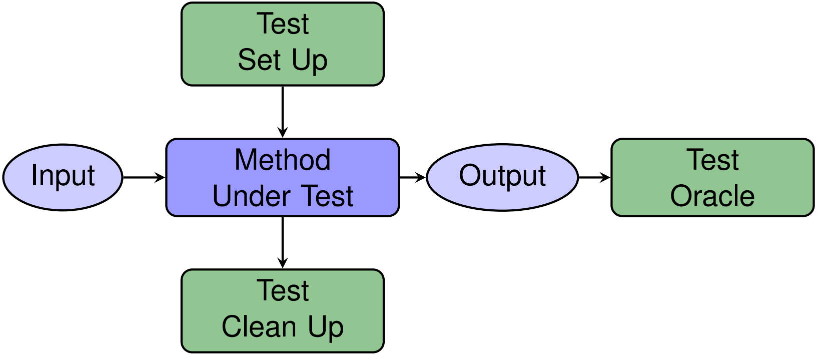

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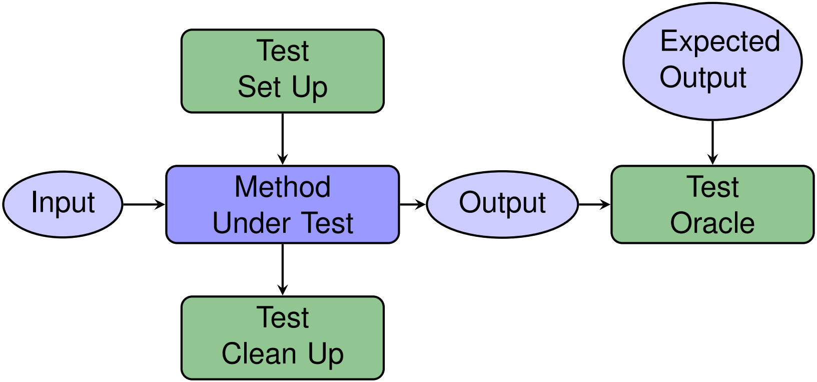

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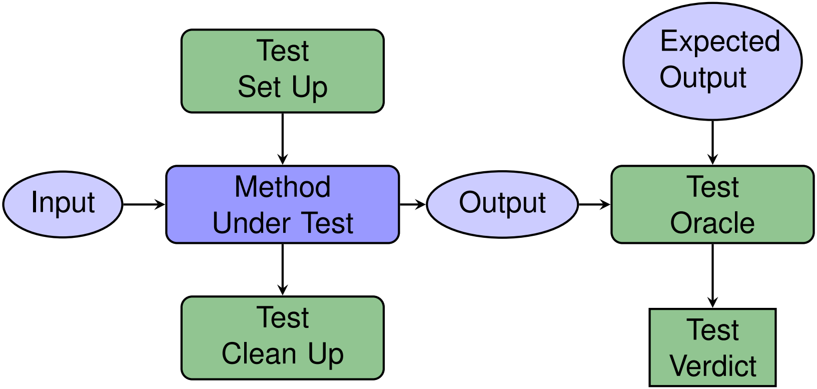

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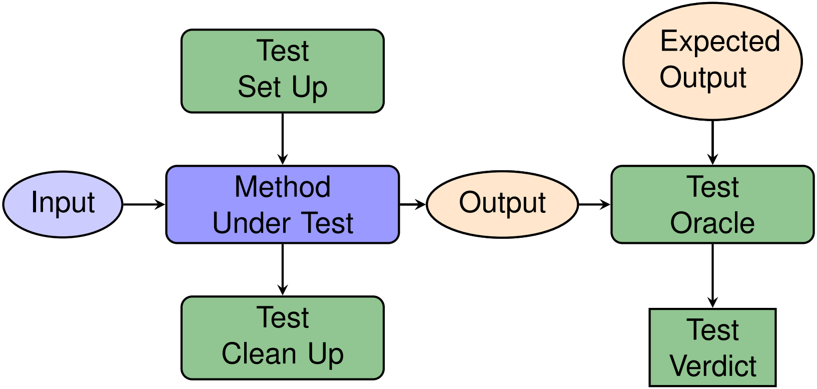

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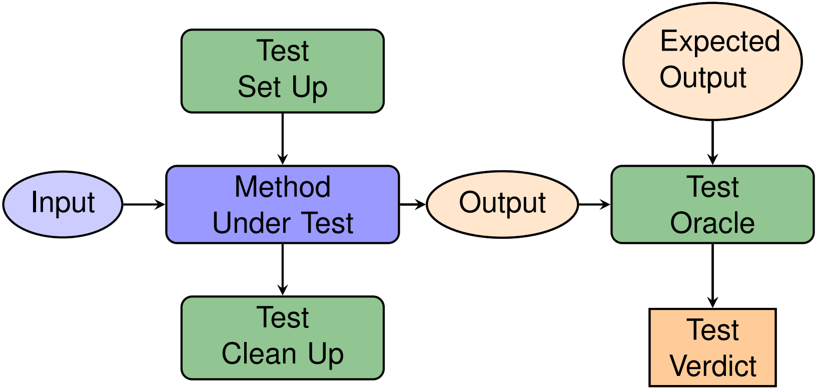
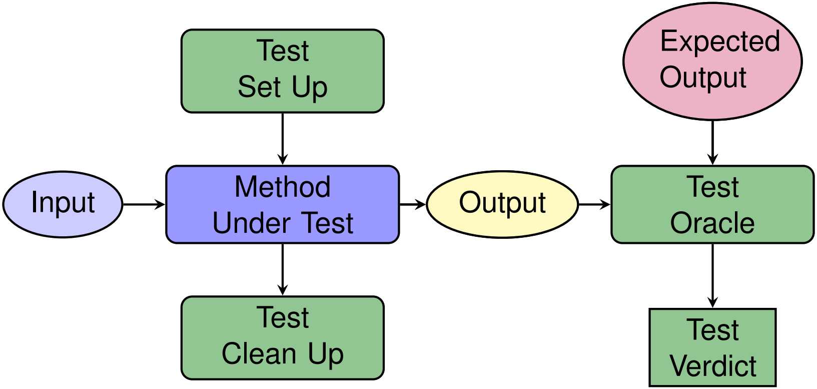


The test case passes and the code is correct!

What is a Test Case?



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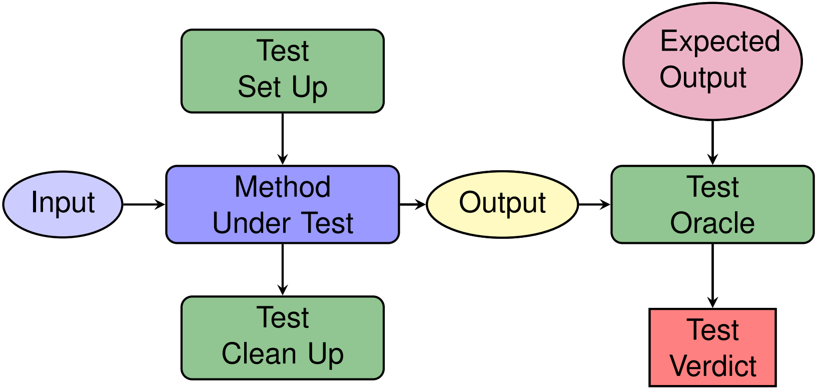
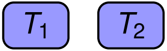


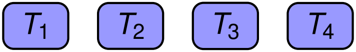
The test case fails and a defect is found!

What is a Test Suite?



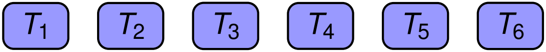
T_1 T_2

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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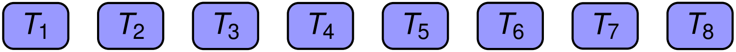

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8

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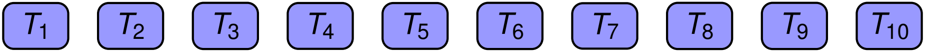
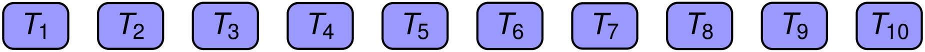


T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

What is a Test Suite?

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



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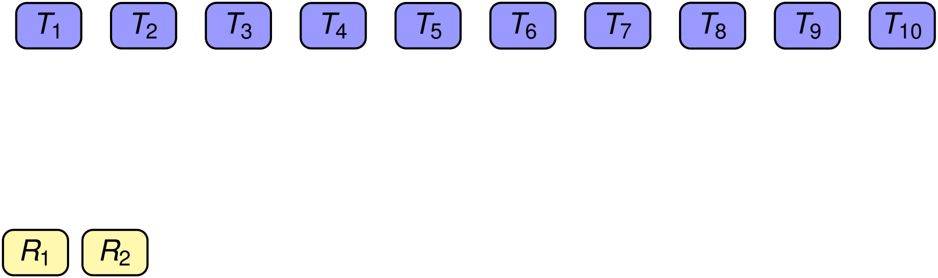

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

R_1 R_2

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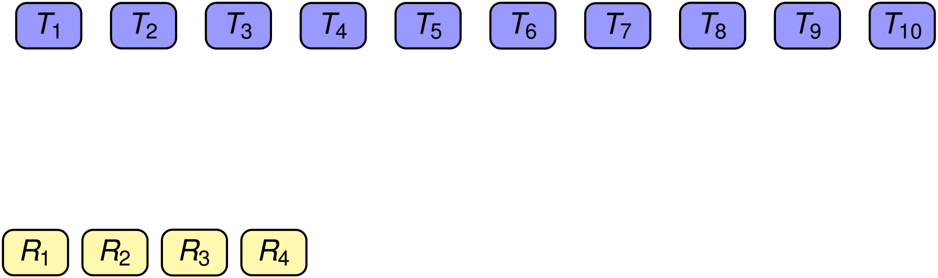
Test Suite $T = \langle T_1, T_2, \ldots, T_9, T_{10} \rangle$



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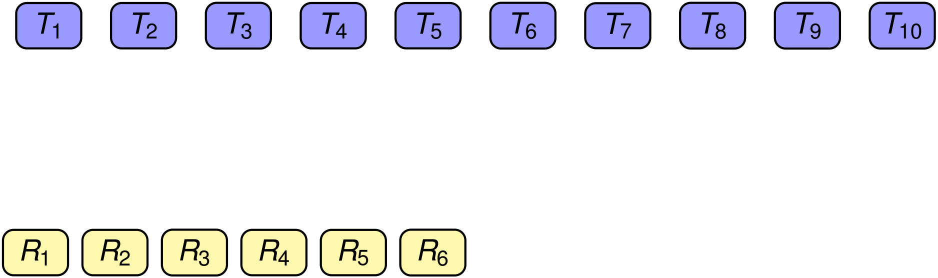

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

R_1 R_2 R_3 R_4 R_5 R_6

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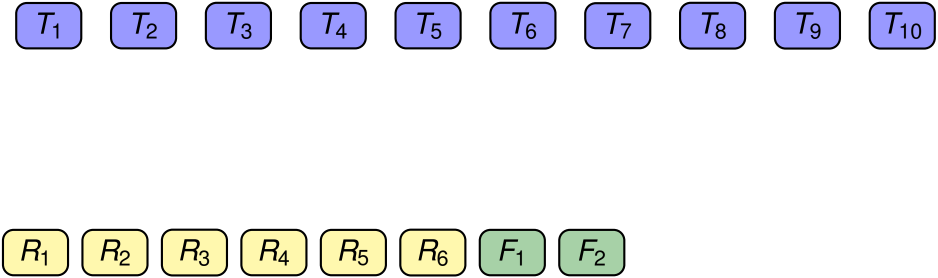

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

R_1 R_2 R_3 R_4 R_5 R_6 F_1 F_2

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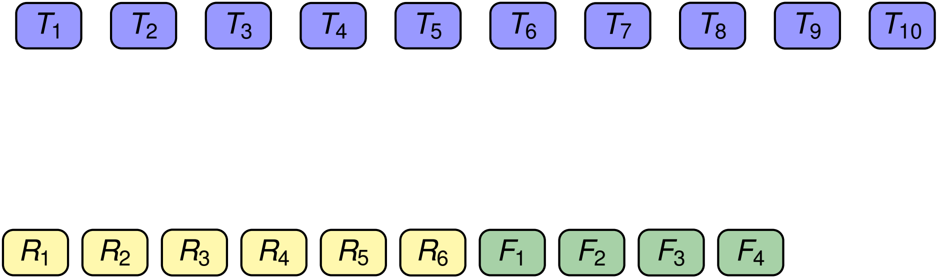

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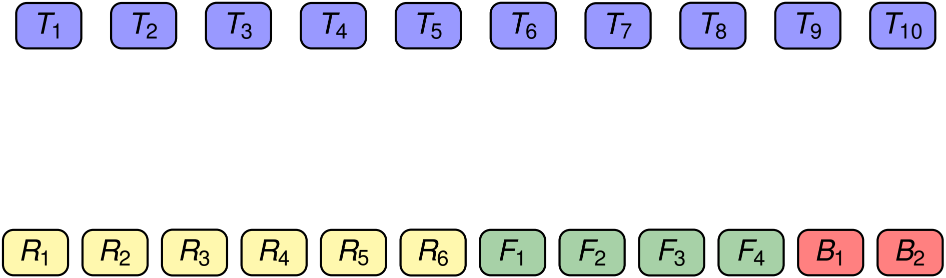

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

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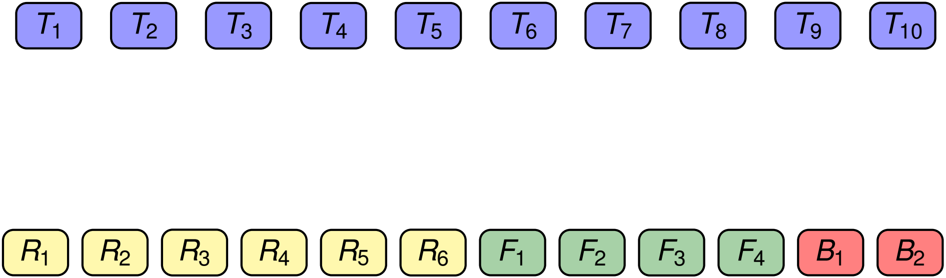

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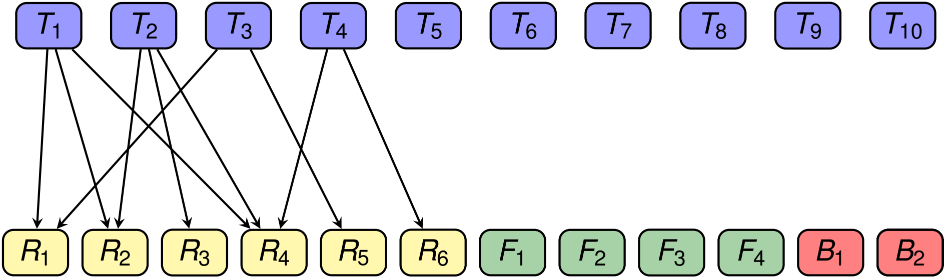

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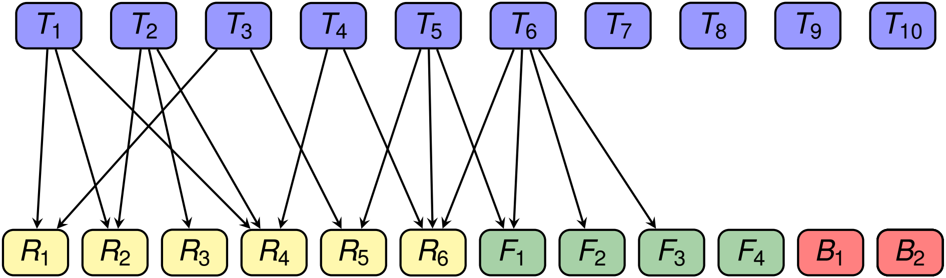

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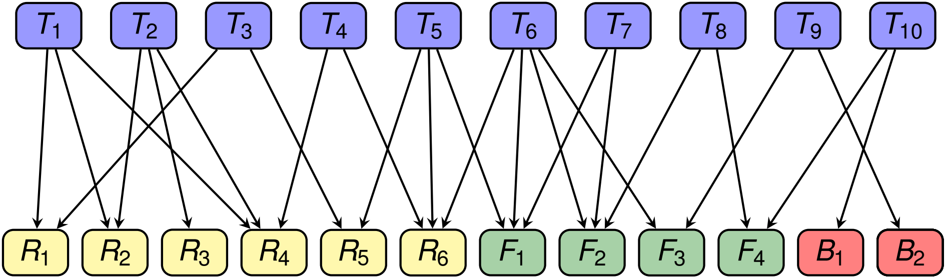

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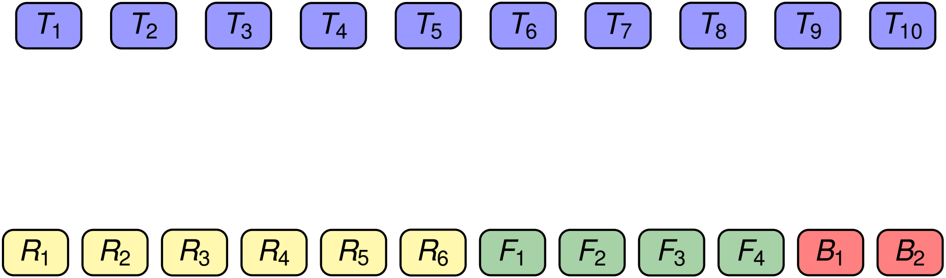

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

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

How Good is Test Suite T?

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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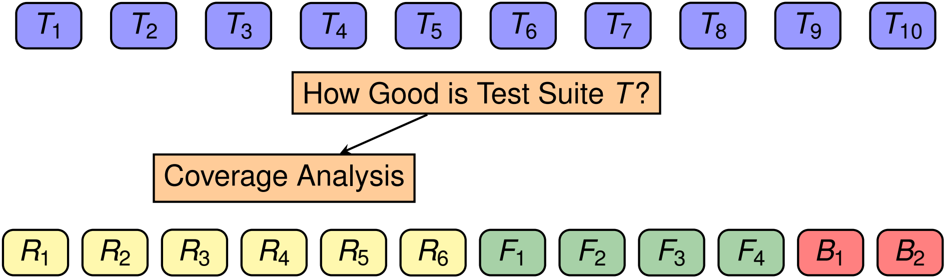

T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

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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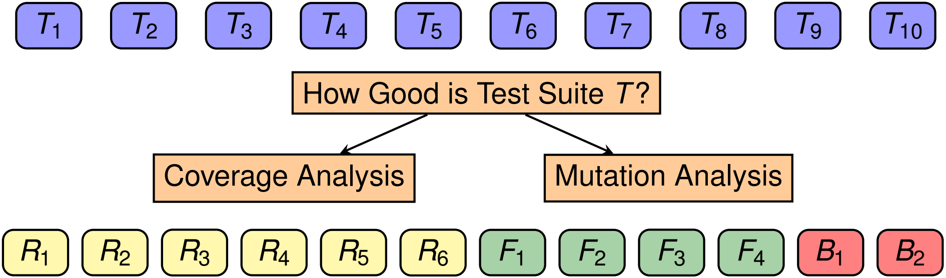


T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9 T_{10}

How Good is Test Suite T?

Coverage Analysis

Mutation 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

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

Conceptual Faults

```
if(a > 10)
```

Conceptual Faults

```
if(a > 10)
```

```
if(a >= 10)
```

Conceptual Faults

```
if(a > 10)
```

```
if(a >= 10)
```

Implemented

Conceptual Faults

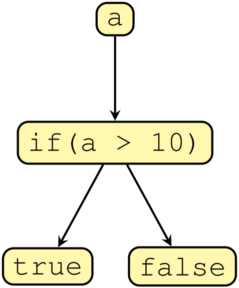
```
if(a > 10)
```

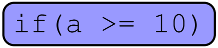
```
if(a >= 10)
```

Implemented

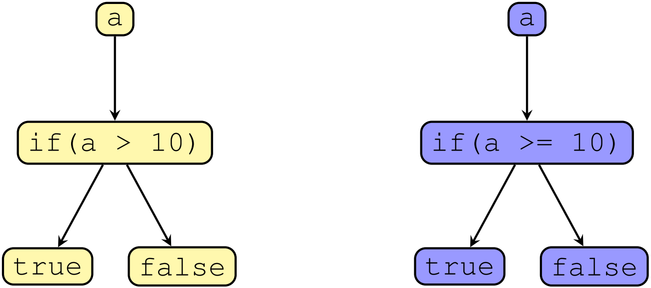
Potential Fault

Conceptual Faults





Conceptual Faults



a

if(a > 10)

true

false

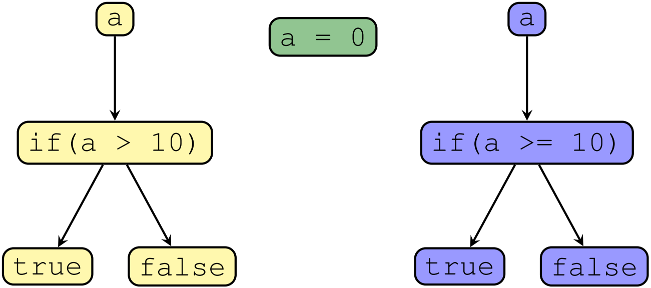
a

if(a >= 10)

true

false

Conceptual Faults



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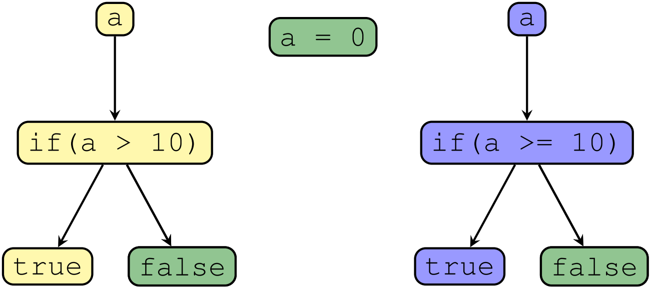

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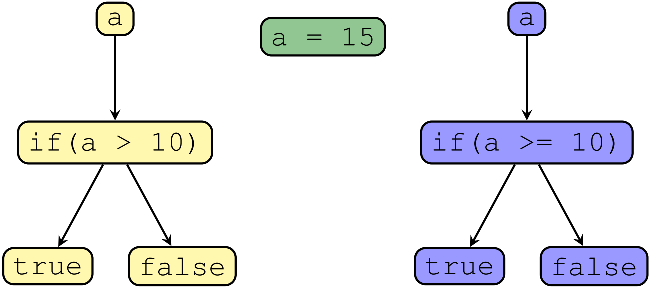

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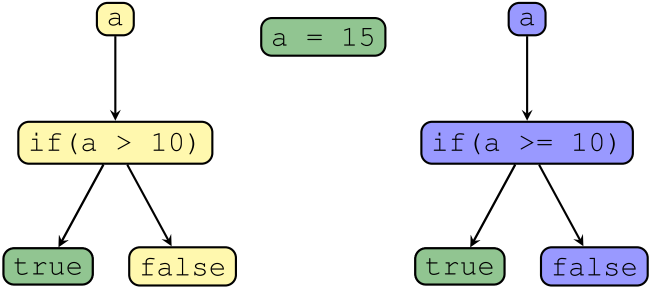

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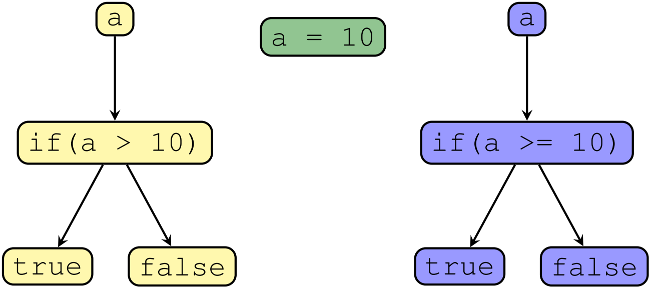

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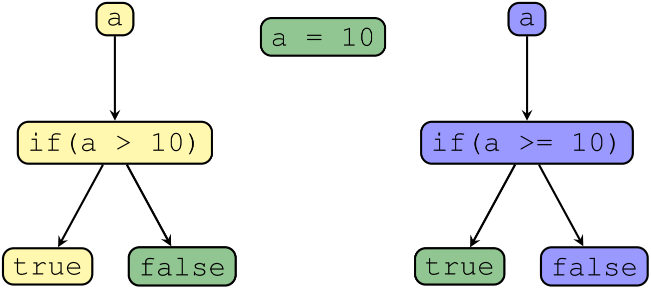

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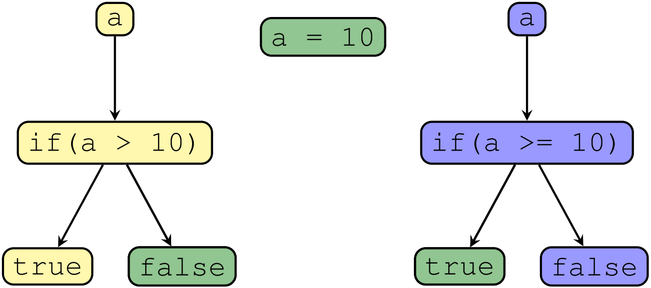
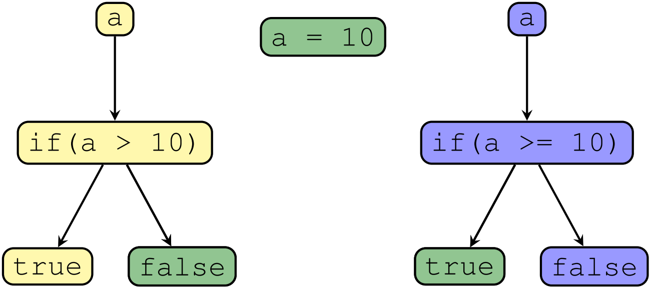


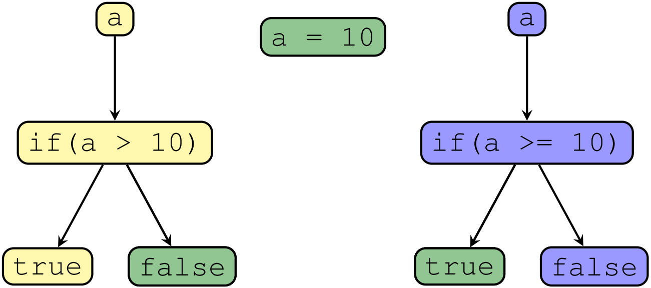
Can the tests differentiate between *implemented* and *potential fault*?

Conceptual Faults



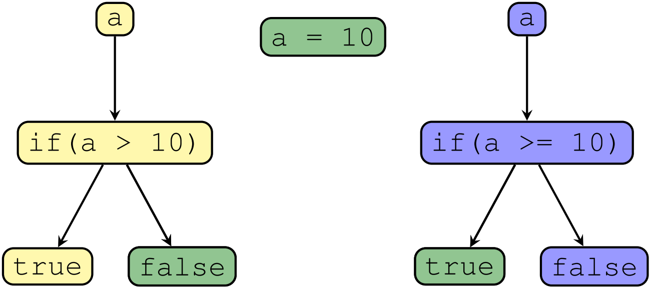
If *yes*, then the tests are *adequate*!

Conceptual Faults



If *no*, then the tests must be *improved*!

Conceptual Faults

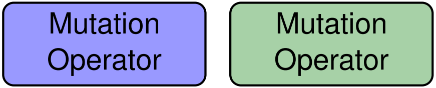


Purposefully insert faults in order to implement quality software!

Overview of Mutation Analysis

Mutation Operator

Overview of Mutation Analysis



Mutation Operator

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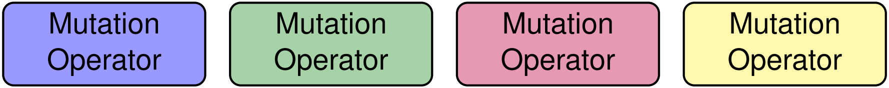

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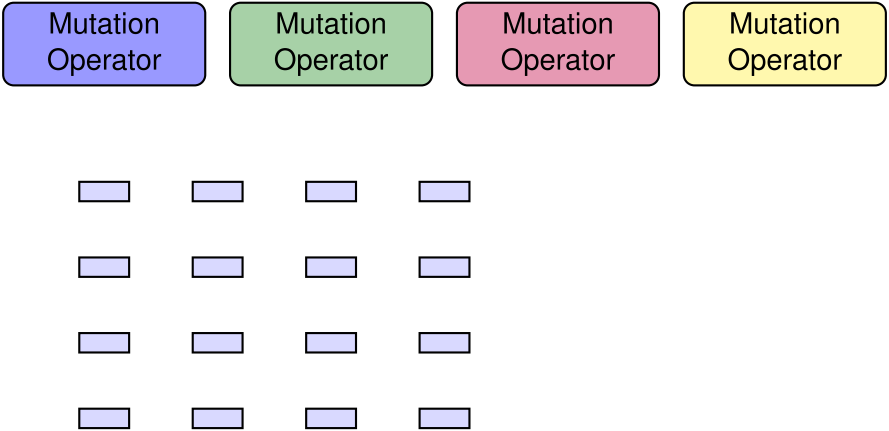

Mutation Operator

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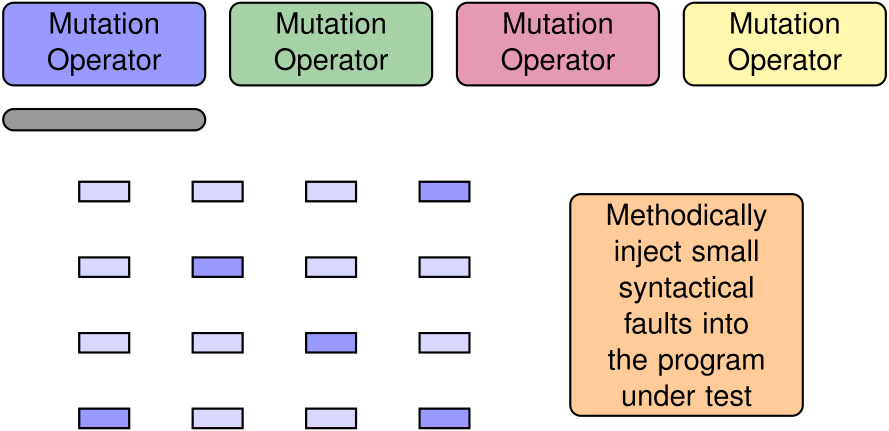
Mutation Operator

Overview of Mutation Analysis



Mutation Operator

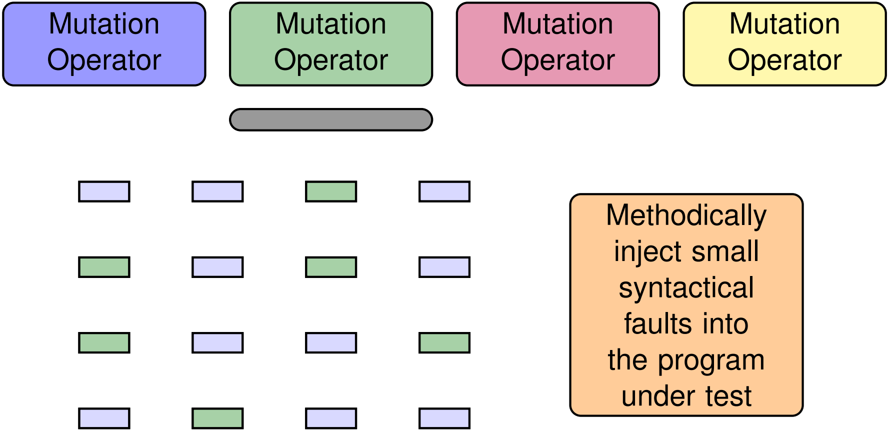
Mutation Operator

Mutation Operator

Mutation Operator

Methodically inject small syntactical faults into the program under test

Overview of Mutation Analysis



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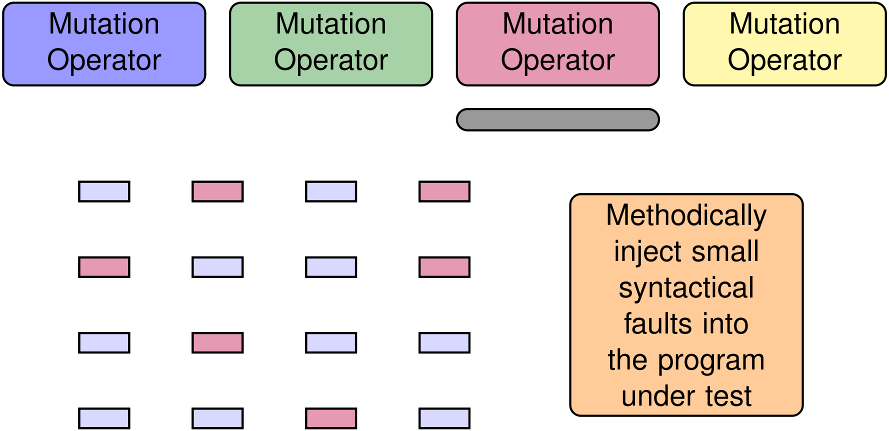
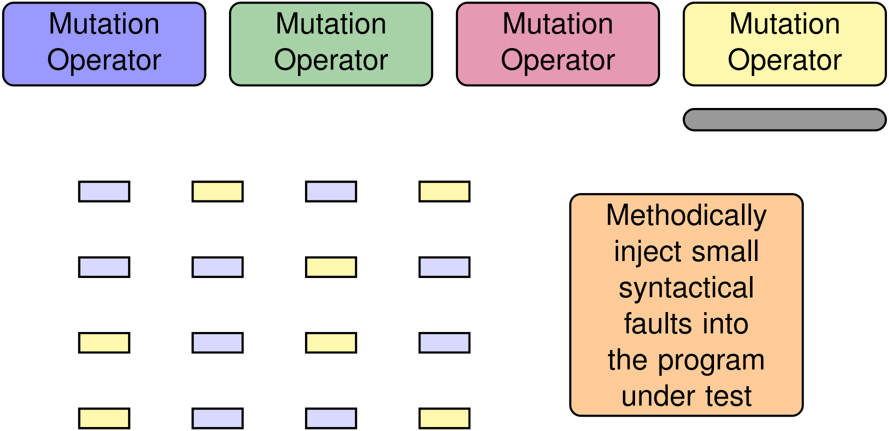


Methodically inject small syntactical faults into the program under test

Overview of Mutation Analysis



Mutation Operator

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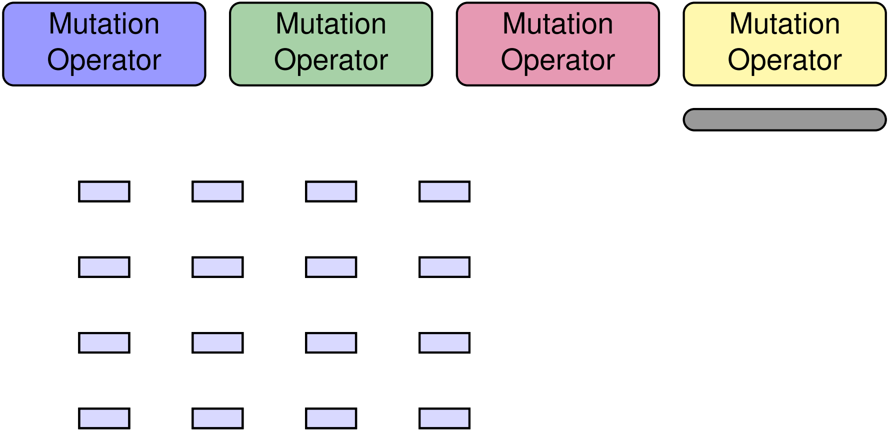
Methodically inject small syntactical faults into the program under test

Overview of Mutation Analysis



Mutation Operator

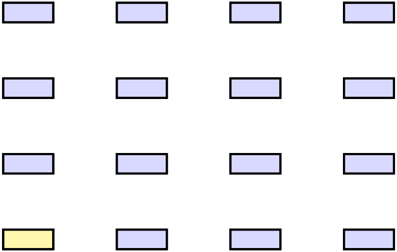
Mutation Operator

Mutation Operator

Mutation Operator

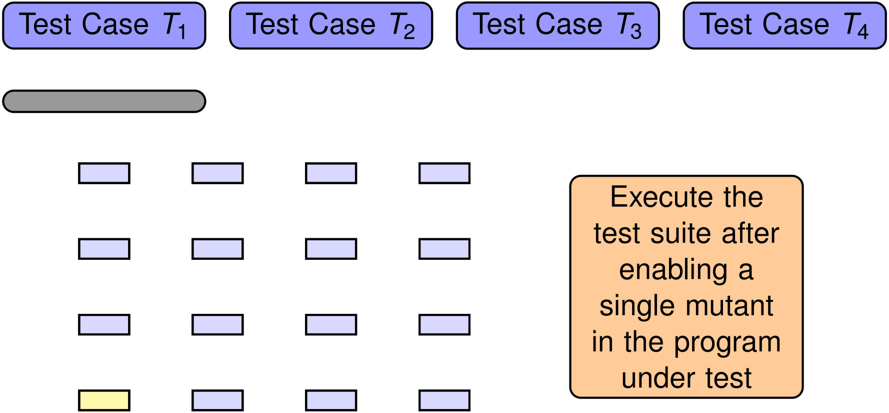
Overview of Mutation Analysis

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



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

Overview of Mutation Analysis



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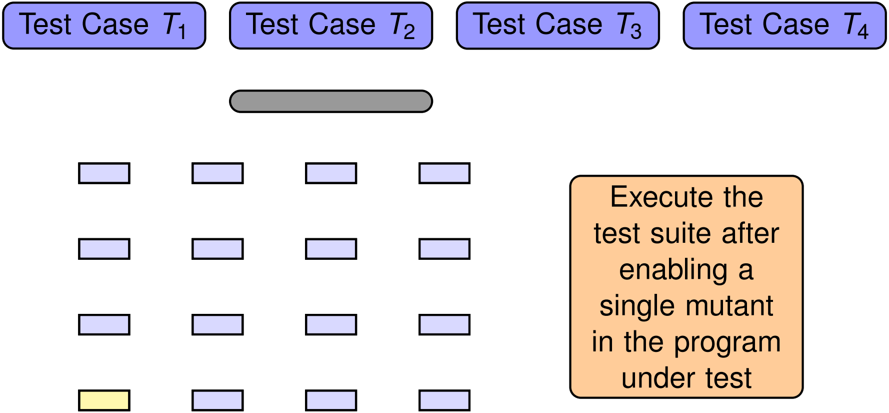

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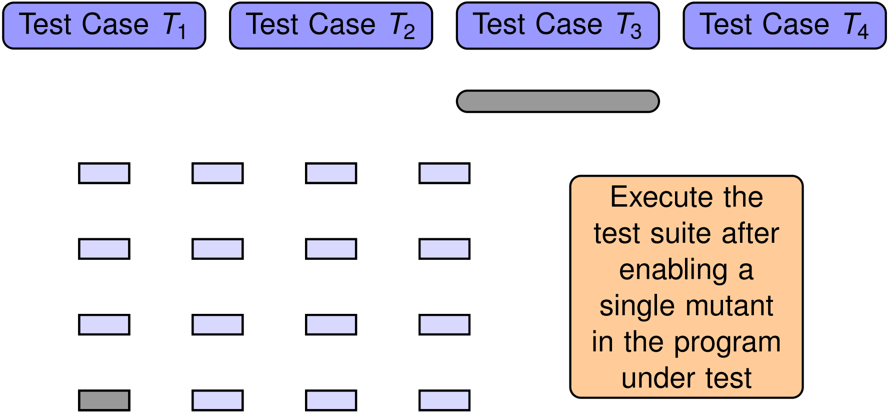

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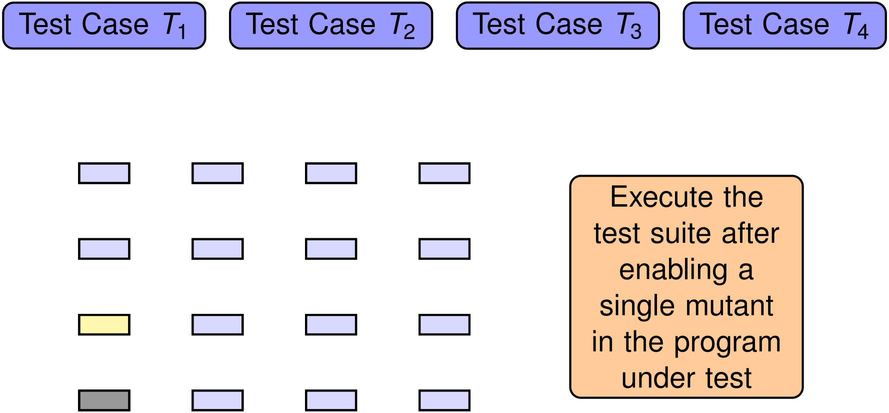

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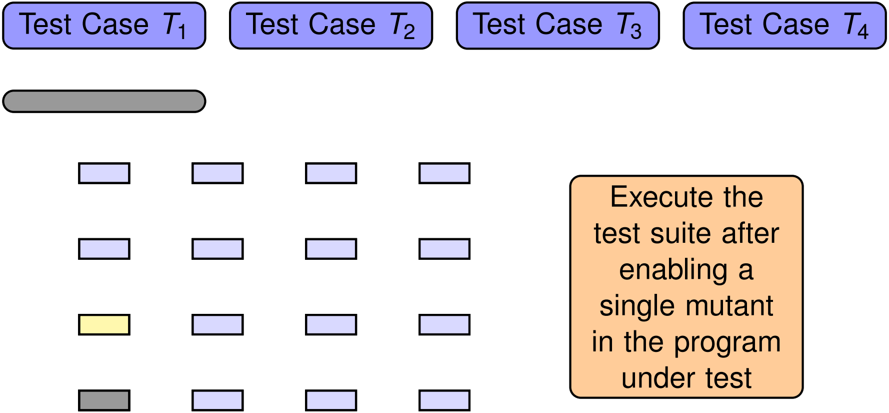

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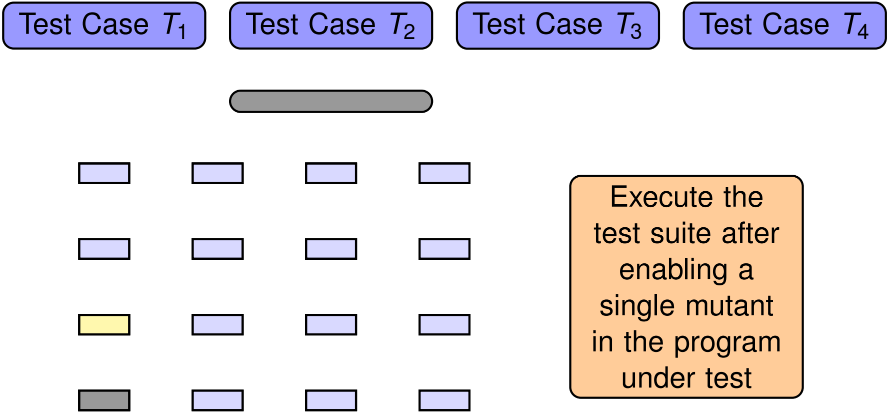
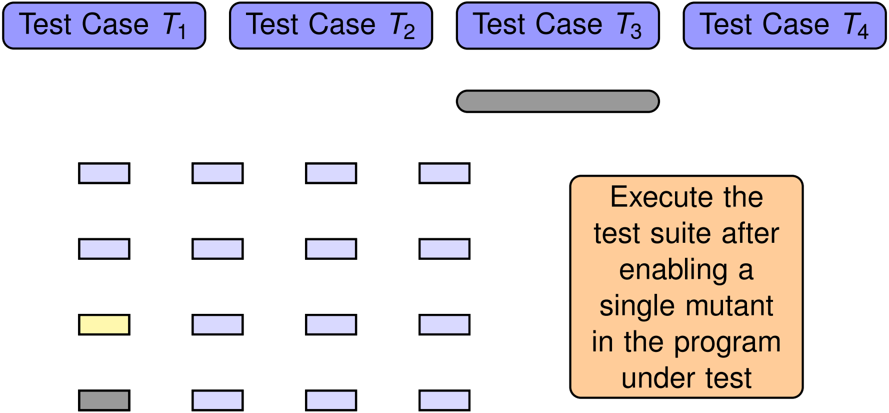


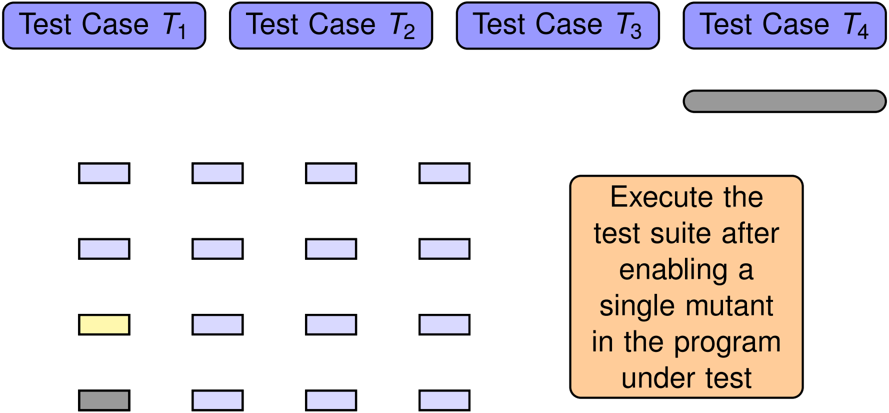
Execute the test suite after enabling a single mutant in the program under test

Overview of Mutation Analysis


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

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

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

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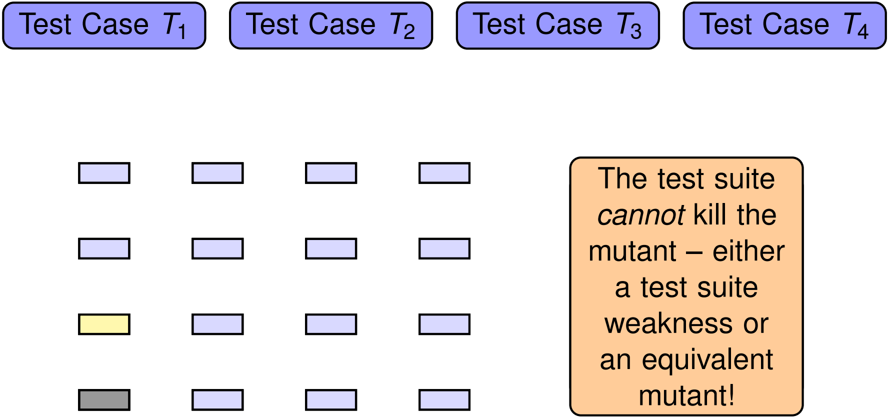
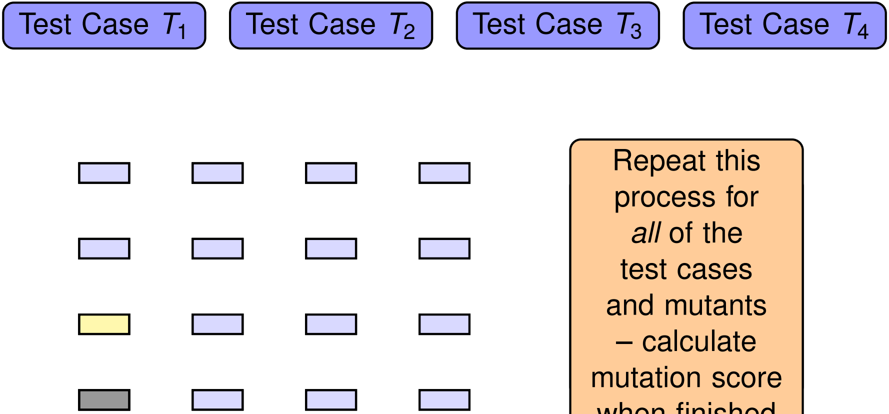


The test suite *cannot* kill the mutant – either a test suite weakness or an equivalent mutant!

Overview of Mutation Analysis



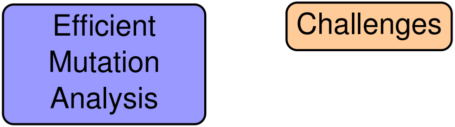
Test Case T_1 Test Case T_2 Test Case T_3 Test Case T_4

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

Contributions of this Presentation

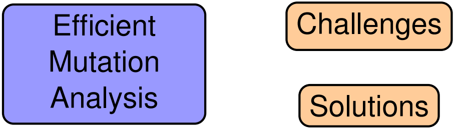
Efficient Mutation Analysis

Contributions of this Presentation


Efficient Mutation Analysis

Challenges

Contributions of this Presentation

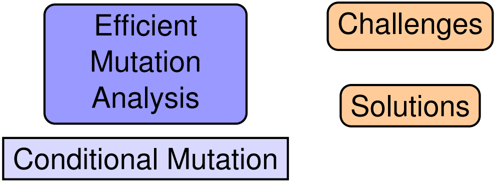


Efficient Mutation Analysis

Challenges

Solutions

Contributions of this Presentation



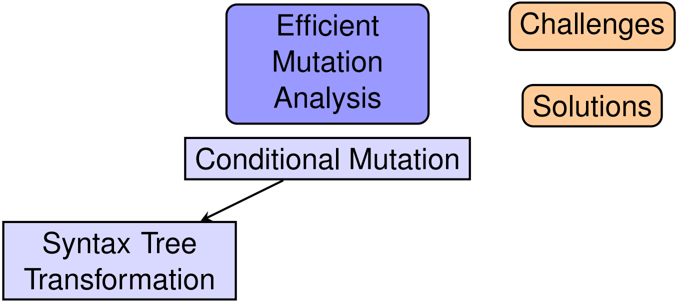
Efficient Mutation Analysis

Challenges

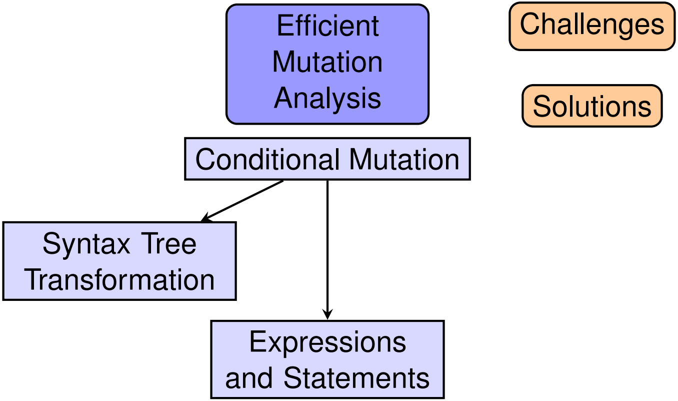
Solutions

Conditional Mutation

Contributions of this Presentation



Contributions of this Presentation


Efficient Mutation Analysis

Challenges

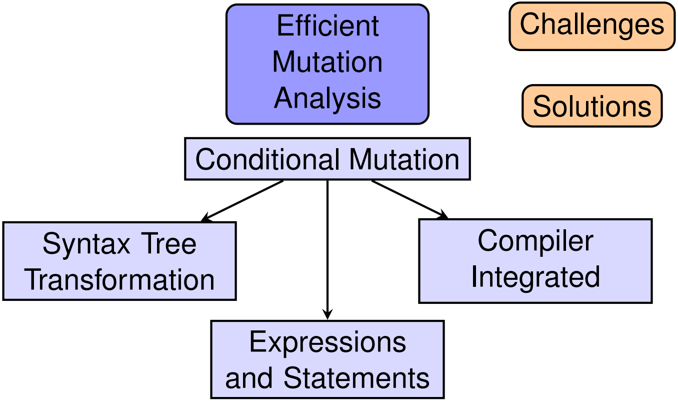
Solutions

Conditional Mutation

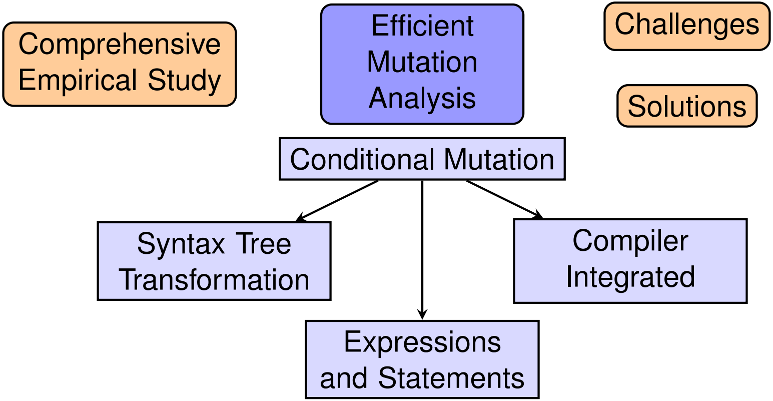
Syntax Tree Transformation

Expressions and Statements

Contributions of this Presentation


Efficient Mutation Analysis
Challenges
Solutions
Conditional Mutation
Syntax Tree Transformation
Expressions and Statements
Compiler Integrated

Contributions of this Presentation


Comprehensive Empirical Study
Efficient Mutation Analysis
Challenges
Solutions
Conditional Mutation
Syntax Tree Transformation
Compiler Integrated
Expressions and Statements

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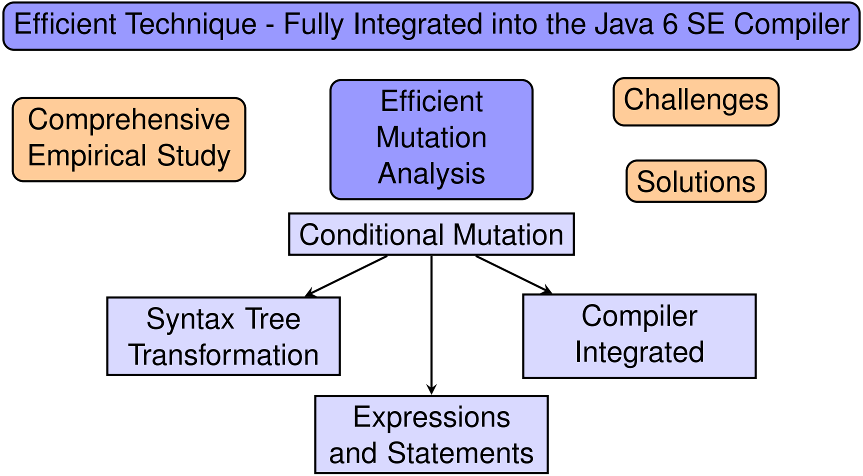
Efficient Technique - Fully Integrated into the Java 6 SE Compiler
Comprehensive Empirical Study
Efficient Mutation Analysis
Challenges
Solutions
Conditional Mutation
Syntax Tree Transformation
Expressions and Statements
Compiler Integrated

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;
}
```

Understanding Mutation Analysis

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Methodically inject small syntactical faults into the program under test

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Understanding Mutation Analysis

```
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    y = a * x;

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

⟹

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

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

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

    return max;
}
```

⟹

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

Understanding Mutation Analysis

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

    y = a * x;

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    return y;
}

public int max(int a, int b){
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Unbiased and powerful method for assessing oracles and input values

Understanding Mutation Analysis

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```

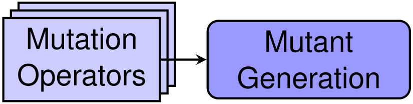
Unbiased and powerful method for assessing oracles and input values

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

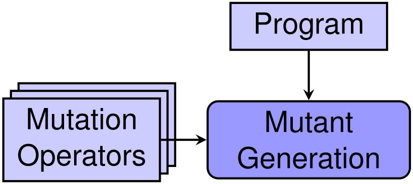
Mutation Analysis Challenges

Mutant Generation

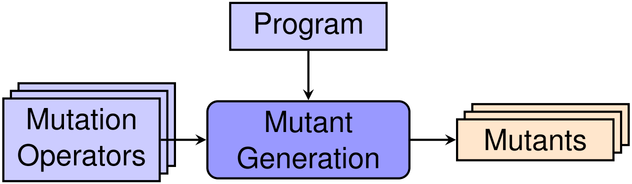
Mutation Analysis Challenges



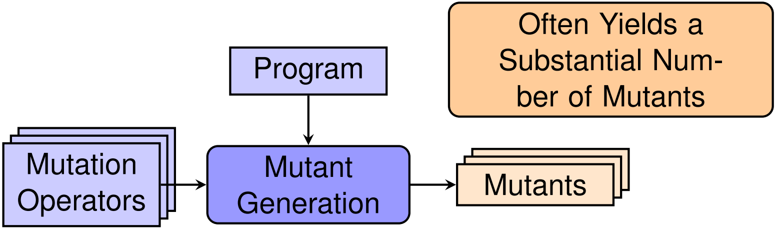
Mutation Analysis Challenges



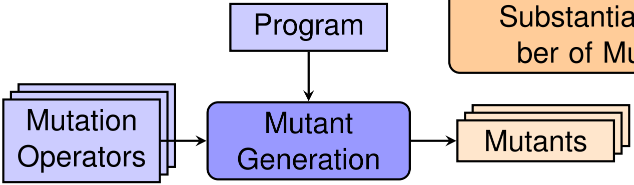
Mutation Analysis Challenges



Mutation Analysis Challenges



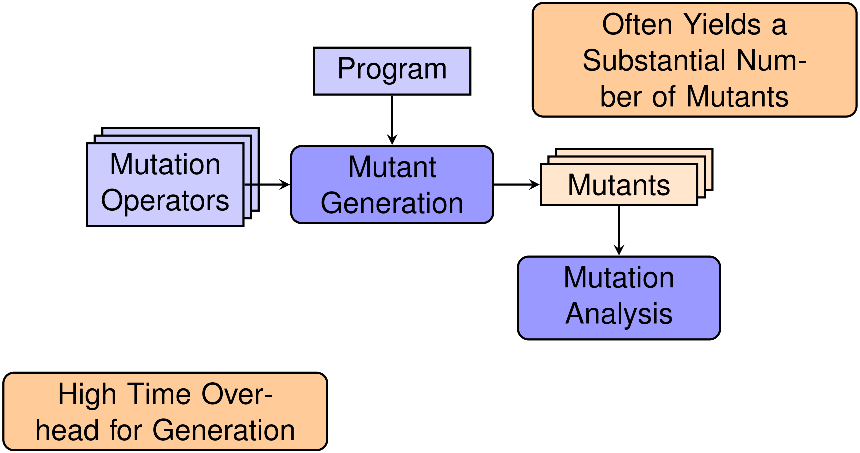
Mutation Analysis Challenges



Often Yields a Substantial Number of Mutants

High Time Overhead for Generation

Mutation Analysis Challenges



Program

Mutation Operators

Mutant Generation

Mutants

Mutation Analysis

Often Yields a Substantial Number of Mutants

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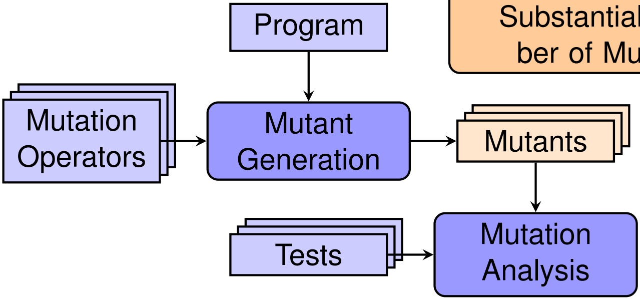
Mutation Analysis Challenges

Often Yields a Substantial Number of Mutants



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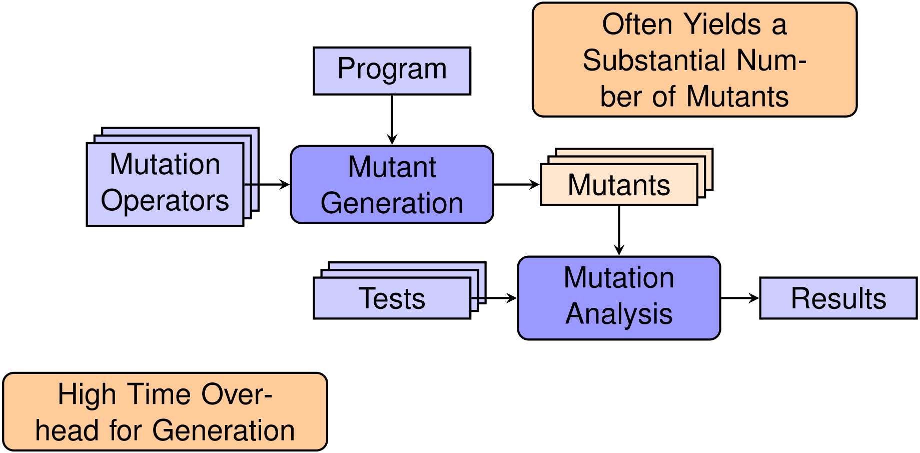
Mutation Analysis Challenges



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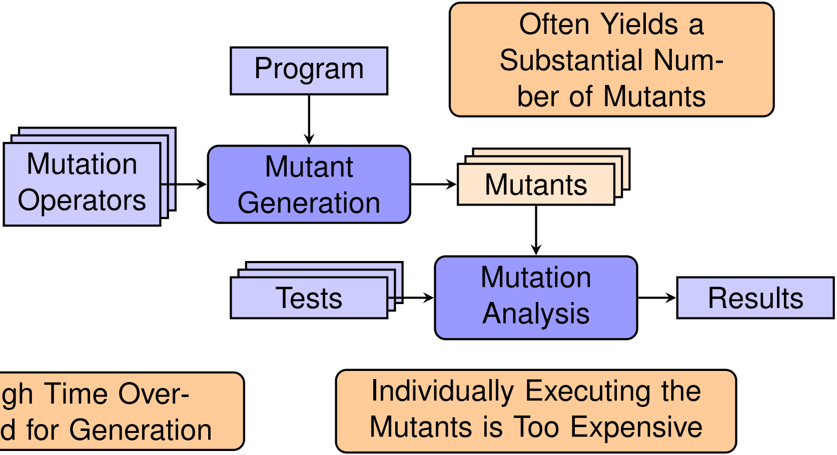
Mutation Analysis Challenges

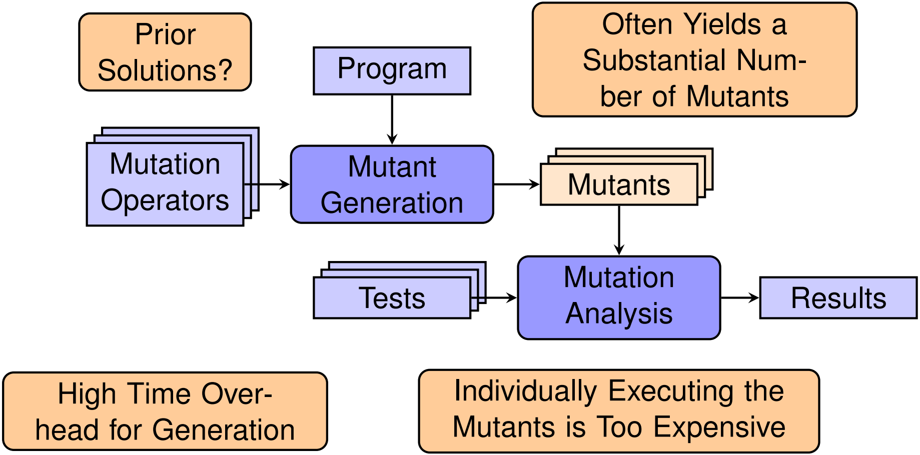


Often Yields a Substantial Number of Mutants

High Time Overhead for Generation

Individually Executing the Mutants is Too Expensive

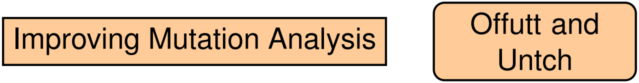
Mutation Analysis Challenges


Prior Solutions?
Program
Often Yields a Substantial Number of Mutants
Mutation Operators
Mutant Generation
Mutants
Tests
Mutation Analysis
Results
High Time Overhead for Generation
Individually Executing the Mutants is Too Expensive

Prior Work in Mutation Analysis

Improving Mutation Analysis

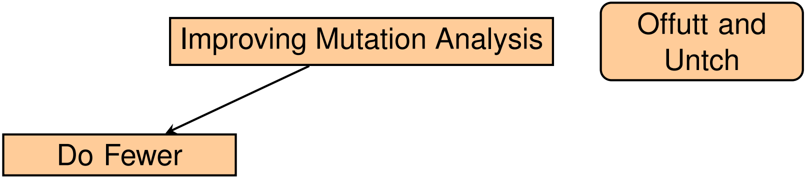
Prior Work in Mutation Analysis



Improving Mutation Analysis

Offutt and Untch

Prior Work in Mutation Analysis



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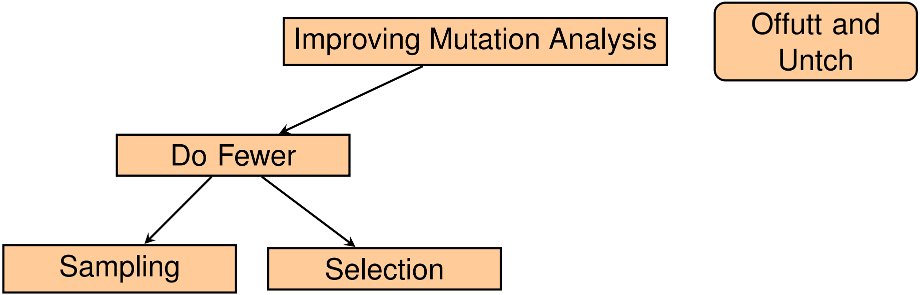

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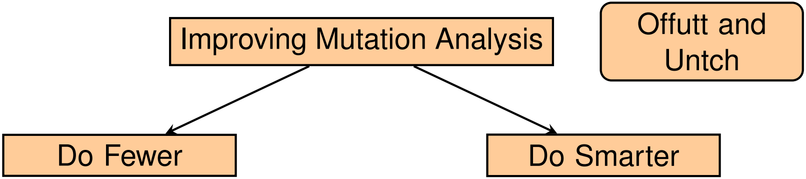

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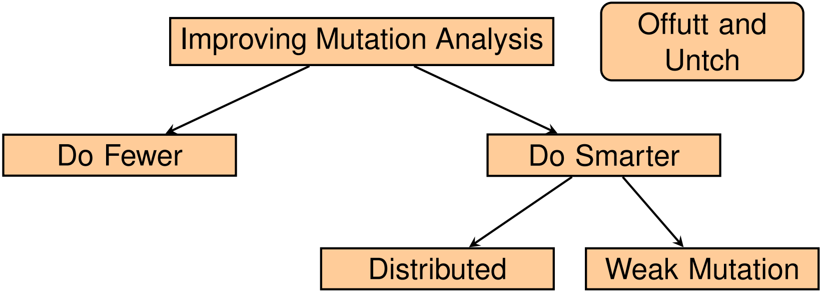

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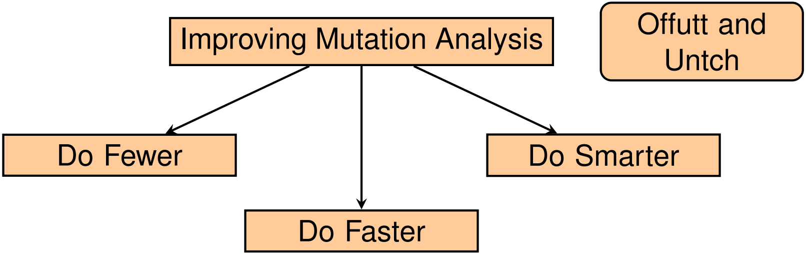

Improving Mutation Analysis

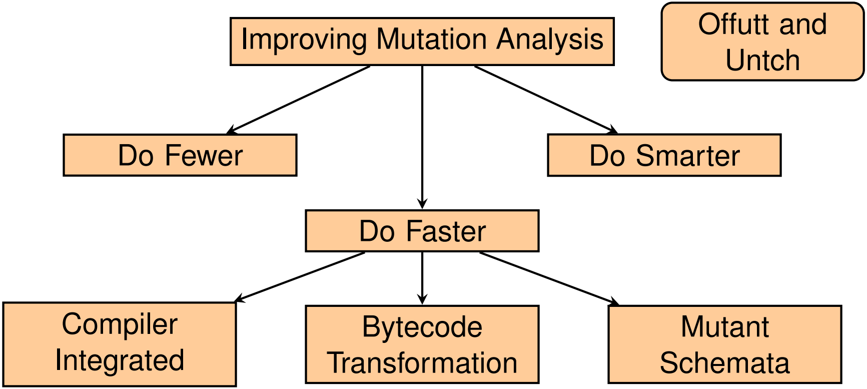
Offutt and Untch

Do Fewer

Do Smarter

Do Faster

Prior Work in Mutation Analysis



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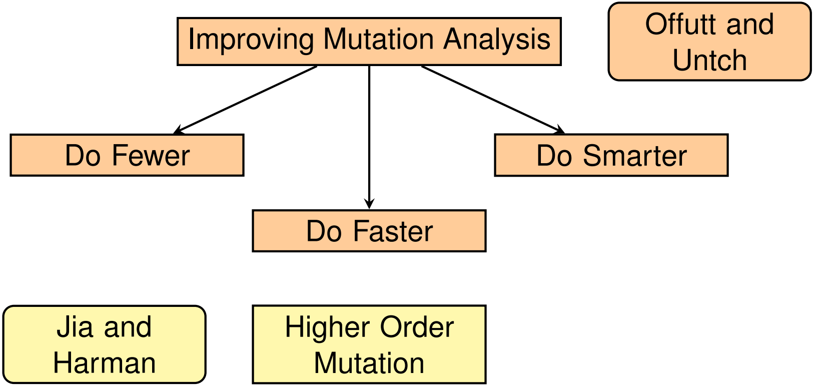
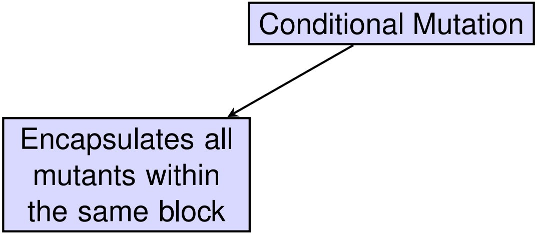


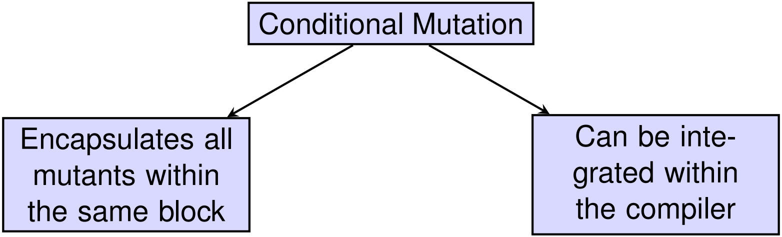
Conditional Mutation

Conditional Mutation

Conditional Mutation



Conditional Mutation

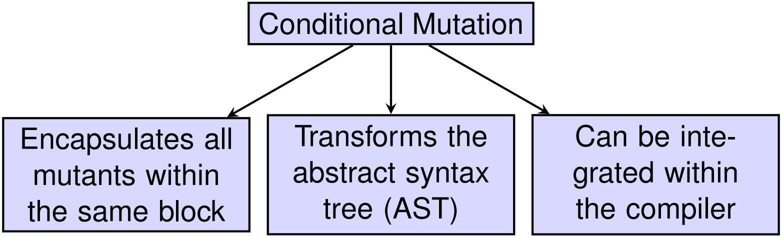


Conditional Mutation

Encapsulates all mutants within the same block

Can be integrated within the compiler

Conditional Mutation



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Encapsulates all mutants within the same block

Transforms the abstract syntax tree (AST)

Can be integrated within the compiler

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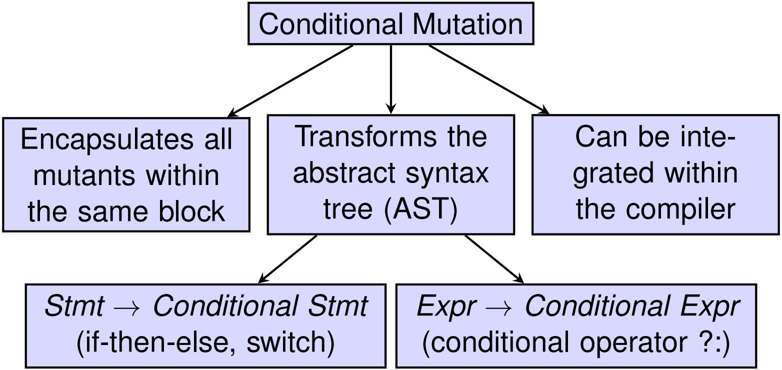

Conditional Mutation

Encapsulates all mutants within the same block

Transforms the abstract syntax tree (AST)

Can be integrated within the compiler

Stmt → *Conditional Stmt* (if-then-else, switch)

Expr → *Conditional Expr* (conditional operator ?:)

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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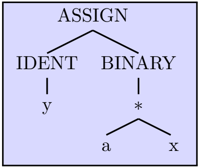
⇓



Transforming the AST

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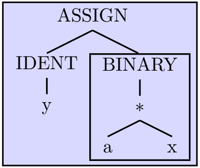

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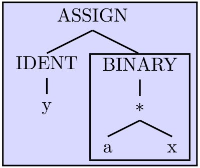
⇓



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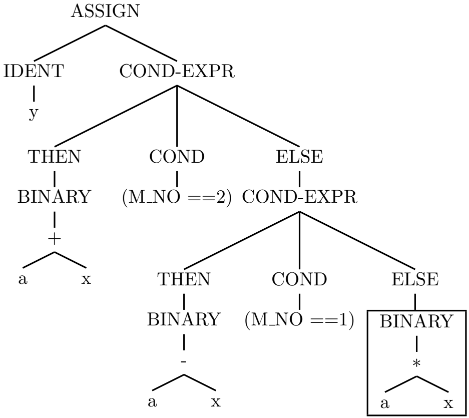

Source Code View of Inserting Mutants

```
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 = (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 $MOP(x * y) = \{x - y, x + y, x/y\}$
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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 $MOP(x * y) = \{x - y, x + y, x/y\}$
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Collecting and Using Mutation Coverage

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        (M_NO==0 &&
         COVERED(1,3))?
           a * x : a * x;

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Mutants that are not executed cannot be killed

Determine covered mutants with additional instrumentation

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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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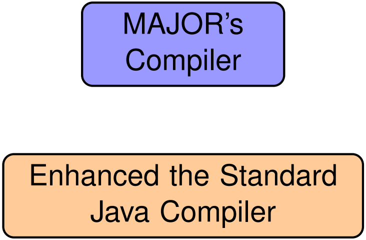
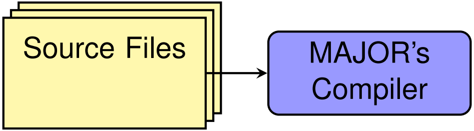


MAJOR’s Compiler

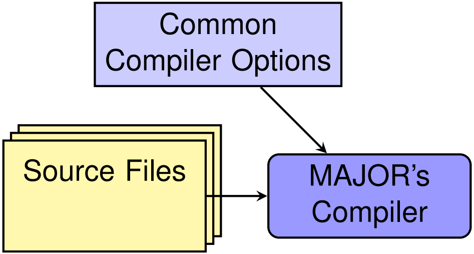
Enhanced the Standard Java Compiler

MAJOR's Compiler



Enhanced the Standard Java Compiler

MAJOR's Compiler



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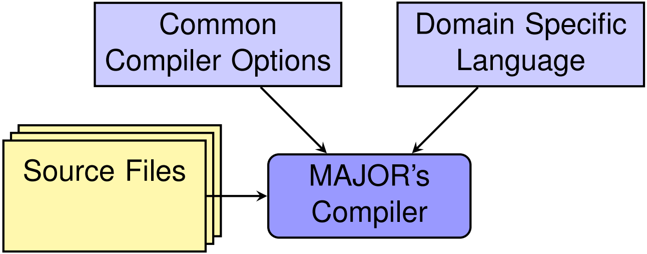

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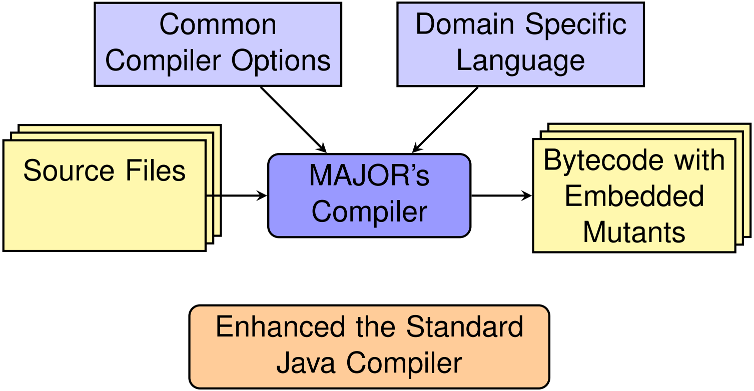
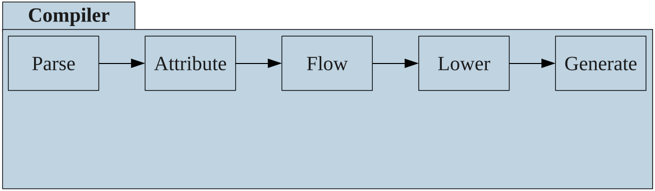


Integration into the Java Compiler



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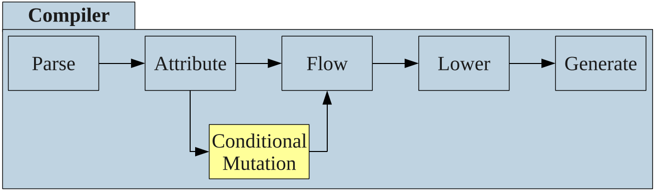

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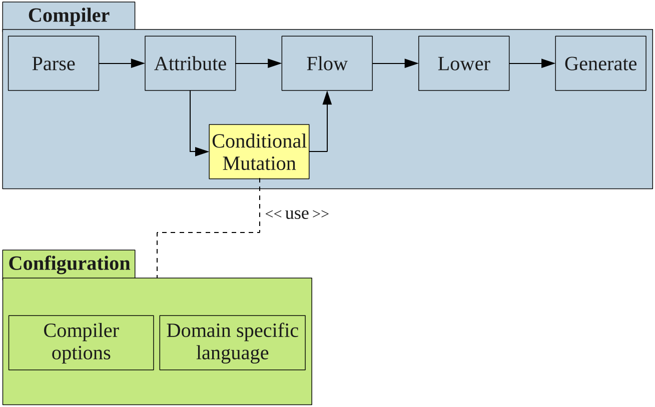

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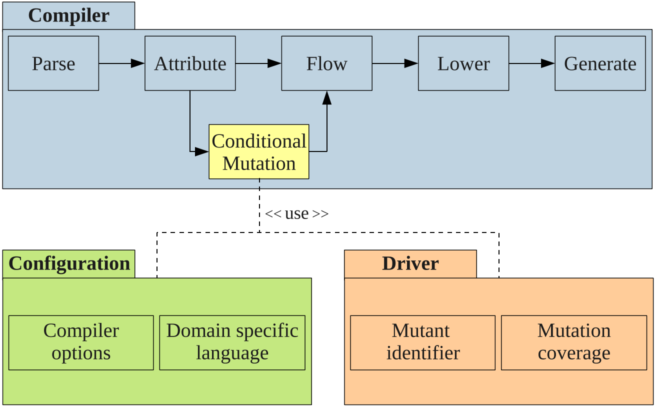

MAJOR's Domain Specific Language

```
// 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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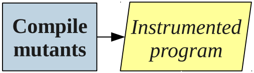
Specify mutation operators in detail

Define own mutation operator groups

Enable operators for a specific package, class, or method

Optimized Mutation Analysis Process



1. Embed and compile all mutants
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4. Perform mutation analysis with reordered test suite

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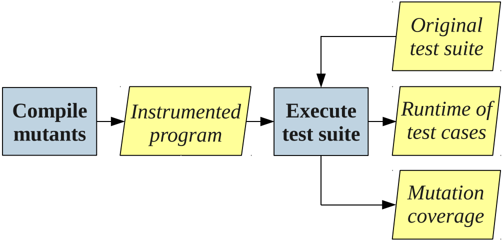

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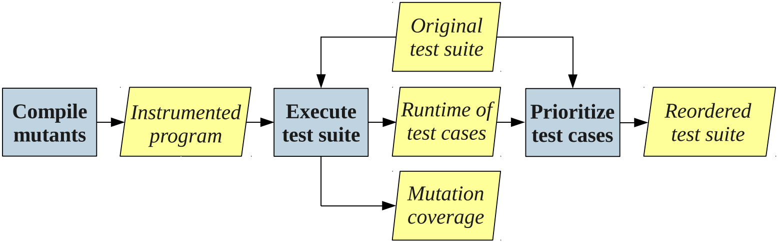

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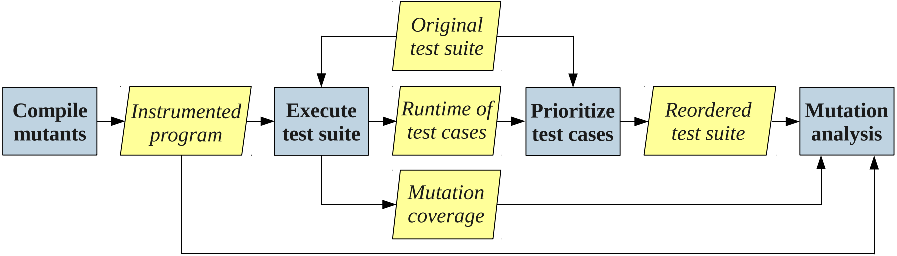

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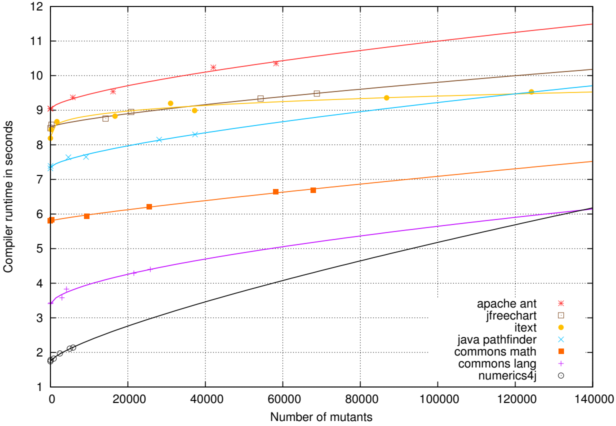
Mutant Generation and Compilation



Overhead for generating and compiling mutants is negligible

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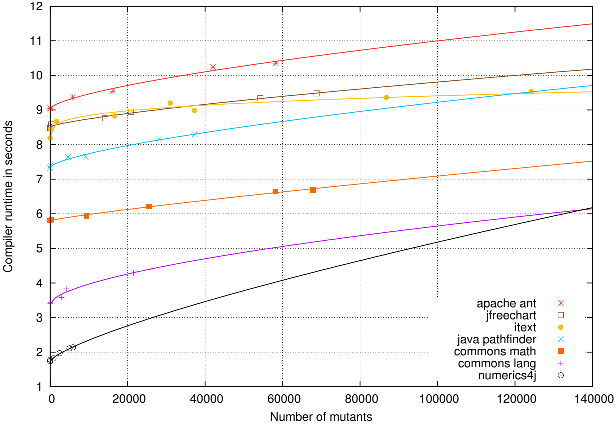

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Time and Space Overhead

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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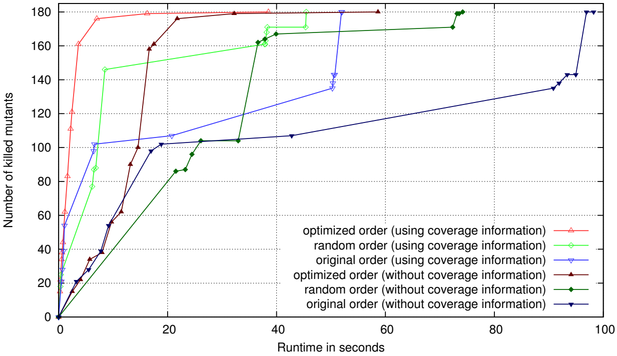
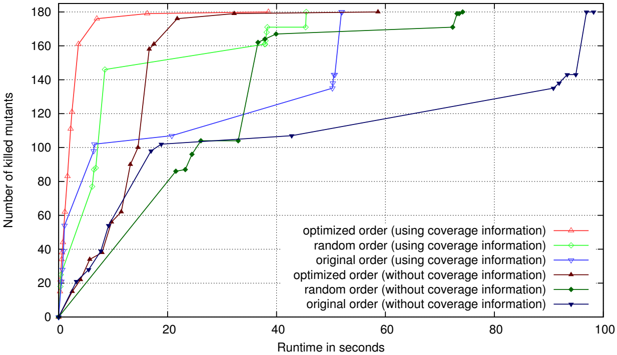
Evaluating and Improving Mutation Analysis



- 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

Evaluating and Improving Mutation Analysis



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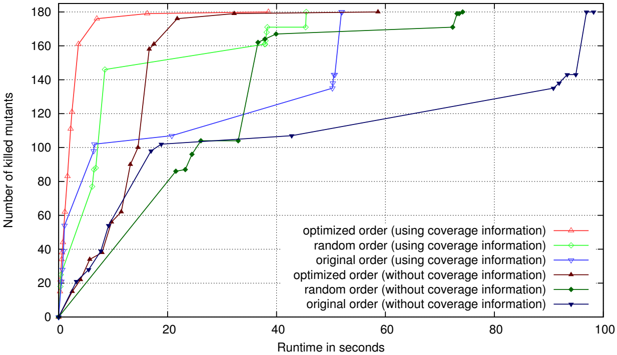

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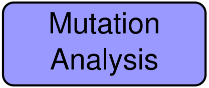
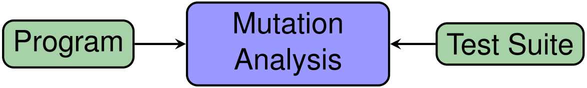
Improving Test Suite Quality



Mutation Analysis

Improving Test Suite Quality



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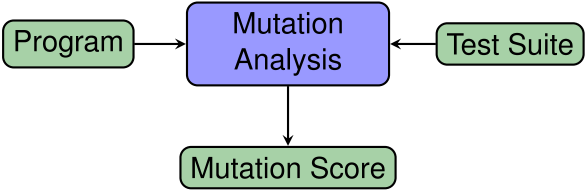

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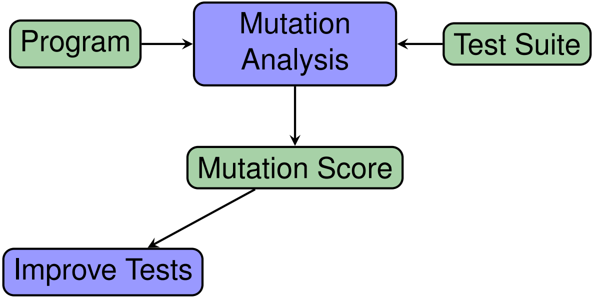

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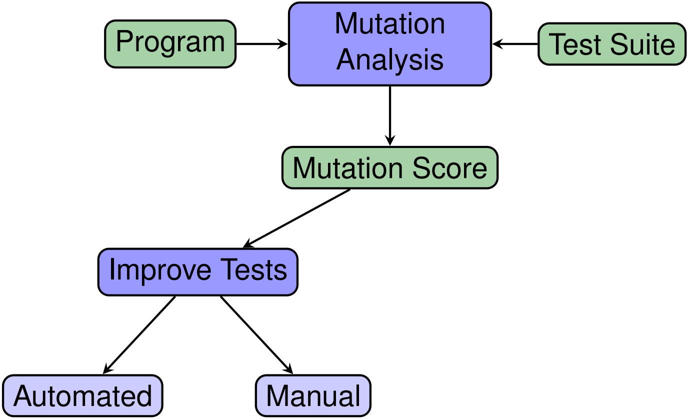

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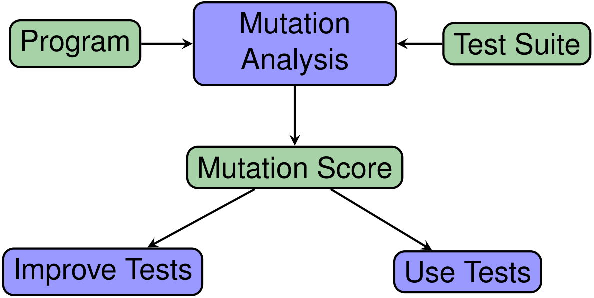

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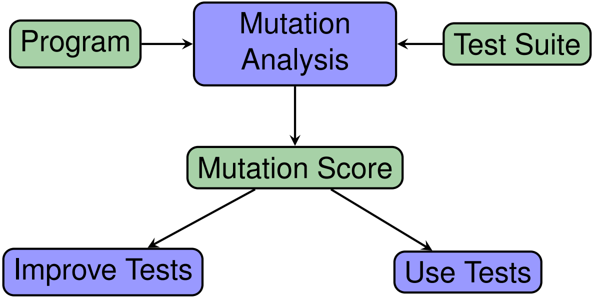

Test improvement is only effective if mutation analysis is efficient!

Reviewing MAJOR's Contributions

Mutation Analysis

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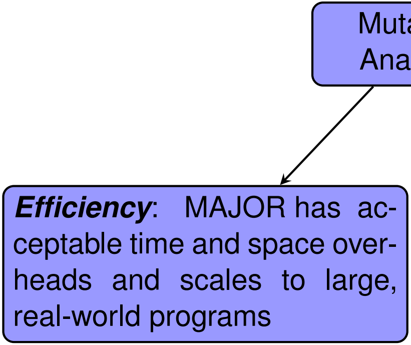

Mutation Analysis

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

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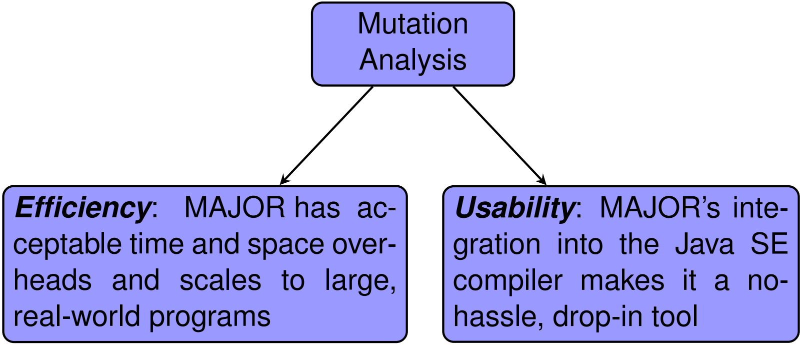

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Usability: MAJOR's integration into the Java SE compiler makes it a no-hassle, drop-in tool

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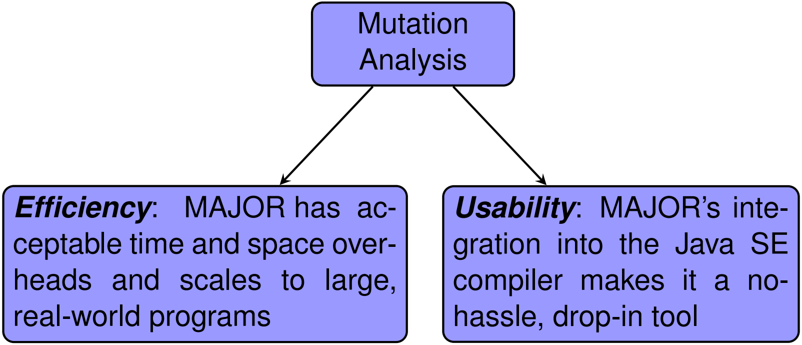

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We will release MAJOR as free and open source software

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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- Compiler-integrated solution
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Characteristics of MAJOR:

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

Recently Published Papers

- René Just, Gregory M. Kapfhammer, and Franz Schweiggert. Using conditional mutation to increase the efficiency of mutation analysis. In *Proceedings of the 6th International Workshop on the Automation of Software Test*, Honolulu, Hawaii, May 2011.
- René Just, Franz Schweiggert, and Gregory M. Kapfhammer. MAJOR: An efficient and extensible tool for mutation analysis in a Java compiler. In *Proceedings of the 26th IEEE/ACM International Conference on Automated Software Engineering* (Tool Paper), Lawrence, Kansas, November 2011.

Efficient and Effective Mutation Testing: Supporting the Implementation of Quality Software by Purposefully Inserting Defects

Gregory M. Kapfhammer

Department of Computer Science
Allegheny College
http://www.cs.allegheny.edu/~gkapfham/

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