Grammar-based Testing

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Outcomes

At the end of Today's Lecture you will be able to:

- Understand the use of mutation testing in source code
- Understand several of the Java Mutation operators
- Understand mutation coverage criteria for source code

Inspiration

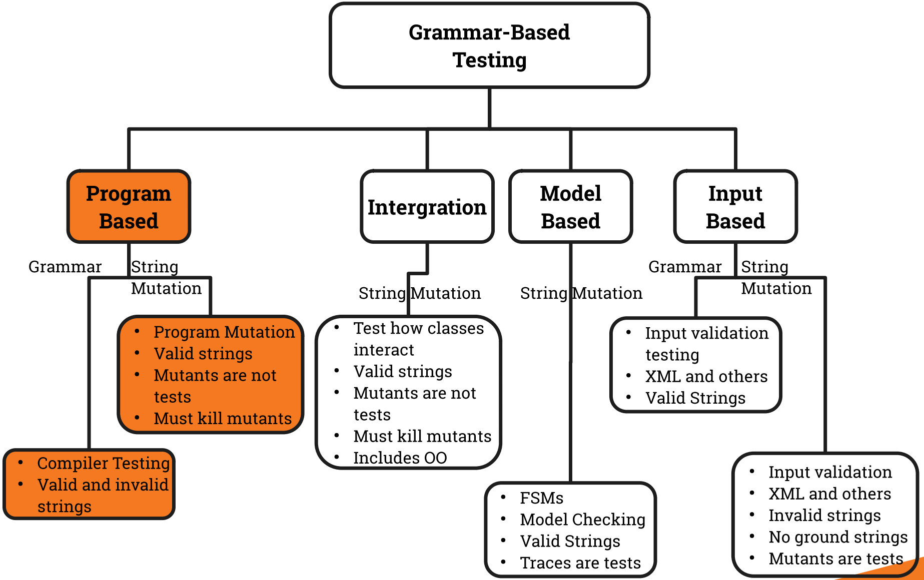
”A tester has the heart of a developer…

in a jar on the desk…” – Anonymous

Applying Syntax-Based Testing

- 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

- 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 all language features that compilers must process
- This is a very **specialized** application and not discussed in detail

Program-based Grammars

- 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 program**
- Mutant programs must compile correctly (**valid strings**)
- Mutants are **not tests**, but used to find tests
- Once mutants are defined, **tests** must be found to cause mutants to fail when executed
- This is called “**Killing Mutants**”

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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 form 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 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
  - **Trivial mutant**: almost every test can kill it
  - **Equivalent mutant**: No test can kill it (same behavior as original)

ROAR

Program-based Grammars

Original Method

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

With Embedded Mutants

```
int Min(int A, int B) {
     int minVal;
     minVal = A;
Δ1   minVal = B;
     if (B < A)
Δ2   if (B > A)
Δ3   if (B < minVal)
     {
         minVal = B;
Δ4       Bomb();
Δ5       minVal = A;
Δ6       minVal = failOnZero(B);
     }
     return(minVal);
} // end Min
```

Replace one variable with another

Replaces operator

Immediate runtime failure … if reached

Immediate runtime failure if B == 0, else does nothing

6 mutants

Each represents a separate program

Syntax-Based Coverage Criteria

Mutation Coverage (MC):

For each $m \in M$, TR contains exactly one requirement, to kill m.

- The RIPR model form 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 Criterai

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 iff 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 iff 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**

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:

```
    minVal = A;
Δ1  minVal = B;
    if (B < A)
        minVal = B;
```

- The complete test specification to kill mutant 1:
  - **Reachability**: `true // Always get to that statement`
  - **Infection**: $A \neq B$
  - **Propagation**: `(B < A) = false // skip the next assignment`
  - **Full Test Specification**: $true \land (A \neq B) \land ((B < A) = false)$
    $\equiv (A \neq B) \land (B \geq A)$
    $\equiv (B > A)$
  - Weakly kill mutant 1, but not strongly?

Equivalent Mutation Example

- Mutant 3 in the Min() example is equivalent:

```
    minVal = A;
    if (B < A)
Δ3  if(B < minVal)
```

- The infection condition is "**(B < A) != (B < minVal)**"
- However, the previous statement was "**minVal = A**"
  - Substituting, we get: "**(B < A) != (B < A)**"
  - This is a logical **contradiction**!
- **Thus no input can kill this mutant**

Strong Versus Weak Mutation

```
1     boolean isEven(int X)
2     {
3         if (X < 0)
4             X = 0 – X;
Δ4            X = 0;
5         if ((double) (X / 2) == ((double) X) / 2.0)
6             return true;
7         else
8             return false;
9     }
```

Reachability: X < 0

Infection: X != 0

(X = -6) will kill mutant 4 under weak mutation

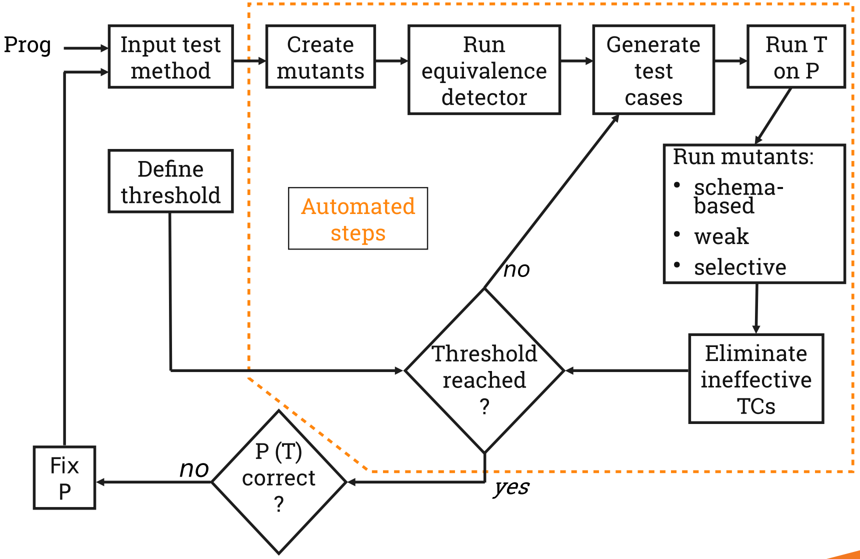
Propagation:

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

That is, X is not even …

Thus (X = -6) does not kill the mutant under strong mutation

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...

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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 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

Mutation Operators for Java

❶ 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));
```

❷ AOR – Arthmetic 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);
```

Mutation Operators for Java (2)

❸ ROR – Relational Operator Replacement:
Each occurrence of one of the relation operators ($<, \leq, >, \geq, =, \neq$) 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

❹ 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 (3)

❺ 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 if b
```

❻ 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 (4)

❼ 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);
```

❽ 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 (5)

❾ 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)
```

❿ 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);
Δ1  a = o * (o + p);
Δ2  a = m * (m + p);
Δ3  a = m * (o + o);
Δ4  p = m * (o + p);
```

Mutation Operators for Java (6)

⓫ BSR – Bomb Statement Replacement:
Each statement is replaced by a special Bomb() function

```
Examples:
    a = m * (o + p);
Δ1  Bomb() // Raises exception when reached
```

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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**

ROAR

Are there any questions?