CHALMERS UNIVERSITY OF TECHNOLOGY | UNIVERSITY OF GOTHENBURG

Lecture 12: Fault-Based Testing

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Space Shuttle Challenger

- January 28, 1986 - seal failure in a rocket booster causes the shuttle to explode, killing all seven astronauts.
- Three year investigation found technical and organizational issues.
- Became a case example studied in many forms of engineering.
  - **Learn from your failures.**

Fault-Based Testing

By studying faults in previous designs, we can predict and prevent similar faults in future product designs.

Many testing techniques based on what we *think should happen*. We can also test based on knowledge of *what has gone wrong before.*

Used in Language Design

- Automated Garbage Collection
  - Prevents dangling pointers, memory leaks, other memory management faults.
- Automatic Array Bounds Checking
  - Does not prevent bad indexes from being used, but ensures they are noticed and limits damage.
- Type Checking
  - Prevents malformed values from being used as input or in computations.

Fault-Based Testing

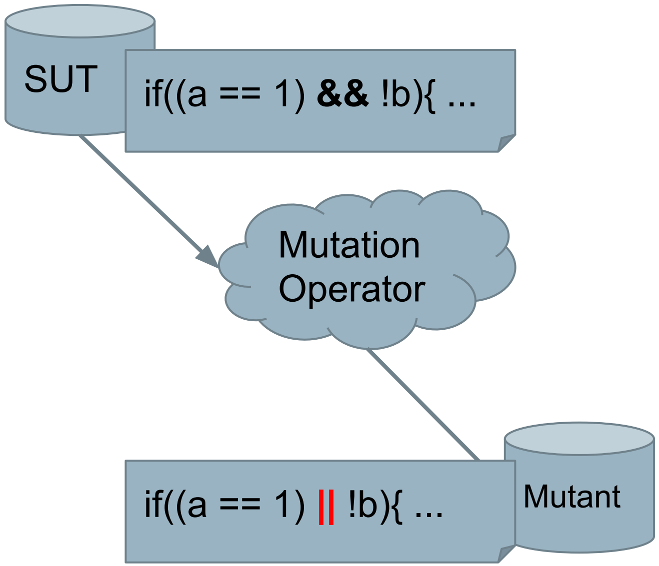
- Consider the types of faults we expect to see.
  - Create alternate *mutated* versions of the program.
  - Design tests that distinguish the real program from the mutated program.
- Process of *fault seeding* - deliberately creating programs with faults to see if our tests can find those *intentional* faults.

Uses of Fault Seeding

- *Fault seeding* can be used to:
  - Judge the adequacy of a test suite.
  - Select test cases to augment a suite.
- Provides evidence that we have done a good job.
  - If our tests have not found faults, are there no more major issues, or are they bad tests?
  - Fault seeding helps answer this question.
    - Can the existing tests find the seeded faults?

Mutation Testing

- Encode common syntactic faults as *mutation operators.*
  - Functions that take in candidate program statements and insert the modeled fault.
- Produces a *mutant.*
  - A clone of the program with 1+ seeded faults.



Mutation Operators

Mutation Operators

- Intended to model common types of faults.
- Designed to be applied to any type of code, without human intervention.
- Tend to be simple syntactic faults.
  - Replacing one variable reference with another.
  - Changing a comparison from < to <=.
  - Referencing a parent class instead of a child.

Operand Modifications

- X for Y replacement
  - Replace constant *C1* with constant *C2*.
    - `int X = 72;` -> `int X = 135;`
  - Replace constant *C* with variable *S*.
    - `int Y = 135; int X = 72;` -> int Y = 135; int X = **Y**;
  - Replace variable *S* for constant *C*.
    - `int X = Y;` -> `int X = 72;`
  - Replace variable *S1* with variable *S2*.
    - `int X = Y;` -> `int X = Z;`

Operand Modifications

- X for Y replacement
  - Replace variable/constant with array reference *A[I]*.
    - `int X = Y; -> int X = A[4];`
  - Replace array reference *A[I]* with variable/constant.
    - `int X = A[4]; -> int X = Y;`
  - Replace array reference with another array reference.
    - Either another array or another index in the same array.
    - `int X = A[4]; -> int X = A[10];`

Expression Modifications

- Arithmetic Operators
  - Binary operators: `x (+, -, *, /, %) y`
  - Unary operators: `+x, -x, &x, *x`
  - Shortcut operators: `x++, ++x, x--, --x`
- Arithmetic Operator Replacement
  - Replace binary/unary/shortcut operator with another.
    - `Z = X + Y;` -> `Z = X - Y;`
  - Replace shortcut/unary operator with a unary/shortcut.
    - `Z = --X;` -> `Z = -X;`

Expression Modifications

- Arithmetic Operator Insertion
  - Insert an additional operator into an expression.
  - `int Z = X;` -> `int Z = X + Y;`
  - `int Z = X;` -> `int Z = X++;`
- Arithmetic Operator Deletion
  - Remove an operator from an expression.
  - `int Z = X + Y;` -> `int Z = X;`
  - `int Z = X++;` -> `int Z = X;`

Expression Modifications

- Conditional Operators
  - Binary: `x (&&, ||, &, |, ^) y`
  - Unary: *`(~, !)x`*
- Relational Operators
  - `x (>, >=, <, <=, ==, !=) y`
- Shift Operators
  - `x (>>, <<, >>>>) y`
- Operator Replacement, Insertion, Deletion
  - Works like arithmetic operators.

Expression Modifications

- Shortcut Operators
  - `x (+=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=) y`
  - Shortcut Operator Replacement
- Absolute Value Insertion
  - Replace a subexpression with *abs(e)*.
    - `int Z = X + Y; -> int Z = abs(X + Y);`
- Constant for Predicate Replacement
  - Replace boolean predicate with a constant value *(T/F)*.
    - `bool Z = (A || B) && C; -> bool Z = (A || true) && C;`

Statement Modifications

- Statement Deletion
  - Remove a random statement from the program.
- Switch Case Replacement
  - Replace the label of one case with another.
- End Block Shift
  - Move closing brackets to an earlier or later location.

Encapsulation/Inheritance

- Access Modifier Change
  - Change a modifier to *(public/protected/private)*
  - **public** void DoThis(int x) -> **private** void DoThis(int x)
- Hiding Variable Modifications
  - Hiding variable - a variable in a subclass that has the same name and type as a variable in the parent.
  - Class Parent { .. int X; ..}
    Class Child implements Parent {.. int X; ..}

Encapsulation/Inheritance

- Hiding Variable Deletion
  - Deletion causes references to that variable to access the version in the parent instead.
  - `Class Child implements Parent {.. int X; .. int Y = X;}`
    `-> Class Child implements Parent { ..int Y = X;}`
- Hiding Variable Insertion
  - Insert a hiding variable into a subclass.
  - Now, two variables of the same name exist.
  - `Class Child implements Parent {.. int Y = X; ..} ->`
    `Class Child implements Parent {.. int X; .. int Y = X;}`

Inheritance Modifications

- Overriding Method Deletion
  - Delete an overriden method from a subclass.
  - References call the version inherited from a parent.
  - ```
    Class Child implements Parent { …
    @Override public int doThis(){ .. } …
     int X = doThis(); }
    ->
    Class Child implements Parent { …
    int X = doThis(); }
    ```
    ```

Inheritance Modifications

- Overridden Method Calling Position Change
  - Overridden methods can call the parent method.
  - Moves calls to the parent version to other positions.
  - ```
    @Override
    public int doThis(){
        int x = super(); int y = 5; ...  }   ->
    @Override
    public int doThis(){
        int y = 5; ... int x = super();  }
    ```
    ```

Inheritance Modifications

- Super Keyword Insertion/Deletion
  - Inserts or deletes the `super()` keyword.
  -
```
@Override
public void doSomething(){
    super(); … } ->
@Override
public void doSomething(){
    … }
```

Inheritance Modifications

- Overridden Method Renamed
  - Rename a method in the parent class that was overridden by the child.
  - Ensures that the overridden version is always called instead of the parent version.
  - `Class Parent { … `**`public void doThis();`**` } Class Child implements Parent { … `**`@Override`**` public void doThis(); }`
    `->`
    `Class Parent { … `**`public void doThat();`**` } Class Child implements Parent { … public void doThis(); }`

Inheritance Modifications

- Explicit Parent Constructor Call Deletion
  - Deletes *super()* call in a constructor.
  - To detect, tests must trigger an incorrect initial state.
  - Class Child implements Parent {

    int x;

    public Child () { **super();** ... } } ->

    Class Child implements Parent {

    int x;

    public Child () { ... } }

Polymorphism Modifications

- New Method Call with Child Class Type
  - Replace a declaration with a valid child instance.
    - `Parent a = new Parent();` -> `Parent a = new Child();`
- Variable Declaration With Parent Class Type
  - Change the declared type of a variable to its parent.
    - `Child a = new Child();` -> `Parent a = new Child();`
    - `boolean equals(Child c){..}` -> `boolean equals(Parent c){..}`

Polymorphism Modifications

- Type Cast Operator Insertion/Deletion
  - Cast the type of an object reference to the parent or child of the original type.
    - `p.toString() -> ((Child) p).toString()`
  - Or delete a type cast operator.
    - `((Child) p).toString()-> p.toString()`
- Cast Type Change
  - Changes a cast to another valid data type.
  - `((SomeChild) c).toString() -> ((OtherChild) c).toString()`

Polymorphism Modifications

- Reference Assignment with Other Compatible Type
  - Change an object reference to point to another compatible variable.
  -

```
Object obj;
String s = “hello”;
Integer i = new Integer(4);
obj=s;
```

->

```
Object obj;
String s = “hello”;
Integer i = new Integer(4);
obj=i;
```

Polymorphism Modifications

- Overloading allows 2+ methods to have the same name if they have different signatures.
- Overloading Method Contents Change
  - Replace the body of a method with the body of another method with the same name.
  - ```
    public void doThis (int x) { … int Z … }
    public void doThis (int x, int y) { … int W … }     ->
    public void doThis (int x) { … int W … }
    public void doThis (int x, int y) { … int Z … }
    ```
    ```

Polymorphism Modifications

- Overloading Method Deletion
  - Deletes one of the overloading methods.
  - ```
    public void doThis (int x) { … }
    public void doThis (int x, int y) { … }    ->
    public void doThis (int x) { … }
    ```
- Argument of Overloading Method Change
  - Changes order or number of arguments in an invocation, as long as there is a version that will accept the list.
  - ```
    public void doThis (int x, int y) { … }    ->
    public void doThis (int y, int x) { … }
    ```

Language-Specific Modifications

- Mutation operators can be written for a particular language.
- Java:
  - *this* insertion/deletion
  - Static modifier insertion/deletion
  - Member variable initialization deletion
  - Default constructor deletion
  - Getter/Setter method replacement

Let’s Take a Break

Mutation Testing

Mutation Testing

- **Select *mutation operators*** - code transformations representing interesting types of faults.
- **Generate *mutants*** by applying mutation operators to the program.
- Execute the same tests against the program and mutants to ***kill* mutants**.
  - A mutant is **killed** if the test passes on the original program and fails on the mutant.
  - A mutant not killed is considered ***live***.

Mutation Testing

- Mutation operators reflect small syntactic mistakes.
- Programmers do make such mistakes.
- However, many faults are actually **conceptual** mistakes.
  - Mistaken assumptions about requirements.
  - Forgotten requirements.
- Is mutation testing a reasonable technique?

Viability of Mutation Testing

- Mutation testing is valid if seeded faults are *representative* of real faults.
- *Competent Programmer Hypothesis*
  - A faulty program differs from a correct program only by a small textual change.
  - If so, we only have to distinguish the program from all such small variants.
  - Assumption: the SUT is “close to” correct.

Coupling Effect

- Many faults are small syntactical errors.
- Conceptual faults often manifest as syntax errors.
- Complex faults result in larger textual differences.
  - However, mutation testing is still valid if test cases for simple issues can detect complex issues.
  - *Coupling Effect Hypothesis* - complex faults can be modeled as a set of small faults.

Coupling Effect

- A complex change is a series of small changes.
- If one small change is not covered up, a test case that can expose that small change can also detect a more complex change.
- Mutation testing is effective if **both** the competent programmer hypothesis and coupling effect hypothesis hold.

Sensitivity Analysis

- Mutants are often simpler than real faults.
  - Must be fairly simple to be inserted by automated tooling.
- Mutation best used to judge **sensitivity** of your tests to minor changes in the code.
  - If tests can distinguish all mutants from the real code, then your tests execute the code *thoroughly*.
  - If you miss mutants, you can add new tests to detect them and make your suite more sensitive.

Mutant Quality

To be used in testing, mutants must be:

- Syntactically correct (*valid*)
  - Mutants must compile and execute.
- Plausible (*useful*)
  - Must provide valuable information on how the system works for testers working to improve the system.

Can a mutant be valid, but not useful?

Mutant Quality

Mutants might remain live if:

- They are *equivalent* to the original program.
  - `for(i=0; i < 10; i++) ->`
  - `for(i=0; i != 10; i++)`
  - Identifying equivalency is NP-hard.
- Test suite is *inadequate* for that mutation.
  - `(a <= b)` and `(a >= b)` cannot be differentiated if `a==b` in the test case.

Mutation Coverage

Adequacy of the suite can be measured as:

$$\frac{\text{(\# mutants killed)}}{\text{(total mutants)}}$$

- Helps ensure that the test suite is *robust* against the modeled mutation types.
- Ensures that the test suite is sensitive to small changes in the code.

Mutation and Structural Coverage

Mutation coverage can subsume structural coverage.

- Statement Coverage
  - Apply statement deletion to all statements.
  - To kill a mutant where statement *S* has been deleted requires executing *S* in the original program.
- Branch Coverage
  - Apply constant replacement to all predicates.
  - To kill a mutant where a predicate is set to true, a test must execute the original with a false value.

Practical Considerations

Mutation testing is **expensive**.

- Must run *all* tests against *all* mutants.
- Many mutants typically generated.
  - One mutation operator applied per mutant.

- If cost is an issue, use "weak" mutation testing:
  - Apply multiple mutation operators per mutant.

Weak Mutation Testing

- Seed multiple faults into a single mutant.
  - Called a “meta-mutant”
- Divide the program into segments and track internal state of both original and all mutants when executing a segment.
  - If internal state differs, we consider mutants detected from that segment.
  - Program output does not need to differ.
- Decreases the number of test executions.
  - Also reduces threshold for what we consider detected.

Statistical Mutation Testing

- A test suite that kills *some* mutants may be as effective at finding real faults as one that kills *all* mutants.
- Mutation testing can obtain a statistical estimate of the ability of the suite to detect mutations.
    - Randomly generate *N* mutants.
    - Samples must be a valid statistical model of occurrence frequencies of real faults.
    - Target 100% coverage over the sample.

Activity

1. How many mutations are possible for Relational Operator Replacement, Arithmetic Operator Replacement
2. Apply relational operator replacement operation to statement 4, design a test that would kill that mutant.
3. Design an equivalent mutant.
4. Design a valid, but useless mutant.

```
public int[] makePositive(int[] a){
    int threshold = 0;
    for(int i=0; i < a.length; i++){
        if(a[i] < threshold){
            a[i]= -a[i];
        }
    }
    return a;
}
```

Activity - Solution

- How many mutations are possible:
  - Relational Operator Replacement:
    - `for(int i=0; i < a.length; i++){`
      - (>=, >, <=, ==, !=), 5 mutations
    - `if(a[i] < threshold){`
      - (>, >=, <=, ==, !=), 5 mutations

Activity - Solution

- How many mutations are possible:
  - Arithmetic Operator Replacement
    - `for(int i=0; i < a.length; i++){`
      - Shortcut replacement, (++*i*, *i*--, --*i*), 3 mutations
    - `a[i]= -a[i];`
      - Unary replacement, (+a[i]), 1 mutation
      - Unary to shortcut replacement, *(a[i]*++, ++*a[i]*, *a[i]*--, --*a[i]*), 4 mutations

Activity - Solution

- Apply the relational operator replacement operation to statement 4:
  - `if(a[i] < threshold){    ->`
  - `if(a[i] == threshold){`
- Design a test case that would kill that mutant.
  - a[-1,0,1]
  - -1 would not become positive.

Activity - Solution

- **Design an equivalent mutant.**
  - Can do so by applying the relational operator replacement operation to statement 4:
    - `if(a[i] < threshold){` becomes:
    - `if(a[i] <= threshold){`
  - Since threshold=0, and -0 = 0, no test would detect.
  - Does not help us test, as the fault cannot cause a failure.

Activity - Solution

- **Design a valid, but useless mutant.**
  - For example: mutant that compiles, but trivially fails.
  - Apply the relational operator replacement operation to statement 4:
    - `if(a[i] < threshold){` becomes:
    - `if(a[i] > threshold){`
    - Any positive numbers are made negative, all negative remain negative. Almost any test would detect this.
  - **Many** mutants are useless for detecting real faults.

We Have Learned

- Mutation testing is the process of inserting faults to help develop a test suite that can detect unknown real faults.
- Mutation operators automatically create faulty versions of a program.
  - Operators model expected fault types.
- Tests are judged according to their ability to detect faults - useful sensitivity analysis.

Next Time

- Exercise Session: More Mutation Testing
  - Bring a laptop with MeetingPlanner code.
- Next class: Model-Based Testing
  - Optional Reading - Pezze and Young, Chapters 5.5 and 14
- Assignment 2 due Sunday, March 1.
  - And Assignment 3 is up.

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