Introduction to Software Testing
Chapter 9.2
Program-based Grammars

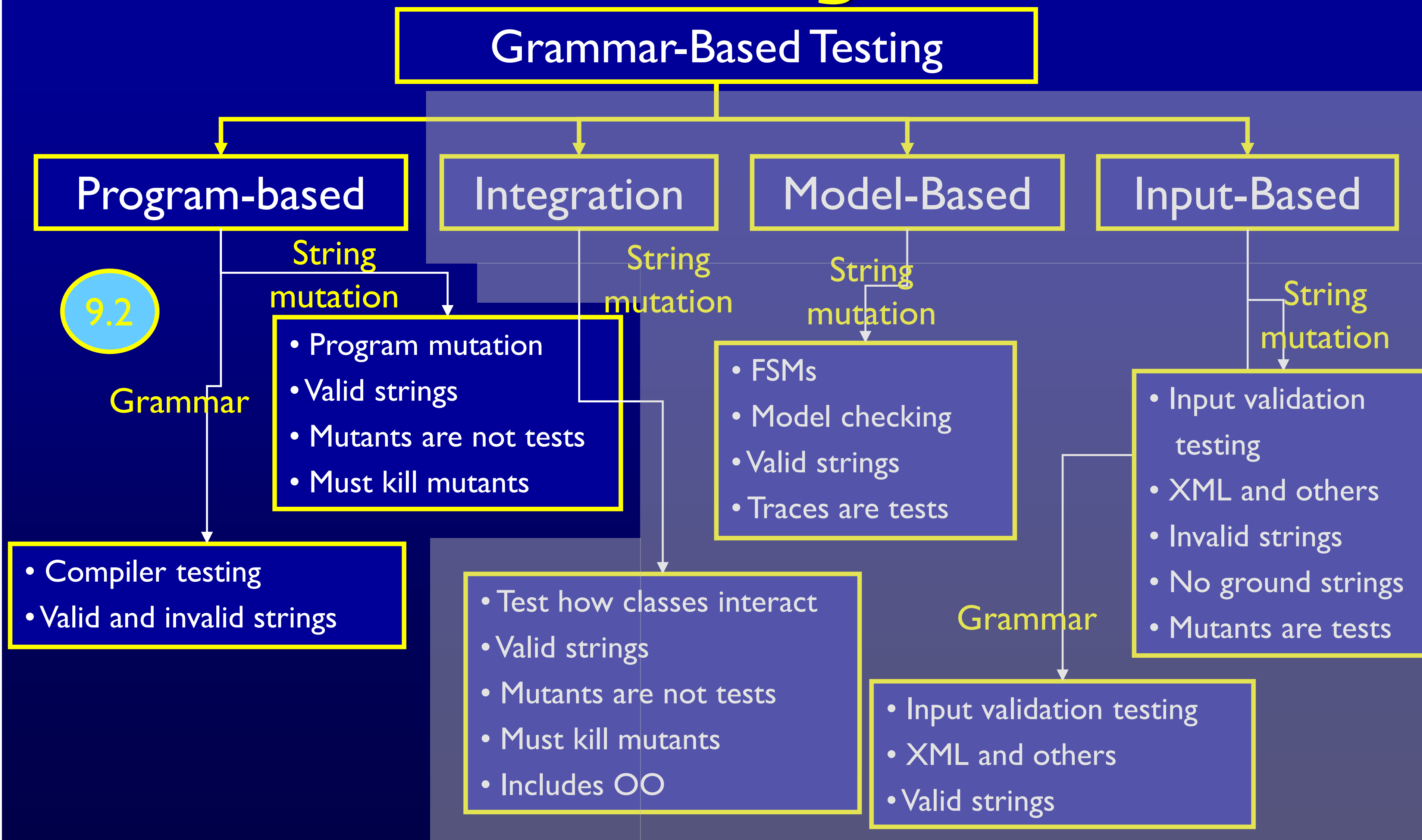
Paul Ammann & Jeff Offutt

http://www.cs.gmu.edu/~offutt/softwaretest/

Applying Syntax-based Testing to Programs

- Syntax-based criteria originated with programs and have been used mostly with programs
- BNF criteria are most commonly used to test compilers
- Mutation testing criteria are most commonly used for unit testing and integration testing of classes

Instantiating Grammar-Based Testing



BNF Testing for Compilers (9.2.1)

- Testing compilers is very complicated
  - Millions of correct programs !
  - Compilers must recognize and reject incorrect programs
- BNF criteria can be used to generate programs to test <u>all language features</u> that compilers must process
- This is a very specialized application and <u>not</u> discussed in detail

Program-based Grammars (9.2.2)

- The original and most widely known application of syntax-based testing is to modify programs
- Operators modify a ground string (program under test) to create mutant programs
- Mutant programs must compile correctly (valid strings)
- Mutants are not tests, but <u>used to find tests</u>
- Once mutants are defined, tests must be found to <u>cause mutants to fail</u> when executed
- This is called "killing mutants"

Killing Mutants

Given a mutant $m \in M$ for a ground string program P and a test t, t is said to kill m if and only if the output of t on P is different from the output of t on m.

- If mutation operators are designed well, the resulting tests will be very powerful
- Different operators must be defined for different programming languages and different goals
- Testers can keep adding tests until all mutants have been killed
  - *Dead mutant* : A test case has killed it
  - *Stillborn mutant* : Syntactically illegal (can be caught by compiler)
  - *Trivial mutant* : Almost every test can kill it
  - *Equivalent mutant* : No test can kill it (same behavior as original)
    - are infeasible test requirements

Program-based Mutation

- Program-based mutation has traditionally been applied to individual statements for unit level testing
- It is hard to quantify the number of test requirements for mutation
  - It depends on the specific set of operators used and the language that the operators are applied to
  - The number of program-based mutants is roughly proportional to the product of the number of references to variables times the number of variables that are declared (O(Refs*Vars))
- The mutation operators are defined to satisfy one of two goals.
  - One goal is to mimic typical programmer mistakes, thus trying to ensure that the tests can detect those mistakes
  - The other goal is to force the tester to create tests that have been found to effectively test software
- When applying program-based mutation, the direct goal of the tester is to kill mutants; an indirect goal is to create good tests
  - Even less directly, the tester wants to find faults. Tests that kill mutants can be found by intuition, or if more rigor is needed, by analyzing the conditions under which a mutant will be killed

Program-based Grammars

Original Method

```
int Min (int A, int B)
{
      int minVal;
      minVal = A;
      if (B < A)
      {
           minVal = B;
       }
       return (minVal);
} // end Min
```

6 mutants

Each represents a separate program

With Embedded Mutants

```
int Min (int A, int B)
{
        int minVal;
        minVal = A;
∆ 1  minVal = B;
        if (B < A)
∆ 2  if (B > A)
∆ 3  if (B < minVal)
        {
                minVal = B;
∆ 4           Bomb ();
∆ 5           minVal = A;
∆ 6           minVal = failOnZero (B);
        }
        return (minVal);
} // end Min
```

Replace one variable with another

Replaces operator

Immediate runtime failure … if reached *(it forces every statement to be executed)*

Immediate runtime failure if B==0, else does nothing *(return the value of the B if B<>0)*

Syntax-Based Coverage Criteria

Mutation Coverage (MC) : For each *m* $\in$ *M*, TR contains exactly one requirement, to kill *m*.

- The RIPR model from chapter 2:
  - *Reachability* : The test causes the faulty statement to be reached (in mutation – the mutated statement)
  - *Infection* : The test causes the faulty statement to result in an incorrect state
  - *Propagation* : The incorrect state propagates to incorrect output
  - *Revealability* : The tester must observe part of the incorrect output
- The RIPR model leads to two variants of mutation coverage …

Syntax-Based Coverage Criteria

1) Strongly Killing Mutants:

Given a mutant $m \in M$ for a program *P* and a test *t*, *t* is said to *strongly kill m* if and only if the output of *t* on *P* is different from the output of *t* on *m*

2) Weakly Killing Mutants:

Given a mutant $m \in M$ that modifies a location *l* in a program *P*, and a test *t*, *t* is said to *weakly kill m* if and only if the state of the execution of *P* on *t* is different from the state of the execution of *m* on *t* immediately after *l*

- Weakly killing satisfies reachability and infection, but not propagation

Strong mutation may require more tests to satisfy coverage than weak mutation

Weak Mutation

Weak Mutation Coverage (WMC) : For each $m \in M$, TR contains exactly one requirement, to weakly kill m.

- "Weak mutation" is so named because it is easier to kill mutants under this assumption
- Weak mutation also requires less analysis
- A few mutants can be killed under weak mutation but not under strong mutation (no propagation)
- Studies have found that test sets that weakly kill all mutants also strongly kill most mutants

Weak Mutation Example

Mutant 1 in the Min( ) example is:

```
int Min (int A, int B)
{
      int minVal;
      minVal = A;
∆ 1  minVal = B;
      if (B < A)
      {
          minVal = B;
       }
       return (minVal);
} // end Min
```

With one or two partners :

1. Find a test that weakly kills the mutant, but not strongly
2. Generalize : What must be true to weakly kill the mutant, but not strongly?
3. Try to write down the conditions needed to (i) reach the mutated statement, (ii) infect the program state, and (iii) propagate to output

Weak Mutation Example

```
      minVal = A;
Δ 1  minVal = B;
      if (B < A)
          minVal = B;
```

1. Find a test that weakly kills the mutant, but not strongly

   A = 5, B = 3

2. Generalize : What must be true to weakly kill the mutant, but not strongly?

   B < A // minVal is set to B on for both

3. RIP conditions

Reachability : *true* // we always reach

Infection : *A ≠ B // minVal has a different value*

Propagation : *(B < A) = false // Take a different branch*

(A = 5, B = 7) should cause mutant 1 to result in a failure (strong kill)

Equivalent Mutation Example

Mutant 3 in the Min() example is equivalent:

```
int Min (int A, int B)
{
      int minVal;
      minVal = A;
      if (B < A)
∆ 3   if (B < minVal)
      {
          minVal = B;
      }
      return (minVal);
} // end Min
```

With one or two partners

1. Convince yourselves that this mutant is equivalent
2. Briefly explain why
3. Try to prove the equivalence

   Hint : Think about what must be true to kill the mutant

Thus no input can kill this mutant

Equivalent Mutation Example

```
    minVal = A;
    if (B < A)
Δ 3 if (B < minVal)
```

1. Convince yourselves that this mutant is equivalent
2. Briefly explain why

   A and minVal have the same value at the mutated statement

3. Try to prove the equivalence

   Hint : Think about what must be true to kill the mutant

   Infection : (B < A) != (B < minVal)
   Previous statement : minVal = A
   Substitute : (B < A) != (B < A)
   Contradiction … therefore, **equivalent**

Strong Versus Weak Mutation

```
1     boolean isEven (int X)
2     {
3         if (X < 0)
4             X = 0 - X;
Δ 4           X = 0;
5         if (double) (X/2) == ((double) X) / 2.0
6             return (true);
7         else
8             return (false);
9     }
```

<u>Reachability</u> : $X < 0$

<u>Infection</u> : $X \mathrel{!=} 0$

($X = -6$) will kill mutant 4 under <u>weak mutation</u>

<u>Propagation</u> :

((double) ((0-X)/2) == ((double) 0-X) / 2.0)

!= ((double) (0/2) == ((double) 0) / 2.0)

That is, X is <u>not</u> even …

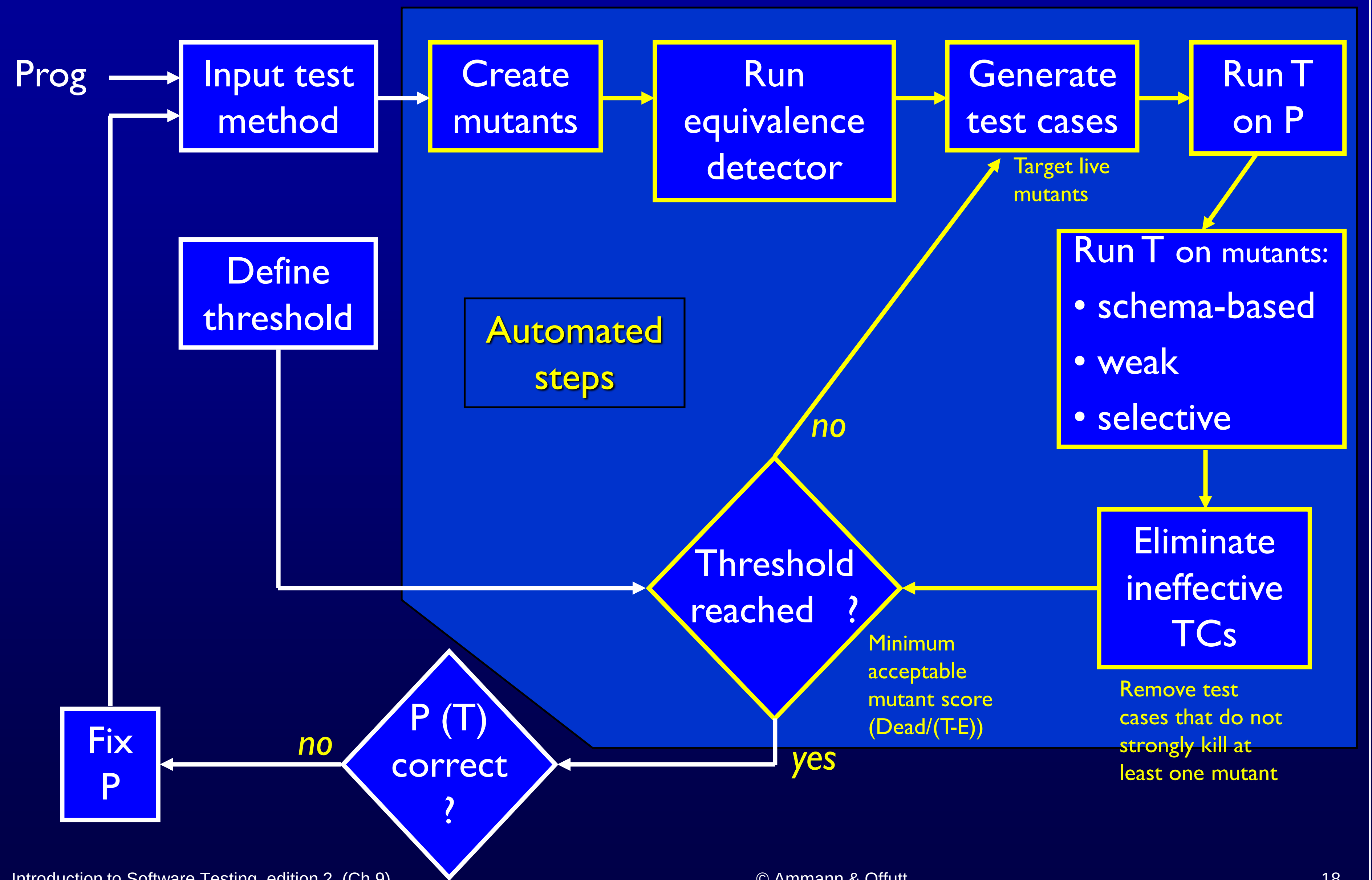
Thus ($X = -6$) does <u>*not*</u> kill the mutant under strong mutation

To satisfy the strong mutation criterion, we require $(X < 0) \wedge (X \mathrel{!=} 0) \wedge \mathit{odd}(X)$, which can be simplified to *X* is an odd, negative integer

Testing Programs with Mutation

- Choosing a test process for mutation is particularly difficult because
  - mutation analysis is actually a way to measure the quality of the test cases
  - the actual testing of the software is a side effect
- In practical terms, the software is tested, and tested well, or the test cases do not kill mutants

Testing Programs with Mutation



Why Mutation Works

Fundamental Premise of Mutation Testing

If the software contains a fault, there will usually be a set of mutants that can only be killed by a test case that also detects that fault

- This is not an absolute !
- The mutants guide the tester to an effective set of tests
- A very challenging problem :
  - Find a fault and a set of mutation-adequate tests that do not find the fault
- Of course, this depends on the mutation operators …

Designing Mutation Operators

- At the method level, mutation operators for different programming languages are similar
- Mutation operators do one of two things :
  - Mimic typical programmer mistakes (incorrect variable name)
  - Encourage testers to follow common test heuristics (cause expressions to be 0)
- Researchers design lots of operators, then experimentally *select* the most useful

Effective Mutation Operators

If tests that are created specifically to kill mutants created by a collection of mutation operators $O = \{o_1, o_2, \ldots\}$ also kill mutants created by all remaining mutation operators with very high probability, then O defines an *effective* set of mutation operators

Mutation Operators for Java

1. ABS — Absolute Value Insertion
2. AOR — Arithmetic Operator Replacement
3. ROR — Relational Operator Replacement
4. COR — Conditional Operator Replacement
5. SOR — Shift Operator Replacement
6. LOR — Logical Operator Replacement
7. ASR — Assignment Operator Replacement
8. UOI — Unary Operator Insertion
9. UOD — Unary Operator Deletion
10. SVR — Scalar Variable Replacement
11. BSR — Bomb Statement Replacement

Full definitions …

Mutation Operators for Java

1. ABS — *Absolute Value Insertion:*

Each arithmetic expression (and subexpression) is modified by the functions *abs()*, *negAbs()*, and *failOnZero()*.

Examples:

```
     a = m * (o + p);
Δ1   a = abs (m * (o + p));
Δ2   a = m * abs ((o + p));
Δ3   a = failOnZero (m * (o + p));
```

2. AOR — *Arithmetic Operator Replacement:*

Each occurrence of one of the arithmetic operators +, −, *, /, and % is replaced by each of the other operators. In addition, each is replaced by the special mutation operators *leftOp*, and *rightOp*.

Examples:

```
     a = m * (o + p);
Δ1   a = m + (o + p);
Δ2   a = m * (o * p);
Δ3   a = m leftOp (o + p); // leftOp returns result of left operand, i.e., m
```

Mutation Operators for Java (2)

3. ROR — Relational Operator Replacement:

Each occurrence of one of the relational operators (<, ≤, >, ≥, =, ≠) is replaced by each of the other operators and by *falseOp* and *trueOp*.

Examples:

```
    if (X <= Y)
Δ1  if (X > Y)
Δ2  if (X < Y)
Δ3  if (X falseOp Y)  // always returns false
```

4. COR — Conditional Operator Replacement:

Each occurrence of one of the logical operators (and - &&, or - || , and with no conditional evaluation - &, or with no conditional evaluation - |, not equivalent - ^) is replaced by each of the other operators; in addition, each is replaced by *falseOp*, *trueOp*, *leftOp*, and *rightOp*.

Examples:

```
    if (X <= Y && a > 0)
Δ1  if (X <= Y || a > 0)
Δ2  if (X <= Y leftOp a > 0) // returns result of left clause
```

Mutation Operators for Java (4)

5. SOR — Shift Operator Replacement:

Each occurrence of one of the shift operators <<, >>, and >>> is replaced by each of the other operators. In addition, each is replaced by the special mutation operator *leftOp*.

Examples:

```
     byte b = (byte) 16;
     b = b >> 2;
Δ1   b = b << 2;
Δ2   b = b leftOp 2; // result is b
```

6. LOR — Logical Operator Replacement:

Each occurrence of one of the logical operators (bitwise and - &, bitwise or - |, exclusive or - ^) is replaced by each of the other operators; in addition, each is replaced by leftOp and rightOp.

Examples:

```
     int a = 60;    int b = 13;
     int c = a & b;
Δ1   int c = a | b;
Δ2   int c = a rightOp b; // result is b
```

Mutation Operators for Java (5)

7. ASR — Assignment Operator Replacement:

Each occurrence of one of the assignment operators (+=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=, >>>=) is replaced by each of the other operators.

Examples:

```
    a = m * (o + p);
Δ1  a += m * (o + p);
Δ2  a *= m * (o + p);
```

8. UOI — Unary Operator Insertion:

Each unary operator (arithmetic +, arithmetic -, conditional !, logical ~) is inserted in front of each expression of the correct type.

Examples:

```
    a = m * (o + p);
Δ1  a = m * -(o + p);
Δ2  a = -(m * (o + p));
```

Mutation Operators for Java (6)

9. UOD — Unary Operator Deletion:

Each unary operator (arithmetic +, arithmetic -, conditional !, logical~) is deleted.

Examples:

```
     if !(X <= Y && !Z)
Δ1   if (X > Y && !Z)
Δ2   if !(X < Y && Z)
```

10. SVR — Scalar Variable Replacement:

Each variable reference is replaced by every other variable of the appropriate type that is declared in the current scope.

Examples:

```
      a = m * (o + p);
Δ 1   a = o * (o + p);
Δ 2   a = m * (m + p);
Δ 3   a = m * (o + o);
Δ 4   p = m * (o + p);
```

Mutation Operators for Java (7)

11. BSR — Bomb Statement Replacement:

Each statement is replaced by a special Bomb() function.

Example:

```
a = m * (o + p);
```

∆1 *Bomb*() // Raises exception when reached

Summary : Subsuming Other Criteria

- Mutation is widely considered the strongest test criterion
  - And most expensive !
  - By far the most test requirements (each mutant)
  - Usually the most tests
- Mutation subsumes other criteria by including specific mutation operators
- Subsumption can only be defined for weak mutation – other criteria only impose local requirements
  - Node coverage, Edge coverage, Clause coverage
  - General active clause coverage: Yes–Requirement on single tests
  - Correlated active clause coverage: No–Requirement on test *pairs*
  - All-defs data flow coverage